AN INVESTIGATION OF SQUISH GENERATED TURBULENCE IN. I.C. ENGINES

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ABSTRACT

Experiments were performed with a single cylinder C.F.R. engine to provide data for the evaluation of the squish designs. Several reference squish chambers were manufactured for the C.F.R. engine. Flow field data was obtained via hot wire anemometer measurements taken in the cylinder during motored operation of the engine. Pressure data recorded while the engine was operated on natural gas yielded mass burn rate information.

Mass burn rate analysis of cylinder pressure data shows the squish design to have greatest impact on the main combustion period (2% to 85% mass burned). A comparison of the reference squish design in these experiments to the disc chamber shows a 32% reduction in the combustion duration and a 30% increase in peak pressure occuring 5 crank angle degrees earlier. The squish-jet design provided the additional effect of a reduction in the ignition delay time (spark to 2% mass burned). The squish-jet design resulted in a reduction of the ignition delay time by 3 crank angle degrees and in a 4% increase in peak pressure occuring 3 crank angle degrees earlier compared to the reference squish chamber. The total combustion duration was 5% less with the squish-jet design.

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NOMENCLATURE

A	area, m^2
a,b	calibration constants for hot wire correlation
C_p	constant pressure specific heat, J/kg K
D	engine bore, m
d	wire diameter, m
H	depth of bowl in squish piston, m
h	heat transfer coefficient, W/m^2 K
h_c	clearance height, m
I	electric current, amps
k	thermal conductivity, W/m K
L_t	integral time scale, s
l	wire length, m
N	number of engine cycles
Nu	Nusselt number
P	pressure, Pa
R	resistance, ohms
R_{op}	resistance of wire at operating condition, ohms
R_τ	autocorrelation coefficient
S	distance of piston from TDC, m
T	temperature, K
U	velocity, m/s
$U(i,\theta)$	instantaneous velocity at crank angel θ in cycle i, m/s
$\bar{U}$	mean velocity with respect to time, m/s
$\bar{U}(\theta)$	true ensemble averaged mean velocity, m/s

$\bar{U}_\theta(i)$ average (time) velocity in window θ for record i, m/s

$\bar{U}_\theta$ U(i) ensemble averaged over N cycles, m/s

U_{rms} cyclic variation in mean velocity, m/s

$u'(\theta)$ true ensemble averaged turbulence intensity, m/s

$u'_\theta(i)$ time averaged turbulence intensity in cycle i, m/s

u'_θ u(i) ensemble averaged over N cycles

V volume, m^3

α temperature coefficient of resistance, ohms/°C

β orientation angle

γ specific heat ratio

λ_t micro time scale, s

θ crank angle

τ correlation time, s

μ viscosity, $N \cdot s/m^2$

subscripts

0   reference condition

B   squish piston bowl

g   gas

P   piston

Ref   reference condition

SA   squish piston A

SB   squish piston B

SC   squish piston B channel

t   time, s

w   wire

x   length, m

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1. INTRODUCTION

1.1 General Discussion

The combustion rate in an internal combustion (I.C.) engine plays a key role in engine performance. Fast burning in engines produces a greater resistance to knock which allows operation at higher compression ratios and thus leads to increased engine efficiency. Fast burning also permits the use of leaner air-fuel mixtures [1]. Furthermore, fast combustion rates have been shown to reduce NO_x emissions and the cyclic variation of engine performance [1,2]. Combustion rate is thought to depend primarily upon flame front area, turbulence and the chemical kinetics of the mixture. To increase the combustion rate in engines engineers must address two questions; how to increase the flame front area, and how to increase the propagation rate of the flame front into the unburned region. Combustion chamber geometry and turbulence enhancement during the combustion period are the major design variables investigators have focussed on to answer these questions.

The effects of chamber geometry and the flow field are directly linked since chamber configuration does affect turbulence generation. Modern combustion chambers are designed with a large volume to surface area ratio (compact chambers) minimizing contact between the flame and the cylinder walls. With central ignition in these chambers designers achieve a large flame front area and a reduction in heat transfer (due to minimal contact between flame and walls). Both are factors which contribute to an increase in burn rate.

The turbulent flow field in an engine is the more dominant factor in determining the combustion rate. The mechanism responsible for increased

burn rate is still a subject of debate among researchers. The two most widely accepted theories of turbulent combustion in engines are the wrinkled flame front and turbulent entrainment theories.

The wrinkled flame front model, first proposed by Damkohler [3], states that the turbulence distorts (wrinkles) the flame front thereby increasing the area available for molecular transport. Entrainment models have been developed by Tabaczynski [4] and Blizzard and Keck [5]. These models propose that a turbulent entrainment process is responsible for increased flame propagation. It is assumed that laminar burning takes place in cells of size characterized by the Taylor micro-scale and rapid burning takes place along vortex tubes of size characterized by the Kolmogorov scale. The entrainment velocity is assumed to be proportional to the turbulence intensity.

Irrespective of these theories, the link between increased flame speed and turbulence has been firmly established through experiment. The work of Andrews et al. [6] demonstrates that turbulence can be used to increase flame speeds.

1.2 The Turbulent Flow Field in an Engine

The flow field in an engine is primarily governed by the valve events and the piston motion. The shear flow past the intake valve is a major source of turbulence generation prior to the combustion period. After the intake valve closes this turbulence decays rapidly during the compression stroke. In conventional disc chambers very little additional turbulence is generated during the compression stroke as a result of the piston movement. This is the critical period for the combustion process.

Designers have taken two approaches towards the enhancement of

turbulence during compression. Modifications to the inlet port which produce high swirl in the intake jet have proven to increase turbulence levels prior to the combustion period. Also the combustion chamber can be designed so that turbulence is generated on the compression stroke as a result of the piston motion. This type of design is called a squish chamber.

A bowl in piston type of squish chamber design is shown schematically in Figure 1.1. As the piston approaches TDC on the compression stroke a pressure differential between the outside annualar area (squish area) and the inner area drives a radial jet inward. Thus an additional source of turbulence is generated by the strong shear flow in the jet motion during the latter phase of compression.

The flow field quantities of interest in an engine are the mean velocity, turbulence intensity, and the macro and micro scales of turbulence. The mean velocity characterizes the gas motion due to the valve events and the piston travel. The mean velocity is defined to be the time average over a specific interval of the instantaneous velocity. The mean velocity $\bar{U}$, is:

$$\bar{U} = \frac{1}{T} \int_0^T U \, dt \tag{1.1}$$

where U is the instantaneous velocity and T is the time interval. In an engine where the mean velocity is periodic this type of definition can cause problems since the calculated mean will be dependent upon the time interval chosen. This problem is discussed in detail in the data analysis chapter.

The turbulence intensity, u', is the root mean square of the velocity

fluctuations about the mean. If the instantaneous velocity is written as:

$$U = \bar{U} + u \qquad (1.2)$$

where u represents the fluctuation from the mean, then the turbulence intensity u', may be expressed as:

$$u' = \left\{ \frac{1}{T} \int_0^T [U - \bar{U}]^2 \, dt \right\}^{1/2} \qquad (1.3)$$

The scales of length and time describe the structure of the flow field. Length scale measurements are very difficult to obtain since they require measurements at two points simultaneously and correlation of vast amounts of data. Because of this, in engine research time scales are used to characterize the eddy size distribution. The integral scale L_t, is evaluated from the integral of the autocorrelation coefficient of the fluctuating velocity at a single point. The autocorrelation coefficient R_τ, is expressed by:

$$R_\tau = \frac{1}{T} \int_0^T \frac{u(\tau)u(t+\tau)}{\bar{u}^2} \, d\tau \qquad (1.4)$$

where τ is the correlation time. The integral time scale is then given as:

$$L_t = \int_0^T R_\tau \, d\tau \qquad (1.5)$$

The integral scale characterizes the larger eddies of the flow field and

can be thought of as the mixing time scale.

The Taylor micro scale is also obtained from the autocorrelation coefficient. For small values of the correlation time τ the Taylor series expansion of the autorcorrelation function describes a parabola. The microscale is defined to be the point at which this parabola intersects the time correlation (τ) axis: intersects the time correlation axis (τ axis):

$$\lambda_t^2 = -2 \, (\partial^2 R_\tau / \partial \tau^2)|_{\tau=0} \qquad (1.6)$$

The micro scale describes the small scale structure of the flow. In the model proposed by Tennekes [7] in which a turbulence structure can be thought of as consisting of tangled vortex tubes (much like spaghetti) the micro scale can be viewed as the typical time between vortex tubes as they are convected past a stationary observer.

The turbulence intensity is thought to be primarily responsible for the increased flame speed observed for turbulent conditions. This view is supported by the results of Andrews et al. [6] in which a strong correlation between the intensity and turbulent burning velocity is demonstrated. The role of turbulence scale is thought to be important only in the initial stages of combustion. There is little evidence that scale affects the flame speed in a fully developed turbulent flame, although there is some indication that the micro scales are important to the ignition delay process. The ignition delay time is arbitrarily defined here to be the time required to burn two percent of the charge mass. Variation in the ignition delay time is usually considered to be responsible for the cyclic variation observed in cylinder pressure [5].

1.3 Objectives and Scope of Work

The objective of this thesis was to investigate the effects of the squish chamber design on the flow field and combustion process in an I.C. engine. The specific focus of the investigation was the comparison of a reference squish chamber design to a new squish-jet chamber design proposed by Evans [8]. The squish-jet is intended to be an improvement over the conventional design by providing enhanced turbulence production and mixing in the combustion region. It was the purpose of this study to provide experimental data for an initial evaluation of the basic squish-jet design.

A comparison of mass burn rate, combustion duration and pressure history was made for the two chamber designs; as well as flow field charateristics mean velocity and turbulence intensity.

A series of experiments were designed to meet the objectives of the investigation. Several variations of the two squish designs were manufactured for a single cylinder C.F.R. engine. For each design flow field data were obtained with a hot wire anemometer for motored conditions, and pressure data was recorded while the engine was operated on natural gas. The experiments were also conducted for the standard C.F.R. disc chamber design as a basis of comparison.

The data were processed to yield mass burn rate, combustion duration and the turbulence parameters of interest. The designs were then analyzed on a comparative basis.

2. LITERATURE REVIEW

2.1 Introduction

This chapter reviews the literature in two areas relevant to the investigation. The first section reviews fundamental turbulence measurements in engines. The second section is concerned with combustion experiments made in engines of different types of geometry, and the correlation of combustion data with turbulence data.

2.2 Turbulence Measurements in Engines

Semenov [9] was one of the pioneers in engine turbulence studies. He investigated the intake and compression process in a C.F.R. engine with a shrouded intake valve and disc combustion chamber. By traversing a hot wire probe across the bore of the chamber he obtained spatial velocity gradients as well as the mean velocity and turbulence intensity. Evidence of large velocity gradients during the intake process confirmed the jet nature of the incoming flow. In comparison velocity gradients near TDC on the compression stroke were insignificant. He also found very little spatial variation of the turbulence intensity near TDC.

Semenov observed a strong correlation between the turbulence intensity during compression and the velocity gradient during intake. From this he concluded the shear flow through the intake valve was the primary source for turbulence during the compression stroke. Increased engine speed resulted in increased mean velocity and turbulence intensity; however, compression ratio increases yielded relatively small decreases in the two quantities.

Dent and Salama [10] were among the first investigators to measure turbulent time scales in engines. A fast Fourier Transform analyzer was used to obtain the correlation coefficient and spectral density function. The macro and micro time scales were computed from the correlation coefficient.

The measurements were performed in two engines of different geometry; a disc chamber design, and a wedge (squish) design. In the disc chamber they found a general decrease in the mean velocity and turbulence intensity during the compression stroke. In the squish chamber however, they found an increase in the mean velocity during compression, although a corresponding increase in the turbulence intensity was not observed.

The micro time scale was found to be virtually independent of geometry and the mean velocity during compression. Calculated values of the micro length scale ranged from 0.2 to 0.6 mm. The macro length scales were three to four times larger than this.

Lancaster [11] studied the effects of engine speed, volumetric efficiency, and compression ratio on the flow field of an engine. The tests were performed in a C.F.R. engine with a disc chamber and two intake configurations; shrouded valve (swirl), and a standard valve. A hot wire anemometer probe was used to obtain measurements of mean velocity, turbulence intensity, and turbulence time scales.

Regardless of intake configuration, Lancaster found increased engine speed resulted in increased mean velocity and turbulence intensity. Throttling or decreased volumetric efficiency yielded similar trends. However, the values near TDC attained with the standard valve were approximately half of those achieved with the shrouded valve. This was attributed to the high swirl velocity generated by the shrouded valve. The micro

time scale decreased with increased engine speed but was otherwise inde-
pendent of operating conditions. The micro-time scale ranged from 0.05 to
0.25 milliseconds. Compression ratio had a relatively insignificant effect
on mean velocity and turbulence intensity. The spectral distribution of
the turbulent energy near TDC was also studied for the shrouded valve
configuration. Most of the energy was contained in frequencies below 1
kHz.

Lancaster used single point measurements with a triaxial probe. Close
agreement between the intensities measured by the three sensors near TDC
led him to conclude that the turbulence was isotropic.

Witze [12] did a similar set of measurements in an engine with a
squish combustion chamber. His major conclusions were that the mean velo-
city and turbulence intensity are proportional to engine speed, and that
the time scale is inversely proportional to the engine speed. He also
measured the spatial variation of the turbulence intensity near TDC and
concluded the structure was not homogeneous.

Witze's results for the mean velocity and turbulence intensity show an
increase of both quantities during the compression stroke. The increase
can be attributed to the bulk gas motion caused by the squish chamber.
However, Witze argued that this is not the production of new turbulence;
but simply a magnification of the intake turbulence due to compression.

James and Lucas [13] studied flow conditions within several frequency
ranges. They used both a squish chamber and a disc chamber in their
investigation. They found most of the turbulence energy was in the
frequency range below 700 Hz. They reported that the major effect of the
squish chamber was the enhancement of the magnitude of the fluctuating
velocities in the frequency range below 1600 Hz. Higher frequency

fluctuations appeared to be unaffected by combustion chamber geometry. They also found that the effectiveness of the squish chamber was a strong inverse function of the squish or clearance height.

Haghgooie et al. [14] took a somewhat different approach than other investigators by using uncalibrated hot wire signals to determine micro time scales in an engine. Their work was based on the assumption that there is a definable small scale structure of the turbulence in an engine similar to that postulated by Tennekes [7]. They analyzed the anemometer data to obtain the statistical distribution of the peak to peak time separation. They then interpreted the most probable time of this distribution as the characteristic time of the small scale structure. This time scale was in the range of 0.1 to 0.25 milliseconds. They reported a shift to higher frequencies as engine speed increased.

In summary then, fundamental turbulence measurements in engines established the following:

i)   shear flow past the intake valve is a major source of turbulence,

ii)   turbulence intensity and mean velocity are proportional to engine speed,

iii) turbulence length and time scales are inversely proportional to engine speed,

iv)   turbulence micro time scales are on the order of tenths of milliseconds,

v)   turbulence micro length scales are on the order of tenths of millimeters,

vi)   turbulence is isotropic near TDC compression however it is not homogeneous, and

vii) turbulence energy is concentrated in the low frequencies, below 1000 Hz.

2.3 Combustion Experiments in Engines

Studies in which turbulence and combustion data are correlated for engines of different geometry are rare. Lancaster et al. [15] correlated turbulence and combustion data for a disc chamber with and without "swirl". A modified Kreiger-Borman [16] heat release model was used to obtain the turbulent flame speed from cylinder pressure history. To separate thermal effects from those of turbulence the turbulent flame speed was normalized by the laminar flame speed. Operating conditions were identical to those for which turbulence measurements were obtained [11]. Turbulence intensity was varied by using shrouded and standard intake valves, as well as by changing engine speed.

Lancaster et al. concluded that the normalized flame speed was a linear function of turbulence intensity. The effect of turbulence scale on flame speed was found to be insignificant. However these tests were conducted for a limited range of turbulent micro scale, 1 to 2 mm.

Nagayama et al. [17] examined the effect of swirl and squish geometries on combustion duration. No flow measurements were taken in these experiments. They had four chamber configurations; disc, swirl, squish, and squish plus swirl. They found that squish and swirl both reduced combustion duration and that furthermore, they had distinctly separate effects on the combustion interval. Swirl was effective in the initial stage of combustion; whereas, squish was most effective during the main stage of combustion. The two effects were additive and thus the combination squish plus swirl chamber yielded the best results.

More recently investigators have used engine simulation models to predict the effect of chamber geometry on combustion duration [18-21]. In general these models predict that squish type chambers give better

performance than disc chambers. In addition, the importance of central

spark plug location is established by these models.

Although there is an abundance of engine performance data for a

variety of chamber designs available in the literature [2,15,18,19,21-25],

very few attempts have been made to isolate the effects which result in one

design's superiority over another. Thus progress towards defining the

criteria for optimal chamber design has been slow.

3. THE SQUISH COMBUSTION CHAMBER

3.1 Introduction

An illustration of the conventional bowl in piston squish design is shown in Figure 1.1. Although the chamber shown is in the piston it is also possible to achieve the same effect with a flat piston and a recessed chamber in the head.

The squish design is intended to provide an additional source of turbulence on the compression stroke. In Figure 3.1 a schematic of the squish process is shown. As the piston approaches TDC (compression) the relative compression in volume V_1 in the figure is higher than that in volume V_2. Thus, there is a 'squish' velocity, U_{SA}, as air moves from V across the boundary A_3 into V_2.

In this investigation a variation of the squish design, the squish-jet design proposed by Evans [8] will be studied as well. A schematic of this design is illustrated in Figure 3.2. The concept here is similar to that discussed above except that the channels (see Figure 3.2) provide an additional route for the squished air. The desired results are an increase in the relative turbulence intensity and enhanced mixture turbulence at the center of the chamber where the jets collide. Several embodiments of this design have been described by Evans [8].

In Figure 3.1 the conventional squish design is labelled Piston A and the squish-jet design in Figure 3.2 is labelled Piston B. This convention will be used throughout the thesis.

3.2 Squish Velocity Calculations

In this section a very simplified model will be used to predict the squish velocity during the final stage of the compression stroke for each of the two designs.

To predict the squish velocity for the conventional design the basic assumption is that the density is uniform throughout the chamber. The squish velocity is calculated for the piston movement over one crank angle degree. From mass conservation the following equation can be written,

$$\frac{U_P A_2}{V_2} + \frac{U_{SA} A_3}{V_2} = \frac{U_P A_1}{V_1} - \frac{U_{SA} A_3}{V_1} \qquad (3.1)$$

The quantities U_P, U_{SA}, A_1, A_2, A_3, V_1, and V_2 are defined in Figure 3.1. Equation (3.1) can then be solved for the squish velocity U_{SA},

$$U_{SA} = \frac{U_P}{A_3} \left\{ (A_1 V_2 - A_2 V_1)/(V_1 + V_2) \right\} \qquad (3.2)$$

From Equation (3.2) it can be seen that squish velocity is proportional to the piston speed (or engine speed) and that it is inversely proportional to area A_3. The area A_3 is a function of the bowl diameter D_B, the clearance height h_c, and the distance of the piston from TDC, S.

The prediction of the squish velocity for the squish-jet design is similar to that above except that now there is an additional route for the gas. The design is Piston B in Figure 3.2. Equation (3.1) is rewritten as:

$$\frac{U_P A_2}{V_2} + \frac{U_{SB} A_3}{V_2} + \frac{U_{SC} A_4}{V_2} = \frac{U_P A_1}{V_1} - \frac{U_{SB} A_3}{V_1} - \frac{U_{SC} A_4}{V_1} \qquad (3.3)$$

In this equation U_{SB} is the squish velocity normal to the area A_3 and U_{SC} is the squish velocity (hereafter called squish-jet velocity) normal to A_4. The other terms in the equation are defined in Figure 3.2. An additional equation is required to solve for the new velocity term U_{SC}. This

is obtained by treating the problem with a parallel pipe flow method. The assumption is that the pressure drop of the flow across the boundary A_3 is equal to that of the flow through the channels and across the boundary A_4. The pressure drop will be a function of the hydraulic radius and the velocity head. Simultaneous solution of the equations for conservation of mass and head loss yields expressions for the squish velocity U_{SB}, and the squish-jet velocity U_{SC}. The squish velocity U_{SB} is:

$$U_{SB} = \frac{U_p\{A_2 - (A_1 + A_2)[A_2(h_c + S)]/(V_1 + V_2)\}}{A_3 + [2D_B(S + h_c)/(D_H(D_B + S + h_c)]^{1/2}} \qquad (3.4)$$

and the squish-jet velocity U_{SC} is:

$$U_{SC} = \frac{U_{SB}}{\{2D_B(S + h_c)/D_H(D_B + S + h_c)\}^{1/2}} \qquad (3.5)$$

It can be seen from both Equations (3.2) and (3.4) that the squish velocity across the piston face (U_{SA} and U_{SB}) will be a strong function of the clearance height. In Figure 3.3, the squish velocity calculated from Equation (3.2) is shown for two clearance heights, 3.5 and 1.5 mm. The geometric parameters for the C.F.R. engine were used in the calculations. From the graph it can be seen that the squish velocity reaches a maximum at approximately 10° BTDC and decays rapidly to zero at TDC. It is clear from this figure that clearance height is very important. The peak mean velocity calculated for a clearance height of 1.5 mm is almost twice that for a clearance height of 3.5 mm. In Figure 3.4 the effect of adding the squish-jet channels is shown. The squish velocity across the face of the

piston is reduced by about 30%. The squish-jet velocity is consistently lower than U_{SB} except near the peak which occurs at approximately 10° BTDC.

3.3 The Squish Chamber Experiments

The method of predicting squish velocities outlined above was very simplified and not intended to yield quantitative results. Rather it was employed as an aid in designing the experiments.

As a result of the calculations it was decided to vary the clearance height and observe the effect. Three heights were selected 1.5, 2.5, and 3.5 mm. Both chamber designs were tested at these heights. The clearance height of 1.5 mm was the minimum that could be attained due to the clearance between the valves and the piston.

The piston wall thickness and the placement of the channels for Piston B were the constraints governing the selection of bowl diameter. A bowl diameter of 1.5 inches resulted in a 78% squish area expressed here as a percent and is defined to be the ratio of the area A_1 (see Figure 3.1) to the total area ($A_1 + A_2$).

Because it was desirable to compare both flow and combustion data from case to case the compression ratio was kept constant. The bowl depth was varied to accommodate the various clearance heights.

Hot wire anemometer measurements were made at the edge of the bowl and at the center of the chamber for each configuration. In addition, for Piston B a measurement was made with the probe inside the bowl opposite a channel at TDC.

In summary, the experiments were designed to observe the effects of clearance height, and squish-jet channels on the flow field and combustion process. Tests were also conducted with a disc chamber operating at the same compression ratio as a standard for comparison.

4.   APPARATUS AND INSTRUMENTATION

4.1 Introduction

This investigation required test results operating with several combustion chamber designs. To facilitate changes of configuration for each test, a C.F.R. engine with a flat head was used in conjunction with a squish piston design. Thus a change in combustion geometry required only a change of pistons. The engine was then instrumented to obtain pressure and flow field information. The instrumentation and engine are described in detail in the following sections.

4.2 Engine and Test Bed

A schematic of the experimental apparatus is shown in Figure 4.1 The engine used for the tests was a single cylinder C.F.R. coupled to a synchronous reluctance type motor by twin v-belts. Specifications for the engine are presented in Table I. The C.F.R. cylinder and head is cast in one piece which has an adjustable height above the TDC postion of the piston to allow for variable compression ratio.

For these experiments the following changes were necessary to the basic C.F.R. configuration:

i)   the pulley set was replaced to obtain a higher operating speed than the standard 900 RPM. The speed achieved was 1140 RPM,

ii) the shrouded intake valve was replaced by a standard intake valve to reduce the effects of inlet swirl,

iii) the gasoline carburetor was removed and replaced with a venturi element so that the engine could be operated with natural gas, and

iv) the C.F.R. ignition system was replaced with a capacitive discharge

ignition circuit.

The synchronous motor was used to start the engine, to maintain

constant speed, and to absorb the power developed by the engine when fired.

The engine and motor are shown in Figure 4.2.

4.3 Squish Piston Inserts

Seven pistons were required for the tests. Rather than manufacture a

piston for each test, the original C.F.R. piston was bored through the

crown and the inside wall threaded. Threaded inserts were then

manufactured for each experiment.

The piston material was cast iron so steel was used in the production

of the inserts. Three basic designs were manufactured; the basic squish

design (Piston A), the squish-jet design (Piston B), and the flat disc

chamber design. The design drawings of these piston inserts are in Figure

4.3 and a photograph is in Figure 4.4. In Figure 4.3 case 1 corresponds to

a clearance height of 1.5 mm; case 2 corresponds to a clearance height 3.5

mm.

The two squish designs were altered to accommodate the three clearance

heights used. The bowl diameter was held constant at 1.5 inches. Because

the bottom of the insert had to clear the top of the oil ring the maximum

depth of the bowl that could be achieved was 1.4 inches. This maximum

depth was used for the test of minimum clearance height (1.5 mm). The bowl

depth was decreased for the other tests so that a constant compression

ratio was maintained throughout the experiments. The center line of the

access port for the hot wire anemometer probe was 9 mm below the head.

Because of this and the small clearance heights used a slot was milled in

the inserts to accommodate the probe.

4.4 Air Supply

The intake air for the engine was drawn into a 2.5 inch pipe through an orifice plate and into a surge tank. The air was then filtered as it left the surge tank and passed into the venturi. The intake air was not throttled at anytime.

4.5 Gas Supply

The natural gas used as fuel was supplied from the building mains at a pressure of 5 psig to a pressure regulator where the pressure was reduced to 3 inches of water above atmospheric pressure. From the regulator the gas flowed first through a laminar flow element then through a control valve which was used to adjust the air/fuel ratio. From the control valve the gas flowed through 1/2 inch tubing to the venturi.

4.6 Instrumentation

A schematic of the instrumentation layout is shown in Figure 4.1.

Pressure measurements were made for combustion and motored operation. The location of the transducer for each of the operational modes is shown in Figure 4.5. The pressure transducer installed in the cylinder was a Kistler 609C piezo electric transducer mounted in a steel sleeve. The transducer was recessed 2 mm to eliminate thermal shock effects as recommended by Benson [26]. The transducer signal was transmitted via low noise cable to a Kistler 5004 charge amplifier. The amplified signal was sent to an analogue to digital converter which was interfaced to an I.B.M. personal computer. The digitized pressure signals for 120 engine cycles were then stored on floppy discs.

The air flowrate was monitored with an orifice plate mounted on top of

the surge tank. The pressure drop across the plate was measured on an inclined manometer. Volumetric flowrate was calculated from the calibration curve for the orifice plate. The orifice plate was calibrated against a Meriam Laminar Flow Element Model 50MW-1.5. The calibration curves for both instruments are in Appendix A.

The natural gas flowrate was metered with a Meriam Laminar Flow Element Model 50MW-1.5 positioned in the gas line between the pressure regulator and control valve. The pressure drop was recorded on an inclined manometer. Volumetric flowrate was determined from the calibration supplied by the manufacturer with appropriate correction factors applied for the effects of natural gas viscosity (see Appendix F).

Air movement within the cylinder during motored operation was measured with a hot wire anemometer probe. The probe used was a TSI Model 1226 which is designed for high temperature environments. The sensor, Platinum-Iridium wire of 6.3 micrometer diameter, was mounted on the support needles by spot welding. The probe was installed in the side port of the cylinder through an airtight fitting. The fitting is shown in Figure 4.6. The access port for the probe is shown in Figure 4.5. A Disa Model 50D anemometer bridge unit, operated in the constant temperature mode, was used in conjunction with the probe. The specifications for the probe and the anemometer are listed in Table II.

The anemometer voltage signal was sent to a Hewlett Packard Model 3968A tape recorder where it was recorded on analogue tape. This was necessary because high resolution was required for the hot wire data. A sample rate of every 0.2 crank angle degrees was selected. However the data acquisition system could not perform analogue to digital conversions this fast, so the anemometer signal was first recorded on tape and then

played back to the data acquisition system at a slower speed. This

procedure is described in more detail in the following section. The anemo-

meter signal was recorded on two channels; one with a passband of 70 to

64,000 Hz, and the other with a passband of DC to 5,000 Hz. The data

stored on the channel with the broad passband was processed to obtain

frequency distribution information. The data recorded in the narrow band

was used to obtain mean velocity and turbulence intensity information.

4.7 Data Acquisition System

The basic data acqusition system consisted of an optical crank angle

trigger, a trigger and clock circuit, an analogue to digital converter, and

an I.B.M. PC. In addition, for turbulence measurements a Hewlett Packard

Model 3968A tape recorder was used for data acquisiton. A schematic of the

system is shown in Figure 4.7. A photograph of the system is shown in

Figure 4.8.

Optical pickups mounted on a slotted wheel coupled to the engine

crankshaft provided pulses every two crank angle degrees and at BDC. The

optical pickup system is shown in Figure 4.9. These pulses were fed to the

trigger and clock circuit simultaneously with the pressure and the signal

being sampled. The two degree signal was passed through a phase lock loop

which multiplied the frequency by ten. The BDC input pulse and pressure

signal were used to start the A/D process. The analogue pressure signal

was input to a comparator whose output was sent to a flip flop. The output

of the flip flop and the BDC pulse were fed to a NOR gate. The flip flop

went low when a preset pressure threshold was reached at the start of

compression and thus when the next BDC pulse arrived at the NOR gate a

trigger pulse was sent out. This pulse served two functions; it signaled

the computer to initiate data acquisition, and it enabled an AND gate which

allowed the 0.2 degree pulses to flow to a counter. If a slower sample rate was desired (0.4, 1.0, and 2.0 degrees), this could be set at the counter and the frequency of the pulses reduced by 2, 5, or 10. The output of this counter was then fed to a clock counter where pulses were counted until 16,000 pulses had been detected. After this threshold was reached the clock counter shut off the pulses until the whole process was started again. For each pulse leaving the clock counter the signal of interest was sampled and an analogue to digital conversion performed. When 16,000 points were collected the data was transferred to a floppy disc for further processing off-line.

The analogue-to-digital converter had an upper frequency limit of 27 kHz. The pressure signal from combustion experiments was sampled every degree and posed no problem. High resolution was required, however, for the hot wire data and hence a sample rate of every 0.2 degrees was selected. At a speed of 1140 rpm the 0.2 degree pulses arrive at the clock counter at a frequency of 34.2 kHz. To overcome this problem a tape recorder was used to record the two degree and BDC pulses, pressure, and anemometer signals at a tape speed of 15 inches per second. The signals were then played back to the trigger and clock circuit at a speed of 7.5 inches per second. Thus the clock counter saw pulses with a frequency of 17.1 kHz but because the anemometer signal was "stretched" the same amount as the original 2 degree pulses the effective sample rate was 34.2 kHz as desired.

Data acquisition was performed with the aid of the program CDAQ which was loaded into the I.B.M. microcomputer. This program was interactive and allowed the user to issue commands to the analogue-to-digital conversion system. This program is described in Appendix C.

5.   EXPERIMENTAL METHOD

5.1 Introduction

The goal of the experiments was to provide combustion and turbulence data for the combustion chambers under study. For each combustion chamber geometry two types of experiments were performed; combustion tests in which the pressure trace was recorded, and motored tests in which the air movements were monitored.

All of the tests were conducted at a constant engine speed of 1140 rpm, a compression ratio of 11.3, and with a wide open throttle. The combustion tests were performed with a stoichiometric air-fuel ratio.

5.2 Motored Engine Tests

These tests yielded flow field data for each of the configurations. The quantities of primary interest were the mean velocity and turbulence intensity for several locations in the chamber: at the edge of the bowl (i.e. a measurement of squish velocity as it left the squish region); at the center of the chamber. For configurations with channels (Piston B) the probe was positioned so that it would be directly opposite a channel exit at TDC in an attempt to measure the jet entering the bowl via the channels. These positions are shown schematically in Figure 5.1.

The majority of these tests were performed with the wire axis oriented perpendicular to the cylinder axis (parallel to the piston face). This position is shown in Figure 5.2 as $\alpha = 0$. This orientation was selected since the radial (or squish) velocity was of primary interest. However, in one set of tests the sensor was rotated 90° (see Figure 5.2) to obtain an indication of the tangential velocity.

5.2.1 Hot Wire Preparation

Wire breakage was a frequent occurrence during the course of the experiments and thus it became necessary to establish a routine procedure for repair and calibration. Sensors were repaired by spot welding Platinum-Iridium wire onto the support needles. The welding was done with the aid of a microscope and a Disa welding unit. Each wire was inspected to ensure that the weld was of acceptable quality and that the wire was free of any dirt or defects.

The sensor was calibrated in a wind tunnel against a pitot tube. The operating temperature of the wire was 600°C. The probe was calibrated for air speeds of 0.5 to 20 meters per second. From the velocity obtained from the pitot tube a Reynolds number was formed based on the wire diameter and the ambient conditions. From the corresponding anemometer voltage a Nusselt number was calculated based on the free stream gas properties. The method used to determine the Nusselt number from the anemometer voltage is that proposed by Witze [27]. This involves solving the one-dimensional heat balance equation for the hot wire (neglecting radiation) to obtain an expression for the mean wire temperature in which the heat transfer coefficient is the only unknown. The heat transfer coefficient is determined through iteration and the Nusselt number formed. This technique is discussed more fully in the following chapter and in Appendix B. From the calibration data set a correlation of the form

$$Nu = a + b\,Re^n \tag{5.1}$$

was found using a non-linear curve fitting procedure [27].

After calibration the probe was placed into the three-piece fitting shown in Figure 4.6. This assembly was then positioned in a measurement test rig. There the probe orientation was set (0° or 90°) with spirit levels and by lining up sight lines on the probe and test rig. In addition the length of the probe to extend into the chamber was set. The pressure fitting was then tightened to secure the probe position within the fitting.

5.2.2 Routine Experimental Procedure

At the start of each experiment the one-piece cylinder head and cylinder were lifted off the engine block and the appropriate piston inserted. After careful cleaning of all parts the head was replaced. To adjust the clearance height the flywheel was rotated until the piston was at TDC. A plug gauge was inserted between the head and the piston crown in the top access port shown in Figure 4.5 and the cylinder was cranked up (via a worm gear) to the proper position. A dial micrometer mounted between the stationary crankcase and the cylinder was set to a reference point. The cylinder was then clamped into position, the flywheel rotated beyond TDC and the plug gauge removed. The pressure transducer was then installed.

Next the valve rocker arm linkage was lifted over the cylinder and the pushrods removed to allow for insertion of the probe. The threaded portion of the probe fitting assembly (part A in Figure 4.6) was first tightened into the side access port. The remainder of the assembly with probe tightened into position was pressed into the threaded sleeve. The fitting was then rotated in the sleeve until the probe was properly oriented. This was done by lining up sight lines on the fitting and on the engine. Finally a nut was threaded onto the sleeve to secure the entire assembly.

The pushrods were replaced, the rocker arm linkage brought down into position, tightened, and the valve clearances set. The engine was started and allowed to come to speed before data acquisition was initiated.

5.2.3 Flow Measurement Locations

For each of the squish chambers tested the probe was positioned 10 mm from the bowl edge for one set of measurements, and then at the chamber center for another set. In addition, measurements were taken in the bowl for the squish-jet chamber. For the disc chamber one measurement was made at the center of the chamber. These positions are shown in Figure 5.1 and labelled R1, R2 nd R3, respectively.

For each of the clearance heights tested the probe was positioned so that the sensor was 2 mm below the chamber head. These positions are also shown in Figure 5.1 and labelled Z1, Z2, and Z3, respectively.

5.3 Combustion Tests

These combution tests provided the pressure history of the combustion process for each of the configurations. Combustion tests were performed after the motored tests as the configuration was already in place. For these tests the hot wire probe was removed from the side port and the pressure transducer mounted. The spark plug was installed in the top access port. These positions are shown in Figure 4.5. After the instrumentation was in place the valve clearance and TDC clearance height were checked.

The engine was started with the motor. Once speed was achieved the ignition was switched on and the gas flow started. The air-fuel mixture was maintained at the stoichiometric point by adjusting the gas control valve. Spark timing was varied from 20 to 40 degrees BTDC in 5 degree increments. For each setting 120 cycles of data was collected.

6. DATA ANALYSIS

6.1 Introduction

The techniques employed for data reduction and analysis are described in this chapter. Two types of signals were processed, hot-wire anemometer and pressure data. The first part of this chapter briefly describes the method of processing the analogue signals to obtain meaningful data. The second part describes in detail the methods used to interpret this data.

6.2 Pressure Signal Processing

The raw digital data was first ensemble-averaged over 120 engine cycles. The digital data was then transformed to pressures with the appropriate conversion factor. This conversion factor was a function of the system gain and the charge amplifier setting. The pressures obtained from this conversion were relative pressures and had to be shifted by the appropriate value to obtain the absolute cylinder pressure. The method of Lancaster et al. [29] was used to determined the reference condition. This involves assuming that the pressure in the cylinder at BDC after intake is equal to the average intake manifold pressure. The intake manifold pressure was estimated by subtracting the measured losses through the intake system from the ambient pressure. After the absolute cylinder pressures were evaluated the pressure trace was smoothed using cubic spline interpolation.

6.3 Anemometer Signal Processing

The hot wire anemometer registers the change in resistance (electrical) which results from the heat transfer from the sensor due to the

cooling effect of the flow. Because the heat transfer process is a function of the driving temperature differential and fluid properties such as viscosity, density, and conductivity the sensor response is highly sensitive to changes in temperature and pressure in the flow. Ideally a probe should be calibrated over the range of temperatures and pressures encountered in the engine cylinder. However, this time-consuming procedure is not practical in light of the frequent occurrence of wire breakage. Thus it becomes necessary to rely on analytical models to correct for variations from the calibrated conditions.

The two most widely used models of heat transfer from a hot-wire are those of Collis and Williams [30] and Davies and Fisher [31]. Both models are modifications to the theory developed by King [32], known as King's Law which gives the Nusselt number as a function of the Reynolds number:

$$Nu = a + b\ Re^{1/2} \tag{6.1}$$

where a and b are determined by calibration. Collis and Williams [30] developed a heat transfer correlation in which convection was the only significant form of heat transfer considered. They were able to justify this by using wires with a length to diameter ratio greater than 2000. In the work of Davies and Fisher conduction to the wire supports was considered to be significant. Their theory involves solving the one dimensional heat balance equation along the wire to obtain an expression for the mean wire temperature in which the heat transfer coefficient is the only unknown. The heat transfer coefficient is determined through iteration.

In this study neither of these universal correlations was used; however, an approach similar to that of Davies and Fisher as proposed by Witze [27] was taken. In this method the one-dimensional energy equation for the wire is solved to obtain an expression for the temperature distribution along the wire. This temperature distribution is integrated along the wire to yield a mean wire temperature:

$$T_M = \frac{2(T_p - C_1)}{\sqrt{C_2}\, \ell} \tanh [\sqrt{C_2}\, \ell/2] + C_1 \tag{6.2}$$

where

$$C_1 = \frac{hT_g + I^2 R_0 (1 - \alpha_0 T_0)/(\pi d\ell)}{h - I^2 R_0 \alpha_0/(\pi d\ell)} \tag{6.3}$$

and

$$C_2 = 4[h - I^2 R_0 \alpha_0/(\pi d\ell)]/k_w d \tag{6.4}$$

where h is the heat transfer coefficient, T_p is the sensor support temperature, T_g is the gas temperaure, k_w is the mean thermal conductivity of the wire, R_0 is the resistance of the wire at the reference temperature T_0, α_0 is the temperature coefficient of resistance for the wire, and I is the current through the wire.

The mean wire temperature can be calculated from the probe resistance and the wire temperature coefficient of resistance. All other quantities except the heat transfer coefficient h are known. The heat transfer coefficient is determined from iteration. Thus for a given flow condition the heat transfer coefficient can be determined from the measured probe current, and a Nusselt number formed. Then a Reynolds number may be found from Equation (5.1). The fluid velocity is then determined from the Reynolds number.

There are several important points to make about this procedure. First in the correlation both the Reynolds number and the Nusselt number are based on the free stream gas temperature. In an extensive study in which hot wire anemometer results were compared to LDV results Witze [27] found that this choice of reference temperature gave the best agreement between the two results.

The support temperature T_p in Equation (6.2) was taken as room temperature and invariant. The support needles are much larger than the wire and are not appreciably heated by the electric current. Their temperature can be assumed to follow the instantaneous gas temperature somewhat. However, unless a direct measurement of the needle temperature is made, as Lancaster [10] did, there is no straight forward method to estimate the temperature. Again using LDV results as a standard for comparison Witze found that the choice of invarient room temperature for the supports gave adequate results.

Determination of the gas temperature in the cylinder is very important to the results. In this study the air temperature was calculated from:

$$(T_g)_i = (T_g)_{i-1}(P_i/P_{i-1})^{\frac{\gamma-1}{\gamma}} \qquad (6.5)$$

where γ is the temperature dependent specific heat ratio evaluated at $(T_g)_{i-1}$.

The initial reference condition was taken at the point of intake valve closing, where the pressure and temperature were taken as ambient conditions. The temperature dependent specific heat ratio was calculated by assuing the air was 21% O_2 and 79% N_2. The constant pressure specific heats of N_2 and O_2 were evaluated from expressions given in Van Wylen and Sontag [33]:

$$(C_p)_{N_2} = 39.060 - 512.79\theta^{-1.5} + 1072.7\theta^{-2} - 820.40\theta^{-3} \qquad (6.6)$$

and

$$(C_p)_{O_2} = 37.432 + 0.020102\theta^{1.5} - 178.57\theta^{-1.5} + 236.88\theta^{-2} \qquad (6.6)$$

where $\theta = T(\text{kelvin})/100$. Witze [27] compared mean velociites obtained using measured and calculated temperatures. His results show that the adiabatic computation gives good results during the compression process but tends to perform poorly beyond approximately 50 degrees after TDC. Since the region of interest in this study was the combustion period (from 60 degrees before TDC to 40 degrees after TDC) the adiabatic calculation was deemed adequate for temperature evaluation.

The thermal conductivity and viscosity of the air were calculated from the expressions used by Collis and Williams [30]:

$$\frac{K_g}{K_{Ref}} = \left(\frac{T_g}{T_{Ref}}\right)^{0.80} \qquad (6.8)$$

and

$$\frac{\mu_g}{\mu_{Ref}} = \left(\frac{T_g}{T_{Ref}}\right)^{0.76} \qquad (6.9)$$

Details of the calculation procedure for the determination of the instantaneous velocity from the anemometer are presented in Appendix B.

From the foregoing discussion it can be seen that there are many sources for uncertainties in the evaluation of the instantaneous velocity from the anemometer signal. The main uncertainties are: wire physical properties such as uniformity of diameter, sensing length, and temperature coefficient of resistance; imperfections of the weld at the supports; and fouling of the wire during measurement. Uncertainty in the experimental

value of pressure, the reference temperature, the computed gas temperature,
and the selected sensor support temperature lead to uncertainty in the heat
transfer coefficient and thus the computed velocity. For these experiments
the uncertainty in the reference temperature is estimated to be 5% and in
the reference pressure 5%. Sensitivity analysis shows this leads to
uncertainty on the order of 35% in the calculated instantaneous velocity.
In addition to uncertainty arising from the analytical procedure the
effects of probe interference and the probe's insensitivity to flow
direction also contribute to error in the interpreted results. In light of
the high uncertainty associated with hot wire measurements caution should
be exercised when they are interpreted, especially when absolute magnitudes
of mean velocity or turbulence intensity are to be applied to empirical
models. However, hot wire measurements do provide a qualitative indication
of the flow field in an engine and are valuable in studies such as this one
where evaluation is based on a relative comparison rather than the absolute
magnitudes of the flow field characteristics.

6.4 Flow Field Data

Interpretation of hot wire measurements in engines poses several
dilemmas. Because of the complex nature of the flow field generated by the
valve events and piston motion the directional characteristics are diffi-
cult to determine since the sensor cannot distinguish between forward and
reverse flow conditions. Although analytical models can be used to predict
the sensor response to conditions different from the calibration, there are
many assumptions and variables involved in the computation of the instan-
taneous velocity, and thus many sources of error exist.

The major obstacle to data interpretation and processing arises from
the periodic and thus nonstationary nature of the flow field in the engine.
Because of this, most investigators have resorted to ensemble averaging
techniques. There are two problems with this approach. The first is that

the fundamental equations which define turbulence characteristics use time
averages. For most stationary processes time averages of the statistical
properties are equal to ensemble averages. These are called ergodic
processes. Since many turbulent flows may be considered as stationary and
ergodic the substitution of ensemble averages for time averages poses no
problem. However the flow field in an engine is unsteady and non-
stationary. This means that the time averaged mean will be dependent upon
the length of the averaging interval and furthermore ensemble averages will
not equal time averages. The second objection to ensemble averaging is
that not only is the "mean" velocity periodic but there is also a cycle to
cycle variation in the mean velocity itself. This cyclic variation in the
mean velocity is included in the computed turbulence intensity when
ensemble averaging is used.

Time averaging methods also present difficulties. The main problem
arises in the selection of a window size for averaging. The calculated
mean velocity will be highly dependent upon the length of the averaging
interval. Ideally the window size should be as small as possible since the
mean velocity can change quite rapidly. If the window size is made too
large then information is lost. The same problem arises in calculation of
the turbulence intensity; if the window size is too small then low
frequency turbulence data is lost. Thus a compromise must be made.

In this investigation both techniques (time and ensemble averaging)
were employed to interpret the data and the results were compared.

6.4.1 Ensemble Averaged Mean and RMS Velocity

An ensemble average is performed on a series of records each consist-
ing of a sequence of equally spaced samples in time. If the instantaneous

velocity is written as $U(i,\theta)$ where i denotes the engine cycle (record) and θ the crank position (time) within the cycle then the ensemble averaged mean velocity for the position θ obtained from an ensemble of N cycles is:

$$\bar{U}(\theta) = \frac{1}{N} \sum_{i=1}^{N} U(i,\theta) \qquad (6.10)$$

The turbulence intensity is defined as the rms of the velocity fluctuations about the mean and is:

$$u'(\theta) = \left\{ \frac{1}{N} \sum_{i=1}^{N} (U(i,\theta) - \bar{U}(\theta))^2 \right\}^{1/2} \qquad (6.11)$$

There are several variations on this method. Rask [34] compared two methods; a window ensemble and a smoothed ensemble. In the window ensemble a crank angle interval was selected and data points within averaged to obtain a single point. The window averages were then ensembled as described above. In the smoothed ensemble a curve was fitted to the window averages for each cycle using cubic spline interpolation. The smoothed curves were then ensembled to obtain mean and rms velocities. He also performed a cycle by cycle analysis on the smoothed mean velocity curves. This involved evaluating the rms velocity from the smoothed curves for each cycle. The respective mean and rms velocity curves were then ensembled. He found that the turbulence intensity obtained by a cycle by cycle analysis was lower than that obtained from the other methods. This confirmed the fact that conventional ensemble averaging includes the cyclic variation of the mean flow in computed intensity.

In this study conventional ensemble averaging was compared to a cycle by cycle time averaging technique. The ensemble averaging was taken over 100 engine cycles. Each cycle consisted of samples for every 1/5 of a

crank angle degree. The mean velocity was obtained from Equation (6.10) and the turbulence intensity in Equation (6.11) was obtained by:

$$u'(\theta) = \{\frac{1}{N} \sum_{i=1}^{N} U^2(i,\theta) - \bar{U}^2(\theta)\}^{1/2} \qquad (6.12)$$

Details of the calculation and the computer program used are in Appendix D.

6.4.2 Cycle by Cycle Time Averaged Mean and RMS Velocity

Two approaches for evaluating the mean and rms velocities on a cycle by cycle time averaged basis were studied. The majority of data was processed with a method similar to that of Catania and Mittica [35]. This technique is similar to the cycle-by-cycle smoothed ensemble proposed by Rask [34] except that time averages were performed in the windows rather than arithmetic averages. In their study Catania and Mittica evaluated a mean velocity curve for each cycle. This was done by finding the time average of the instantaneous velocity for specific time intervals (crank angles) within the engine cycle. The average values, taken at the center of the window, were then used with cubic spline interpolation to generate a smoothed mean velocity curve. The turbulence intensity was then obtained in a similar fashion from the instantaneous velocity and smoothed mean velocity for each cycle. The mean and rms velocity curves for each cycle were then ensembled.

They investigated the effect of different averaging intervals on computed mean and rms velocities. They found that window sizes ranging from 4 to 12 crank angle degrees had no significant effect on the mean velocity. For turbulence intensity calculations they varied the windows

from 1 to 20 crank angle degrees. They found that for intervals less than

8° the intensity values decreased. Between 8° and 20° however, there was

relatively little difference. This interval (8° to 20°) corresponded to a

time interval of between 0.83 and 2.08 milliseconds which corresponds to

the range of macro time scales that can be expected in an engine. The fact

that the turbulence intensity decreased for averaging intervals less than

8° indicates that low frequency turbulence information was being lost.

In the present study the same type of technique was employed. The

mean velocity within specified time intervals for each cycle i was

calculated by:

$$\bar{U}_\theta(i) = \frac{1}{\Delta} \int_0^\Delta U(i,\theta) \, d\theta \qquad (6.13)$$

Window sizes ranging from 2 to 8 crank angle degrees were examined. Since

these window sizes had relatively little effect on the resulting mean

velocity curve a 4 degree window was selected for computational ease. Mean

velocity curves were then obtained using cubic spline interpolation [28]

between the evaluated points for each cycle. The turbulence was then

computed for each cycle by:

$$u_\theta'(i) = \frac{1}{\Delta} \int_0^\Delta \left\{ [U(i,\theta) - \bar{U}_\theta(i)]^2 \, d\theta \right\}^{1/2} \qquad (6.14)$$

where the averaging window θ was 12 crank angle degrees. Window sizes

ranging from 2 to 14 degrees were studied. There was a decrease in the

turbulence intensity for windows smaller than 6 crank angle degrees,

however there was relatively little difference for windows larger than

this. Based on these results, an averaging interval of 12° was used

throughout for evaluating the turbulence intensity from Equation (6.14).

The mean velocity and turbulence intensity curves were then ensembled over 40 cycles to obtain one representative curve for each of the two properties, the ensemble averaged mean velocity:

$$\bar{U}_\theta = \frac{1}{40} \sum_{i=1}^{40} \bar{U}_\theta(i) \qquad (6.15)$$

and the ensemble averaged turbulence intensity without the cyclic variation of the mean velocity:

$$u'_\theta = \{\frac{1}{40} \sum_{i=1}^{40} [\frac{1}{\Delta} \int_0^\Delta (U(i,\theta) - \bar{U}_\theta(i))^2 \, d\theta]\}^{1/2} \qquad (6.16)$$

The cyclic dispersion of the mean velocity was determined from the difference between the ensembled mean velocity of Equation (6.15) and the individual mean velocity curves for each cycle:

$$U_{RMS} = \{\frac{1}{40} \sum_{i=1}^{40} [\bar{U}_\theta(i) - \bar{U}_\theta]^2\}^{1/2} \qquad (6.17)$$

Also the nonstationary analysis proposed by Lancaster [10] was studied for comparative purposes. Lancaster redefined the instantaneous velocity to be the sum of a stationary mean velocity $\bar{U}(i)$, a time varying mean velocity $\bar{U}(\theta)$, and a turbulent fluctuation $u(i,\theta)$:

$$U(i,\theta) = \bar{U}(i) + \bar{U}(\theta) + u(i,\theta) \qquad (6.18)$$

In the present study the mean velocity obtained from ensemble averaging was first evaluated. Then the stationary mean velocity $\bar{U}(i)$ was calculated from:

$$\bar{U}(i) = \frac{1}{\Delta} \int_0^\Delta [U(i,\theta) - \bar{U}(\theta)] \, d\theta \qquad (6.19)$$

for each engine cycle (record). The window size θ was varied from 40 to 100 crank angle degrees about TDC. The intensity was then computed from:

$$u'(i) = \{\frac{1}{\Delta} \int_0^\Delta [U(i,\theta) - \bar{U}(\theta) - \bar{U}(i)]^2 \, d\theta\}^{1/2} \qquad (6.20)$$

The intensity records were then ensembled.

Details of the calculation and the computer program used are in Appendix D.

6.4.3 Time Scale Analysis

An analysis similar to that of Haghgooie et al. [13] was performed on uncalibrated hot wire anemometer signals to obtain relative probability distributions of the peak-to-peak time separation. This analysis depends on the assumption of a definable small scale structure of turbulence in an engine similar to that proposed by Tennekes [7].

The technique involves the determination of an amplitude threshold for peak discrimination. This is obtained by operating the probe in quiescent ambient air. The problem with this technique is that the "noise" level sampled in quiescent air will be a turbulence signal resulting from natural convection. This "noise" will be insigificant in forced convection flow. Thus by setting a discrimination level for peak identification some of the high frequency turbulence information is lost. After the amplitude threshold is set the signal is sampled and a relative probability distribution is formed for the peak-to-peak time separation. Haghgooie et al. [13] concluded that the most probable frequency obtained in this fashion appears to be related to the small scale structure of the turbulence.

Based on the assumption that there is a definable small scale structure of turbulence in an engine similar to that proposed by Tennekes and that the method of Haghgooie et al. can be used to detect differences in the turbulent frequency distribution in engines a peak-to-peak time separation analysis was performed on the anemometer data obtained for the chambers studied. The noise amplitude threshold was obtained by evaluating the probability distribution from data collected while operating he probe

in quiescent ambient air. The relative distrtibution of the peak-to-peak time separation was then formed. It was found that this distribution was relatively insensitive to variations of up to 30% in the amplitude threshold. This could mean that high frequency turbulence data was lost. A window of 60° around TDC compression was used in the evaluation of the relative probability distribution. Details of the procedure and a listing of the computer program are in Appendix D.

6.5 Combustion Data

The pressure recorded during combustion tests was processed to yield mass burn rate curves for the configurations under study. The raw digital data was processed as detailed earlier in the chapter. The computer program used to process the data was developed by Jones [36]. The thermodynamic model in the program is based on the two zone approach and is similar to that of Keck [37] and Lavoie et al. [38]. The basic assumptions are that a thin spherical flame front separates the charge into two zones; the unburned region containing the reactants, and the burned region containing the products. Properties are assumed to be spatially uniform throughout each region. Furthermore both products and reactants have varying specific heats and obey the equation of state for an ideal gas. The unburned gas is assumed to be isentropically compressed due to the expansion of the burned region. The heat transfer is calculated using the Annand [39] equation. Six dissociation reactions are accounted for.

With the assumptions above and the application of the first law and conservation of mass an iterative procedure is followed from which the mass fraction burned is obtained at each crank angle degree. Minor changes to the program were necessary to accommodate the C.F.R. combustion chamber geometries. A complete discussion of these changes and a program listing is in Appendix E. A detailed discussion of the calculation procedure is given in [36].

7. DISCUSSION OF RESULTS

7.1 Introduction

In this chapter the results obtained from the experiments conducted on the C.F.R. engine are presented and discussed. In the first section results from flow field measurements are presented, while in the second section results from the combustion tests are presented and discussed.

7.2 Flow Field Results

This section is divided into four parts. In part one the different methods of processing the data (discussed in Chapter 6) are examined and compared. In part two results obtained for the standard squish chamber, Piston A, are presented. In the following section results for Piston B the squish chamber with channels are given. The final section deals with a comparison of the geometries investigated.

In the following sections flow velocities are presented plotted against crank angle degrees. The convention used is that 0° is BDC and 180° is TDC compression. Most of the plots are shown from 60 to 220 degrees. This is the portion of the engine cycle important to the combustion process. At 60° the intake generated flow has decayed and in a disc chamber would continue to decrease through TDC. The combustion period ranges from 30° BTDC to approximately 30° ATDC. At 220° the combustion period is finished.

7.2.1 Ensemble Averaging vs. Time Averaging

In this section the averaging techniques discussed in the previous chapter are compared. The results shown in this section were obtained with

the standard squish chamber (Piston A) at a clearance height of 1.5 mm. Three consecutive instantaneous velocity traces are shown in Figure 7.1. The basic mean velocity trend is evident and repeatable although there is considerable variation in the individual traces from cycle to cycle.

In Figure 7.2 the mean velocity trace obtained from conventional ensemble averaging techniques (Equation (6.10)) is shown with the mean velocity evaluated from Equation (6.15) using a window of 4 crank angle degrees as the time averaging window. From the figure it is clear that the two techniques yield almost indistinguishable results for the mean velocity trace. The cyclic variation of the mean velocity is shown in Figure 7.3. This curve was formulated from Equation (6.17). The cyclic variation can be seen to be fairly consistent throughout the compression stroke with a slight increase near TDC.

In Figure 7.4 the turbulence intensities obtained from conventional ensemble averaging using Equation (6.12) and from the time averaged window, cycle-by-cycle analysis of Equation (6.16) are shown. The window size used in Equation (6.16) was 12 degrees for the reasons discussed in the previous chapter. It is evident that the ensembled intensity has included in it some of the cyclic variation of the mean velocity. This is shown even more by comparing Figures 7.3 and 7.4.

The turbulence intensity obtained from Equation (6.11) using the non-stationary analysis proposed by Lancaster [10] is shown in Figure 7.5 for averaging windows of 40, 60, 80, and 100 degrees around TDC. Comparison of Figures 7.4 and 7.5 shows that the computed values lie between the ensembled and time averaged results. The problem with this formulation is the assumption that the difference between the ensembled mean and the instantaneous mean is constant during an individual cycle; that is, that

the curves are in phase and simply shifted up or down with respect to one another. However inspection of Figures 7.1 and 7.3 shows that this is not the case.

In the following sections the mean velocity was evaluated using the method described in Chapter 6 from Equation (6.15). A four degree window was used for the averaging interval. Turbulence intensities were computed from Equation (6.16) with an averaging interval of 12 crank angle degrees. The basis for the selection of these windows was discussed in Chapter 6.

7.2.2 Standard Squish Piston (Piston A) Results

In Figure 7.6 the mean velocity and turbulence intensity traces for a clearance height of 3.5 mm are shown. This data was taken at the edge of the bowl. The mean velocity decays steadily as TDC is approached. At approximately 10° BTDC there is a slightly increase in the mean velocity. After the small peak the mean velocity decreases until 10° ATDC. Another peak is then reached at 20° ATDC. A comparison of these results with the calculations in Chapter 3 (see Figure 3.2) shows that although the magnitude of the velocities do not agree the timing of the velocity peaks in Figure 7.6 corresponds to the trend predicted for the squish velocity. The turbulence intensity remains relatively constant throughout.

The effect of squish for a clearance height of 1.5 mm is clearly evident in Figure 7.7. The mean velocity is steady throughout the compression stroke until about 20° BTDC where there is a sharp increase which comes to a peak near TDC and then decays.

The interesting effect here is that the previous case (h_c = 3.5 mm) showed the effect of squish on both sides of TDC (as the model presented in Chapter 3 predicts); however, in this case (h_c = 1.5 mm) only one peak

centered approximately around TDC is shown. The results of James [25] showed a similar trend to the previous case (h_c = 3.5 mm); that is, squish effects before TDC and reverse squish on the expansion stroke. However he used large clearance heights and did not achieve pronounced squish effects. The results of both Witze [12] and Dent and Salama [10] show only one velocity peak near TDC similar to the trend exhibited in the data for h_c = 1.5 mm. The calculations in Chapter 3 predict the trend of two velocity peaks as shown in the data for h_c = 3.5 mm. However this model was very simplified and did not account for effects such as momentum and viscosity. It is possible that there is another flow regime at work (such as a piston generated vortex) with the squish; however, without flow visualization it is difficult to determine exactly what is happening.

At 10° BTDC a comparison of Figures 7.6 and 7.7 shows that the mean velocity achieved for a clearance height of 1.5 mm is approximately four times that for the lower clearance height. This is in agreement with the trend predicted by the calculations in Chapter 3 and demonstrates the critical effect of clearance height.

In Figure 7.8 the velocity trace obtained with the probe postioned at the center of the chamber (h_c = 1.5 mm) is shown. Again there is a large velocity peak at TDC. However careful examination of the figure shows that the point at which the mean velocity starts to increase comes approximately 5° later than it did for the measurement taken at the cup edge. This trend is to be expected since the arrival time of the squish-jet should be later as the probe is moved away from the cup edge.

To get an indication of how much swirling motion was present the probe was rotated 90° (see Figure 5.4) so that the probe axis was perpendicular to the piston face. Results obtained at the cup edge and at the chamber

center are shown in Figures 7.9 and 7.10. Both mean velocity and turbu-
lence intensity are slightly higher indicating the presence of a tangential
velocity component. However because only single sensor measurements were
made it was not possible to resolve this component. The later arrival time
of the squish-jet to the center can be seen more clearly from these two
figures.

In Figure 7.11 the mean velocity curves obtain at clearance heights of
3.5 and 1.5 mm are compared. Although the two curves are similar in the
early part of the compression stroke the effect of the squish can be seen
as they begin to deviate from one another at approximately 30° BTDC.
Measurements were also made for the clearance height of 2.5 mm. The
resulting velocity traces were not that different from the 3.5 mm case and
are not presented. From these results it can be seen that the clearance
height is important in the observed squish effect as predicted by the
calculations in Chapter 3.

A comparison of the relative turbulence intensities for the two
heights is shown in Figure 7.12. It is evident that although the magni-
tudes of the velocity traces vary considerably, the relative quantities
show only a maximum increase of about 25% for the clearance height of 1.5
mm during the squish period.

7.2.3 Squish-Jet Combustion Chamber (Piston B) Results

Measurements were made at the same locations and conditions as for
Piston A. The mean velocity and turbulence intensity profiles for a clear-
ance height of 3.5 mm are shown in Figure 7.13. In this case it is diffi-
cult to detect any effect of squish at all prior to TDC and only a small
peak occurs after TDC. However from calculations in Chapter 3 this trend

could be expected if the gas is now using the additional routes provided by the channels.

At the smaller clearance height shown in Figure 7.14 the squish effect can be seen again. In this case the peak effect at TDC is not as pronounced as it was for Piston A although the same general trend for both mean velocity and turbulence intensity is exhibited. Examination of the figure shows that the mean velocity trace is consistently lower for Piston B. The most probable explanation for this is that there was leakage past the piston rings for the previous measurements. All hot wire measurements except those for Piston B at a clearance height of 1.5 mm were obtained before a failure in the C.F.R. engine required that the cylinder be honed out and the piston rings replaced. If there was considerable blow-by past the piston rings then the velocity measurements would be artificially inflated. This could explain the observed differences in the velocity traces before the squish could start affecting the flow.

In Figure 7.15 the mean velocity trace and turbulence intensity traces are shown for Piston B at the center of the chamber (h_c = 1.5 mm). The interesting effect here is the character of the mean velocity trace after top dead center. After the peak starts to decay the velocity is relatively flat for a few degrees and then there is a small peak. This could be the separate effects of squish, and another flow regime.

In Figure 7.16 the velocity and intensity traces for the measurement taken inside the cup are shown. This was an attempt to get an idea of the jet velocity leaving the channel as it entered the bowl. Unfortunately geometric constraints would only permit the probe to be aligned with the channel centerline right at TDC. Although calculations in Chapter 3 indicate the velocity of the channel jet should be zero at TDC it was hoped

that the probe would detect the final part of the jet as the top of the channel passed the probe. As can be seen from Figure 7.15 the jet was not detected at all. However this is most probably due to the inability to position the probe properly rather than the lack of a jet velocity.

In Figure 7.17 the relative turbulence intensities for the clearance heights of 3.5 and 1.5 mm are shown. The maximum difference between the two is approximately 10 percentage points, on the same order as the difference between relative intensities for Piston A at the same height.

7.2.4 Comparison of Geometries

In this section a comparison between the two geometries is made. The two mean velocity traces (h_c = 1.5 mm) are compared in Figure 7.18. As was mentioned earlier it is believed that the mean velocity trace of Piston A is artificially inflated due to leakage past the piston rings. There is no other explanation for the difference between the two curves between 60 and 140 degrees. The points to notice from this figure are that the trends are basically similar; the mean velocity begins to increase about 20° BTDC, the peak occurs near TDC, and about 20° ATDC there is a slight secondary peak. In Figure 7.19 the relative intensities are compared for the probe located at the cup edge (h_c = 1.5 mm). The relative intensity of Piston B is consistently higher than for Piston A. The maximum difference between the two is 11 percentage points; that is, Piston B shows a 29% improvement. However it is difficult to say how much of this is due to increased turbulence generation by Piston B design. This is because although flow induced by leakage past the rings would create a higher mean velocity it might not generate new turbulence. Thus the relative intensity for Piston A might be artificially low. However a comparison of Figures 7.12 and 7.17 shows that even at the clearance height of 3.5 mm the relative turbulence

intensity was higher from Piston design B. In this case the relative turbulence intensities of the two designs were approximately equal until 30° BTDC through 20° ATDC. In this region the maximum difference between the two curves was approximately 6 percentage points. This trend indicates that the squish-jet piston design is more effective at generating turbulence during the compression stroke (or squish period). This would be important to combustion since it is the level of turbulence and not the mean velocity that enhances combustion.

The relative probability distributions of the peak-to-peak time separation are shown in Figures 7.20 to 7.23. These measurements were performed for the clearance heights of 1.5 mm and for the disc chamber for comparison. The distributions presented are for a crank angle window of 60° around TDC. The distributions were obtained using the peak to peak time separation technique described in Chapter 6.

In Figure 7.20 the distributions for Piston A at the bowl edge and at the chamber center are shown. From the graph it can be seen that there is a slight broadening of the distribution towards the center of the chamber. In Figure 7.21 the distribution for the flat piston is compared to that of Piston A at the center of the chamber. From this graph it is evident that there is some clustering of frequency bands for the flat piston chamber. In general the relative probability for Piston A is higher in the high frequency range than it is for the flat piston; however the differences are minor.

In Figure 7.22 the distributions of Pistons A and B are compared for the probe position at the cup edge. Although the most probable frequency for the two designs is the same, approximately 1 millisecond, the distribution for B shows less skew to the left (higher frequencies) than that of

Piston A. In Figure 7.23 the distributions for the two designs are shown

for the center probe location. Here there has been a definite shift in

Piston B's distribution to the right and lower frequencies; whereas for

Piston A, although there has been some broadening of the distribution, the

most probable time has not changed.

Although there are differences in the distributions they are minor and

the results indicate that the squish chamber has a small effect on the

turbulent frequency distribution in the chamber. However in view of the

limitations of the analytical method the reults are somewhat inconclusive

since it is possible that high frequency information was lost.

7.3 Combustion Results

In this section results from the combustion tests are presented. The

pressure traces for each of the pistons A and B as well as the flat piston

were analyzed for mass fraction burned history. The final mass fraction

burned for the tests was about 93%. There are a number of reasons 100%

burned was not achieved; blow by could not be adequately accounted for in

the calculations, combustion may have been incomplete, and there could have

been an error in the heat transfer calculations. The uncertainty in the

initial reference pressure is estimated to be 5%. However this gives an

insignificant percentage error (<.1%) in peak pressure. The major source

of uncertainty in the mass burn rate analysis arises in the evaluation of

the initial energy of the charge in the cylinder. The uncertainty in the

initial energy is a function of uncertainty in pressure, temperature, and

charge mass. The uncertainty in the charge mass arises from measurement of

air and fuel rates, and estimation of the residual fraction. The total

uncertainty in the mass is estimated to be 5%. This leads to an

uncertainty of 15% in the mass fraction burned.

In Figure 7.24 the pressure histories for Pistons A and B (h_c = 1.5 mm) and the flat piston are shown for a spark timing of 30° BTDC. The maximum cylinder pressure of 63.3 Bar was achieved with Piston B at 8° ATDC. The maximum pressure obtained with Piston A was 61.1 Bar at a crank position of 11° ATDC. The flat piston yielded the poorest results with a maximum pressure of 46.0 Bar occuring 16° ATDC. In Figure 7.25 the mass fraction burned curves for the flat piston and Piston A are shown (spark timing 30° BTDC). It can be seen that the basic squish design appears to have very little effect on the ignition delay time. The ignition delay time here is defined to be the time taken to burn 2% of the charge mass. The effect of squish is seen in the main stage of combustion, defined here to be the period for 2 to 85% mass burned. The burn time for the flat piston was 38 crank angle degrees whereas for Piston A this time was reduced by 26% to 28 crank angle degrees. These results are in agreement with Nagayama et al. [17] who found that squish increased burning rate in the main combustion stage and resulted in higher maximum pressures. In Figure 7.26 the mass fraction burned curves are compared for Pistons A and B. The spark timing was again in both cases 30° BTDC. It can be seen from this figure that the main effect of the squish jet channels is a reduction in the ignition delay time. The ignition delay time is 3° less for Piston B; a 17% reduction. However the main stage of combustion does not appear to have been affected. The burn time for both designs is approximately 28 crank angle degrees. In Figure 7.27 the three curves are plotted together and the separate effects of faster burn rate during the main combustion period due to the squish, and reduced ignition delay due to the channels can be clearly seen. The total combustion duration is defined here to be the time from spark to 85% mass burned. The total combustion durations for

the flat piston and Pistons A and B were 58, 44 and 42 crank angle degrees
respectively.

In Figure 7.28 the mass fraction burned curves for the two squish
designs are compared for a spark timing of 25° BTDC. Again the only real
effect appears to be a reduction in ignition delay time in the case of
Piston B. However the effect is not as pronounced in this case. This is
to be expected since ignition delay effects will be enhanced for earlier
spark timing (as in the 30° BTDC case) since the initial pressure and
temperature of the mixture is lower. In this case (25° BTDC) there is only
2° difference in the ignition delay period for the two designs.

8. CONCLUSIONS AND RECOMMENDATIONS

The objective of this thesis was to investigate the effects of the squish chamber design on the combustion process and flow field of an I.C. engine and particularly to compare the reference squish design to the squish-jet design [8]. A number of conclusions may be drawn on the basis of the experimental data.

Cylinder pressure data shows the squish design to be effective in increasing the mass burn rate during the main combusion period. For a spark timing of 30° BTDC the combustion duration for the disc chamber was 58° compared to 45° for Piston A at h_c = 1.5 mm. The peak pressure achieved with Piston A was 30% higher and occurred 5° earlier.

Comparisons of cylinder pressure data for Pistons A and B show the squish-jet chamber design to give superior performance. For a spark timing of 30° BTDC the maximum pressure attained with Piston B was 4% higher and occurred 3° earlier. The major effect of the squish-jet chamber design was the reduction in ignition delay time by 3° for a 17% improvement. The main stage of combustion does not appear to have been affected. The combustion duration for Piston B was 42°; 3° less than for Piston A.

Although the uncertainty in the computed flow field parameters is high, because the experiments were performed from case to case with conditions as identical as possible some of the uncertainty is systematic. From the flow field data it appears that the clearance height has a significant effect on the mean velocity. The mean velocity computed for Piston B was less than that for Piston A for identical clearance heights. The peak-to-peak time separation analysis results indicated no significant difference in the turbulence frequency distributions for the two designs.

Further work is recommended for the combustion experiments in this study it was not possible to vary the operating conditions nor to obtain adequate performance data. Pressure history was the only obtainable data. Therefore, it is recommended that extensive performance tests be carried out with the two squish chamber designs. Also in this study the engine used had a side point ignition. It is recommended that further experiments be performed in an engine with a central ignition to study the full benefit of the mixing in the combustion chamber due to the squish-jet channels.

Further flow field experiments are also recommended. Flow visualization would be valuable. Measurement of length scales in the squish-jet chamber could provide valuable insight into the link between ignition delay and small scale turbulence structure.

BIBLIOGRAPHY

1. MATTAVI, J.N., "The Attributes of Fast Burning Rates in Engines", SAE 800920, 1980.

2. MAYO, J., "The Effect of Engine Design Parameters on Combustion Rate in Spark-Ignited Engines", SAE 750355, 1975.

3. DAMKOHLER, G., "The Effects of Turbulence on the Flame Velocities in Gas Mixtures", NACA TM 1112, 1947.

4. TABACZYNSKI, R.J., FERGUSON, C.R. and RADNAKRISHNAN, K., "A Turbulent Entrainment Model for Spark Ignition Engine Combustion", SAE 770   , 1975.

5. BLIZARD, N.C. and KECK, J.C., "Experimental and Theoretical Investigation of Turbulent Burning Model for Internal Combustion Engines", SAE 740191, 1974.

6. ANDREWS, G.E., BRADLEY, D. and LWAKABAMBA, S.B., "Turbulence and Turbulent Flame Propagation - A Critical Appraisal", Combustion and Flame, Vol. 24, pp. 285-304, 1975.

7. TENNEKES, H., "Simple Model for the Small-Scale Structure of Turbulence", Physics of Fluids, Vol. 11, No. 3, 1968.

8. EVANS, R.L., Patent Applications.

9. SEMENOV, E.S., "Studies of Turbulent Gas Flow in Piston Engines", Otedelenie Technicheskikh Navk, No. 8, 1958 (English Translation: NASA Technical Translation, F97).

10. DENT, J.C. and SALAMA, N.S., "The Measurement of the Turbulence Characteristics in an Internal Combustion Engine Cylinder", SAE 750886, 1975.

11. LANCASTER, D.R., "Effects of Engine Variables on Turbulence in a Spark-Ignition Engine", SAE 760159, 1975.

12. WITZE, P.O., "Measurements of the Spatial Distribution and Engine Speed Dependence of Turbulent Air Motion in an I.C. Engine", SAE 770220, 1977.

13. JAMES, E.H. and LUCAS, G.G., "Turbulent Flow in Spark Ignition Engine Combustion Chambers", SAE 750885, 1975.

14. HAGHGOOIE, M., KENT, J.C. and TABACZYNSKI, R.J., "Turbulent Time Scale Measurements in a Spark-Ignition Engine Using Hot Wire Anemometry and Fast Response Ion Probes", Symposium on Flows in I.C. Engines, ASME WAM, 1982.

15. LANCASTER, D.R., KRIEGER, R.B., SORENSON, S.C. and HULL, W.L., "Effects of Turbulence on Spark-Ignition Engine Combustion", SAE 760160, 1976.

16. KRIEGER, R.B. and BORMAN, G.L., "The Computation of Apparent Heat Release for Internal Combustion Engines", ASCE 66-WA/DGP-4, 1966.

17. NAGAYAMA, I., ARAKI, Y. and IOKA, Y., "Effects of Swirl and Squish on S.I. Engine Combustion and Emission", SAE 770217, 1977.

18. LUCAS, G.G. and BRUNT, M.F., "The Effect of Combustion Chamber Shape on the Rate of Combustion in a Spark Ignition Engine", SAE 820165, 1982.

19. DAVIS, G.C., TABACZYNSKI, R.J. and BELAIRE, R.C., "The Effect of Intake Valve Lift on Turbulence Intensity and Burnrate in S.I. Engines-Model Versus Experiment", SAE 240030, 1984.

20. POULOS, S.G. and HEYWOOD, J.B., "The Effect of Geometry on Spark-Ignition Engine Combustion", SAE 830334, 1983.

21. WITZE, P.O., MARTIN, J.K. and BORGNAKKE, C., "Measurements and Predictions of the Precombustion Fluid Motion and Combustion Rates in a Spark Ignition Engine", SAE 831697, 1983.

22. GROFF, E.G. and MATEKUNAS, F.A., "The Nature of Turbulent Flame Propagation in a Homogeneous Spark-Ignited Engine", SAE 800133, 1980.

23. BRANDL, F., REVERENCIC, I., CARTELLIERI, W. and DERT, J.C., "Turbulent Air Flow in the Combustion Bowl of a D.I. Diesel Engine and its Effect on Engine Performance", SAE 790040, 1979.

24. CHARBONGSAI, S., KADOTA, T. and HENEIN, N.A., "The Burning Velocity in a C.F.R. Engine with Different Turbulent Flow Fields Generated by Intake Valve", SAE 800860, 1980.

25. JAMES, E.H., "Investigations of Combustion in 'Squish' Chamber Spark Ignition Engines", ASME 84-DGP-10, 1984.

26. BENSON, R.S. and PICK, R., "Recent Advances in Internal Combustion Instrumentation with Particular Reference to High Speed Data Acquisition and Automated Test Bed", SAE 740695, 1974.

27. WITZE, P.O., "A Critical Comparison of Hot-Wire Anemometry and Laser Doppler Velocimetry for I.C. Engine Applications", SAE 800132, 1980.

28. MOORE, C., "UBC Curve, Curve Fitting Routines", Computing Centre, University of British Columbia, 1984.

29. LANCASTER, D.R., KRIEGER, R.B. and LIENESCH, J.H., "Measurement and Analysis of Engine Pressure Data", SAE 750026, 1975.

30. COLLIS, D.C. and WILLIAMS, M.J., "Two Dimensional Convection From Heated Wires at Low Reynold's Numbers", Journal of Fluid Mechanics, Vol. 6, 1959, pp. 357-384.

31. DAVIES, P.O.A.L. and FISHER, M.J., "Heat Transfer From Electrically Heated Cylinders", Proc. Roy. Soc. A., Vol. 280, 1964, pp.

32. KING, L.V., "On Convection of Heat From Small Cylinders in a Stream of Fluid in Determination of the Convective Constants of Small Platinum Wires with Application to Hot Wire Anemometry", Proc. Roy. Soc., Vol. 214A, No. 14, 1974.

33. VAN WYLEN, G.J. and SONNTAG, R.E., "Fundamentals of Classical Thermodynamics", John Wiley & Sons, 1978.

34. RASK, R.B., "Comparison of Window, Smoothed-Ensemble, and Cycle-by-Cycle Data Reduction Techniques for Laser Doppler Anemometer Measurements of In-Cylinder Velocity", Symposium on Fluid Mechanics of Combustion Systems, ASME FED, Spring Meeting, 1981.

35. CATANIA, A.E. and MITTICA, A., "A Contribution to the Definition and Measurement of Turbulence in a Reciprocating I.C. Engine", ASME 85-DGP-12, 1985.

36. JONES, A.L., "The Performance of a Turbocharged Spark-Ignition Engine Fuelled with Natural Gas and Gasoline", M.A.Sc. Thesis, University of British Columbia, 1985.

37. KECK, J.C., "Turbulent Flame Structure and Speed in Spark Ignition Engines", Nineteenth Symposium {International} on Combustion, The Combustion Institute, 1982, p. 1451-1466.

38. LAVOIE, G., HEYWOOD, J.B. and KECK, J.C., "Experimental and Theoretical Study of Nitric Oxide Formation in Internal Combustion Engines", Combustion, Science & Technology 1, 313, 1970.

39. ANNAND, W.J.D., "Heat Transfer in the Cylinders of Reciprocating Internal Combustion Engines", Proc. I. Mech. E., Vol. 177, No. 36, 1963.

40. VINES, R.F., "The Platinum Metals and Their Alloys", The International Nickel Company, Inc., New York, New York, 1941.

41. NICOL, T., "Integration (Quadrature) Routines", Computing Centre, University of British Columbia, 1982.

APPENDIX A - CALIBRATION CURVES

In this appendix the calibration curves for the Meriam laminar flow element, used to monitor natural gas flow, and the orifice plate used to monitor air intake flow to the C.F.R., are presented. The calibration for the laminar flow element was supplied by the manufacturer. The laminar flow element was used to calibrate the orifice plate.
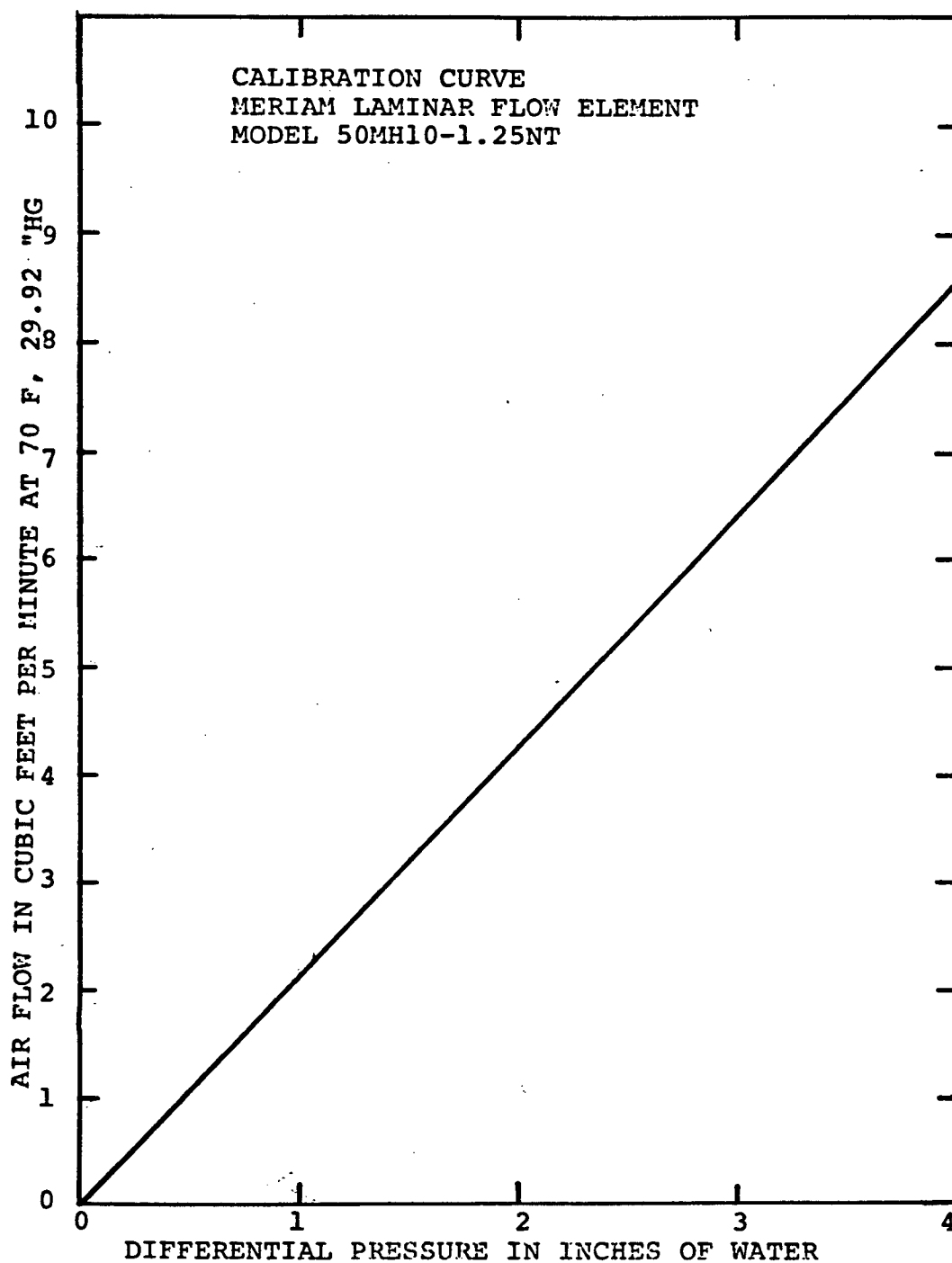
Figure A.1. Calibration curve for laminar flow element.
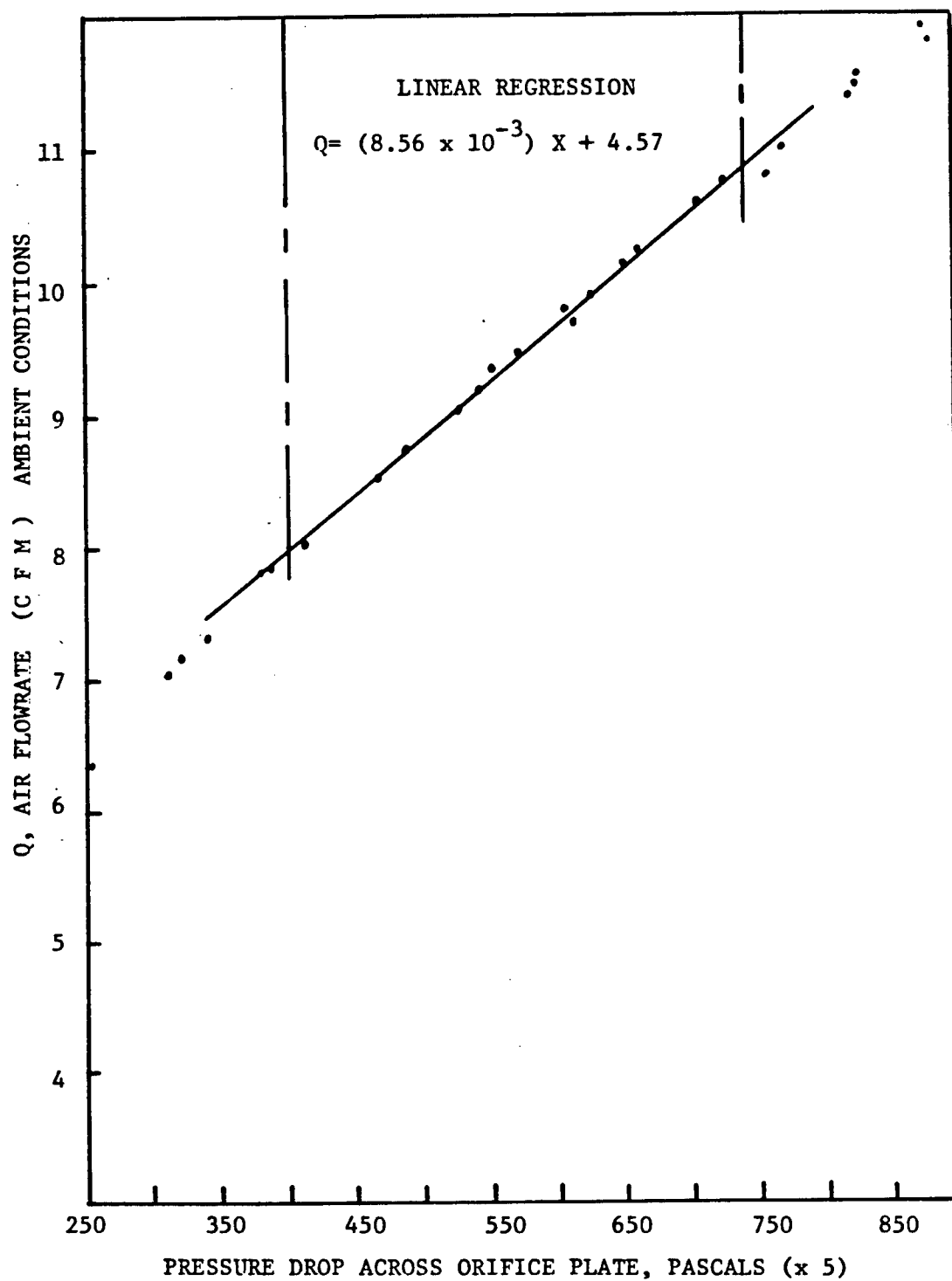
Figure A.2.   Calibration curve for orific metre.

APPENDIX B - HOT WIRE CALIBRATION PROCEDURE

In this appendix the preparation and calibration of hot wire probes for measurement of air movement within the C.F.R. cylinder are described.

1. Welding and Preparation

Wire breakage was a frequent occurence during the course of experiments and thus it became necessary to establish a routine repair procedure.

Platinum Iridium wire (diameter = 6.3 micrometers) obtained from TSI Incorporated was spot welded onto the support needles. The welding was performed with the aid of a microscope and a Disa welding unit model 55A12. Each welded wire was inspected visually for any defects or contamination after welding.

The resistance of the sensor was measured by placing it into the anemometer bridge circuit and adjusting the variable load resistance until bridge balance was achieved. The resistance of the cable and the internal resistance of the probe were accounted for in this procedure. The internal resistance of the probe varied from weld to weld but was generally between 0.58 and 0.80 ohms. Some sensors were found to have a high weld resistance after repair. These wires were maintained at a high overheat ratio until the resistance dropped and stabilized. If the weld resistance remained high the wires were discarded.

2. Calibration

The probes were calibrated in an open wind tunnel with a pitot tube at ambient conditions for air speeds ranging from 0.5 to 20 m/s. The wire was operated at a temperature of 600°C. The operating temperature of 600°C ws

selected because Vines [40] has reported that above this temperature platinum-iridium wire undergoes a phase transformation and thus its resistance characteristics are altered. The operating resistance of the wire was determined from:

$$R_{OP} = R_0 + R_0 \alpha_0 (T_{OP} - T_0) \qquad (A.1)$$

where α_0, R_0, T_0 were supplied by the manufacturer.

From the pitot tube data a Reynolds number was formed based on the wire diameter and the ambient air conditions. From the corresponding anemometer voltage a Nusselt number was calculated again based on the air conditions. From the calibration data a correlation was formed. The analytical method is described in the next section.

3. Analytical Procedure for Correlation

The hot wire anemometer registers the change in resistance (electrical) which results from the heat transfer from the sensor. Heat is transferred by radiation, buoyant convection, forced convection by the flow, and conduction along the wire to the supports. The radiation portion is small and can be neglected. Also for all applications except those involving very small velocities buoyancy may be neglected. Thus forced convection induced by the flow and conduction to the supports are the main modes of heat transfer.

Because the convection heat transfer process is a function of the driving temperature differential and fluid properties such as viscosity, density, and conductivity the sensor response is sensitive to changes in temperature and pressure in the flow. Ideally a probe should be calibrated

over the range of temperatures and pressures encountered in the engine cylinder. However this is not a practical solution in light of the frequent occurence of wire breakage. Thus it becomes necessary to rely on analytical models to correct for variations from the calibrated conditions.

Most of the universal calibrations developed are modifications to the theory of King [32] and express the Nusselt number as a function of the Reynolds number in the form:

$$Nu = a + b\, Re^h \tag{A.2}$$

where a, b, and n are determined from calibration. The Nusselt number is also a function of the Prandtl number; however, since the Prandtl number is almost constant in air (about 0.7) it is not considered explicitly in the correlation.

In this study an approach similar to that of Davies and Fisher as proposed by Witze [27] was taken. In this method the one dimensional energy equation for the wire is solved to obtain an expression for the temperature distribution along the wire. This temperature distribution is integrated along the wire to yield a mean wire temperature:

$$T_M = \frac{2(T_p - C_1)}{\sqrt{C_2}\,\ell}\, \tanh\,[\sqrt{C_2}\,\ell/2] + C_1 \tag{A.3}$$

where

$$C_1 = \frac{hT_g + I^2 R_0 (1 - \alpha_0 T_0)/(\pi d\ell)}{h - I^2 R_0 \alpha_0/(\pi d\ell)} \tag{A.4}$$

and

$$C_2 = 4[h - I^2 R_0 \alpha_0/(\pi d\ell)]/k_w d \tag{A.5}$$

where h is the heat transfer coefficient, T_p is the sensor support temperature, T_g is the gas temperature, k_w is the mean thermal conductivity of the wire, R_0 is the resistance of the wire at the reference temperature T_0, α_0 is the temperature coefficient of resistance for the wire, and I is the current through the wire. Since the mean wire temperature is fixed at 600°C, the only unknown in the above equations is h, the heat transfer coefficient. Iteration can be used to find h. The Nusselt number is then formed.

4. Hot Wire Calibration Computer Program HWCAL

This program uses the data obtained to fit a correlation of the form of Equation (A.2). The program uses a nonlinear least squares method [28] to fit the data.

Inputs to the program are the ambient conditions temperature and pressure, operating resistance of the wire, and the calibration data pressure differential and anemometer bridge voltage.

The data is processed within the subroutine ANEM to obtain Nusselt number, as described in the previous section, and Reynolds numbers from the pitot tube data. The arrays of Reynold and Nusselt numbers are then passed to the curve fitting program NL2SOL from the U.B.C. curve fitting library [20]. The outputs of the program are the calibration constants a,b,n and the residuals.

A program listing and flow chart follows.

DEFINITION OF PROGRAM SYMBOLS

A	Constant
ALFAO	Temperature coefficient of wire resistance
B	Constant
C2	Constant C2 in Equation A.5
D	Diameter of wire
EV	Anemometer bridge voltage corresponding to flow measurement
H	Heat transfer coefficient
IV	Working array of curve fit routine
KG	Thermal conductivity of gas
KW	Thermal conductivity of wire
L	Length of wire
NV	Nusselt number
P	Coefficient array
RE	Reynolds number
RHO	Density of gas
RO	Ice point resistance of wire
RW	Operating resistance of wire
V	Pressure differential corresponding to pitot tube measurement
VISC	Kinematic viscosity of gas

HWCAL FLOWCHART
CALL SUBROUTINE ANEM

```
┌─────────────────────────────────────────────────────────────────┐
│                            INPUTS                                 │
│   RW, TO, TG, KG, KW, L, D, RHO, ALFAO, RO, RT, V, EV, VISC      │
└─────────────────────────────────────────────────────────────────┘
```

INITIAL CALCULATION

$$A = \frac{EV^2(1-ALFAO*TO)RO}{PI*D*L*RT^2}$$

$$B = \frac{EV^2*ALFAO*RO}{PI*D*L*RT^2}$$

$$HI = \frac{EV^2*RW}{KG*RT^2*PI*D*L(\Delta T)}$$

VELOCITY CALCULATION

$$V = 2*V/RHO$$

HEAT TRANSFER COEFFICIENT

$$C2 = 4*(HI-B)/(KW*D)$$

$$E = \frac{TANH(C2\ L/2)}{C2\ L}$$

$$H = \frac{(A(1-2*E)+B(TW-2*TO*E))}{TW - TG + 2*E(TG-TO)}$$

$$TOL = (H-HI)/HI$$

$$HI = H$$

NO

TOL<0.0001?

H │ YES

NUSSELT NUMBER
NU = H*D/KG

REYNOLDS NUMBER
RE = V*D/VISC

CALL NL2SOL

a, b, n
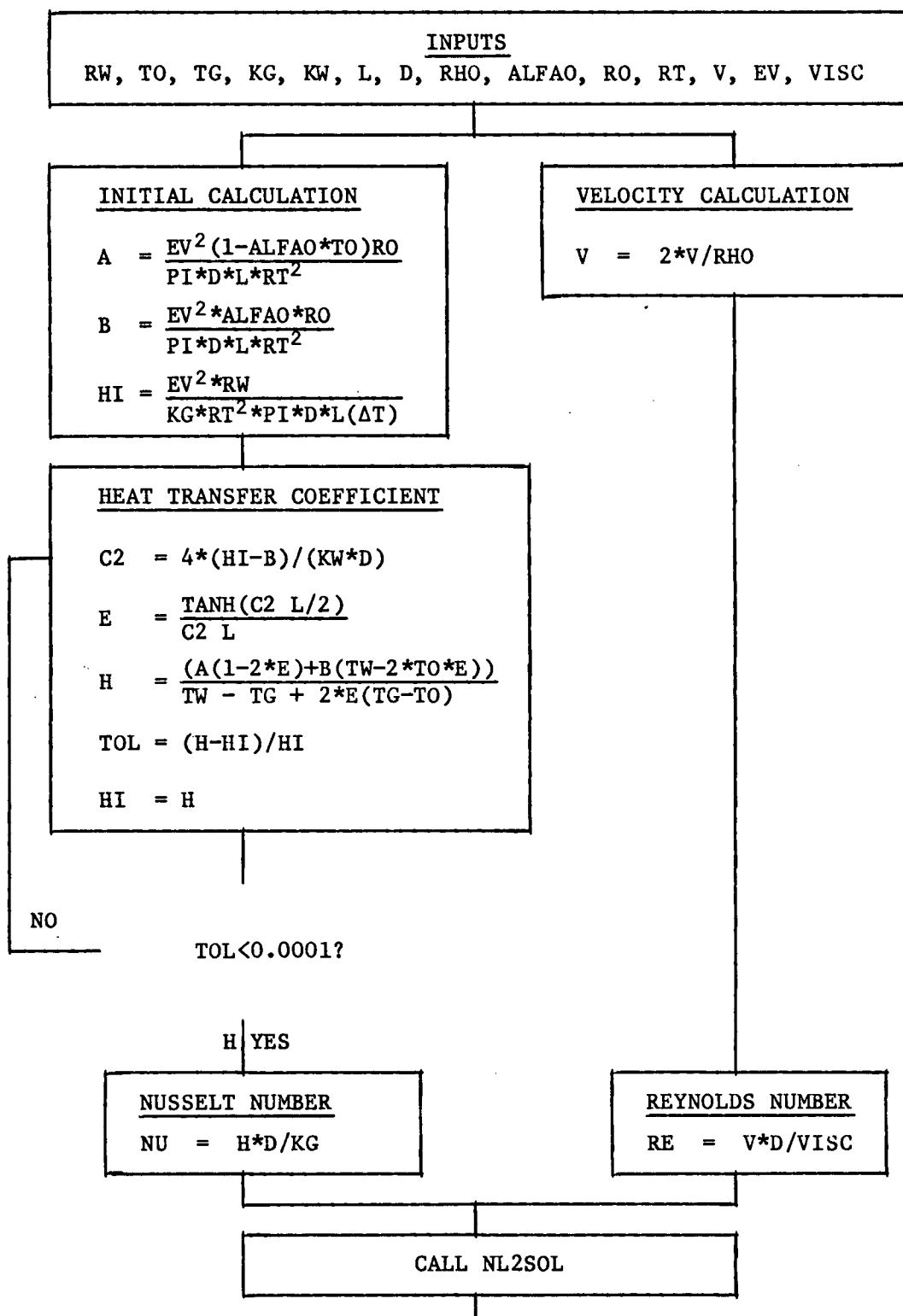
```
  1              IMPLICIT REAL*8 (A-H,O-Z)
  2              DIMENSION P(3),IV(65),V(350)
  3              EXTERNAL CALCR,CALCJ
  3.5            COMMON X(20),Y(20)
  4              M=3
  5              CALL ANEM(N)
  8              P(1)=0.25DO
  9              P(2)=0.25DO
 10              P(3)=0.45DO
 10.5            FIND (7'1000)
 11              DO 88 JJ=1,N
 11.5            READ(7,89) X(JJ),Y(JJ)
 11.7     89     FORMAT(2F20.2)
 11.8     88     CONTINUE
 12              IV(1)=O
 17              CALL NL2SOL(N,M,P,CALCR,CALCJ,IV,V,IPARM,RPARM,FPARM)
 18              WRITE(6,300) IV(1)
 19      300     FORMAT(' RETURN CODE = ',I2)
 20              WRITE(6,301) (P(I),I=1,3),V(10)
 21      301     FORMAT(' SOLUTION: ',1P3G16.8/
 22        1            ' SUM OF SQUARES/2 =',1PG16.8)
 31              STOP
 32              END
 33              SUBROUTINE CALCR(N,M,P,NF,R,IPARM,RPARM,FPARM)
 34              IMPLICIT REAL*8(A-H,O-Z)
 35              DIMENSION P(M),R(N)
 36              COMMON X(20),Y(20)
 37              DO 100 I=1,N
 38              R(I)= P(1) + P(2)*X(I)**P(3) - Y(I)
 40      100     CONTINUE
 43              RETURN
 44              END
 45              SUBROUTINE CALCJ(N,M,P,NF,D,IPARM,RPARM,FPARM)
 46              IMPLICIT REAL*8(A-H,O-Z)
 47              DIMENSION P(M),D(N,M)
 47.2            COMMON X(20),Y(20)
 47.7            DO 100 I=1,N
 47.8            D(I,1)=1.DO
 47.9            D(I,2)=X(I)**P(3)
 47.95           D(I,3)=P(2)*(X(I)**P(3))*DLOG(X(I))
 47.97    100    CONTINUE
 48              RETURN
 49              END
 50              SUBROUTINE ANEM(NDAT)
 51              REAL*8  KW,KG,L,D,RO,ALFAO,TO,TG,RW,TW,A,B,HI,C2,E,H
 52              REAL*8 RE(18),NU(18),EV(18),V(18),VO
 53              KW=18.DO
 54              KG=0.0251DO
 55              L=1.5E-03
 56              D=6.30E-06
 57              ALFAO=0.0009
 58              TO=293.15
 59              WRITE(6,1)
 60        1     FORMAT(' AMBIENT TEMPERATURE  = ?')
 61              CALL FREAD('GUSER','R:',TO)
 62              WRITE(6,2)
 63        2     FORMAT(' GAS TEMPERATURE = ?')
 64              CALL FREAD('GUSER','R:',TG)
```

```
65              WRITE(6,3)
66      3       FORMAT(' AMBIENT RESISTENCE OF WIRE = ?')
67              CALL FREAD('GUSER','R:',RAMB)
68              WRITE(6,4)
69      4       FORMAT(' OPERATING RESISTANCE OF WIRE = ?')
70              CALL FREAD('GUSER','R:',RW)
71              WRITE(6,5)
72      5       FORMAT(' NUMBER OF DATA POINTS = ?')
73              CALL FREAD('GUSER','I:',NDAT)
74              DO 999 J=1,NDAT
75              WRITE(6,6)
76      6       FORMAT(' PRESSURE DIFFERENTIAL = ?')
77              CALL FREAD('GUSER','R:',V(J))
78              WRITE(6,7)
79      7       FORMAT(' ANEMOMETER VOLTAGE = ?')
80              CALL FREAD('GUSER','R:',EV(J))
81      999     CONTINUE
82              WRITE(6,8)
83      8       FORMAT('ICE POINT RESISTANCE OF WIRE ? ')
84              CALL FREAD('GUSER','R:',RO)
85              TW=(RW-RO)/(ALFAO*RO)
86              TG=TG+273.15
86.5            RA=RAMB
87              TO=TO+273.15
87.5            TL=TO-273.15
88              RT=RW+50.214
89              TW=TW+273.15
90              ALFAO=0.0009
91              DO 10 J=1,NDAT
92              NCOUNT=0
93              V(J)=DSQRT(2.0*V(J)/1.144)
94              A=EV(J)**2*(1.-ALFAO*(273.15))/(3.141593*D*L*RT**2)*RC
95              B=EV(J)**2*ALFAO/(3.141593*D*L*RT**2)*RO
96              HI=EV(J)**2/(KG*(RT**2)*3.141593*D*L*(TW-TG))*RW
97      22      C2=4*(HI-B)/(KW*D)
98              NCOUNT=NCOUNT+1
99              IF (NCOUNT .GT. 100) GO TO 100
100             E=DTANH(DSQRT(C2)*L/2)/(DSQRT(C2)*L)
101             H=(A*(1.-2*E)+     B*(TW-2*TO*E))/(TW-TG+2*(TG-TO)*E)
102             TOL=    DABS((H-HI)/HI)
103             HI=H
104             IF    (TOL    .GT.    0.001)    GO    TO    22
105             NU(J)=H*D/KG
106             RE(J)=     V(J)*D/15.7E-06
111     10      CONTINUE
111.2           DO 102 J=1,NDAT
111.5           WRITE(7,101) RE(J),NU(J)
111.7   101     FORMAT(2F20.2)
111.8   102     CONTINUE
112             GO TO 98
113     100     WRITE(6,99)
114     99      FORMAT(' ','ERROR, TOO MANY ITERATIONS N=100!')
115     98      CONTINUE
116             RETURN
117             END
```

APPENDIX C - DATA ACQUISITION PROGRAMS

In this appendix the computer programs used for data acquisition are presented. The first program CDAQ, was used to collect data directly from the experiments. The second program BYTRD was used to transfer the digital data from floppy discs to the MTS system.

1. Data Acquisition from C.F.R. CDAQ

This program was used to acquire pressure and anemometer data from the C.F.R. engine. The program CDAQ was loaded into the I.B.M. microcomputer which was interfaced with an ananlogue to digital conversion board. The program CDAQ was linked with PCLAB software [41] so that commands for analogue to digital conversions could be issued from the terminal.

CDAQ is an interactive program which allows the user to select sample rate, gain, and amount of data to be taken. The user may also view stored data digitally or graphically.

CDAQ acquires data in blocks of 32K bytes. Each analogue data point is converted to a half word (2 byte) integer. Thus each block contains 16K data points. Once data acquisition is initiated CDAQ allows 16K analogue to digital conversions to occur. Each data point is stored in a 16K array. Once a block is complete CDAQ transfers the block to a file on a diskette. If more than one block was requested CDAQ then goes back for more.

A flow chart and the program listing follows.

CDAQ FLOWCHART

```
┌─────────────────────────────────┐
│   INITIALIZATION PROCEDURES      │
│  FOR DATA ACQUISITION SYSTEM     │
└─────────────────────────────────┘
┌─────────────────────────────────┐
│    INPUT DESIRED GAIN FACTOR     │
└─────────────────────────────────┘
        ┌──────────┐
        │   TAKE   │
        │    OR    │
        │   VIEW   │
        │   DATA   │
        └──────────┘
┌─────────────────────────────────┐
│   INPUT DESIRED SAMPLE RATE      │
│    AND NUMBER OF DATA BLOCKS     │
└─────────────────────────────────┘
┌─────────────────────────────────┐
│      START DATA ACQUISITION      │
└─────────────────────────────────┘
┌─────────────────────────────────┐
│     PERFORM A/D CONVERSION,      │
│   PUT RESULT IN THE INTEGER      │
│     ARRAY ANALOG. DATA%          │
└─────────────────────────────────┘
NO  ┌──────────────┐
    │  REM = REM - 1 │
    └──────────────┘
    ┌──────────────┐
    │   REM 50?    │
    └──────────────┘
┌─────────────────────────────────┐
│  WRITE DATA BLOCK TO RAMDRIVE    │
│      NBLCK = NBLK - 1            │
└─────────────────────────────────┘
NO  ┌──────────────┐
    │   NBLK = 0?  │
    └──────────────┘
┌─────────────────────────────────┐
│        VIEW THE DATA?           │   NO
└─────────────────────────────────┘
┌─────────────────────────────────┐
│     WHICH BLOCK AND CYCLE?       │
└─────────────────────────────────┘
    ┌──────────────┐
    │  VIEW MORE?  │
    └──────────────┘
YES
┌─────────────────────────────────┐
│   WRITE DATA TO FLOPPY DISC      │
└─────────────────────────────────┘
            STOP
```

MANUAL
SWITCH

```
10 ' CFRDAQ.BAS    This program acquires pressure or anemmometer data from
20 ' ==========    the C.F.R. engine.
30 '
40 PRINT "THIS PROGRAM ACQUIRES CYLINDER PRESSURE OR HOT WIRE ANEMOMETER"
50 PRINT "DATA FROM THE CFR ENGINE AND STORES THE VALUES ON DISK."
60 PRINT
70 '
80 TIMEOUT% = 20
90 CALL SET.TIMEOUT(TIMEOUT%)
100 '
110 PORT.SELECT% = 2
120 CALL ENABLE.FOR.OUTPUT(PORT.SELECT%)    'Enable both output ports
130 '
140 NCHAN%=0
148 PRINT
149 INPUT; "INPUT DESIRED GAIN (1,2,4, OR 8)";GAIN%
150 TIMING.SOURCE% = 3
190 START.CHAN% = NCHAN%
200 END.CHAN% = NCHAN%
210 '
220 CALL SETUP.ADC(TIMING.SOURCE%, START.CHAN%, END.CHAN%, GAIN%)
230 '
240 DEFINT V,X,Y,N,I,M,Z
250 DIM DUMMY%(14000),ANALOG.DATA%(16100)
260 INC%=0
270 PRINT
280 INPUT; "TAKE NEW DATA (1) OR VIEW DATA IN RAMDRIVE (2) "; Q%
290 RATE=1
300 IF Q%=1 GOTO 320
310 IF Q%=2 GOTO 1110
320 PRINT
330 PRINT "TO SET THE SAMPLE RATE, ADJUST THE THUMBWHEEL SWITCHES ON THE FRONT"
340 PRINT "OF THE CIRCUIT BOX TO: 01, 02, 05, OR 10, CORRESPONDING TO SAMPLING"
350 PRINT "AT EVERY 0.2, 0.4, 1, OR 2 DEGREES CRANK ANGLE RESPECTIVELY, ALSO,"
360 PRINT "INPUT THE RATE SELECTED (0.2, 0.4, 1.0 OR 2.0)"
370 INPUT; RATE
380 PRINT
390 INPUT; "HOW MANY BLOCKS OF DATA DO YOU WANT (MAX. 10) "; NBLOCK
400 PRINT
410 PRINT
420 N = 16000            'Sets the number data points taken in each block
430 K%=RATE*4300         'Sets the delay time for data acquisition
440 NUMBER.OF.ELEMENTS% = N
450 M=N*2                'Sets the number of bytes of memory for data
460 '
470 INPUT; "PRESS RETURN KEY TO START   "; A$
480 PRINT
490 PRINT "DATA BEING ACQUIRED........ "
500 PRINT
510 INC%=INC%+1 '           'Counts number of blocks of data acquired
520 '
525 PRINT "FLIP TOGGLE ON"
526 PRINT
530 'The following section sends the number of data points to be taken per
540 'block to the circuit boards. Only this number of clock pulses will be
550 'allowed through to the data acquisition board.
560 '
570 D.MASK% = &H8000     'Mask all the lines except 15 (load line)
580 D.VALUE% = &H0       'Set load line low
590 CALL OUTPUT.DIGITAL.VALUE(PORT.SELECT%, D.MASK%, D.VALUE%)
600 '
610 D.MASK% = &H7FFF     'Mask line number 15
620 D.VALUE% = N+2       'Set the other lines to the number of samples
```

```
630 CALL OUTPUT.DIGITAL.VALUE(PORT.SELECT%, D.MASK%, D.VALUE%)
640 '
650 FOR I = 1 TO 80        'Delay for sufficient load time
660 NEXT I
670 '
680 D.MASK% = &H8000       'Mask every line except 15
690 D.VALUE% = &H8000      'Set line 15 high (load line)
700 CALL OUTPUT.DIGITAL.VALUE(PORT.SELECT%, D.MASK%, D.VALUE%)
710 '
720 'Start data acquisition....
730 '
740 CALL CONTINUOUS.ADC.DMA(NUMBER.OF.ELEMENTS%, ANALOG.DATA%(1))
750 CALL TEST.ADC.DMA(COUNT.REM%)
760 IF COUNT.REM%>50 GOTO 750
770 '
780 '
790 CALL STOP.ADC.DMA
800 PRINT "COUNT.REM = ", COUNT.REM%
810 NEG%=-INC%
820 A$=STR$(NEG%)
830 B$="C:DATA."+A$
840 '
850 Z=0
860 Z=VARPTR(ANALOG.DATA%(1))    'Finds the memory location of start of array
870 BSAVE B$,Z,M                 'Saves the 16k data block to Ramdrive C:
880 '
885 PRINT
886 PRINT "FLIP TOGGLE OFF"
900 IF INC% < NBLOCK  GOTO 510
910 PRINT
920 PRINT "<<<<<<< DATA ACQUISITION COMPLETE >>>>>>>"
930 PRINT
940 INPUT; "DO YOU WANT TO VIEW THE DATA (Y/N)  "; ANS$
950 IF ANS$="Y" THEN 1110
960 IF ANS$="y" THEN 1110
970 PRINT
980 PRINT "DATA RESIDES IN RAMDRIVE C: AND CAN NOW BE TRANSFERED TO DISK B:"
990 PRINT
1000 INPUT; "DO YOU WANT TO STORE THE DATA "; ANS$
1010 IF ANS$="Y" GOTO 1070
1020 IF ANS$="y" GOTO 1070
1030 PRINT
1040 INPUT; "DO YOU WISH TO TAKE MORE DATA? "; ANS$
1050 IF ANS$="Y" GOTO 260
1060 IF ANS$="y" GOTO 260
1070 END
1080 '
1090 '
1100 '
1110 PRINT
1120 INPUT; "WHICH DATA BLOCK DO YOU WISH TO VIEW  "; NVIEW%
1130 PRINT
1140 INPUT; "INPUT N TO VIEW CYCLES 1,1+N,1+2N ETC";V%
1150 PRINT
1160 '
1170 S%=1
1180 NEG=-NVIEW%
1190 A$=STR$(NEG)
1200 B$="C:DATA."+A$
1210 PRINT B$
1220 Z=VARPTR(ANALOG.DATA%(1))
1230 BLOAD B$,Z
1235 S%=S%-1
1240 INPUT; "DO YOU WISH TO LIST THE DATA "; ANS$
1250 IF ANS$="N" GOTO 1340
```

```
1270 L1=540/RATE-50
1280 L2=540/RATE+50
1290 PPC%=720/RATE
1300 FOR I = L1 TO L2
1310 PRINT I,ANALOG.DATA%(I+S%*PPC%)
1320 NEXT I
1330 INPUT; U%
1340 KEY OFF
1350 SCREEN 2,,0,0
1360 LINE (100,90)-(460,90)
1370 LINE (100,1)-(460,1)
1380 LINE (100,180)-(460,180)
1390 LINE (100,1)-(100,180)
1400 LINE (460,1)-(460,180)
1410 LINE (100,45)-(105,45)
1420 LINE (460,45)-(455,45)
1430 LINE (460,135)-(455,135)
1440 LINE (100,135)-(105,135)
1450 LINE (280,180)-(280,176)
1460 LOCATE 12,7,0 :PRINT "0.00";
1470 LOCATE 1,7,0 :PRINT "10.0";
1480 LOCATE 6,7,0 :PRINT " 5.0";
1490 LOCATE 23,6,0 :PRINT "-10.0";
1500 LOCATE 18,7,0 :PRINT "-5.0";
1510 LOCATE 25,40,0 :PRINT "DEGREES C.A.";
1520 LOCATE 9,1,0 :PRINT "VOLTS";
1530 LOCATE 1,20,0 :PRINT " ENGINE PRESSURE TRACE ";
1540 LOCATE 24,13,0 :PRINT "0";
1550 LOCATE 24,35,0 :PRINT "360";
1560 LOCATE 24,57,0 :PRINT "720";
1570 LOCATE 1,1,0
1580 FOR X = 100 TO 460
1590 Y = 180 - ANALOG.DATA%(((X-99)*2/RATE)+(S%*PPC%))/23
1600 PSET(X,Y)
1609 NEXT X
1610 INPUT; ST$
1611 SCREEN 0
1612 S%=S%+V%+1
1615 IF S%<=(22*RATE) GOTO 1235
1640 '
1650 INPUT; "DO YOU WANT TO VIEW ANOTHER BLOCK? "; ANS$
1660 IF ANS$="Y" GOTO 1110
1670 IF ANS$="y" THEN 1110 ELSE 960
1680 '
1690 'PROGRAM END.
```

2. Conversion of Digital Data to MTS (BYTRD)

This program was used to convert integer data from CDAQ into a form which could be read by the MTS system. This was necessary because the IBM microcomputer stored half word integers with the low order byte first, high order byte second and MTS uses the opposite order. The program reads the integer data as logical variables, in array form. The array indexes are interchanged and then the logical array is read into an integer array. BYTRD also strips off the seven byte label placed before each block of data by CDAQ.

A flow chart and program listing follow.

BYTRD FLOWCHART

```
┌─────────────────────────────────────────────────┐
│    LOGICAL*1 PC(64), MTS(64), SAVE, SAVB          │
│           INTEGER LNUM, NLINE                     │
│         INTEGER*2 LEN, DAT(32)                    │
└─────────────────────────────────────────────────┘
┌─────────────────────────────────────────────────┐
│            EQUIVALENCE (DAT,MTS)                  │
└─────────────────────────────────────────────────┘
┌─────────────────────────────────────────────────┐
│         CALL READ (PC,LEN,0,LNUM,5)              │
└─────────────────────────────────────────────────┘
┌─────────────────────────────────────────────────┐
│                    J = 8                          │
└─────────────────────────────────────────────────┘
┌─────────────────────────────────────────────────┐       ┌───────────┐
│                  K = J-7                          │       │ J = J + 2 │
└─────────────────────────────────────────────────┘       └───────────┘
┌─────────────────────────────────────────────────┐
│              MTS(K) = PC(J+1)                     │
└─────────────────────────────────────────────────┘
┌─────────────────────────────────────────────────┐
│               MTS(K+1) = PC(J)                    │
└─────────────────────────────────────────────────┘
┌─────────────────────────────────────────────────┐
│                   J < 62?                         │   NO
└─────────────────────────────────────────────────┘
┌─────────────────────────────────────────────────┐
│                SAVE = PC(64)                      │
└─────────────────────────────────────────────────┘
┌─────────────────────────────────────────────────┐
│         WRITE DAT(K), K=1,28 TO FILE             │
└─────────────────────────────────────────────────┘
┌─────────────────────────────────────────────────┐
│      INPUT NUMBER OF LINES IN FILE, NLINE         │
└─────────────────────────────────────────────────┘
┌─────────────────────────────────────────────────┐
│               NLINE = NLINE - 1                   │
└─────────────────────────────────────────────────┘
┌─────────────────────────────────────────────────┐
│         CALL READ (PC,LEN,0,LNUM,5)              │
└─────────────────────────────────────────────────┘
┌─────────────────────────────────────────────────┐
│                MTS(1) = PC(1)                     │
│                MTS(2) = SAVE                      │
└─────────────────────────────────────────────────┘
┌─────────────────────────────────────────────────┐
│                    K = 3                          │
└─────────────────────────────────────────────────┘
┌─────────────────────────────────────────────────┐       ┌───────────┐
│                MTS(K) = PC(K)                     │       │ K = K + 2 │
│               MTS(K+1) = PC(K-1)                  │       └───────────┘
└─────────────────────────────────────────────────┘
┌─────────────────────────────────────────────────┐   NO
│                   K < 63                          │
└─────────────────────────────────────────────────┘
┌─────────────────────────────────────────────────┐
│                SAVE = PC(64)                      │
└─────────────────────────────────────────────────┘
┌─────────────────────────────────────────────────┐
│         WRITE DAT(K), K=1,32 TO FILE             │
└─────────────────────────────────────────────────┘
   NO    ┌─────────────────────────────────────────────────┐
         │                  NLINE = 0?                       │
         └─────────────────────────────────────────────────┘
                              STOP
```
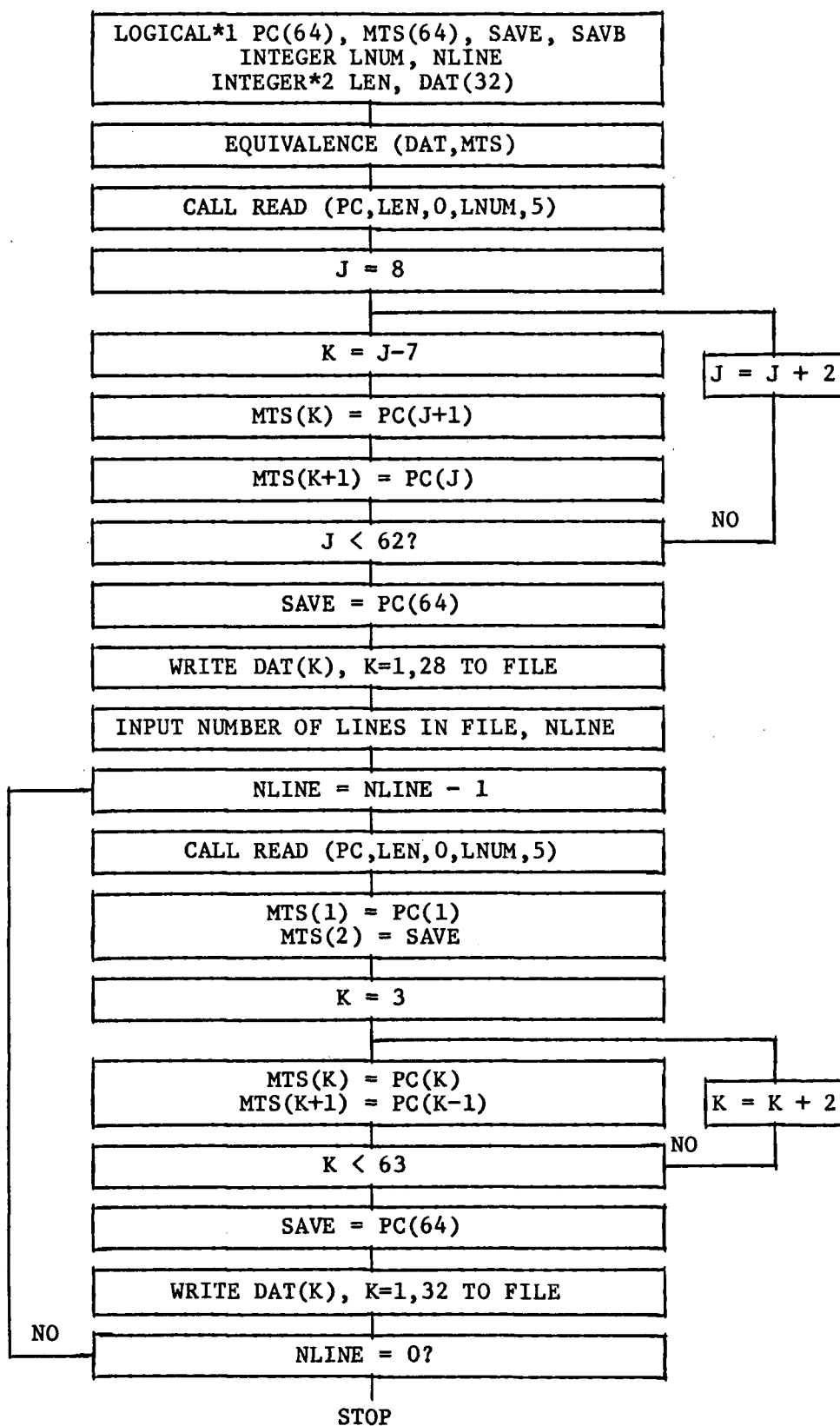
```
    1                  LOGICAL*1 PC(64),MTS(64),SAVB,SAVE
    2                  INTEGER LNUM,NLINE
    3                  INTEGER*2 LEN,DAT(32)
    4                  EQUIVALENCE(DAT,MTS)
    5                  LEN=2
    5.5                JJ=1
    6                  CALL READ(PC,LEN,O,LNUM,5)
    7        10        DO 1 J=8,62,2
    8                  K=J-7
    9                  MTS(K)=PC(J+1)
   10                  MTS(K+1)=PC(J)
   11         1        CONTINUE
   11.5                NFLG=1
   12                  SAVE=PC(64)
   13                  WRITE(7,99) (DAT(K),K=1,28)
   13.5                IF (JJ.GT. 1 ) GO TO 11
   14                  WRITE(6,100)
   15       100        FORMAT(' ','HOW MANY LINES ARE IN YOUR FILE ?')
   16                  CALL FREAD('GUSER','I:',NLINE)
   18        11        JJ=JJ+1
   19                  NREC=JJ*1000
   20                  FIND(7'NREC)
   21                  CALL READ(PC,LEN,O,LNUM,5)
   21.5                NFLG=NFLG + 1
   21.7                IF (NFLG .EQ. 503) GO TO 10
   22                  MTS(1)=PC(1)
   23                  MTS(2)=SAVE
   24                  DO 2 K=3,63,2
   25                  MTS(K)=PC(K)
   26                  MTS(K+1)=PC(K-1)
   27         2        CONTINUE
   28                  SAVE=PC(64)
   29                  WRITE(7,99) (DAT(K),K=1,32)
   29.5      99        FORMAT(' ',32I5)
   30                  IF (JJ .LE. NLINE) GO TO 11
   31                  STOP
   32                  END
```

APPENDIX D - HOT WIRE ANEMOMETER DATA PROCESSING PROGRAMS

1. Instantaneous Velocity Evaluation and Ensemble Averaging (ANEM)

In this section the program used to process the digitized anemometer signal to obtain an instantaneous velocity is described. All anemometer data for which velocity was required was processed with this program. Included in this program is the ensemble technique described in Chapter 6.4.1. The outputs of this program are the instantaneous velocity every 1/5 of a crank angle degree for 40 or more engine cycles, the ensemble averaged mean velocity, and the ensemble averaged turbulence intensity.

The inputs to this program are the digitized anemometer voltage; the calibration constants a,b, and n for the hot wire correlation (Equation (5.1)), and the ensemble averaged pressure trace. The pressure trace contains data points for every crank angle degree in the engine cycle. At each point the temperature of the cylinder air is calculated assuming an adiabatic process (Equation (6.5)); the thermal conductivity is calculated from Equation (6.8), and the kinematic viscosity is calculated from Equation (6.9). The reference condition was taken at the point of intake valve closing, where the pressure and temperature were taken as the ambient condition.

The anemometer data is first converted back to a voltage using the appropriate system gain and offset. Then the heat transfer coefficient from Equations 6.2, 6.3, and 6.4 is solved for using the iteration technique described in Appendix B. Once the heat transfer coefficient has been determined the Nusselt number may be formed and from the correlation (Equation (5.12) the velocity may be solved for.

The instantaneous velocity obtained for each point is stored for later

processing by other programs. In addition as the program runs through the data a cumulative sum of the instantaneous velocity as well as the square of the instantaneous velocity is kept. After all the data has been processed the ensemble average mean velocity and turbulence intensity is obtained from Equation 6.10 and 6.12 respectively.

A flow chart and a program listing follow.

Definition of Program Symbols (ANEM)

AA	Intercept for Nu-Re Correlation
ALFAO	Temperature Coefficient of Resistance for Wire
BB	Slope for Nu-Re Correlation
CEV	Anemometer Voltage Obtained from Digital Data
D	Wire Diameter
EV	Digitized Anemometer Voltage
H	Heat Transfer Coefficient
KG	Thermal Conductivity of Gas
KW	Thermal Conductivity of Wire
LN	Wire Length
NBLK	Number of 32K Byte Data Blocks
NEW	Kinematic Viscosity of Gas
NEXP	Exponent for Nu-Re Correlation
NU	Nusselt Number
P	Pressure
PPC	Data Points Per Engine Cycle
RAMB	Ambient Resistance of Wire
RATE	Data Acquisition Rate
RE	Reynolds Number
RO	Ice Point Resistance of Wire
RW	Operating Resistance of Wire
TG	Temperature of Gas
TO	Ambient Temperature
VENS	Ensemble Averaged Mean Velocity
UPRIME	Ensemble Averaged RMS Velocity
UTOT	Instantaneous Velocity

```
┌─────────────────────────────────────────────────────────────┐
│  INPUTS                                                        │
│                                                                │
│  TO,RAMB,RW,RO,AA,BB,NEXP,NCYC,KW,ALFAO,LN                     │
│  P,TG,KG,NEW,EV                                                │
└─────────────────────────────────────────────────────────────┘
┌─────────────────────────────────────────────────────────────┐
│               NCYC = NCYC -1                                   │
└─────────────────────────────────────────────────────────────┘
┌─────────────────────────────────────────────────────────────┐
│        CONVERT DIGITIZED DATA TO VOLTAGE                       │
└─────────────────────────────────────────────────────────────┘
```

INITIAL CALCULATION

$$A = \frac{EV^2(1-ALFAO*TO)RO}{PI*D*L*RT^2}$$

$$B = \frac{EV^2*ALFAO*RO}{PI*D*L*RT^2}$$

$$HI = \frac{EV^2*RW}{KG*RT^2*PI*D*L(\Delta T)}$$

HEAT TRANSFER COEFF

$$C2 = 4*(HI - B)/(KW*D)$$

$$E = \frac{TANH(\ C2\ L/2)}{C2\ L}$$

$$H = \frac{(A(1-2*E)+B(TW-2*TO*E))}{TW - TG + 2*E(TG - TO)}$$

$$TOL = (H - HI)/HI$$

$$HI = H$$

TOL < 0.0001?

NO

YES

```
┌─────────────────────────────────────────┐
│ NUSSELT NUMBER CALC                       │
│                                           │
│ NU =H*D/KG(IND)                           │
└─────────────────────────────────────────┘

┌─────────────────────────────────────────┐
│ REYNOLDS NUMBER CALC                      │
│                                           │
│ RE = ((NU-AA)/BB)**NEXP                    │
└─────────────────────────────────────────┘

┌─────────────────────────────────────────┐
│ INSTANTANEOUS VELOCITY CALC               │
│                                           │
│ UTOT=RE*NEW/D                             │
│                                           │
│                                           │
│ UENS(INC)=UENS(INC) + UTOT                │
│ U2(INC) = U2(INC) + UTOT**2               │
└─────────────────────────────────────────┘

          ┌──────────────────┐        NO
          │   NCYC=0  ?       │ ─────────────►
          └──────────────────┘

┌─────────────────────────────────────────┐
│ ENSEMBLE AVERAGE                          │
│                                           │
│ UENS(J)= UENS(J)/NCYC                      │
│ UPRIME(J)=SQRT[U2(J)/NBLK - UENS(J)**2     │
└─────────────────────────────────────────┘

              STOP
```

```
1              REAL      KW,LN,D,RO,ALFAO,TO,TG(720),RW,TW,A,B,HI,C2,E,H
2              REAL      RE,NU,P(720),KG(720),NEW(720),NEXP,AA,BB,RATE,TEMP
2.5            REAL      X(1801),Y1(1801),Y2(1801)
3              REAL      UTOT(3600),UENS(1801),VO,NEV,CEV,U2(1801),UPRIME(1801)
4              INTEGER EV(22,3600),PPC,NCYC,NBLK,ULIM,NREC,IND,DD(3600)
5              KW=18.
7              LN=1.5E-03
8              D=6.3E-06
9              ALFAO=9.0E-04
10             DO 11 J=1,1801
10.5           UENS(J)=0.
10.7           UTOT(J)=0.
10.75          U2(J)=0.
10.77          UPRIME(J)=0.
10.8      11   CONTINUE
11             WRITE(6,1)
12        1    FORMAT(' AMBIENT TEMPERATURE  = ?')
13             CALL FREAD('GUSER','R:',TO)
14             WRITE(6,2)
15        2    FORMAT(' AMBIENT RESISTENCE OF WIRE = ?')
16             CALL FREAD('GUSER','R:',RAMB)
17             WRITE(6,3)
18        3    FORMAT(' OPERATING RESISTANCE OF WIRE = ?')
19             CALL FREAD('GUSER','R:',RW)
20             WRITE(6,4)
21        4    FORMAT(' ICE POINT RESISTANCE OF WIRE = ?')
22             CALL FREAD('GUSER','R:',RO)
23             WRITE(6,5)
24        5    FORMAT(' INTERCEPT FOR NU-RE CORRELATION = ?')
25             CALL FREAD('GUSER','R:',AA)
26             WRITE(6,6)
27        6    FORMAT(' SLOPE FOR NU-RE CORRELATION = ?')
28             CALL FREAD('GUSER','R:',BB)
29             WRITE(6,7)
30        7    FORMAT(' EXPONENT FOR NU-RE CORRELATION = ?')
31             CALL FREAD('GUSER','R:',NEXP)
32             WRITE(6,8)
33        8    FORMAT(' WHAT WAS THE DATA ACQUISITION RATE ?')
34             CALL FREAD('GUSER','R:',RATE)
35             WRITE(6,9)
36        9    FORMAT(' HOW MANY BLOCKS OF DATA WERE TAKEN ?')
37             CALL FREAD('GUSER','I:',NBLK)
38             DO 10 J=1,720
39             READ(4,100) Z,P(J),TG(J),KG(J),NEW(J)
40        10   CONTINUE
41        100  FORMAT(' ',F8.2,2X,F12.2,2X,F12.2,2X,F12.8,2X,F14.10)
42             PPC=720/RATE
43             NCYC=22*RATE
44             ULIM=713/RATE
47             TW=600. + 273.15
48             TO=TO+273.15
48.5      C READ IN THE DIGITIZED HOT WIRE DATA
49             DO 50 J=1,NBLK
49.5           WRITE(6,987) J
49.7      987  FORMAT(' ',I4)
50             NREC=(502*(J-1)+1)*1000
51             FIND(5'NREC)
52             READ(5,200) (EV(1,N),N=35,PPC),((EV(M,N),N=1,PPC),M=2,NCYC),
```

```
52.2          1 (EV(1,N),N=1,34)
53      200     FORMAT(' ',32I5)
53.8            RT=RW+50.214
53.95           NCT=0
54              DO 40 K=1,NCYC
55              DO 30 L=1800,PPC
56              IND=L*RATE
56.7            NCT=NCT+1
57              NCOUNT=0
57.5    C CONVERT THE DIGITIZED DATA TO A VOLTAGE
58              CEV=0.004883*EV(K,L) - 10.
59              NEV=CEV
59.5    C BEGIN ITERATION FOR HEAT TRANSFER COEFFICIENT
60              A=NEV**2*(1.-ALFAO*(273.15))/(3.141593*D*LN*RT**2)*RO
61              B=NEV**2*ALFAO/(3.141593*D*LN*RT**2)*RO
62              HI=NEV**2/(KG(IND)*3.141593*D*LN*(TW-TG(IND))*RT**2)*RW
63      20      C2=4*(HI-B)/(KW*D)
64              NCOUNT=NCOUNT+1
65              IF (NCOUNT .GT. 100) GO TO 70
66              E=TANH(SQRT(C2)*LN/2)/(SQRT(C2)*LN)
67              H=(A*(1.-2*E)+B*(TW-2*TO*E))/(TW-TG(IND)+(TG(IND)-TO)*2*E)
68              TOL=    ABS((H-HI)/HI)
69              HI=H
70              IF    (TOL    .GT.    .001)  GO TO 20
70.5    C ITERATION COMPLETE   EVALUATE NUSSELT NUMBER
71              NU=H*D/KG(IND)
71.5            IF (NU-AA .LT. 0.) GO TO 21
72              RE=((NU-AA)/BB)**(1/NEXP)
72.5    C CALCULATE INSTANTANEOUS VELOCITY
73      22      UTOT(L)=RE*NEW(IND)/D
73.5            INC=L-1799
74              UENS(INC)=UENS(INC)+UTOT(L)
74.5            U2(INC)=U2(INC)+UTOT(L)**2
75      30      CONTINUE
76              WRITE(7,31) (UTOT(M),M=1800,3600)
77      31      FORMAT(' ',10F7.2)
78      40      CONTINUE
79      50      CONTINUE
79.5    C DO ENSEMBLE AVERAGING
80              DO 60 J=1,1801
81              UENS(J)=UENS(J)/(NCYC*NBLK)
81.5            U2(J)=U2(J)/(NCYC*NBLK)
82      60      CONTINUE
83              GO TO 80
84      70      WRITE(6,400)
85      400     FORMAT(' ','ERROR, TOO MANY ITERATIONS N=100!')
86      80      CONTINUE
86.2            WRITE(8,500)
86.3    C CALCULATE ENSEMBLED INTENSITY
86.5            DO 90 K=1,1801
86.7            UPRIME(K)=SQRT(U2(K)-UENS(K)**2)
86.77           CA=359.8+ K*RATE
86.8            WRITE(8,600)CA,UENS(K),UPRIME(K)
86.9    500     FORMAT(' ',' CA ',5X,'UBAR',3X,'UPRIME')
86.95   600     FORMAT(' ',F5.1,3X,F6.2,3X,F6.2)
86.955  C PLOT OUT THE RESULTS
86.96           X(K)=K/1801.    *20.
86.965          Y1(K)= UENS(K)/5. *2.
```

```
36.967          Y2(K)=UPRIME(K)/5. *2.
86.968          IF (Y1(K) .GT. 20.)Y1(K)=20.
86.969          IF (Y2(K) .GT. 20.)Y2(K)=20.
86.97   90      CONTINUE
86.98           CALL AXPLOT('CA DEGREES;',0.,20.,0.,1.)
86.99           CALL AXPLOT('ENSEMBLES;',90.,20.,0.,1.)
86.995          CALL LINE(X,Y1,1801,1)
86.997          CALL LINE(X,Y2,1801,1)
86.998          CALL PLOTND
87              STOP
88              END
```

2. Cycle by Cycle Time Averaged Mean and RMS Velocity (TRAP)

This program was used to obtain the mean velocity and turbulence intensity from the instantaneous velocity records processed with program ANEM.

The program begins by reading in the instantaneous velocity $U(i,\nu)$ obtained every 1/5 of a crank angle degree over 40 engine cycles. For each velocity $U(i,\nu)$, the area under the curve, $A(i,\nu)$, is calculated for a grid size of 1/5 of a crank angle degree using the trapezoidal approximation:

$$A(i,\nu) = U(i,\nu) + U(i,\nu+1)/2/5 \qquad (D.1)$$

The mean velocity is calculated by constructing a 4 degree averaging interval. This is accomplished by summing the individual areas calculated above in blocks of 20 and averaging:

$$\bar{U}_\theta(i) = \sum_{\theta-10}^{\nu+10} A(i,\nu)/4 \qquad (D.2)$$

The average is taken as the mid-point of each interval. The resulting curve is the mean velocity $\bar{U}_\theta(i)$ for the engine cycle being processed.

Next the turbulence intensity is computed. First cubic spline interpolation is used to generate points along the mean velocity record at every crank angle degree. The velocity fluctuation u_θ is then calculated as the difference between the mean velocity and the instantaneous velocity at each point:

$$u_\theta = U(i,\theta) - \bar{U}_\theta(i) \qquad\qquad (D.3)$$

The average of u_θ^2 was then calculated using a 12 degree averaging window in the same manner as described for the mean velocity evaluation.

This procedure was performed for each of the 40 engine cycles evaluated. The ensemble averaged mean velocity was then obtained from:

$$\bar{U}_\theta = \frac{1}{40} \sum_{i=1}^{40} \bar{U}_\theta(i) \qquad\qquad (D.4)$$

and the ensemble averaged turbulence intensity from:

$$u_\theta' = \{\frac{1}{40} \sum_{i=1}^{40} [\frac{1}{\theta} \int_0^\theta (U(i,\theta) - \bar{U}_\theta(i))^2 \, d\theta]\}^{1/2} \qquad (D.5)$$

The cyclic dispersion was also evaluated in this program from:

$$U_{RMS} = \{\frac{1}{40} \sum_{i=1}^{40} [\bar{U}_\theta(i) - \bar{U}_\theta]^2\}^{1/2} \qquad\qquad (D.6)$$

A program listing and flow chart follow.

Definition of Program Symbols (TRAP)

A	Trapezoidal Area Under Instantaneous Velocity
AT	Sum of Areas in Averaging Interval for Mean Velocity
AT12	Sum of Areas in Averaging Interval for Intensity
P	Tension Array for Interpolation
SI	Working Array of Interpolation Routine
S	Interpolated Valves Returned
S1	First Derivative at End Points
S2	Second Derivative at End Points
T	Crank Angle Degrees for Which Interpolated Velocity Valves are Required
U	Instantaneous Velocity
UE	Ensemble Averaged Mean Velocity
UP12	Turbulence Intensity Values
UPE12	Ensemble Averaged RMS Velocity
URMS	Cyclic Variation in Mean Velocity
UT	Interpolated Mean Velocity Values

FLOWCHART FOR PROGRAM TRAP

```
| INPUTS        U(1801,40)                                    |
```

```
| IJK=0                        |
| IJK=IJK + 1                  |
```

```
| TRAPAZOIDAL AREA CALC                                      |
| J=0                                                        |
| J=J+1                                                      |
| A(J)=(U(J,IJK)+U(J+1,IJK)/2/5                              |
| J<1801        NO                                           |
```

```
| MEAN VELOCITY CALC FOR 4  WINDOW                           |
| J=0 , K=0                                                  |
| J=J+1                                                      |
|   K=K+1                                                    |
|   L=(J-1)*20 +20                                           |
|   AT(J)= AT(J)+A(L)                                        |
|   K<20                          NO                         |
| Y(J)=AT(J)/4                                               |
| J <90                           NO                         |
```

```
| INTERPOLATION CURVE                                        |
|                                                           |
| FIT A CUBIC SPLINE TO POINTS                              |
| GENERATE INTERPOLATION POINTS,S(J)                        |
| ADJUST TENSION                                            |
| UT(J,IJK)=S(J),J=1,360                                    |
```

```
| IJK = 40                     |        NO
```

```
| ENSEMBLE AVERAGE MEAN VELOCITY CURVES                      |
| J=0,K=0                                                    |
| J=J+1                                                      |
| K=K+1                                                      |
| UE(J)=UE(J)+UT(J,K)           NO                          |
| K <40                                                     |
| UE(J)=UE(J)/40                                            |
| J < 360                       NO                          |
```

```
| AREA CALCULATION FOR INTENSITY                             |
| IJK=0,KIND=0,IND=1,J=0                                    |
| IJK=IJK+1                                                 |
| KIND=KIND+1, J=J+1                                        |
|  IF (KIND=6) IND=IND+1, & KIND=1                          |
| Z1=U(J,IJK)-UT(IND,IJK)                                   |
| Z2=U(J+1,IJK)-UT(IND,IJK)                                 |
| A(J)=(Z1**2 + Z2**2)/2./5    NO                           |
| J <1800                                                   |
```

12 WINDOW AVERAGE

```
J=0,K=0
J=J+1
  K=K+1
  L=(J-1)*60+K+11
  AT(J)=AT(J)+A(L)
  K <60 ─────────────── NO
UP12(J,IJK)=AT12(J)/12
J <30 ──────────────────────── NO
IJK  40 ──────────────────────────── NO
```

ENSEMBLE AVERAGE

```
J=0,IJK=0
J=J+1
IJK=IJK+1
UPE12(J)=UPE12(J)+UP12(J,IJK)
IJK <40 ─────────────────── NO
UPE12(J)=SQRT(UPE12(J)/40)
J <30 ──────────────────────── NO
```

WRITE DATA TO FILE

```
UPE12(J),J=1,30
UE(J),J=1,360
```

STOP

88.

```
1              REAL UT(357,40),UE(357),U(1801,40),A(1800),AT(180)
2              REAL X(200),Y(200),P(1400),SI(2),S(357),Z1,Z2,URMS(357)
3              REAL UP12(36,40)
4              REAL UPE12(36)
5              REAL AT12(90)
6              REAL S1(357),S2(357),T(357)
7              DO 13 J=1,357
8              URMS(J)=0.
9      13      UE(J)=0.
10             DO 11 J=1,357
11             DO 12 K=1,40
12             UT(J,K)=0.
13     12      CONTINUE
14     11      CONTINUE
15     C READ IN THE INSTANTANEOUS VELOCITY FOR 40 CYCLES
16             DO 10 IJK=1,40
17             READ(5,1) (U(J,IJK),J=1,1801)
18     1       FORMAT(' ',10F7.2)
19             DO 2 J=1,90
20             AT(J)=0.
21             AT(J+90)=0.
22             AT2(J)=0.
23             AT4(J)=0.
24             AT8(J)=0.
25             AT12(J)=0.
26     2       CONTINUE
27     C EVALUATE TRAPAZOIDAL AREAS UNDER VELOCITY TRACE
28             DO 23 J=1,1800
29             A(J)=(U(J,IJK)+U(J+1,IJK))/2/5.
30     23      CONTINUE
31     C
32     C  USE A 4 DEGREE INTERVAL  FOR MEAN VELOCITY
33     C  ADD UP THE AREAS FOR WINDOW OF 4 DEGREES
34             DO 4 J=1,90
35             DO 3 K=1,20
36             L=(J-1)*20+ K
37             AT(J)=AT(J)+A(L)
38     3       CONTINUE
39     C TAKE THE AVERAGE IN EACH INTERVAL
40             Y(J)=AT(J)/4.
41     4       CONTINUE
42             SI(1)=-1
43             SI(2)=1
44             DO 40 J=1,1400
45     40      P(J)=0.
46             DO 41 J=1,357
47     41      T(J)=361. + FLOAT(J)
48             DO 42 J=1,180
49     42      X(J)=358.+J*4.
50     C FIT A CUBIC SPLINE TO THE POINTS
51             CALL SMOOTH(X,Y,P,90,SI,1,&99)
52     C GENERATE INTERPOLATION POINTS BETWEEN AVERAGES
53             CALL SMTH(T,S,S1,S2,357,&99)
54     C ADJUST TENSION
55             CALL SMOOTH(X,Y,P,90,SI,0,&99)
56             CALL SMTH(T,S,S1,S2,357,&99)
57             DO 43 J=1,357
58     43      UT(J,IJK)=S(J)
```

```
59      10        CONTINUE
60   C CALC ENSEMBLED CURVE FROM INDIVIDUAL TRACES
61                DO 20 J=1,357
62                 DO 19 K=1,38
63                 UE(J)=UE(J)+UT(J,K)
64      19         CONTINUE
65                UE(J)=UE(J)/38.
66      20        CONTINUE
67                WRITE(6,300)
68     300        FORMAT(' ','FINISHED MEAN VELOCITY')
69   C CALCULATE CYCLIC VARIATION IN MEAN
70                DO 800 J=1,357
71                DO 801 K=1,38
72                URMS(J)=URMS(J)+(UT(J,K)-UE(J))**2
73     801        CONTINUE
74                URMS(J)=SQRT(URMS(J)/38.)
75     800        CONTINUE
76                WRITE(6,802)
77     802        FORMAT(' ','CYCLIC VARIATION COMPLETE')
78   C CALCULATE INTENSITY NOW USE A WINDOW OF 12 DEGREES
79                DO 1000 IJK=1,40
80                IND=1
81                KIND=0
82                DO 100 J=11,1799
83                KIND=KIND+1
84                IF (KIND .EQ. 6 ) IND=IND+1
85                IF (KIND .EQ. 6 )KIND=1
86                Z1= U(J,IJK)- UT(IND,IJK)
87                Z2=U(J+1,IJK) -UT(IND,IJK)
88                A(J)=(Z1**2 +Z2**2)/2./5.
89     100        CONTINUE
90   C 12 DEG WINDOW
91                DO 401 J=1,30
92                DO 402 K=1,60
93                L=(J-1)*60 +K +11
94                AT12(J)=AT12(J)+A(L)
95     402        CONTINUE
96                UP12(J,IJK)=(AT12(J)/12.)
97                AT12(J)=0.
98     401        CONTINUE
99    1000        CONTINUE
100               WRITE(6,502)
101     502       FORMAT(' ','INTENSITY CALCS DONE')
102               DO 405 J=1,30
103     405       UPE12(J)=0.
104               DO 407 J=1,30
105               DO 406 IJK=1,40
106     406       UPE12(J)=UPE12(J)+UP12(J,IJK)
107               UPE12(J)=SQRT(UPE12(J)/40.)
108     407       CONTINUE
109               WRITE(6,503)
110     503       FORMAT(' ','ENSEMBLE AVERAGING COMPLETE')
111               DO 21 J=1,357
112               X(J)=361. + FLOAT(J)
113               WRITE(7,22) X(J),UE(J)
114      21       CONTINUE
115               DO 28 J=1,357
116               WRITE(8,22) X(J),URMS(J)
```

```
117     28        CONTINUE
118               DO 410 J=1,30
119               X(J)=370. +(J-1)*12.
120               WRITE(7,22) X(J),UPE12(J)
121     410       CONTINUE
122     22        FORMAT(' ',2F20.2)
123     99        STOP1
124               END
```

3.   Nonstationary Analysis (NOTIME)

This program evaluates the turbulence intensity obtained from the type of nonstationary analysis proposed by Lancaster [10]. In this analysis the turbulent fluctuation u(i,θ) is defined to be the difference between a stationary mean velocity $\bar{U}(i)$, a time varying mean velocity $\bar{U}(θ)$, and the instantaneous velocity U(i,θ):

$$u(i,θ) \;=\; U(i,θ) - \bar{U}(i) - \bar{U}(θ) \qquad\qquad (D.7)$$

In this program the instantaneous velocity and ensemble averaged mean velocity from the program ANEM are inputs.

For each engine cycle the stationary mean is calculated from Equation 6.19 using the trapezoidal rule to evaluate the integral. The averaging window was varied from 40 to 100 degrees about TOC. The average turbulence intensity is evaluated for 12 degree intervals from Equation 6.20. The intensity records were then ensembled to give an ensemble averaged turbulence intensity.

A program listing and flow chart follow.

Definition of Program Symbols (NOTIME)

A   Trapezoidal Areas

UE   Ensemble Averaged Mean Velocity

UI   Instantaneous Velocity

UP40   RMS Velocity for Averaging Window of 40°

UP60   RMS Velocity for Averaging Window of 60°

UP80   RMS Velocity for Averaging Window of 80°

UP100   RMS Velocity for Averaging Window of 100°

UT40   Stationary Velocity for Averaging Window of 40°

UT60   Stationary Velocity for Averaging Window of 60°

UT80   Stationary Velocity for Averaging Window of 80°

UT100   Stationary Velocity for Averaging Window of 100°

FLOWCHART FOR PROGRAM NOTIME

```
┌─────────────────────────────────────────┐
│ INPUTS                                   │
│ UE(500),UI(1800,40)                      │
└─────────────────────────────────────────┘
            │
┌─────────────────────────────────────────┐
│ AREA CALCULATION                         │
│ J=0,IJK=0                                │
│ IJK=IJK+1                                │
│   J=J+1                                  │
│   P1=UI(J,IJK)-UE(J)                     │
│   P2=UI(J+1,IJK)-UE(J+1)                 │
│   A(J)=(P1+P2)/2/5      NO               │
│   J < 500                                │
│                                          │
│ STATIONARY MEAN VELOCITY                 │
│ J=0                                      │
│ J=J+1                                    │
│ UT(IJK)=UT(IJK)+A(J)   NO                │
│ J < 500                                  │
│                                          │
│ UT(IJK)=UT(IJK)/WINDOW                   │
│ UB=UB+UT(IJK)                            │
│                                          │
│ CYCLIC VARIATION OF MEAN VELOCITY        │
│ RMS=RMS+UT(IJK)**2                       │
│                          NO              │
│ IJK < 40                                 │
│ UB=UB/40                                 │
│ RMS=SQRT(RMS/40)                         │
└─────────────────────────────────────────┘
            │
┌─────────────────────────────────────────┐
│ INTENSITY CALCULATION                    │
│ IJK=0                                    │
│ IJK=IJK+1                                │
│ CALL INTENS(UI,UE,UT,1,UP,IJK)   NO      │
│ IJK < 40                                 │
│                                          │
│ J=0                                      │
│ J=J+1                                    │
│ UP(J)=SQRT(UP(J)/40)                     │
│ J < 500/WINDOW          NO               │
└─────────────────────────────────────────┘
            │
┌─────────────────────────────────────────┐
│ WRITE RESULTS                            │
│ UP(J),J=1,500/WINDOW                     │
└─────────────────────────────────────────┘
            │
          STOP
```
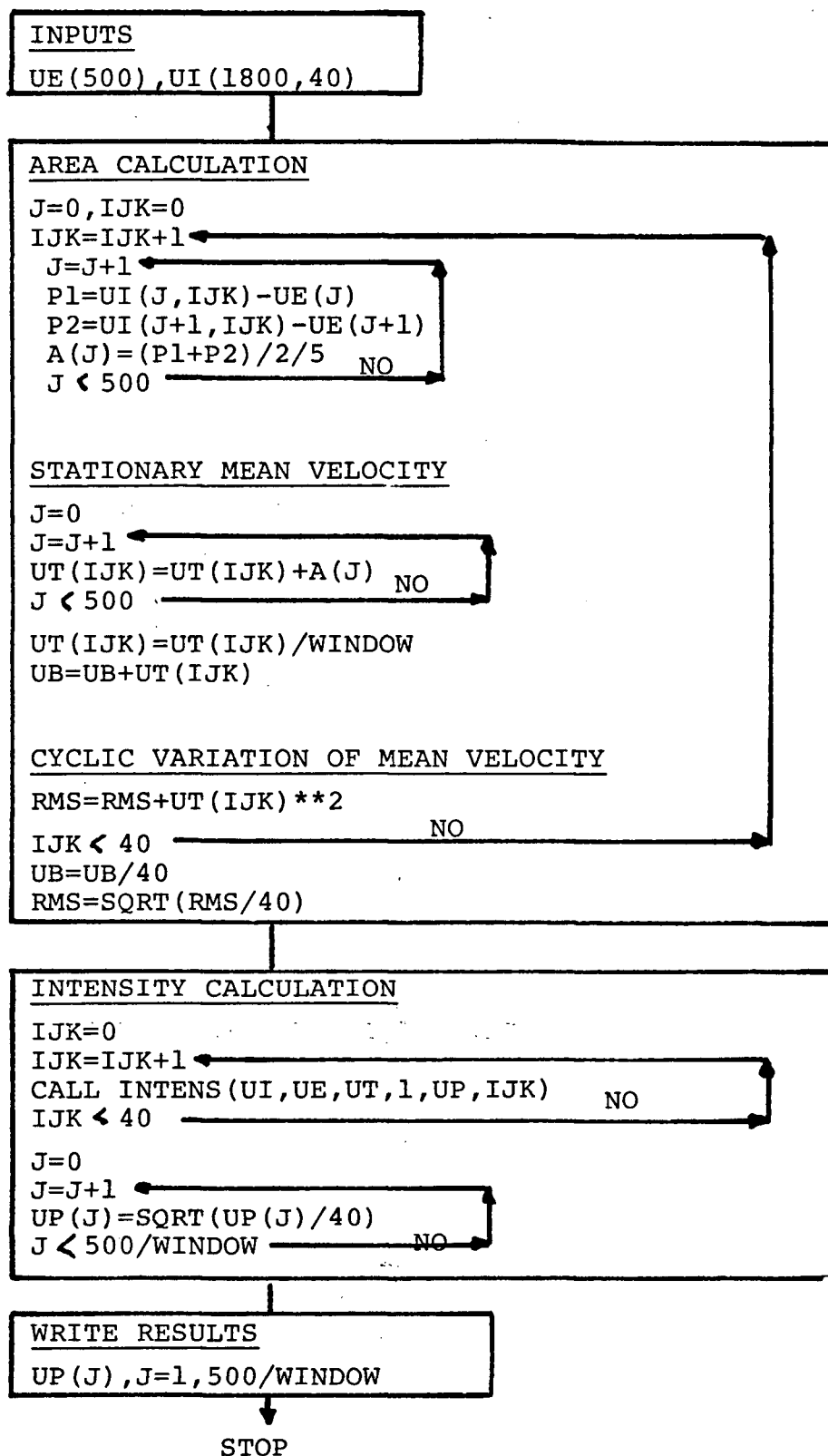
```
1                   REAL UE(500),UI(1801,40),UT40(40),UT60(40),UT80(40),X(20)
2                   REAL UT100(40),A(500),UP40(40),UP60(40),UP80(40),UP100(40)
2.5     C THIS PROGRAM CALCULATES THE STATIONARY MEAN VELOCITY IN A GIVEN
2.7     C WINDOW FROM THE ENSEMBLED MEAN VELOCITY AND THE INSTANEOUA VELOCITY
2.8     C BY THE METHOD OF LANCASTER.  THE TURBULENCE INTENSITY IS THEN
2.9     C CALCULATED FROM THE DIFFERENCE OF THE INSTANTANEOUS VELOCITY
2.95    C AND THE TWO MEANS, ENSEMBLED AND STATIONARY
3                   DO 1 J=1,40
4                   UT40(J)=0.
5                   UT60(J)=0.
6                   UT80(J)=0.
7                   UT100(J)=0.
7.5                 UP40(J)=0.
7.7                 UP60(J)=0.
7.8                 UP80(J)=0.
7.9                 UP100(J)=0.
8       1           CONTINUE
9                   U40B=0.
10                  U60B=0.
11                  U80B=0.
12                  U100B=0.
13                  RMS40=0.
14                  RMS60=0.
15                  RMS80=0.
16                  RMS100=0.
17                  DO 3 J=1,500
17.5    C READ IN THE ENSEMBLED MEAN
18                  READ(5,2) D,UE(J)
19      2           FORMAT(' ',F5.1,3X,F10.2)
20      3           CONTINUE
20.5    C READ IN 40 CYCLES OF THE INSTANTANEOUS MEAN
21                  DO 100 IJK=1,40
22                  READ(4,4) (UI(J,IJK),J=1,1801)
23      4           FORMAT(' ',10F7.2)
23.5    C EVALUATE THE INTEGRAL BT THE TRAPAZOIDAL METHOD
24                  DO 5 J=1,499
25                  P1=UI(J+649,IJK)-UE(J)
26                  P2=UI(J+650,IJK)-UE(J+1)
27                  A(J)=(P1+P2)/2./5.
28      5           CONTINUE
28.5    C CALCULATE THE STATIONARY MEAN VELOCITY
29                  DO 6 J=1,499
30                  UT100(IJK)=UT100(IJK)+A(J)
31                  IF ((J.LT.50) .OR. (J .GE. 450)) GO TO 6
32                  UT80(IJK)=UT80(IJK) + A(J)
33                  IF ((J .LT.100) .OR. (J .GE.400)) GO TO 6
34                  UT60(IJK)=UT60(IJK) + A(J)
35                  IF ((J.LT.150) .OR. (J .GE. 350)) GO TO 6
36                  UT40(IJK)=UT40(IJK) + A(J)
37      6           CONTINUE
37.5                UT40(IJK)=UT40(IJK)/40.
37.7                UT60(IJK)=UT60(IJK)/60.
37.8                UT80(IJK)=UT80(IJK)/80.
37.9                UT100(IJK)=UT100(IJK)/100.
38                  U40B=U40B+UT40(IJK)
39                  U60B=U60B+UT60(IJK)
40                  U80B=U80B+UT80(IJK)
41                  U100B=U100B+UT100(IJK)
```

```
41.5    C EVALUATE THE CYCLIC VARIATION OF THE MEAN VELOCITY
42              RMS40=RMS40 + UT40(IJK)**2
43              RMS60=RMS60 + UT60(IJK)**2
44              RMS80=RMS80 + UT80(IJK)**2
45              RMS100=RMS100 + UT100(IJK)**2
46      100     CONTINUE
47              U40B=U40B/40.
48              U60B=U60B/40.
49              U80B=U80B/40.
50              U100B=U100B/40.
51              RMS40=SQRT(RMS40/40.)
52              RMS60=SQRT(RMS60/40.)
53              RMS80=SQRT(RMS80/40.)
54              RMS100=SQRT(RMS100/40.)
55              DO 200 IJK=1,40
55.5    C EVALUATE THE INTENSITY
56              CALL INTENS(UI,UE,UT40,1,UP40,IJK)
57              CALL INTENS(UI,UE,UT60,2,UP60,IJK)
58              CALL INTENS(UI,UE,UT80,3,UP80,IJK)
59              CALL INTENS(UI,UE,UT100,4,UP100,IJK)
60      200     CONTINUE
61              DO 300 J=1,20
62              UP100(J)=SQRT(UP100(J)/40.)
63              IF (J .GT. 16) GO TO 300
64              UP80(J)=SQRT(UP80(J)/40.)
65              IF (J .GT. 12) GO TO 300
66              UP60(J)=SQRT(UP60(J)/40.)
67              IF (J .GT. 8) GO TO 300
68              UP40(J)=SQRT(UP40(J)/40.)
69      300     CONTINUE
70              WRITE(7,400) U40B,U60B,U80B,U100B
71      400     FORMAT(' ',4F10.2)
72              WRITE(7,400) RMS40,RMS60,RMS80,RMS100
73              DO 500 J=1,8
74              X(J)=522.5+(J-1)*5. -360.
75              WRITE(7,600) X(J),UP40(J)
76      500     CONTINUE
77              DO 501 J=1,12
78              X(J)=512.5+(J-1)*5. - 360.
79              WRITE(7,600) X(J),UP60(J)
80      501     CONTINUE
81              DO 502 J=1,16
81.5            X(J)=502.5+(J-1)*5. -360.
81.7            WRITE(7,600) X(J),UP80(J)
81.8    502     CONTINUE
81.9            DO 503 J=1,20
81.95           X(J)=492.5+(J-1)*5. -360.
81.97           WRITE(7,600) X(J),UP100(J)
81.98   503     CONTINUE
81.99   600     FORMAT(' ',2F20.2)
82              STOP
83              END
83.5    C THIS SUBROUTINE EVALUATES THE INTENSITY
84              SUBROUTINE INTENS(UI,UE,UT,IFLG,UP,IJK)
85              REAL UI(1801,40),UE(500),UT(100),UP(100),A(500)
86              INTEGER IFLG,LOW,HI,IJK
87              TEMP=0.
88              NP=(IFLG-1)*20 + 40
```

```
 89              LOW=(4-IFLG)*50 +1
 90              HI=(LOW)+NP*5 -2
 91              DO 1 J=LOW,HI
 91.5            K=J+649
 92              P1=UI(K,IJK)-UE(J)-UT(IJK)
 93              P2=UI(K+1,IJK)-UE(J+1)-UT(IJK)
 94              A(J)=(P1**2 +P2**2)/2./5.
 95       1      CONTINUE
 96              NP1=NP/5
 97              DO 3 J=1,NP1
 98                DO 2 K=1,25
 99                L=LOW + (J-1)*25 + K -1
100                TEMP=TEMP+A(L)
101       2        CONTINUE
102              UP(J)=(TEMP/5.) + UP(J)
103                TEMP=0.
104       3      CONTINUE
105              RETURN
106              END
```

4. Time Scale Analysis (PEAK)

This program was used to obtain turbulence time scale information from unprocessed anemometer signals. The basic procedure is to scan the signal for peaks. The time separation between peaks is recorded and a relative probability distribution is constructed for this variable. An amplitude threshold is input to the program as a criteria for defining a peak. This amplitude threshold was determined by operating the hot wire probe in quiescent ambient air and forming a distribution of the noise amplitude for this condition. The mean of this distribution was selected as the amplitude threshold.

The program starts by looking at the first two data points. If the second point is less than the first the program begins to search for a valley; otherwise it scans for a peak. The procedure for scanning for a peak or a valley are similar and only one will be described here. The reader should refer to the following flow chart for complete detail.

The data is read to the program in array. The program keeps track of the index and as long as the following data point is greater than or equal to the present one the index is increased by one. When a peak is found the index is saved until the next peak is found. There are many tests to check for the peak validity and the reader is referred to the flow chart for a clear description of these.

Once two peaks have been found with indexes i and j respectively, the difference between the two indexes gives the time separation. This is because the sample rate was set for every 1/5 of a crank angle degree. Thus the time separation t is obtained from:

$$t = \frac{(j-1)}{5} \frac{1}{RPM} \qquad (D.8)$$

Because the time separation between peaks can only occur in multiples of 1/5 of a crank angle degree the program can easily keep track of the occurences of a given time separation. The array PDF keeps track of the number of occurences of a specific separation; for example, Pdf(1) keeps track of the number of occurences of m/5 of a crank angle degree separation between peaks. The relative probability distribution of the time between peaks can then be easily determined.

A program listing and flow chart follow.

Definition of Program Symbols (PEAK)

AMP   Signal Amplitude Array

D   Digital Anemometer Data Array

DAT   Working Array of Digital Data

KCNT   Keeps Track of Number of Peaks

NOISE   Noise Amplitude Threshold

PDF   Keeps Track of Number of Occurences of Specific Peak Time

              Separation

PK   Index of Peak

PICIND   Array of Peak Indexes

RDF   Real Probability Distribution Function of Peak Time Separation

VALE   Valley Value

VALE2   Valley Value

FLOWCHART FOR PROGRAM PEAK

INPUTS

DAT(40,300),NOISE

INITIALIZE ALL ARRRAYS
READ IN THE INTEGER DATA
INITIALIZE ALL COUNTERS
INITIALIZE ALL FLAGS

NCYC = NCYC + 1
J = 1
KCNT=0
PKIND(J)=0,J=1,200

DAT(NCYC,2) < DAT(NCYC, 1)? ——— NO ———→

SEARCH FOR A PEAK

FLG=1

DAT(NCYC,J+1) > DAT(NCYC,J)? ——— NO ———→
J=J+1

DAT(NCYC,J) ≠ DAT(NCYC,J+1) ? ——— NO ———→
PK=J

DAT(NCYC,J) - VALE ≤ NOISE? ——— NO

DAT(NCYC,J) > VALE ? ——— NO

KCNT = KCNT + 1
PKIND(KCNT)=PK
JP=J

SEARCH FOR A VALLEY

FLG = 0

DAT(NCYC,J+1) < DAT(NCYC,J)? ——— NO ———→
J = J+ 1

DAT(NCYC,J) ≠ DAT(NCYC,J+1)? ——— NO ———→

DAT(NCYC,J+1) ≩ DAT(NCYC,J) ? ——— NO
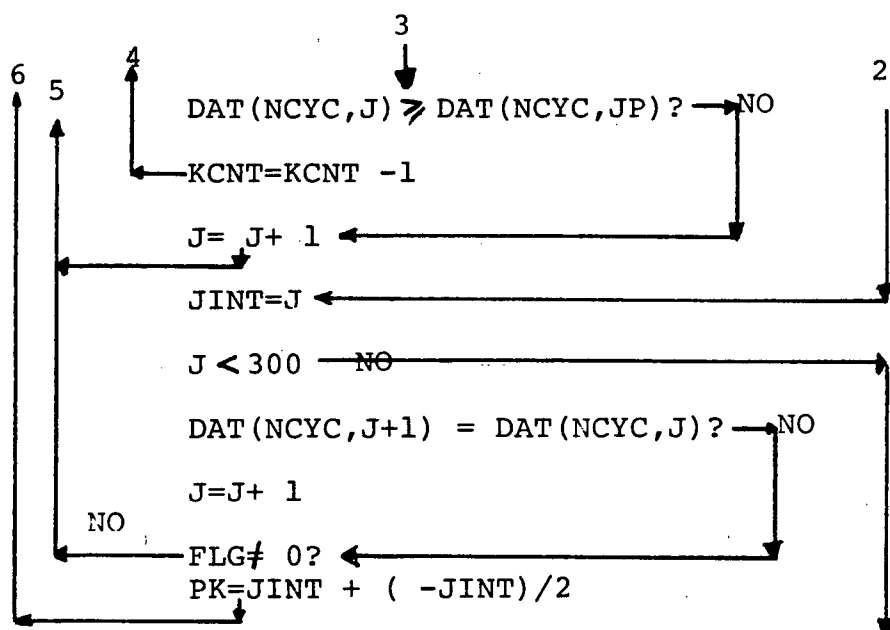
VALE2=DAT(NCYC,J)
TEST=DAT(NCYC,JP)
TEST - VALE2 > NOISE? ——— NO ———→

VALE=VALE2

4   6   5

3

2

01.

3

6 5 4 2

DAT(NCYC,J) $\geqslant$ DAT(NCYC,JP)? —→ NO

KCNT=KCNT -1

J= J+ 1 ←

JINT=J ←

J < 300 — NO

DAT(NCYC,J+1) = DAT(NCYC,J)? —→ NO

J=J+ 1

NO

FLG $\neq$ 0? ←

PK=JINT + (-JINT)/2

PDF EVALUATION

K=0
K=K+1 ←
INDEX=PKIND(K+1)-PKIND(K)
PDF(INDEX)=PDF(INDEX)+1
K $\geqslant$ 300 —

NO

RELATIVE PDF

KSUM=0,K=0
K=K+1 ←
KSUM=KSUM + PDF(K)
K $\geqslant$ 200 —

NO

K=0
K=K+1 ←
RDF(K)=PDF(K)/KSUM
K $\geqslant$ 200

NO

STOP

```
 1              INTEGER DAT(4,300),VALE,VALE2,NOISE,PKIND(200)
 2              INTEGER PK,FLG,PDF(200),D(4,3600),AMP(30)
 2.02   C THIS PROGRAM COUNTS THE TIME SEPARATION BETWEEN PEAKS AND
 2.03   C FORMS A RELATIVE PROBABILITY DISTRIBUTION OF THIS QUANTITY
 2.05           REAL RDF(200)
 2.1            DO 103 K=1,200
 2.15           RDF(K)=0.
 2.2            PKIND(K)=0
 2.3            PDF(K)=0
 2.4    103     CONTINUE
 2.5            DO 98 MM=1,20
 2.7            NREC=((MM-1)*502 + 1)*1000
 2.8            FIND(5'NREC)
 3              READ(5,100)(D(1,M),M=35,3600),((D(M,N),N=1,3600),M=2,4)
 4      100     FORMAT(' ',32I5)
 5              KCNT=0
 6              NOISE=7
 7              PK=0
 8              JP=0
 9              JINT=0
10              VALE=0
11              VALE2=0
12              DO 99 K=1,30
13              AMP(K)=0
14      99      CONTINUE
15              DO 102 K=1,4
16              DO 101 L=1,300
17              M=L + 2549
18              DAT(K,L)=D(K,M)
19      101     CONTINUE
20      102     CONTINUE
25              DO 30 NCYC=1,4
26              J=1
27              KCNT=0
28              DO 104 K=1,200
29              PKIND(K)=0
30      104     CONTINUE
31              IF (DAT(NCYC,2) .GT. DAT(NCYC,1)) GO TO 4
32      1       GO TO 9
33      2       GO TO 4
34      3       IF (J .LE. 300) GO TO 1
35              GO TO 18
36      4       FLG=1
37      C
38      C   SEARCH FOR A PEAK
39      C
40              IF (J .GE. 300) GO TO 18
41      5       IF (DAT(NCYC,J+1) .LE. DAT(NCYC,J)) GO TO 6
42              J=J+1
43              GO TO 5
44      6       IF (DAT(NCYC,J) .EQ. DAT(NCYC,J+1)) GO TO 15
45              PK=J
46              IF ((DAT(NCYC,J)-VALE) .GT. NOISE) GO TO 8
47      7       IF (DAT(NCYC,J).LE. VALE) GO TO 9
48      8       KCNT= KCNT + 1
49              PKIND(KCNT)=PK
50              IAMP=DAT(NCYC,J)-VALE
51              IF (IAMP .GT. 30)IAMP=30
```

```
 52              AMP(IAMP)=AMP(IAMP)+1
 53              JP=J
 54              GO TO 3
 55       9      FLG=0
 56       C
 57       C  SEARCH FOR A VALLEY
 58       C
 59              IF (J .GE. 300) GO TO 18
 60       10     IF (DAT(NCYC,J+1) .GE. DAT(NCYC,J)) GO TO 11
 61              J=J+1
 62              GO TO 10
 63       11     IF (DAT(NCYC,J) .EQ. DAT(NCYC,J+1)) GO TO 15
 64       12     IF (DAT(NCYC,J+1) .LT. DAT(NCYC,J)) GO TO 10
 65              VALE2=DAT(NCYC,J)
 66              TEST=DAT(NCYC,JP)
 67              IF (JP .EQ. 0)TEST=10000
 68              IF ((TEST -VALE2) .LE. NOISE) GO TO 13
 69              VALE=VALE2
 70              GO TO 2
 71       13     IF (DAT(NCYC,J) .LT. DAT(NCYC,JP)) GO TO 14
 72              KCNT=KCNT-1
 73              GO TO 4
 74       14     J=J+1
 75              GO TO 10
 76       15     JINT=J
 77              IF (J .GE. 300) GO TO 18
 78       16     IF (DAT(NCYC,J+1) .NE. DAT(NCYC,J)) GO TO 17
 79              J=J+1
 80              GO TO 16
 81       ·17    IF (FLG.EQ.0)GO TO 12
 82              PK=JINT +(J-JINT)/2
 83              GO TO 7
 84       18     CONTINUE
 85              DO 20 K=1,300
 86              INDEX=PKIND(K+1)-PKIND(K)
 87              IF (INDEX .LE. 0) GO TO 21
 88              PDF(INDEX)=PDF(INDEX) + 1
 89       20     CONTINUE
 90       21     CONTINUE
 91       30     CONTINUE
 91.5     98     CONTINUE
 92              KSUM=0
 93              DO 23 K=1,200
 94              KSUM=KSUM + PDF(K)
 95       C      WRITE(6,22) K,PDF(K),KSUM
 96       C22    FORMAT(' ',3I10)
 97       23     CONTINUE
101.5            DO 26 L=1,200
101.7            RDF(L)=FLOAT(PDF(L))/FLOAT(KSUM)
101.8            X=L/5.*(60./(1140.*360.))*1000000.
101.9            WRITE(7,27) X,RDF(L)
101.95    27     FORMAT(' ',F10.2,2X,F10.3)
101.97    26     CONTINUE
102              STOP
103              END
```
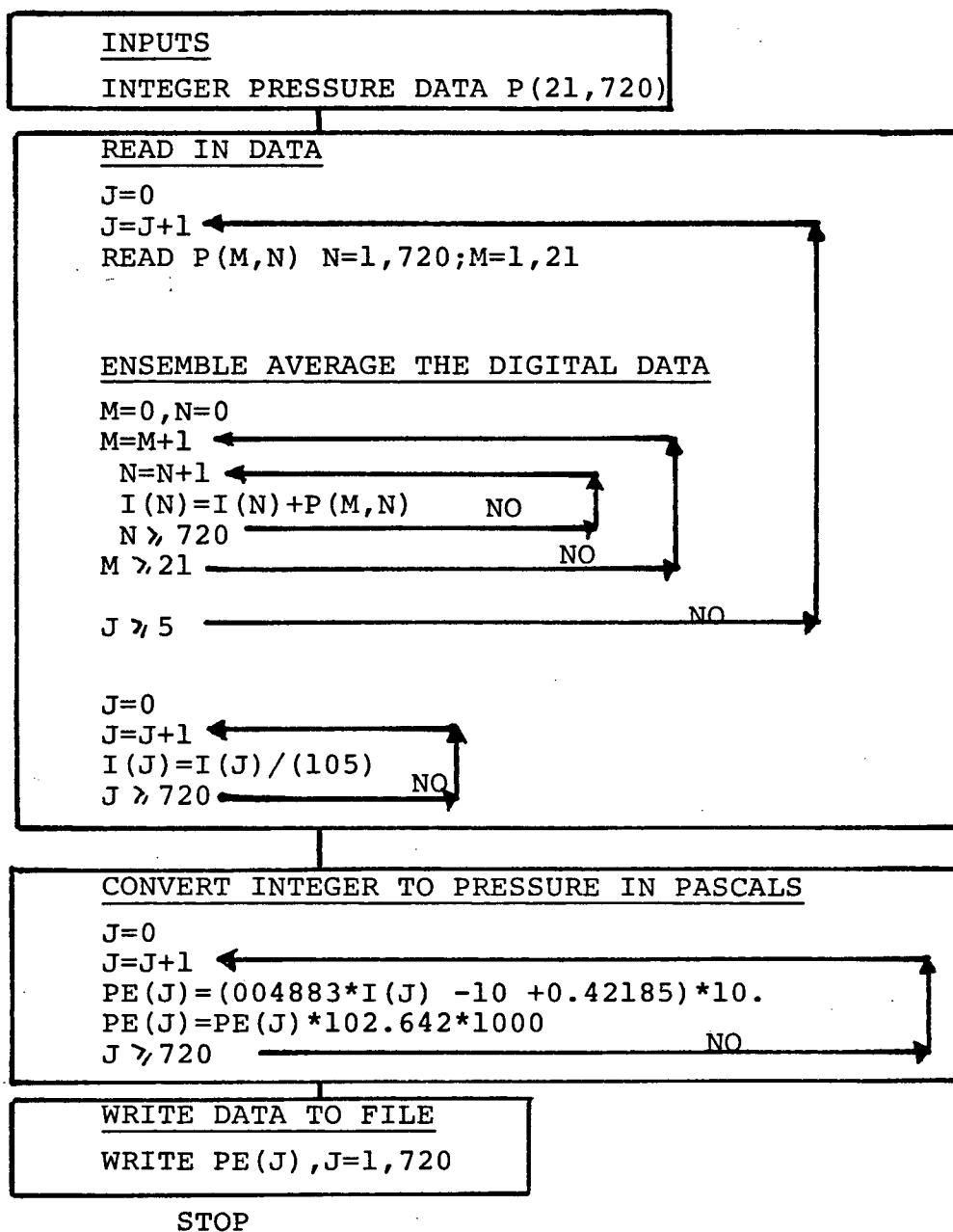
APPENDIX E - COMBUSTION DATA PROCESSING

1. <u>Pressure Evaluation and Ensemble Averaging from Digital Data (PENH)</u>

This program was used to read in the digitized pressure data, ensemble average it, convert the integers to a pressure in bars, and then save the data in a file for later use.

A program listing and flow chart follow.

Definition of Program Symbols (PENH)

I   Integer Array Used to Ensemble Digital Pressure Data

KG   Thermal Conductivity of Air

NV   Kinematic Viscosity of Air

P   Digital Pressure Data

PE   Pressure Converted to Bars

RHO   Density of Air

TG   Temperature of Air

V   Voltage Obtained From Digital Data

FLOWCHART FOR PROGRAM PENH

```
┌─────────────────────────────────────────────────────────┐
│  INPUTS                                                   │
│  INTEGER PRESSURE DATA P(21,720)                          │
└─────────────────────────────────────────────────────────┘

┌─────────────────────────────────────────────────────────┐
│  READ IN DATA                                            │
│  J=0                                                     │
│  J=J+1  ◄─────────────────────────────────────────┐     │
│  READ P(M,N) N=1,720;M=1,21                        │     │
│                                                    │     │
│                                                    │     │
│  ENSEMBLE AVERAGE THE DIGITAL DATA                 │     │
│  M=0,N=0                                           │     │
│  M=M+1  ◄──────────────────────────────┐          │     │
│    N=N+1  ◄──────────────────────┐     │          │     │
│     I(N)=I(N)+P(M,N)       NO    │     │          │     │
│     N ⩾ 720 ─────────────────────┘     │          │     │
│    M ⩾ 21 ────────────────────────NO───┘          │     │
│                                                    │     │
│  J ⩾ 5 ─────────────────────────────────────NO────┘     │
│                                                          │
│                                                          │
│  J=0                                                     │
│  J=J+1  ◄────────────────────────┐                       │
│  I(J)=I(J)/(105)                 │                       │
│  J ⩾ 720 ◄──────────────────NO──┘                        │
└─────────────────────────────────────────────────────────┘

┌─────────────────────────────────────────────────────────┐
│  CONVERT INTEGER TO PRESSURE IN PASCALS                  │
│  J=0                                                     │
│  J=J+1  ◄─────────────────────────────────────────┐     │
│  PE(J)=(004883*I(J) -10 +0.42185)*10.              │     │
│  PE(J)=PE(J)*102.642*1000                          │     │
│  J ⩾ 720 ──────────────────────────────────NO──────┘     │
└─────────────────────────────────────────────────────────┘

┌─────────────────────────────────────────────────────────┐
│  WRITE DATA TO FILE                                     │
│  WRITE PE(J),J=1,720                                    │
└─────────────────────────────────────────────────────────┘
         STOP
```

```
  1      C*******************************************************************
  2      C*                                                               *
  3      C*                                                               *
  4      C*    THIS PROGRAM ENSEMBLES THE DIGITAL DATA FROM THE PRESSURE   *
  5      C*    TRACE. 5-10 GRABS OF 32 K CHUNKS ARE MADE.  THIS CORRESPONDS *
  6      C*    APPROX 22.75 CYCLES PER GRAB.                               *
  9      C*    THE INTEGERS ARE READ INTO A MATRIX, 22 CYCLES AT A TIME AND
 10      C*    ARE THEN  ENSEMBLED THEY ARE THEN CONVERTED TO PRESSURE DATA *
 11      C*    AMBIENT CONDITIONS ARE ASSUMED TO EXIST IN THE CYLINDER FOR  *
 12      C*    THE BDC CRANK POSITION                                      .
 15      C*                                                               *
 16      C*******************************************************************
 17              INTEGER P(21,720),D(720),I(720)
 18              REAL PE(720),TG(720),U(720),KG(720),RHO(720),NU(720)
 19              REAL TO,KO,PO,UO
 22              PO=101300
 24              DO 101 J=1,720
 25              I(J)=0
 26      101     CONTINUE
 27      C READ IN THE DATA
 28              DO 1 J=1,5
 29              NREC=(  502*(J-1) + 1)*1000
 30              FIND(5'NREC)
 31              READ(5,99) K
 32              READ(5,99)(D(L),L=1,685),((P(M,N),N=1,720),M=1,21)
 33      99      FORMAT(' ',32I5)
33.5     C ENSEMBLE AVERAGE THE DATA
 34              DO 2 M=1,21
 35              DO 3 N=1,720
 36              I(N) = I(N) + P(M,N)
 37      3       CONTINUE
 38      2       CONTINUE
 39              NCNT=J
 40      1       CONTINUE
 41              DO 4 J=1,720
 42              I(J)=I(J)/(NCNT*21)
42.5     4       CONTINUE
 43      C
 44      C    THE DATA HAS NOW BEEN READ IN DIGITAL FORM AND ENSEMBLED
 45      C    FOR DIGITIZATION, -10 TO +10 VOLTS CORRESPONDS TO 0 TO 4096
 46      C    CONVERT INTEGERS BACK INTO A VOLTAGE
 47      C    V=(-10 + 0.004883 * I)
 48      C    FOR PRESSURE TRANSDUCER,10 BAR PER VOLT, REF PRESSURE IS AT BDC
48.5     C    AND CORRESPONDS TO THE INTAKE MAINIFOLD PRESSURE
 50      C
50.5             DO 10 J=1,720
 51              V= (.004883*I(J) - 10.)
 52              PE(J)= (V+0.42185  )*10.
 53              PB=PE(J)
 54      C
 55      C    CONVERT TO PASCALS
 56      C
 57              PE(J)= (PE(J)*102.642)*1000.
 61      10      CONTINUE
 62              DO 5 J=1,180
 63              K= 360 +(J-1)*2
 64              WRITE(7,6) PE(K)
 65      5       CONTINUE
 66      6       FORMAT(' ',F12.4)
 67              STOP
 68              END
```

2. Geometric Analysis of a Spherical Flame Front (DFLAME)

This program was written to produce the flame front geometry figures required by the program MASBRN. The required information was the volume, surface area, and wetted perimeter area for a spherical flame front of radius r in an engine cylinder with the CFR squish geometry under study.

The geometry is shown schematically in Figure E.1. The combustion chamber is a cylinder of radius RC and variable height H. The spark is on the side. The flame is assumed to expand spherically into the chamber from the spark location.

First the equations to solve for a geometry without squish will be developed. Then the procedure to incorporate squish in the calculation will be outlined.

From Figure E.1 it can be seen that the volume of the flame V_F may be expressed as:

$$V_F = \int_0^h [\text{Area of flame section}] \, dz \qquad (E.2)$$

where the area of the flame section AFS1 is given by:

$$AFS1 = R^2\alpha + Rc^2 (\beta - \sin\beta) \qquad (E.3)$$

and the flame front area AFF1 is:

$$AFF1 = 2R_F \int_0^H \alpha \, dz \qquad (E.4)$$

Similarly the area of the wetted perimeter AWP1 is expressed by:
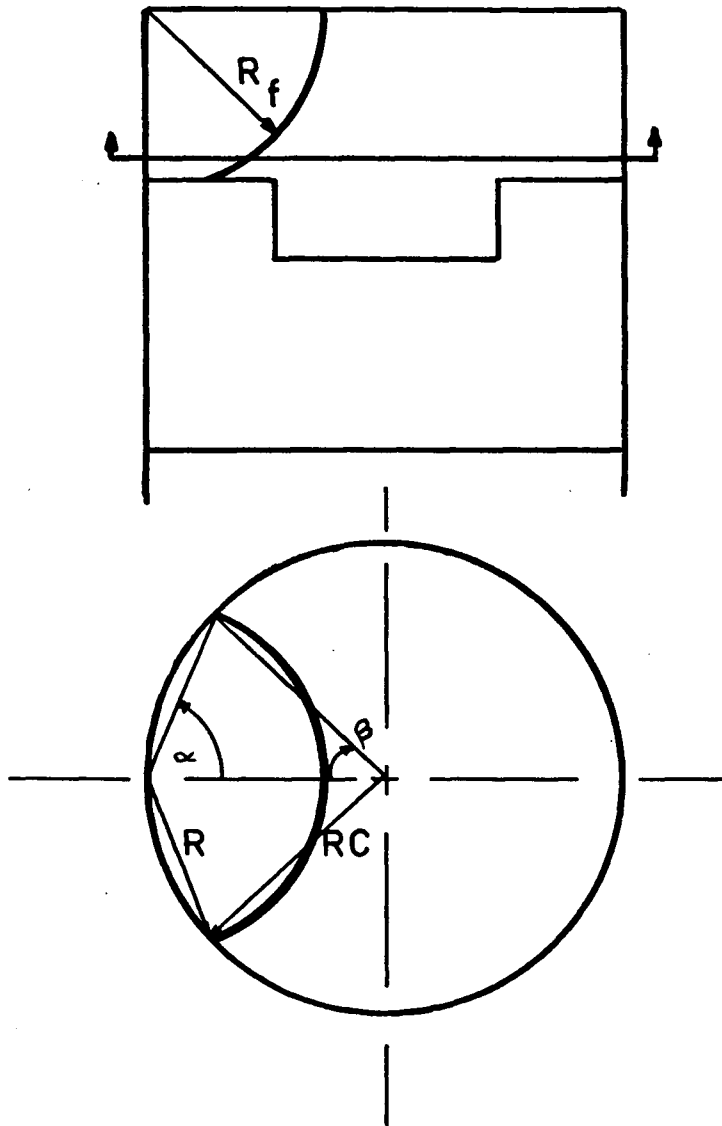
Figure E.1   Flame geometry for a section through a flame
above the piston bowl (Flame Section 1).
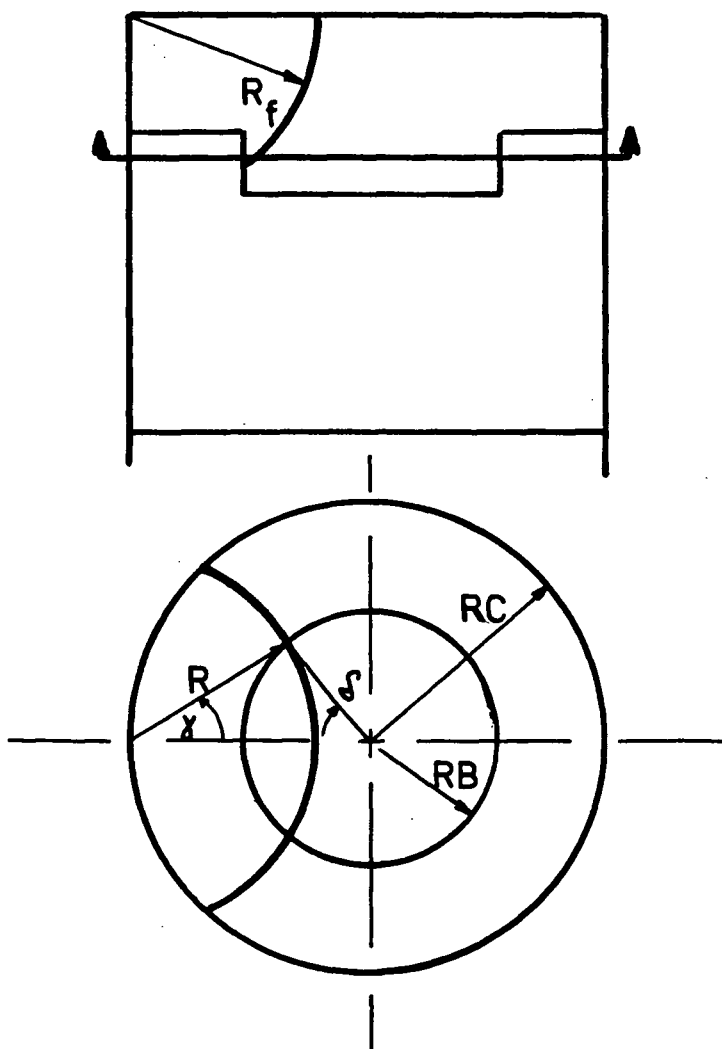
Figure E.2 Flame geometry for a section through a
flame in the piston bowl (Flame Section 2).

$$AWP1 = 2RC \int_0^H \beta \, dz + AFS1(z=0) + AFS1(z=H) \qquad (E.5)$$

If the flame radius is small enough that the flame does not contact the bowl then the above equations are sufficient. However when the flame enters the bowl the geometry of the flame section shown in Figure E.2, AFS2 becomes important. The area AFS2 is given by:

$$AFS2 = \gamma R^2 + \delta RB^2 - R^2 \sin\gamma - RB^2 \sin\delta \qquad (E.6)$$

The expressions for the volume, flame front area, and wetted perimeter are similar to those given previously except that the lower limit of integration is now H and the upper limit H+D (D is the bowl depth).

The program DFLAME generates a table of volumes and areas for combinations of flame radius and cylinder height. All calculations are done in two parts. The first for a cylinder without a squish bowl and the second adds in the effect of the squish bowl if required. The integration is performed with the aid of UBC DCADRE [41].

A program listing and flow chart follow.

Definition of Program Symbols (DFLAME)

AFLAM1   Area of Flame Front 1

AFLAM2   Area of Flame Front 2

AFND   Nondimensional Area of Flame Front

AFS1   Area Function for Section 1

AFS2   Area Function for Section 2

ALF   Function for Angle Alfa

APND   Nondimensional Area of Wetted Perimeter

AWP1   Area of Wetted Perimeter, Section 1

AWP2   Area of Wetted Perimeter, Section 2

BET   Function for Angle Beta

D   Depth of Piston Bowl

DEL   Function for Angle Delta

ERRAF   Error in Flame Area

ERRAP   Error in Wetted Perimeter Area

ERRV   Error in Volume

GAM   Function for Angle Gamma

H   Piston Distance from Head

HND   Nondimensional H

HU1   Upper Integration Limit for Section 1

HU2   Upper Integration Limit for Section 2

RB   Radius of Piston Bowl

RC   Radius of Cylinder

RF   Radius of Flame

RND   Nondimensional Radius

VOLF   Volume of Flame

VND   Nondimensional Flame Volume

FLOWCHART FOR PROGRAM DFLAME

INITIALIZE ALL VARIABLES TO ZERO

K=0
K=K+1
CA=(K-1)*PI/180.

CALC PISTON HEIGHT

B=ARCSIN(R/S * SIN(CA))
H=S + R - S*COS(B) - R*COS(CA) + HC
HND(K)= H/HC

START FLAME GEOMETRY CALC

J=0
J=J+1

SET FLAME RADIUS

RF=J*0.08125/2
RND(J)=RF/RC

VOLUME CALC

HU1=RF
NO — HU1 > H   ?
HU1=H
VOLF1=DCADRE(AFS1,0,HU1,DEPS,DREL,ERROR)
NO — HU1 ⩾ H ?
HU1 ≠ RF ?
NO
HU2=RF
NO RF > H+D?
HU2=H+D
VOLF2=DCADRE(AFS2,H,HU2,DEPS,DREL,ERROR)
VOLF=VOLF1+VOLF2
VOLF1=0
VOLF2=0
VND(J)=VOLF/(PI*(RC**2 *H + RB**2 *D))

AREA OF FLAME FRONT CALC

AFLAM1=DCADRE(ALF,0,HU1,DEPS,DREL,ERROR)
NO — HU2 ⩾ H   ?
AFLAM2=DCADRE(GAM,H,HU2,DEPS,DREL,ERROR)
AFLAME=(AFLAM1+AFLAM2)*2*RF
AFLAM1=0
AFLAM2=0
AFND(J)=AFLAME/(2*PI*RC**2)

1   2

WETTED PERIMETER CALC

AWP=(DCADRE(BET,0,HU1,DEPS,DREL,ERROR))*2*RC

AWP1=AWP+AFS1(0.0)

NO HU2 ⪈ H ?

AWP2=DCADRE(DEL,H,HU2,DEPS,DREL,ERROR)*2*RB

AWP2=AWP2+AFS1(H)-AFS2(H)

NO HU2 = HT ?

AWP2=AWP2 + AFS2(HT)

APND(J) =(AWP1 + AWP2)/(2*PI(RC*H + RB*D + RC**2)

AWP1=0

AWP2=0

HU1=0

HU2=0

NO VND(J) < 1 ?   NO

J ⪈ 1000 ?

WRITE RESULTS TO FILE

WRITE RND(J),VND(J),AFND(J),APND(J):J=1,N

K > 45   NO
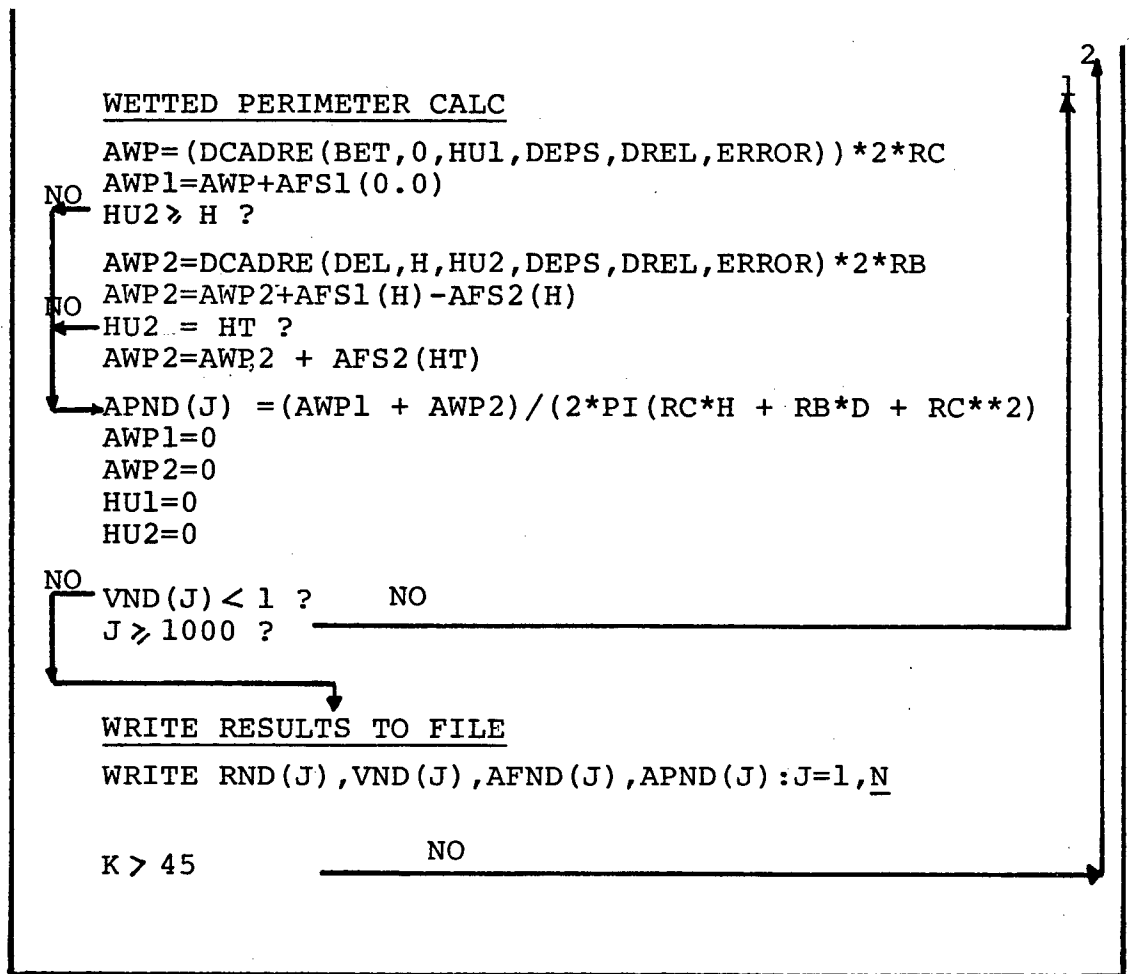
STOP

```
FUNCTION AFS1(Z)

R=SQRT(RF**2 - Z**2)
ALFA=ARCOS(R/(2*RC))
BETA=ARCOS((2*RC**2-R**2)/(2*RC**2))
BETA < PI/2 ?

AFS1=R**2*ALFA + RC**2(BETA-SIN(BETA))

AFS1= R**2 (ALFA- SIN(ALFA) + BETA*RC**2
         +(R*COS(GAMMA) - RC)*R*SIN(ALFA)

RETURN
```

```
FUNCTION AFS2(Z)

R=SQRT(RF**2 - Z**2)
GAMMA=ARCOS(R/(2*RB))
DELTA=ARCOS((2*RB**¶-R**2)/(2*RB**2))
DELTA < PI/2 ?

AFS2=R**2*GAMMA + RB**2*DELTA - R**2*SIN(GAMMA)
       - RB**2*SIN(DELTA)

AFS2=R**2*(GAMMA-SIN(GAMMA)) + DELTA*RB**2
       + (R*COS(GAMMA)-RC)*R*SIN(GAMMA)

RETURN
```

```
FUNCTION ALF(Z)

R=SQRT(RF**2 - Z**2)
ALF= ARCOS(R/(2*RC))
RETURN
```

```
FUNCTION GAM(Z)

R=SQRT(RF**2-Z**2)
GAM=ARCOS(R/(2*RB))
RETURN
```

```
FUNCTION DEL(Z)

R=SQRT(RF**2-Z**2)
DEL=ARCOS((2*RB**2 - R**2)/(2*RB**2))
RETURN
```

```
FUNCTION BET(Z)

R=SQRT(RF**2 - Z**2)
BET= ARCOS((2*RC**2 - R**2)/(2*RC**2))
RETURN
```

```
  1               IMPLICIT REAL*8(A-H,O-Z,$)
  2               EXTERNAL AFS1,AFS2,ALF,GAM,BET,DEL
  3               REAL*8 RND(100),VND(100),AFND(100),APND(100),HND(100)
  3.5             REAL*8 ERRV(100),ERRAF(100),ERRAP(100)
  4        C      HU1 IS THE UPPER LIMIT OF INTEGRATION FOR SECTION 1
  5        C      HU2 IS THE UPPER LIMIT OF INTEGRATION FOR SECTION 2
  6        C      RND IS THE NONDIMENSIONAL RADIUS; RF/RC
  7        C      VND IS THE NONDIMENSIONAL VOLUME; VOLF/VC
  8        C      AFND IS THE NONDIMENSIONAL FLAME FRONT AREA; AFLAME/AC
  9        C      APND IS THE NONDIMENSIONAL WET PERIMETER AREA; AWP/(AC + AB)
 10        C      S IS THE CONNECTING ROD LENGTH
 11        C      H IS S+HC,(HC IS THE CLEARANCE HEIGHT)
 12        C      RF IS THE FLAME RADIUS
 13        C      RC IS THE CYLINDER RADIUS
 14        C      RB IS THE BOWL RADIUS
 15        C      VOLF IS THE VOLUME ENCLOSED BY THE SPHERICAL FLAME FRONT
 16        C      D IS THE DEPTH OF THE BOWL
 17               COMMON RF,RC,RB
 18               PI=3.141593
 18.1             VOLF2=0.0
 18.2             AWP=0.0
 18.3             AWP1=0.0
 18.4             AWP2=0.0
 18.5             AFLAM1=0.0
 18.6             AFLAM2=0.0
 19               S=10.0
 20               R=2.25
 21               DO 2000 K=1,45
 22               CA=(K-1)*PI/180.0
 23               B=DARSIN(R/S* DSIN(CA))
 24               H= S + R - S*DCOS(B) - R*DCOS(CA)
 25               DEPS=0.0
 25.5             DREL=0.00000001
 26               D=1.337
 27               RC=3.25/2
 28               RB=0.83
 29               HC=.059
 30               H=H+HC
 31               HU2=0.
 32               HT=H+D
 35               RF=.00
 36               HND(K)=H/HC
 37               WRITE(6,20) HND(K)
 38        20     FORMAT('1',' DIMINSIONLESS HEIGHT OF PISTON H/RC = ',F8.5)
 39               DO 1000 J=1,100
 39.5             DEPS=1.00E-11
 42               N=J
 43               RF=J*.08125/2.
 44               RND(J)=RF/RC
 45        C      FIRST CALC THE VOLUME OF THE FLAME. THE CALC IS DONE IN
 46        C      TWO PARTS. PART ONE ASSUMES A DISC CHAMBER OF HEIGHT H
 47        C      PART TWO BRINGS IN THE EXTRA VOLUME OF BOWLS OR DEPRESSIONS
 48        C      IN THE CYLINDER HEAD OR PISTON
 49               HU1=RF
 50        C      THE UPPER LIMIT OF INTEGRATION IS SET TO THE FLAME RADIUS
 51               IF (HU1 .GT. H) HU1=H
 52               VOLF1=DCADRE(AFS1,O.DO,HU1,DEPS,DREL,ERROR)
 52.2             ERRV(J)=ERROR
```

```
53                    IF (HU1 .LT. H) GO TO 98
54                    IF (HU1 .EQ. RF) GO TO 98
55       C     THIS MEANS THE SPHERE DOES NOT INTERSECT THE PISTON & THEREFORE
56       C     NO FURTHER VOLUME CALC IS REQUIRED.
57                    HU2=RF
58                    IF (RF .GT. H+D)HU2=H+D
59                    VOLF2=DCADRE(AFS2,H,HU2,DEPS,DREL,ERROR)
59.2                  ERRV(J)=ERRV(J)+ERROR
60       98           VOLF=VOLF1 + VOLF2
60.5                  ERRV(J)=100.000-(VOLF - ERRV(J))/VOLF *100.
61                    VOLF1=0.
62                    VOLF2=0.
63                    VND(J)=VOLF/(3.14*(RC**2*H + RB**2*D))
64       C   NOW CALCULATE AREA OF FLAME FRONT
65       C     THE CALCULATION IS SIMILAR TO THE VOLUME CALC
66                    AFLAM1=DCADRE(ALF,0.,HU1,DEPS,DREL,ERROR)
66.5                  ERRAF(J)=ERROR
67                    IF (HU2 .LT. H) GO TO 99
68                    AFLAM2=DCADRE(GAM,H,HU2,DEPS,DREL,ERROR)
68.5                  ERRAF(J)=ERRAF(J)+ERROR
69       99           AFLAME=(AFLAM1 + AFLAM2)*2*RF
69.2                  IF ((AFLAM1+AFLAM2).LE. 0.0)GO TO 33
69.5                  ERRAF(J)=100.-((AFLAM1+AFLAM2)-ERRAF(J))/(AFLAM1+AFLAM2)*100.
69.7                  GO TO 34
69.8     33           ERRAF(J)=100.00- ERRAF(J)*100.0
70       34           AFLAM1=0.
71                    AFLAM2=0.
72                    AFND(J)=AFLAME/(2*3.14*RC**2)
73       C   NOW CALCULATE AREA OF WETTED PERIMETER
74       C
75                    AWP=(DCADRE(BET,0.,HU1,DEPS,DREL,ERROR))*2*RC
75.2                  AWP1=AWP+AFS1(0.D0)
75.5                  ERRAP(J)=ERROR
76                    IF (HU2 .LT. H)GO TO 100
77                    AWP2=(DCADRE(DEL,H,HU2,DEPS,DREL,ERROR))*2*RB
77.2                  AWP=AWP+AWP2
77.5                  ERRAP(J)=ERRAP(J)+ERROR
78                    AWP2=AWP2+ AFS1(H)-AFS2(H)
79                    IF (HU2 .EQ. HT) AWP2=AWP2+AFS2(HT)
80       100          APND(J)=(AWP1 + AWP2)/(2*3.14*(RC*H + RB*D +RC**2 ))
80.5                  ERRAP(J)=100.00-(AWP-ERRAP(J))/(AWP)*100.
80.7                  AWP=0.0
81                    AWP1=0.
82                    AWP2=0.
83                    HU1=0.
84                    HU2=0.
85                    IF (VND(J).GE. 1.) GO TO 2
86       1000   CONTINUE
87       2      CONTINUE
88              WRITE(6,3) N
89       3      FORMAT('-','N = ',I3)
90              WRITE(6,30)
91       30     FORMAT('-',4X,'RF/RC',9X,'VF/VT',9X,'ERROR%',7X,'AFF/AFT',
91.5          1 8X,'ERROR%',7X,'AWP/APT',8X,'ERROR%')
92              DO 10 J=1,N
93              WRITE(6,1) RND(J),VND(J),ERRV(J),AFND(J),ERRAF(J),APND(J),
93.5          1 ERRAP(J)
94       1      FORMAT('0',2(F12.10,2X),F12.9,2X,2(F12.10,2X,F12.9,2X))
```

```
 95     10        CONTINUE
 96     2000      CONTINUE
 97               STOP
 98               END
 99               DOUBLE PRECISION FUNCTION AFS1(Z)
100               IMPLICIT REAL*8(A-H,O-Z,$)
101               COMMON RF,RC,RB
101.5             PI=3.141593
102               R=DSQRT(RF**2 - Z**2)
103               IF (R .GT. 2*RC)R=2*RC
104               ALFA=DARCOS(R/(2*RC))
105               BETA=DARCOS((2*RC**2 - R**2)/(2*RC**2))
106               IF(BETA .GT. PI/2) GO TO 1
107               AFS1=R**2 * ALFA +RC**2*(BETA-DSIN(BETA))
108               GO TO 2
109     1         AFS1=R**2*(ALFA-DSIN(ALFA)) + BETA*RC**2 +
110              1 (R*DCOS(GAMMA)- RC)*R*DSIN(ALFA)
110.5   2         CONTINUE
111               RETURN
112               END
113               DOUBLE PRECISION FUNCTION AFS2(Z)
114               IMPLICIT REAL*8(A-H,O-Z,$)
115               COMMON RF,RC,RB
115.5             PI=3.141593
116                DIFF= RF**2-Z**2
120               R=DSQRT(RF**2 - Z**2)
121               IF (R .GT. 2*RB) R=2*RB
122               GAMMA=DARCOS(R/(2*RB))
123               DELTA=DARCOS((2*RB**2-R**2)/(2*RB**2))
124               IF (DELTA .GT. PI/2) GO TO 1
125               AFS2=R**2*GAMMA +RB**2*DELTA - R**2*DSIN(GAMMA) -
125.2            1 RB**2*DSIN(DELTA)
126               RETURN
129     1         AFS2=R**2*(GAMMA-DSIN(GAMMA)) + DELTA*RB**2
130              1 + (R*DCOS(GAMMA)-RC)*R*DSIN(GAMMA)
131               RETURN
132               END
133               DOUBLE PRECISION FUNCTION ALF(Z)
134               IMPLICIT REAL*8(A-H,O-Z,$)
135               COMMON RF,RC,RB
136               R=DSQRT(RF**2-Z**2)
137               IF (R .GT. 2*RC)R=2*RC
138               ALF=DARCOS(R/(2*RC))
139               RETURN
140               END
141               DOUBLE PRECISION FUNCTION GAM(Z)
142               IMPLICIT REAL*8(A-H,O-Z,$)
143               COMMON RF,RC,RB
144               R=DSQRT(RF**2-Z**2)
145               IF (R .GT. 2*RB)R=2*RB
146               GAM=DARCOS(R/(2*RB))
147               RETURN
148               END
149               DOUBLE PRECISION FUNCTION DEL(Z)
150               IMPLICIT REAL*8(A-H,O-Z,$)
151               COMMON RF,RC,RB
152               R=DSQRT(RF**2 - Z**2)
153               IF (R .GT. 2*RB)R=2*RB
```

```
154           DEL=DARCOS((2*RB**2 - R**2)/(2*RB**2))
155           RETURN
156           END
157            DOUBLE PRECISION FUNCTION BET(Z)
158           IMPLICIT REAL*8(A-H,O-Z,$)
159           COMMON RF,RC,RB
160           R=DSQRT(RF**2-Z**2)
161           IF (R .GT. 2*RC)R=2*RC
162           BET=DARCOS((2*RC**2 - R**2)/(2*RC**2))
163           RETURN
164           END
```

3. Burning Rate Analysis (MASBRN)

The program used to perform the mass burn rate analysis was developed by Jones [36] and a complete description and flow chart may be found. Only alterations concerned with the CFR cylinder geometry were made. These occur in statements defining cylinder volume. The other change was in the way the flame front geometry is evaluated. The old geometry was calculated based on a cylindrical chamber with a hemispherical head. The program DFLAME was used to produce a table of values which MASBRN reads in when required. No other changes were made.

```
1      C  MB    THIS PROGRAM CALCULATES MASS BURNING RATE AND
2      C  ===   FLAME SPEED FROM MEASURED PRESSURE DATA TAKEN
3      C           FROM THE CFR ENGINE.
4      C
5            IMPLICIT REAL*8(A-H,O-Z)
6            REAL*8 MPV,K,L,M,N,NO,N2,NO2,NCH,KK,NUM,NUM1,NMIX,MOLFL,
7           -NM,NM1,NNM1,NNM2,NN2,NNO2,MEP,LENG,MTOT,MWMIX,MFX1,NNCH,
8           -MFX2,MW(14),MMFX2,NRN2,NRES,NRO2,NRCO2,NRH2O,NNFUEL
9           -,MF(5,200),IGNDEL,MWBMIX
10     C
11           COMMON /AREA1/ NCH,NO2,K,L,M,N,KFUEL
12           COMMON /AREA2/ MOLFL,NMIX,HF1,NNO2,NN2,NNFUEL,KOM
13           COMMON /AREA3/ AREAB,HTEXP,MPV,HTFCN,TWALL,VISC,THCOND
14           COMMON /AREA4/ NDISS,IPRINT
15     C
16           DIMENSION X(10),PP(5,200),VV(5,200),VV2(5,200),VVX(20),
17          -DH(20),CPG(20),PP2(5,200),DI(5,200),TIM(5,200),XX(5,200),
18          -CCA(10),DL(5,200),ZZ(5,200),DC(5,200),YY(5,200),POUT(180),
19          -UUU(10),CC(10),PDAT(5,200),CB(5,200),TB(5,200),
20          -FS(5,200),RB(5,200)
21     C
22           INTEGER IPRES(5,200),NREP,NMODE
23     C
24     C  STATEMENT FUNCTION USED THROUGHOUT PROGRAM TO CALCULATE CYLINDER
25     C  VOLUME (DVOL) AT A GIVEN CRANK ANGLE (DALFA). VOLUME OBTAINED MUST
26     C  BE ADDED TO THE CLEARANCE VOLUME TO GIVE TOTAL CYLINDER VOLUME
27     C
29           DVOL(DALFA)=3.14159*((BORE/2.)**2.)*((STROK/2.)*(1.-DCOS(DALFA*
30          -0.0174532))+LENG*(1.-DSQRT(1.-(DSIN(DALFA*0.0174532)*DSIN(DALFA
31          -*0.0174532)*((STROK/2./LENG)**2.)))))
31.5         PI=3.14159
32           NUMBR=1
33           IPRINT=0
33.5         JFLG=0
34           IGRAPH=0
35           DO 222 IL=1,NUMBR
36     C
37     C
38     C  READ TYPE OF FUEL (11=CH4, 12=C8H18, 13=C3H8 ):
39     C  TEMP. (T1)(K) AT START OF COMBUSTION;
40     C  ENGINE SPEED (RPM);  COMPRESSION RATIO (COMPR); REL. AIR/FUEL
41     C  RATIO, LAMBDA (AF); SPARK ADVANCE (SPKAD)(DEG. B.T.D.C.);
42     C  HEAT TRANSFER MULTIPLIER (HTFCN);
43     C  HEAT TRANSFER EXPONENT (HTEXP);
44     C  RESIDUAL GAS FRACTION (%),(F); PERCENTAGE CONSTITUENTS IN
45     C  RES. FRACTION (PRO2,PRCO2,PRH2O,PRN2);
46     C  WHETHER FULL DISSOCIATION (NDISS=O), OR PARTIAL (NDISS=1);
47     C  CRANK ANGLE ITERATION INCREMENT (PDCA); CYL. WALL TEMP. (TWALL);
48     C
49     C  THERE IS AN OPTION TO ENTER DATA IN THE INTERACTIVE MODE OR
50     C  CONVENTIONALLY THRU A DATA FILE
51     C
52           WRITE(6,1)
53     1     FORMAT(' ','DO YOU WANT TO READ THE DATA FILE (0) OR ENTER DATA
54          1INTERACTIVELY (1) ?')
55           CALL FREAD('GUSER','I:',NMODE)
55.5         JFLG=0
56           IF (NMODE .EQ. 1) GO TO 3
```

```
57            READ(5,47) KFUEL,T1,SPEED,COMPR,AF,SPKAD,HTFCN,HTEXP
58       47   FORMAT(I3,2F7.1,3F6.2,F6.3,F5.2)
59            READ(5,46) F,PRO2,PRCO2,PRH2O,PRN2,NDISS,PDCA,TWALL
60       46   FORMAT(5F7.3,I3,F6.2,F7.1)
61            READ(5,2) PINLET,AIRFLO,IGNDEL,SCONST,IPRNTS,PAMB
62            READ(5,22) CUPD,CUPH,HC
63       22   FORMAT(3F8.3)
64        2   FORMAT(F6.1,3F6.2,I3,F6.2)
64.5          JFLG=1
64.7          WRITE(6,5)
64.8      5   FORMAT(' ','DO YOU WANT TO CHANGE ANY OF THE INPUTS 1=Y,O=N ?')
64.9          CALL FREAD('GUSER','I:',NREP)
65            IF ( NREP .EQ. O)GO TO 4
66        3     CALL INPUTS(JFLG,KFUEL,T1,SPEED,COMPR,AF,
67            1 SPKAD,HTFCN,HTEXP,F,PRO2,PRH2O,PRN2,NDISS,PDCA,
68            1 TWALL,PINLET,AIRFLO,IGNDEL,SCONST,IPRNTS,PAMB,CUPD,CUPH,HC)
69        4     CONTINUE
70    C
71    C   READ IN PRESSURE DATA
72    C
73            CALL SMOOTH(POUT,SCONST,IPRNTS)
74    C
75            DO 658 KJ=1,180
76            PDAT(IL,KJ)=POUT(KJ)
77      658 CONTINUE
78    C
79    C   DETERMINE FUEL PROPERTIES: MOL.WEIGHT, LOW HEAT VAL.,
80    C   ENTHAL. OF FORMATION
81    C
82            IF(KFUEL.GT.11) GOTO 10
83            CN=1.O
84            HM=4.O
85            MW(11)=16.04
86            QVS=50050.0
87            HF1=-74873.O
88            WRITE(9,45) CN,HM
89       45   FORMAT(1H ,'FUEL TYPE:-  METHANE  C ',F3.1,' H ',F3.1/)
90            GOTO 30
91    C
92       10   IF(KFUEL.GT.12) GOTO 20
93            CN=8.O
94            HM=18.O
95            MW(12)=114.14
96            QVS=43500.0
97            HF1=-208447.O
98            WRITE(9,43) CN,HM
99       43   FORMAT(1H ,'FUEL TYPE:-  OCTANE  C ',F3.1,' H ',F4.1/)
100           GOTO 30
101   C
102      20   IF(KFUEL.GT.13) STOP
103           CN=3.O
104           HM=8.O
105           MW(13)=44.097
106           QVS=46353.0
107           HF1=-103847.O
108           WRITE(9,44) CN,HM
109      44   FORMAT(1H ,'FUEL TYPE:-  PROPANE  C ',F3.1,' H ',F3.1/)
110   C
```

```
111      C  ENGINE PARAMETERS
112      C
113        30  CONTINUE
114            STROK=4.5*.0254
115            BORE=3.25*.0254
116            LENG=10.0*.0254
117            HTCLRV=HC
118      C   CLEARANCE HEIGHT IS SET FOR EACH GEOMETRY
119            CLRV=HTCLRV*3.141593*(BORE**2)/4.0 +CUPD**2/4.*PI*CUPH+0.0000027
120      C
121      C   GAS CONSTANT (KJ/KMOL K)
122      C
123            RMOL=8.31434
124            JJ=0
125      C
126      C
127      C   CALC STOICH A/F RATIO(STAFR) AND AIR/FUEL RATIO(AFR)
128      C
129            STAFR=((CN+HM/4.)*32.+3.762*(CN+HM/4.)*28.01)/((CN*12)+HM)
130            AFR=STAFR*AF
131      C
132      C   CALCULATE VOLUMETRIC EFFICIENCY FROM AIR MASS FLOW(g/sec),
133      C   INLET TEMP(K) AND PRES(kpa), RPM, AND DENSITY FACTOR
134      C   FOR GASEOUS FUELS
135      C   VOLEFF=AIRFLOW/(P/RT)*FACTOR*SPEED*(SWEPT VOL./2)
136      C   FACTOR=DENSITY CORRECTION FOR FUEL VAPOUR IN CHARGE
137      C   PINLET=PAMB-PLOSS(LOSS THRU VENTURI ELEMENT)
137.5         PLOSS=1.8
138            FACTOR=1
139            IF(KFUEL.EQ.12) GOTO 700
140            FACTOR=1.0+(1.0/AFR)*(29.0/(MW(KFUEL)))
141      C
142      C   INLET PRES REDUCED BY PLOSS
143      C
144        700 VOLEFF=45.858*FACTOR*AIRFLO*T1/(SPEED*(PINLET-PLOSS))
144.5
145      C
146      C   CONVERT PRESSURE DATA IN BAR TO KPA, AND CORRECT DATA FOR
147      C   VOL. EFF.
148      C
149            P1=VOLEFF*(PINLET-PLOSS)
150            PVEFF=(101.3)-P1
151            WRITE(9,701) P1,VOLEFF,FACTOR,PVEFF
152        701 FORMAT(1H ,'P1,VOLEFF,FACTOR,PVEFF ',4F10.3/)
153            DO 267 I=1,180
154            PDAT(IL,I)=PDAT(IL,I)/1000.-PVEFF
155        267 CONTINUE
156      C
157      C
158      C   CALC. NUMBER OF KMOLS OF REACTANTS AND PRODUCTS BEFORE AND AFTER
159      C   COMBUSTION RELATIVE TO ONE KMOL OF FUEL
160      C   (NOT INCLUDING DISSOCIATION).  NCH=HYDROCARBON
161      C   NO2=AVAILABLE OXYGEN, N=NITROGEN, K=CO2, L=H2O, M=UNBURNT OXYGEN
162      C
163            NCH=1
164            NO2=(CN+HM/4)*AF
165            N=3.762*(CN+HM/4)*AF
166            K=CN
```

```
167          L=HM/2
168          M=(CN+HM/4)*(AF-1)
169    C
170          WRITE(9,655) NCH,NO2,N,K,L,M
171      655 FORMAT(1H ,'NCH,NO2,N,K,L,M=',6F9.5/)
172    C
173    C   CALC. TOTAL NUMBER OF KMOLS OF REACTANTS...
174          SUMNS=NCH+NO2+N
175    C CALC. NO. OF KMOLS OF RESIDUAL GAS GIVEN THE VOLUME FRACTION OF
176    C RESIDUAL GASES 'F'....
177          NRES=(F/(1-F))*SUMNS
178    C CALC. NO. OF KMOLS IN CYLINDER PER KMOL OF FUEL...
179          NMIX=SUMNS+NRES
180          SUMNS=NMIX
181    C CALC. NO OF KMOLS OF EACH RESIDUAL GAS...
182          NRO2=PRO2*NRES/100.0
183          NRCO2=PRCO2*NRES/100.0
184          NRH2O=PRH2O*NRES/100.0
185          NRN2=PRN2*NRES/100.0
186    C CALC. NEW VALUES FOR THE TOTAL NO. OF KMOLS OF N2, O2, CO2,& H2O...
187          N=N+NRN2
188          NO2=NO2+NRO2
189          K=K+NRCO2
190          L=L+NRH2O
191          M=M+NRO2
192          WRITE(9,655) NCH,NO2,N,K,L,M
193    C
194    C  CALC. ENERGY OF REACTANTS AT INLET TEMP; 5=O2, 6=N2, 11=CH4
195    C  12=C8H18, 13=C3H8, 1=CO2, 3=H2O,...  (IN KJ/KMOL OF FUEL)
196          DH(1)=((3.096*T1+0.00273*(T1**2)-7.885E-07*(T1**3)
197         1+8.66E-11*(T1**4))-1145.0)*RMOL
198          DH(3)=((3.743*T1+5.656E-04*(T1**2)+4.952E-08*(T1**3)
199         1-1.818E-11*(T1**4))-1167.0)*RMOL
200          DH(5)=((3.253*T1+6.524E-04*(T1**2)-1.495E-07*(T1**3)
201         1+1.539E-11*(T1**4))-1024.0)*RMOL
202          DH(6)=((3.344*T1+2.943E-04*(T1**2)+1.953E-09*(T1**3)
203         1-6.575E-12*(T1**4))-1023.0)*RMOL
204          DH(11)=((1.935*T1+4.965E-03*(T1**2.)-1.244E-06*(T1**3.)
205         1+1.625E-10*(T1**4.)-8.586E-15*(T1**5.))-985.9)*RMOL
206          DH(12)=((-0.72*T1+4.643E-02*(T1**2.)-1.684E-05*(T1**3.)
207         1+2.67E-09*(T1**4.))-3484.0)*RMOL
208          DH(13)=((1.137*T1+1.455E-02*(T1**2.)-2.959E-06*(T1**3.)
209         1)-1552.9)*RMOL
210          UUU(1)=-3.93522E05
211          UUU(3)=-2.41827E05
212    C   CALC. TOTAL ENERGY OF MIXTURE (KJ/KMOL FUEL)
213          ERCT=(NCH*(HF1+DH(KFUEL)-RMOL*T1)+NO2*(DH(5)-RMOL*T1)
214         -+N*(DH(6)-RMOL*T1)+NRCO2*(UUU(1)+DH(1)-RMOL*T1)+NRH2O*
215         -(UUU(3)+DH(3)-RMOL*T1))
216    C
217    C   CALC. SWEPT VOL.(CYLV),CLEARANCE VOL.(CLRV),TOTAL VOL.(V1),
218    C   VOLUME CORRESPONDING TO GIVEN SPARK ADVANCE (DVOLM)...
219          CYLV=3.1415926*((BORE/2.)**2.)*STROK
220          V1=CYLV + CLRV
221          VTOTAL=V1
222          MPV=SPEED*STROK/30.0
223    C  SUBT. SPK ADV. ANGLE FROM 360'AND ADD IGNITION DELAY...
224          ANG=(360.0-SPKAD+IGNDEL)
```

```
225     C    INITIALISE CRANK ANGLE COUNTER AT B.D.C. & SET TIME TO ZERO
226              DLF1=180.0
227              TIME=0.0
228     C    CALC. VOLUME IN CYLINDER AT SPARK TIME (USED LATER)
229              DVOLM=(CLRV+DVOL(ANG))
230              TIME=0.0
231     C TOTAL NO. OF MOLS IN CYL.=NO. OF MOLS OF FUEL*(1+4.76(CN+HM/4).AF)
232     C WHERE (1+4.76(CN+HM/4).AF)=NMIX.
233     C I.E.   NTOT=MOLFL*NMIX
234     C BUT  P1.V1=NTOT.RMOL.T1   OR   NTOT=P1.V1/RMOL.T1 = MOLFL.NMIX
235     C THEREFORE NO. OF MOLS OF FUEL IN CYL. = P1.V1/NMIX.RMOL.T1 .....
236              MOLFL=(P1*V1)/(NMIX*RMOL*T1)
237     C    ENERGY OF CYLINDER CONTENTS IN KJ .....
238              ENGY1=ERCT*MOLFL
239     C    CALC. STOICH. A/F RATIO (STAFR),AIR/FUEL RATIO (AFR),PERCENTAGE
240     C    OXYGEN (NNO2), NITROGEN (NN2) AND FUEL (NNCH) IN MIXTURE...
241              STAFR=((CN+HM/4.)*32.+3.762*(CN+HM/4.)*28.01)/((CN*12)+HM)
242              AFR=STAFR*AF
243              NNO2=(NO2/NMIX)*100.
244              NN2=(N/NMIX)*100.
245              NNCH=100.-(NNO2+NN2)
246              NNFUEL=NNCH
247     C  GIVEN MOLECULAR WEIGHTS OF FUELS, CALC. MOLECULAR WEIGHT OF
248     C  MIXTURE (MWMIX); TOTAL MASS OF MIXTURE (MTOT); AND SPECIFIC
249     C  VOLUME OF MIXTURE.....
250              MWMIX=(NNO2*32.0/100.)+(NN2*28.0/100.)+(NNCH*MW(KFUEL)/100.)
251              MTOT=(PDAT(IL,1)*V1*MWMIX)/(T1*RMOL)
252              VTOT1=V1
253              VSU1=VTOT1/MTOT
254              ETOT1=ERCT/MWMIX/NMIX
255     C
256     C
257              WRITE(9,735) MPV,TWALL,HTFCN,HTEXP
258         735 FORMAT(1H ,'MPV,TWALL,HTFCN,HTEXP ',4E12.4/)
259              WRITE(9,734) ERCT,ENGY1,NMIX,MWMIX,MOLFL,MTOT
260         734 FORMAT(1H ,'ERCT,EG1,NMIX,MWMX,MOLFL,MTOT;',6E12.4//)
261     C
262              WRITE(9,652) SPEED,SPKAD
263         652 FORMAT(1H ,'SPEED (RPM) = ',F7.1,
264             -7X,'SPARK ADVANCE (DEG. BTDC) =',F7.2,3X/)
265              WRITE(9,813) AFR,STAFR,AF,COMPR
266         813 FORMAT(1H ,15HAIR/FUEL RATIO=,F6.2,3X,18HSTOICH. A/F RATIO=,
267             -F6.2,3X,7HLAMBDA=,F6.2,3X,12HCOMP. RATIO=,F5.1/)
268              WRITE(9,31)
269          31 FORMAT(1H ,1X,'STEP',1X,'VOL',3X,'PRESS',3X,'TU',5X,'TB',5X
270             -,'MFX',4X,'VFRBNT',2X,'CBVEL',3X,'TBVEL',3X,'FLMSPD',2X,
271             -'FSR',3X,'RADF',2X,'AREAF',3X,'C.A.',3X,'ENERGY'/)
272              DO 106 KI=1,10
273              X(KI)=0.0
274         106 CONTINUE
275              NI=1
276              V1=V1*(1E+06)
277              WRITE(9,893) NI,V1,PDAT(IL,NI),T1,(X(I),I=1,9),
278             -DLF1,ENGY1
279         893 FORMAT(1H ,I3,1X,F6.1,3F7.1,F9.4,F7.2,2F8.3,F7.2,F7.2,F7.3,
280             -F7.2,F7.1,F9.5)
281              TU1=T1
282              V1=V1/(1E+06)
```

```
283              T2=T1
284              PP2(IL,1)=PDAT(IL,1)
285              VV2(IL,1)=V1
286              TIM(IL,1)=TIME
287              MF(IL,1)=0.0
288              CB(IL,1)=0.0
289              TB(IL,1)=0.0
290              FS(IL,1)=0.0
291              RB(IL,1)=0.0
292              JJJ=1
293              NUT=0
294              DCA=PDCA
295              NDCA=(360./DCA)
296              ADCA=0.0
297      C
298      C    START COMPRESSION STROKE
299      C    ========================
300      C
301      C    THIS SECTION CALCULATES ADIABATIC PRESSURE RISE AT EACH CRANK
302      C    ANGLE INTERVAL AND COMPARES THE RESULT WITH THE CORRESPONDING
303      C    MEASURED PRESSURE VALUE TO DETERMINE IF COMBUSTION HAS STARTED.
304      C
305              DO 40 NI=2,NDCA
306      C    ---------------
307      C    CALC. VOLUME DIVISION (DIV) FOR GIVEN C.A. DIVISION (DCA)
308              DIV=DVOL(DLF1)-DVOL(DLF1+DCA)
309      C    CALC. NEW VOLUME IN CYLINDER & RESET C.A. COUNTER TO NEW VALUE
310              V2=V1-DIV
311              DLF1=DLF1+DCA
312              DTIME=DCA/(6.0*SPEED)
313              DIST=(DVOL(DLF1))/(3.14159*((BORE/2.)**2))
314      C
315      C    CALC. NEW MIXTURE TEMPERATURE USING P.V = R.T
316              T2=(MWMIX*PDAT(IL,NI)*V2)/(MTOT*RMOL)
317              CALL COMP(T2,ENGY2,NRCO2,NRH2O)
318      C
319      C.   IF NEW C.A. < SPK. ADV., CONTINUE WITH COMP. STROKE CALCS.
320              IF(DLF1.GT.ANG) GOTO 610
321      C    IF NEW C.A. > SPK. ADV., CALCULATE ADIABATIC PRESSURE RISE
322      C    AND COMPARE RESULT WITH MEASURED VALUE..
323      C
324      C        IF(IPRINT.EQ.0) GOTO 393
325              CALL GAM(T2,T1,GAMU)
326              PISEN=((V1/V2)**GAMU)*PDAT(IL,(NI-1))
327      C        WRITE(9,257) PDAT(IL,NI),PISEN,T2,GAMU
328      C 257  FORMAT(1H ,'PDAT,PISEN,T2,GAMU ',4F10.3)
329      C
330      C----------------------------------------------------------)
331      C        IF(IDELP.EQ.2) GOTO 217                            )
332      C        DELP1=(PDAT(IL,NI)-PISEN)                          )
333      C        IDELP=2                                            )
334      C        GOTO 51                                            )
335      C                                                          )
336      C217  DELP2=(PDAT(IL,NI)-PISEN)                             )
337      C        IF((DELP2-DELP1).GT.PTHRES) GOTO 610               )
338      C----------------------------------------------------------)
339      C
340      C    CALC. CURRENT TIME; AND PRESS. AT GIVEN VOL. & TEMP.
```

```
341        393 TIME=(DLF1-180.)/(6.0*SPEED)
342     C    RECORD PERMANENT VALUES OF PRESS., VOL., TIME, VOL. DIV, AND
343     C    C.A. DIV, AT END OF EACH C.A. STEP...
344           PP2(IL,NI)=PDAT(IL,NI)
345           VV2(IL,NI)=V2
346           TIM(IL,NI)=TIME
347           DI(IL,(NI-1))=DABS(DIV)
348           DC(IL,(NI-1))=DCA
349           MF(IL,NI)=0.0
350           CB(IL,NI)=0.0
351           TB(IL,NI)=0.0
352           FS(IL,NI)=0.0
353           RB(IL,NI)=0.0
354     C     DELP1=DELP2
355           KTDC=0
356           T1=T2
357           V1=V2
358     C    ADJUST MAGNITUDE OF VOLUME FOR WRITE STATEMENT...
359           V2=V2*(1E+06)
360     C-----------------------------------------------------------------
361           WRITE(9,893) NI,V2,PDAT(IL,NI),T2,(X(I),I=1,9),
362          -DLF1,ENGY2
363     C-----------------------------------------------------------------
364        650 V2=V2/(1E+06)
365         40 CONTINUE
366        610 TU1=T1
367           VSU1=V1/MTOT
368     C    CALCULATE ENERGY OF MIXTURE JUST BEFORE START OF COMBUSTION
369     C
370           CALL COMP(T1,ENGY1,NRCO2,NRH2O)
371           KZZ=2
372     C
373     C  START OF PROGRESSIVE BURNING
374     C  ===============================
375     C
376     C    ITERATION CONTROLS AND INITIALISATION
377           NG=0
378           KOM=0
379           NED=1
380           JJJ=1
381           NDC=1
382           IDTM=1
383           IMX=1
384           MFX1=0.0
385           NNN=1
386           IVOL=1
387           KTDC=0
388           SUMXS=NMIX
389           TB2=1900.0
389.5         MWBMIX=MWMIX
390           THCOND=0.1
391           VISC=0.5E-04
392           VSB2=0.5
393           DQSUM=0.0
394           PDVSUM=0.0
395           ESPARK=ENGY1
396     C
397     C  ------------------------------------------------------------
```

```
398                  DO 333 LMN=1,50
399     C            ===============
400     C
401     C 1500LC. TIME TAKEN FOR PISTON TO TRAVEL THROUGH 'DCA' DEGREES C.A.
402     C
403     C  IF FIRST TIME THROUGH FROM COMPRESSION STROKE, SKIP VOLUME
404     C  CALCULATIONS...
405     C
406            IF(KZZ.EQ.2) GOTO 727
407            NI=NI+1
408      508 DTIME=DCA/(6.0*SPEED)
409     C  UPDATE TIME AND CRANK ANGLE COUNTER...
410            TIME=TIME+DTIME
411            DLF1=DLF1+DCA
412     C  CALC. DISTANCE FROM PISTON TOP TO T.D.C.....
413            DIST=DVOL(DLF1)/(3.14159*((BORE/2.)**2))
414     C  CALC. CHANGE IN VOLUME DUE TO PISTON MOTION...
415            DIV=DVOL(DLF1-DCA)-DVOL(DLF1)
416     C  CALC. NEW TOTAL VOLUME....
417            V2=V1-DIV
418      727 VTOT1=V2
419     C          WRITE(9,461) DTIME,TIME,DLF1,DIST,DIV,V2
420     C 461      FORMAT(1H ,'DTIME,TIME,DLF1,DIST,DIV,V2=',6E11.4)
421     C  UPDATE ITERATION COUNTER AND FIND NO. OF ITERATION AT T.D.C.
422            IF(KTDC.GT.0) GOTO 350
423            IF(DLF1.GE.360.0) KTDC=NI
424     C
425     C  START BURNING...
426     C  ***************
427     C
428      350 IF(NG.EQ.0) AREAB=0.0
429     C
430            PDT1=PDAT(IL,(NI-1))
431            PDT2=PDAT(IL,NI)
432            CALL ENUFLS(PDT2,PDT1,TU1,VSU1,MWMIX,TU2,VSU2,
433           -EU2,TBVEL,AF,T2,NRCO2,NRH2O)
434            HTCOEF=(THCOND/BORE)*((MPV*BORE/(VSB2*VISC))**HTEXP)/1000.0
435            DQ=HTCOEF*AREAB*(TB2-TWALL)*HTFCN*DTIME
435.5          IF (DCA .GT. 60.) WRITE(6,7777) AREAB,DQ,DCA
435.7    7777 FORMAT(' ',3F20.10)
436            NG=1
437            PDV=((PDAT(IL,NI)+PDAT(IL,(NI-1)))/2.)*DIV
438            ENGY2=ENGY1+PDV-DQ
439            PDVSUM=PDVSUM+PDV
440            DQSUM=DQSUM+DQ
441            TRT=(MWBMIX*PDAT(IL,NI)*V2)/(MTOT*RMOL)
442     C----------------------------------------------
443            IF(IPRINT.EQ.0) GOTO 971
444            WRITE(9,737) ENGY2,ENGY1,PDV,DQ,HTCOEF,TRT
445      737 FORMAT(1H ,'E2,E1,PDV,DQ,HTCOEF ',5E12.4,F8.1)
446     C----------------------------------------------
447      971 ETOT1=ENGY2/MTOT
448            CALL TEMP(PDT2,TB2,NNN,CC,MFX2,MTOT,EU2,VSU2,
449           -VTOT1,ETOT1,VSB2,MWBMIX)
450     C
451            IF(MFX2.LT.0.5) GOTO 394
452            IF(MFX2.GT.0.98) GOTO 312
453            IF((MFX2-MFX1).GT.0.01) GOTO 394
```

```
454      312 KZZ=2
455          GOTO 365
456      394 CALL CALFLS(MFX1,MFX2,VSB2,MTOT,DTIME,VSU2,CBVEL,VSU1,
457          -AREAF1,VOLB2,IVOL,VOLB1,AREAF2,RB1,RB2,DLF1,DIST)
458          KOM=0
459    C
460      970 VOLU2=VTOT1-VOLB2
461          FLMSPD=(RB2-RB1)/(DTIME)
462          VFRBNT=(VOLB2/VTOT1)*100.0
463          FSR=CBVEL/TBVEL
464          V=VTOT1*(1E+06)
465          PRB2=RB2*100.0
466          PAREAF=AREAF2*10000.0
467    C----------------------------------------------------------------
468          WRITE(9,893) NI,V,PDAT(IL,NI),TU2,TB2,MFX2,VFRBNT,CBVEL,
469          -TBVEL,FLMSPD,FSR,PRB2,PAREAF,DLF1,ENGY2
470    C----------------------------------------------------------------
471          PP2(IL,NI)=PDAT(IL,NI)
472          TIM(IL,NI)=TIME
473          VV2(IL,NI)=V2
474          DI(IL,(NI-1))=DABS(DIV)
475          DC(IL,(NI-1))=DCA
476          MF(IL,NI)=MFX2
477          CB(IL,NI)=CBVEL
478          TB(IL,NI)=TBVEL
479          FS(IL,NI)=FLMSPD
480          RB(IL,NI)=PRB2
481    C
482          VOLB1=VOLB2
483          AREAF1=AREAF2
484          RB1=RB2
485          TU1=TU2
486          MFX1=MFX2
487          VSU1=VSU2
488          V1=V2
489          T1=T2
490          ENGY1=ENGY2
491          KZZ=1
492          IVOL=2
493      333 CONTINUE
494    C
495      365 T1=MFX2*TB2+(1-MFX2)*TU2
496          ECEND=ENGY2
497    C     WRITE(9,266) MWBMIX,PDAT(IL,NI),V2,MTOT,RMOL
498    C 266 FORMAT(1H ,5E12.4/)
499          TRT=(MWBMIX*PDAT(IL,NI)*V2)/(MTOT*RMOL)
500          CALL ENERGY(TRT,PDAT(IL,NI),EPROD,SUMXS,NNN,CC,X,EB2,VSB2,
501          -GAMMA,MWBMIX)
502          TENGY=EPROD*MOLFL
503          TDQ=(ESPARK-TENGY)-PDVSUM
504          WRITE(9,265) ESPARK,ECEND,TENGY,PDVSUM,DQSUM,TDQ,T1,TRT
505      265 FORMAT(1H ,'ESPK,ECND,TENG,PDVS,DQS,T1,TRT ',6F10.6,2F7.1/)
506          DO 249 KKI=1,10
507      249 X(KKI)=0.0
508          NUT=0
509          JJJ=1
510          NNN=1
511          IF(KZZ.EQ.2) GOTO 396
```

```
512
513        C  START EXPANSION STROKE
514        C  ========================
515        C
516          310 DIV=DVOL(DLF1+DCA)-DVOL(DLF1)
517              V2=V1+DIV
518              IF(V2.LT.497.0E-06) GOTO 851
519              DLF1=DLF1+DCA
520              IF(DLF1.GE.538) JJJ=2
521              TIME=(DLF1-180.0)/(6.0*SPEED)
522              NI=NI+1
523              GOTO 718
524          851 DLF1=DLF1+DCA
525              DIST=DVOL(DLF1)/(3.14159*((BORE/2.)**2))
526              DTIME=DCA/(6.0*SPEED)
527              TIME=(DLF1-180.0)/(6.0*SPEED)
528              NI=NI+1
529              NUT=NUT+1
530              IF(NUT.GT.80) STOP
531          396 ATOT=3.14159*(2.*BORE**2/4 +(HC+DIST)*BORE + CUPD*CUPH)
533              CALL EXP(PDAT(IL,(NI-1)),V1,T1,PDAT(IL,NI),V2,T2,NNN,CC,
534             -SUMXS,ENGY1,ENGY2,ATOT,DTIME,MTOT,MWBMIX)
535          718 ENGY1=ENGY2
536              T1=T2
537              V1=V2
538              PP2(IL,NI)=PDAT(IL,NI)
539              VV2(IL,NI)=V2
540              TIM(IL,NI)=TIME
541              DI(IL,(NI-1))=DABS(DIV)
542              DC(IL,(NI-1))=DCA
543              MF(IL,NI)=MFX2
544              CB(IL,NI)=0.0
545              TB(IL,NI)=0.0
546              FS(IL,NI)=0.0
547              RB(IL,NI)=0.0
548              V4=V2
549              T4=T1
550              V4=V4*(1E+06)
551        C 285 IF(JJJ.EQ.2) GOTO 277
552        C     IF(NUT.GT.2) GOTO 817
553        C---------------------------------------------------------------
554          277 WRITE(9,893) NI,V4,PDAT(IL,NI),X(1),T4,MFX2,VFRBNT,(X(I),I=1,6),
555             -DLF1,ENGY2
556        C---------------------------------------------------------------
557          817 IF (JJJ.EQ.1) GOTO 310
558        C
559              WRITE(9,818) (CC(I),I=1,8)
560          818 FORMAT(1H ,'%CO2=',F7.3,' %CO=',F7.3,' %H2O=',F7.3,' %H2=',F7.3,
561             -' %O2=',F7.3,' %N2=',F7.3,' %NO=',F7.3,' %OH=',F7.3/)
562        C
563        C
564        C  THIS SECTION CALCULATES INTEGRAL OF PDV (PDV),MEAN EFFECTIVE
565        C  PRESSURE (MEP),POWER AND THERMAL EFFICIENCY.
566        C  ============================================================
567        C
568          304 PDV=0.0
569              SUMDI=0.0
570              AREA1=0.0
```

```
571          AREA3=0.0
572          MTDC=KTDC-1
573          DO 300 J=1,MTDC
574      300 AREA1=AREA1+(PP2(IL,J)+PP2(IL,(J+1)))*DI(IL,J)/2.0
575          NTDC=KTDC+1
576          NID=NI-1
577          DO 302 J=NTDC,NID
578      302 AREA3=AREA3+(PP2(IL,J)+PP2(IL,(J+1)))*DI(IL,J)/2.0
579          DO 303 J=1,MTDC
580      303 SUMDI=SUMDI+DI(IL,J)
581          VA1=CYLV-SUMDI
582          VA2=DI(IL,KTDC)-VA1
583          PPTDC=PP2(IL,KTDC)+((VA1/DI(IL,KTDC))*(PP2(IL,NTDC)-
584         -PP2(IL,KTDC)))
585          AREA2=(PPTDC+PP2(IL,KTDC))*VA1/2.0
586          AREA4=(PPTDC+PP2(IL,NTDC))*VA2/2.0
587          IF(IPRINT.EQ.0) GOTO 269
588          WRITE(9,486) AREA1,AREA2,AREA3,AREA4,VA1,VA2,PPTDC,PDV
589      486 FORMAT(1H ,'A1,A2,A3,A4,VA1,VA2,PTDC,PDV',8E12.4/)
590      269 PDV=(AREA3+AREA4)-(AREA1+AREA2)
591          MEP=PDV/(CYLV*100.0)
592          POWER=(PDV*SPEED/120.)
593          EFF=(PDV*100.)/(MOLFL*QVS*(12.*CN+HM))
594  C-----------------------------------------------------------
595          WRITE(9,301) POWER,MEP,EFF
596      301 FORMAT(10X,6HPOWER=,F8.3,5X,9HI.M.E.P.=,F7.3,5X,11HEFFICIENCY=,
597         -F10.5///)
598  C-----------------------------------------------------------
599  C  WRITE VALUES OF PRESSURE, MASS FRACTION BURNT, CALC. BURNING
600  C  VELOCITY, LAMINAR BURNING VELOCITY, AND FLAME SPEED FOR USE
601  C  BY THE PLOTTING PROGRAM 'DP2'....
602  C
603          IJUMP1=0
604          IJUMP2=0
605          IJUMP3=0
606          IJUMP4=1
607          NUMM=1
608          ISPK=IDINT(SPKAD)
609          IF(IL.GT.1) GOTO 799
610  C        WRITE(9,933) NUMBR,IJUMP1,IJUMP2,IJUMP3,IJUMP4
611  C933    FORMAT(5I3)
612      799 WRITE(9,934) NUMM,SPEED,ISPK,KFUEL
613      934 FORMAT(I4,F8.1,I4,I3)
614          DO 928 JK=1,180
615          WRITE(9,929) PP2(IL,JK),MF(IL,JK),CB(IL,JK),TB(IL,JK),FS(IL,JK)
616         -,RB(IL,JK)
617      929 FORMAT(6F10.4)
618      928 CONTINUE
619  C
620  C-----------------------------------------------------------
621  C
622      222 CONTINUE
623  C
624  C###############################################################
625  C
626  C
627  C  THIS SECTION GENERATES A P-V DIAGRAM AND A
628  C  PRESSURE-CRANK ANGLE DIAGRAM.
```

```
629     C     ===========================================
630     C
631           IF(IGRAPH.EQ.0) GOTO 599
632     387 DO 605 IL=1,NUMBR
633           DLF=180.0
634           ZZ(IL,1)=2.0
635           DO 605 J=1,NID
636           VV(IL,J)=VV2(IL,J)*1000.
637           PP(IL,J)=PP2(IL,J)/100.
638           DLF=DLF+DC(IL,J)
639           DL(IL,(J+1))=DLF
640     C     XX(IL,J)=(5.*VV(IL,J))+2.0
641           YY(IL,J)=(PP(IL,J)/20.)+2.0
642           ZZ(IL,(J+1))=((DL(IL,(J+1))-180.0)/60.0)+2.0
643     605 CONTINUE
644     C-----------------------------------------------------
645     C     CALL AXIS(2.,2.,'VOLUME (L)',-10,5.,0.,0.,0.2)
646     C     CALL AXIS(2.,2.,'PRESSURE (BAR)',14,5.,90.,0.,20.)
647     C     DO 607 IL=1,NUMBR
648     C     DO 607 I=1,NID
649     C 607 CALL SYMBOL(XX(IL,I),YY(IL,I),0.05,IL,0.,-1)
650     C     CALL LINE(XX(1,I),YY(1,I),NID,1)
651     C-----------------------------------------------------
652           CALL PLOT(10.,0.,-3)
653           CALL AXIS(2.,2.,'CRANK ANGLE',-11,6.0,0.,180.,60.)
654           CALL AXIS(2.,2.,'PRESSURE (BAR)',14,5.,90.,0.,20.)
655           DO 415 IL=1,NUMBR
656           DO 415 I=1,NID
657     415 CALL SYMBOL(ZZ(IL,I),YY(IL,I),0.05,IL,0.,-2)
658     C     CALL LINE(ZZ(1,I),YY(1,I),84,1)
659           CALL PLOTND
660     599 STOP
661           END
662     C
663
664     C
665     C   SUBROUTINE TEMP   CALCULATES TEMP. OF BURNT GAS AND MASS FRACTION
666     C   ================   BURNED.
667     C
668           SUBROUTINE TEMP(P1,TB2,NNN,CC,MFX,MTOT,EU2,VSU2,VTOT1,ETOT,VSB2,
669          -MWBMIX)
670     C
671           COMMON /AREA1/ NCH,NO2,K,L,M,N,KFUEL
672           COMMON /AREA2/ MOLFL,NMIX,HF1,NNO2,NN2,NNFUEL,KOM
673           COMMON /AREA4/ NDISS,IPRINT
674     C
675           REAL*8 XF,DX,EPS,Y1,Y2,Y3,XX2,YY2,
676          -X1,X2,X3,X3OLD,P1,P2,P3,CC(10),X(10),K,L,M,N,GAMMA,MFX,MTOT
677          -,EU2,VSU2,VTOT1,VSB2,EB2,TB2,ETOT,VTOTC,NMIX,MFXE,MFXV
678          -,EPROD,SUMXS,NCH,NO2,MOLFL,HF1,NNO2,NN2,NNFUEL,GA,MWBMIX
679     C
680           NNN=1
681           KOM=KOM+1
682           IF(KOM.GT.10) GOTO 93
683           NUT=0
684           JDX=1
685           IDX=1
686           X1=1900.0
```

```
687              XF=4000.0
688              DX=100.0
689              EPS=0.00010
690          5 CALL ENERGY(X1,P1,EPROD,SUMXS,NNN,CC,X,EB2,VSB2,GA,MWBMIX)
691              MFXE=(ETOT-EU2)/(EB2-EU2)
692    C         WRITE(9,777) X1,ETOT,VTOT1,P1,EB2,MFXE
693    C 777 FORMAT(1H ,'X1,ETOT,VTOT1,P1,EB2,MFXE',6E12.4)
694              IF(MFXE.GT.0.0) GOTO 10
695              X1=X1+DX
696              IF(X1.GT.XF) GOTO 91
697              JDX=2
698              GOTO 5
699         10 MFXV=(VTOT1/MTOT-VSU2)/(VSB2-VSU2)
700              Y1=MFXV-MFXE
701              IF(JDX.EQ.1) GOTO 30
702              IF (Y1.LT.0.0) GOTO 30
703              DX=-DX/2.
704              IDX=2
705         30 X2=X1+DX
706              IF(X2.GT.XF) GOTO 91
707         20 CALL ENERGY(X2,P1,EPROD,SUMXS,NNN,CC,X,EB2,VSB2,GA,MWBMIX)
708              MFXE=(ETOT-EU2)/(EB2-EU2)
709    C 747 FORMAT(1H ,'X2,MFXE,MFXV,VSB2,VSU2,EB2,EU2;',7E10.3)
710              IF(MFXE.GT.0.0) GOTO 15
711              DX=DX/2.
712              IDX=2
713              X2=X2-DX
714              NUT=NUT+1
715              IF(NUT.GT.30) GOTO 91
716              GOTO 20
717         15 IF(IDX.EQ.1) GOTO 16
718              DX=DX/2.
719         16 MFXV=(VTOT1/MTOT-VSU2)/(VSB2-VSU2)
720              Y2=MFXV-MFXE
721    C         WRITE(9,747) X2,MFXE,MFXV,VSB2,VSU2,EB2,EU2
722              IF(Y1*Y2.LE.0.0) GOTO 25
723              X1=X2
724              Y1=Y2
725              NUT=NUT+1
726              IF(NUT.GT.60) GOTO 91
727              GOTO 30
728         25 IF(Y2.EQ.0.0) GOTO 50
729              IF(X2.GT.X1) GOTO 35
730              XX2=X2
731              YY2=Y2
732              X2=X1
733              Y2=Y1
734              X1=XX2
735              Y1=YY2
736         35 IF.(MFXE.LT.10.0) GOTO 36
737              DX=DX/10.0
738              X2=X2-DX
739              GOTO 20
740         36 X3OLD=X2
741         40 X3=(X1*Y2-X2*Y1)/(Y2-Y1)
742              NUT=NUT+1
743              IF (NUT.LT.150) GOTO 80
744         91 IS=2
```

```
745            RETURN
746         93 WRITE(9,90) KOM
747         90 FORMAT(1H ,'PROGRAM STOP DUE TO TEMP ITERATIONS EXCEEDING',I4)
748            STOP
749         80 IF(DABS((X3-X3OLD)/X3).LT.EPS) GOTO 60
750            X3OLD=X3
751            CALL ENERGY(X3,P1,EPROD,SUMXS,NNN,CC,X,EB2,VSB2,GA,MWBMIX)
752            MFXE=(ETOT-EU2)/(EB2-EU2)
753            MFXV=(VTOT1/MTOT-VSU2)/(VSB2-VSU2)
754            Y3=MFXV-MFXE
755    C       WRITE(9,767) X3,MFXE,MFXV,Y3
756    C 767 FORMAT(1H ,'X3,MFXE,MFXV,Y3',4E12.4)
757            IF(Y1*Y3.LE.O.) GOTO 45
758            X1=X3
759            Y1=Y3
760            GOTO 40
761         45 X2=X3
762            Y2=Y3
763            GOTO 40
764         50 TB2=X2
765            GOTO 70
766         60 TB2=X3
767         70 MFX=(MFXE+MFXV)/2.0
768            IF(IPRINT.EQ.0) GOTO 225
769    C-----------------------------------------------
770            WRITE(9,112) TB2,MFXE,MFXV,EB2,VSB2,GA
771        112 FORMAT(1H ,'TB2,MFXE,MFXV,EB2,VSB2,GA;',6E12.4)
772    C-----------------------------------------------
773        225 IS=1
774            RETURN
775            END
776    C
777    C   SUBROUTINE ENERGY   TO CALCULATE ENERGY (EPROD) OF BURNT GAS
778    C   ================    AT A GIVEN TEMP. AND PRESS. ( INCLUDES
779    C                       DISSOCIATION ).
780    C
781            SUBROUTINE ENERGY(T,P,EPROD,SUMXS,NNN,CC,X,EB2,VSB2,GAMMA,
782           -MWBMIX)
783    C
784            COMMON /AREA1/ NCH,NO2,K,L,M,N,KFUEL
785            COMMON /AREA2/ MOLFL,NMIX,HF1,NNO2,NN2,NNFUEL,KOM
786            COMMON /AREA3/ AREAB,HTEXP,MPV,HTFCN,TWALL,VISC,THCOND
787            COMMON /AREA4/ NDISS,IPRINT
788    C
789            REAL*8 K,L,M,N,X(10),CPG(10),UUU(10),DH(10),KA,KB,KC,KD,
790           -KE,KF,NM,P,T,A1,B1,C1,D1,E1,F1,S,SUMXS,TT,A,B,C,D,E,F,RMOL,
791           -A2,B2,C2,D2,E2,F2,RESA,RESA1,RESB,RESB1,RESC,RESC1,RESD,
792           -RESD1,RESE,RESE1,RESF,RESF1,KK,CC(10),EPROD,GAMMA,MWBMIX
793           -,MW(10),EB2,VSB2,NMIX,NCH,NO2,MOLFL,HF1,NNO2,NN2,NNFUEL
794           -,VCO2,KCO2,VH2O,KH2O,VN2,KN2,VISC,THCOND,AREAB,ATOT,MPV,
795           -HTFCN,TWALL,HTEXP
796    C
797            IF(T.LT.1750.0) GOTO 17
798            IF(NNN.EQ.2) GOTO 15
799    C INITIAL ESTIMATES OF THE NO. OF MOLES OF SPECIES DISSOCIATED
800    C A:- CO2=CO+0.5O2: B:- H2O=OH+0.5H2    C:- H2O=H2+0.5O2
801    C D:- NO2=.5N2+.5O2:E:- H2=2H           F:- O2=2O
802            IF(NDISS.EQ.1) GOTO 747
```

```
803             A=.7
804             B=0.1
805             C=.5
806             D=0.1
807             E=0.0
808             F=0.00
809             GOTO 737
810       747 A=.7
811             B=0.0
812             C=.5
813             D=0.0
814             E=0.0
815             F=0.0
816       737 A2=O
817             B2=O
818             C2=O
819             D2=O
820             E2=O
821             F2=O
822             NNN=2
823     C   CALC. OF EQUILIBRIUM CONSTANTS INCLUDING PRESSURE TERM
824        15  KA=DEXP(DLOG(T)**(-7.4721)*(-65549000)+10.53)
825           1*DSQRT(101.3/P)
826             KB=DEXP(DLOG(T)**(-7.0457)*(-30372100)+10.1590)
827           1*DSQRT(101.3/P)
828             KC=DEXP(DLOG(T)**(-6.8674)*(-18878550)+8.7095)
829           1*DSQRT(101.3/P)
830             KD=DEXP(DLOG(T)**(-7.3355)*(-16592550)+1.80127)
831             KE=DEXP(DLOG(T)**(-6.81208)*(-30743850)+17.8668)
832           1*(101.3/P)
833             KF=DEXP(DLOG(T)**(-6.93319)*(-43428280)+19.3067)
834           1*(101.3/P)
835             RMOL=8.3143
836             NUT=O
837     C   CALC. NO. OF MOLES OF SPECIES DISSOCIATED (A TO F)
838        10  QQ=1
839             NUT=NUT+1
840             IF (NUT.LT.200) GOTO 400
841             WRITE(9,401) NUT
842       401 FORMAT(1H ,'PROGRAM STOP DUE TO ENERGY ITERATIONS
843           1EXCEEDING',I4)
844             STOP
845       400 IF (KA.LE.1E-10) GOTO 2
846        1   S=(A+B+C)/2+E+F+K+L+M+N
847             A1=A
848             IF ((M+((A+C-D)/2)-F).LE.0.0) GOTO 2
849             RESA=A/(K-A)*DSQRT((M+((A+C-D)/2)-F)/S)-KA
850             A=A+.001
851             IF ((M+((A+C-D)/2)-F).LT.O) A=2*(F-M)+D-C
852             RESA1=A/(K-A)*DSQRT((M+((A+C-D)/2)-F)/S)-KA
853             A=A+.001*RESA1/(RESA-RESA1)
854             IF (A.GT.K) A=K-0.0011
855             IF (A.LT.O) A=1E-12
856             IF (A.EQ.A1) GOTO 2
857             IF (DABS((A-A1)/A1).GT.0.01) GOTO 1
858             IF (DABS((A-A2)/A1).GT.0.010) QQ=0
859        2   IF(NDISS.EQ.1) GOTO 3
860             S=(A+B+C)/2+E+F+K+L+M+N
```

```
861          IF (KB.LE.1E-10) GOTO 3
862          B1=B
863          IF ((B/2+C-E).LE.0.0) GOTO 3
864          RESB=B/(L-B-C)*DSQRT((B/2+C-E)/S)-KB
865          B=B+.001
866          IF ((B/2+C-E).LT.0) B=2*(E-C)
867          RESB1=B/(L-B-C)*DSQRT((B/2+C-E)/S)-KB
868          B=B+.001*RESB1/(RESB-RESB1)
869          IF (B.GT.(L-C)) B=L-C-.0011
870          IF (B.LT.0) B=1E-12
871          IF (B.EQ.B1)GOTO 3
872          IF (DABS((B-B1)/B1).GT.0.01) GOTO 2
873          IF (DABS((B-B2)/B1).GT.0.010) QQ=0
874     3    S=(A+B+C)/2+E+F+K+L+M+N
875          IF (KC.LE.1E-10) GOTO 4
876          C1=C
877          IF ((M+((A+C-D)/2)-F).LE.0.0) GOTO 4
878          RESC=(B/2+C-E)/(L-B-C)*DSQRT((M-F+(A+C-D)/2)/S)-KC
879          C=C+.001
880          IF ((M+((A+C-D)/2)-F).LT.0) C=2*(F-M)+D-A
881          RESC1=(B/2+C-E)/(L-B-C)*DSQRT((M-F+(A+C-D)/2)/S)-KC
882          C=C+.001*RESC1/(RESC-RESC1)
883          IF (C.GT.(L-B)) C=L-B-.0011
884          IF (C.LT.0) C=1E-12
885          IF (C.EQ.C1) GOTO 39
886          IF (DABS((C-C1)/C1).GT.0.01) GOTO 3
887          IF (DABS((C-C2)/C1).GT.0.010) QQ=0
888    39    IF(NDISS.EQ.1) GOTO 67
889          IF (N.LT.0.01) GOTO 5
890     4    S=(A+B+C)/2+E+F+K+L+M+N
891          IF (KD.LE.1E-10) GOTO 5
892          D1=D
893          IF (((N-D/2)*(M-F+(A+C-D)/2)).LE.0.0) GOTO 5
894          RESD=D/DSQRT((N-D/2.)*(M-F+(A+C-D)/2.))-KD
895          D=D+.001
896          IF (((N-D/2)*(M-F+(A+C-D)/2)).LE.0.0) GOTO 5
897          RESD1=D/DSQRT((N-D/2.)*(M-F+(A+C-D)/2.))-KD
898          D=D+.001*RESD1/(RESD-RESD1)
899          IF (D.GT.(2*N)) D=2*N-.0011
900          IF (D.LT.0) D=1E-12
901          IF (D.EQ.D1) GOTO 5
902          IF (DABS((D-D1)/D1).GT.0.01) GOTO 4
903          IF (DABS((D-D2)/D1).GT.0.010) QQ=0
904          GOTO 413
905     5    GO TO 67
907          E1=E
908          IF ((B/2+C-E).LE.0.001) E=B/2+C-.002
909          RESE=((2*E)**2)/S/(B/2+C-E)-KE
910          E=E+.001
911          RESE1=((2*E)**2)/S/(B/2+C-E)-KE
912          E=E+.001*RESE1/(RESE-RESE1)
913          IF (E.GT.(C+B/2)) E=B/2+C
914          IF(E.LT.0) E=1E-12
915          IF (E.EQ.E1) GOTO 6
916          IF (DABS((E-E1)/E1).GT.0.01) GOTO 5
917          IF (DABS((E-E2)/E1).GT.0.010) QQ=0
918     6    S=(A+B+C)/2+E+F+K+L+M+N
919          IF (KF.LE.1E-10) GOTO 67
```

136.

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920          F1=F
921          IF ((M-F+(A+C-D)/2).EQ.0) GOTO 67
922          RESF=((2*F)**2)/S/(M-F+(A+C-D)/2)-KF
923          F=F+.001
924          RESF1=((2*F)**2)/S/(M-F+(A+C-D)/2)-KF
925          F=F+.001*RESF1/(RESF-RESF1)
926          IF (F.GT.(M+(A+C-D)/2)) F=M+(A+C-D)/2-.011*F
927          IF (F.LT.0) F=1E-12
928          IF (F.EQ.F1) GOTO 67
929          IF (DABS((F-F1)/F1).GT.0.01) GOTO 6
930          IF (DABS((F-F2)/F1).GT.0.010) QQ=0
931      413 CONTINUE
932       67 A2=A
933          B2=B
934          C2=C
935          D2=D
938          IF(QQ.EQ.0)GOTO 10
939  C    CALCULATING CHANGE IN ENTHALPIES FOR SPECIES 1 TO 10 BET. T AND 289K
940  C    CO2=1, CO=2, H2O=3, H2=4, O2=5, N2=6, NO=7, H=10, O=9, OH=8
941          KK=0
942       17 TT=T/100
943          IF (T.GT.3000.0) GOTO 99
944          DH(1)=((3.096*T+0.00273*(T**2)-7.885E-07*(T**3)
945         1+8.66E-11*(T**4))-1145.0)*RMOL
946          DH(2)=((3.317*T+3.77E-04*(T**2)-3.22E-08*(T**3)
947         1-2.195E-12*(T**4))-1022.0)*RMOL
948          DH(3)=((3.743*T+5.656E-04*(T**2)+4.952E-08*(T**3)
949         1-1.818E-11*(T**4))-1167.0)*RMOL
950          DH(4)=((3.433*T-8.18E-06*(T**2)+9.67E-08*(T**3)
951         1-1.444E-11*(T**4))-1025.0)*RMOL
952          DH(5)=((3.253*T+6.524E-04*(T**2)-1.495E-07*(T**3)
953         1+1.539E-11*(T**4))-1024.0)*RMOL
954          DH(6)=((3.344*T+2.943E-04*(T**2)+1.953E-09*(T**3)
955         1-6.575E-12*(T**4))-1023.0)*RMOL
956          DH(7)=((3.502*T+2.994E-04*(T**2)-9.59E-09*(T**3)
957         1-4.904E-12*(T**4))-1070.0)*RMOL
958          DH(10)=((2.5*T)-745.0)*RMOL
959          DH(9)=((2.764*T-2.514E-04*(T**2)+1.002E-07*(T**3)
960         1-1.387E-11*(T**4))-804.0)*RMOL
961          DH(8)=((81.546*TT-47.48*(TT**1.25)+9.902*(TT**1.75)
962         1-2.133*(TT**2.))*100-10510)
963          GOTO 91
964       99 DH(1)=((5.208*T+0.00059*(T**2)-5.614E-08*(T**3)
965         1+2.05E-12*(T**4))-1126.0)*RMOL
966          DH(2)=((3.531*T+2.73E-04*(T**2)-3.28E-08*(T**3)
967         1+1.565E-12*(T**4))-1042.0)*RMOL
968          DH(3)=((143.05*TT-146.83*(TT**1.25)+55.17*(TT**1.5)
969         1-1.85*(TT**2.))*100-11945.0)
970          DH(4)=((3.213*T+2.87E-04*(T**2)-2.29E-08*(T**3)
971         1+7.666E-13*(T**4))-1018.0)*RMOL
972          DH(5)=((3.551*T+3.203E-04*(T**2)-2.876E-08*(T**3)
973         1+1.005E-12*(T**4))-1044.0)*RMOL
974          DH(6)=((3.514*T+2.583E-04*(T**2)-2.841E-08*(T**3)
975         1+1.242E-12*(T**4))-1043.0)*RMOL
976          DH(7)=((3.745*T+1.950E-04*(T**2)-1.88E-08*(T**3)
977         1+7.703E-13*(T**4))-1106.0)*RMOL
978          DH(10)=((2.5*T)-745.0)*RMOL
979          DH(9)=((2.594*T-3.843E-05*(T**2)+7.514E-09*(T**3)
```

```
980              1-3.209E-13*(T**4))-809.0)*RMOL
981              DH(8)=((81.546*TT-47.48*(TT**1.25)+9.902*(TT**1.75)
982              1-2.133*(TT**2.))*100-10560.)
983       C   CALCULATE CP VALUES
984         91  CPG(1)=-3.7357+30.529*(TT**(0.5))-4.1034*TT+0.024198*(TT**2)
985              CPG(2)=69.145-.70463*(TT**(0.75))-200.77*(TT**(-0.5))
986              -+176.76*(TT**(-0.75))
987              CPG(3)=143.05-183.54*(TT**(0.25))+82.751*(TT**(0.5))
988              --3.69889*TT
989              CPG(4)=56.505-702.74*(TT**(-.75))+1165.0/TT-560.7*(TT**(-1.5))
990              CPG(5)=37.432+0.020102*(TT**1.5)-178.57*(TT**(-1.5))
991              -+236.88*(TT**(-2))
992              CPG(6)=39.060-512.79*(TT**(-1.5))+1072.7*(TT**(-2))
993              --820.4*(TT**(-3))
994              CPG(7)=59.283-1.7096*(TT**0.5)-70.613*(TT**(-0.5))
995              -+74.889*(TT**(-1.5))
996              CPG(8)=81.546-59.35*(TT**0.25)+17.329*(TT**0.75)-4.266*TT
997       C   NUMBER OF MOLES OF EACH SPECIES AFTER DISSOCIATION
998              X(1)=K-A
999              X(2)=A
1000             X(3)=L-B-C
1001             X(6)=N-D/2
1002             X(7)=D
1003             X(4)=C+B/2-E
1004             X(5)=M-F+(A+C-D)/2
1005             X(10)=2*E
1006             X(9)=2*F
1007             X(8)=B
1008      C   CALC. VISCOSITY & THERMAL CONDUCTIVITY OF PRODUCTS...
1009             VCO2=((0.019*T+24.2)*X(1)*1E-06)/(X(1)+X(3)+X(6))
1010             KCO2=((0.041*T+36.1)*X(1)*1E-03)/(X(1)+X(3)+X(6))
1011             VH2O=((0.025*T+15.8)*X(3)*1E-06)/(X(1)+X(3)+X(6))
1012             KH2O=((0.130*T-0.60)*X(3)*1E-03)/(X(1)+X(3)+X(6))
1013             VN2=((0.019*T+24.1)*X(6)*1E-06)/(X(1)+X(3)+X(6))
1014             KN2=((0.039*T+35.8)*X(6)*1E-03)/(X(1)+X(3)+X(6))
1015             VISC=VCO2+VH2O+VN2
1016             THCOND=KCO2+KH2O+KN2
1017      C   HFO FOR EACH SPECIES
1018             UUU(1)=-3.93522E05
1019             UUU(2)=-1.10529E05
1020             UUU(3)=-2.41827E05
1021             UUU(4)=0.00000E00
1022             UUU(5)=0.00000E00
1023             UUU(6)=0.00000E00
1024             UUU(7)=9.05920E04
1025             UUU(10)=2.17986E05
1026             UUU(9)=2.49195E05
1027             UUU(8)=39463.0
1028      C   MOLECULAR WEIGHT FOR EACH SPECIES
1029             MW(1)=44.01
1030             MW(2)=28.01
1031             MW(3)=18.01
1032             MW(4)=2.02
1033             MW(5)=32.00
1034             MW(6)=28.01
1035             MW(7)=30.00
1036             MW(8)=17.00
1037             MW(9)=16.00
```

```
1038            MW(10)=1.00
1039    C    CALC. ENERGY OF PRODUCTS 1 TO 10
1040            EPROD=0.
1041            DO 109 I=1,10
1042            ECOMP=X(I)*(UUU(I)+DH(I)-RMOL*T)
1043            EPROD=EPROD+ECOMP
1044      109   CONTINUE
1045    C  CALCULATE SUM OF X VALUES
1046            SUMXS=O
1047            DO 231 ILG=1,10
1048      231  SUMXS=SUMXS+X(ILG)
1049    C  CALC PERC. OF PRODUCTS AND MOLECULAR WEIGHT OF MIXTURE
1050            MWBMIX=0.0
1051            DO 232 ILH=1,10
1052            CC(ILH)=(X(ILH)/SUMXS)*100.
1053      232  MWBMIX=MWBMIX+(CC(ILH)*MW(ILH)/100.)
1054            EB2=EPROD/MWBMIX/SUMXS
1055            VSB2=RMOL*T/(MWBMIX*P)
1056    C  CALC CP
1057            CP=O
1058            DO 233 ILF=1,8
1059      233  CP=CP+(CC(ILF)*CPG(ILF))/100.
1060            CV=CP-RMOL
1061            GAMMA=CP/CV
1062    C       WRITE(9,889) MWBMIX,EB2,VSB2,GAMMA,NNN,NDISS
1063    C 889 FORMAT(1H ,'MWBMIX,EB2,VSB2,GAMMA,N,NDS ',4E12.4,2I3)
1064            RETURN
1065            END
1066    C
1067    C    SUBROUTINE CALFLS   THIS IS USED TO OBTAIN THE CALCULATED
1068    C    ================   BURNING VELOCITY
1069    C
1070            SUBROUTINE CALFLS(MFX1,MFX2,VSB2,MTOT,DTIME,VSU2,CBVEL,
1071           -VSU1,AREA1,VOLB2,IVOL,VOLB1,AREA2,RB1,RB2,DLF1,DIST)
1072    C
1073            COMMON /AREA4/ NDISS,IPRINT
1074            COMMON /AREA3/ AREAB,HTEXP,MPV,HTFCN,TWALL,VISC,THCOND
1075    C
1076            INTEGER NREC,CA,NDIM
1077            REAL RCA1
1078            REAL*8 RF,DR,EPS,Y1,Y2,Y3,BORE,D,XDOT,ARAVG,AREA,
1079           -R1,R2,R3,R3OLD,DTIME,RMAX,R,VOLB1,MFX2,AREA1,AREA2,RB1,RB2,
1080           -FFF,MFX,VSB2,VSU2,MTOT,MFX1,VOLB2,VOLB,CBVEL,VSUAVG,VSU1,RADBMB
1081           -,DLF1,RFT(100),VFT(100),AFF(100),AWP(100),DIST,AREAB
1082    C
1083            IF (IVOL .GE.2) GO TO 546
1084            RB1=0.DO
1085            AREA1=0.DO
1086      546   RCA1=SNGL(DLF1)
1087            CA=IFIX(RCA1)
1088              IF(CA.LE.360) CA=360-CA
1089              IF (CA .GT. 360)CA=CA-360
1090            CALL BLKRD(CA,RFT,VFT,AFF,AWP,NDIM)
1091            VOLB2=MTOT*MFX2*VSB2
1092            CALL GEOM(NDIM,DIST,VOLB2,RFT,VFT,AFF,AWP,RB2,AREA2,AREAB,CA)
1093            ARAVG=(AREA1+AREA2)/2.
1094            VSUAVG=(VSU1+VSU2)/2.
1095            XDOT=(MFX2-MFX1)/DTIME
```

```
1096            CBVEL=MTOT*XDOT*VSUAVG/ARAVG
1097            RETURN
1098            END
1099      C
1100      C
1101      C  SUBROUTINE ENUFLS   THIS CALCULATES THE PROPERTIES OF THE UNBURNT
1102      C  ================   GAS AT THE GIVEN PRESS. BY FIRST CALCULATING
1103      C                     GAMMA AND THEN ASSUMING ISENTROPIC COMPRESSION
1104      C  THE BURNING VELOCITY IS THEN CALCULATED USING THE UNBURNT GAS
1105      C  TEMP. AND PRESS. USING PUBLISHED FORMULAE FOR GIVEN FUEL.
1106      C
1107            SUBROUTINE ENUFLS(P2,P1,T1,VSU1,MWMIX,TU2,VSU2,EU2,TBVEL,AF,
1108           -T2,NRCO2,NRH2O)
1109      C
1110            COMMON /AREA1/ NCH,NO2,K,L,M,N,KFUEL
1111            COMMON /AREA2/ MOLFL,NMIX,HF1,NNO2,NN2,NNFUEL,KOM
1112            COMMON /AREA4/ NDISS,IPRINT
1113      C
1114            REAL*8 P1,T1,NNO2,NN2,NMIX,TU2,VSU2,EU2,TBVEL,TT,NNFUEL,FFF,
1115           -CPG(14),CP,CV,GAMU,DH(14),ENGY,NO2,N,RMOL,VSU1,POW1,POW2,TT2,
1116           -MWMIX,PU,TU,PBAR2,P2,HF1,T,T2,POW3,C4,AF,PBAR1,GGAM,B1,B2,B3,
1117           -NCH,K,L,M,MOLFL,FI,SUO(15),ALPHA(15),BETA(15),NRCO2,NRH2O,UUU(3)
1118      C
1119            RMOL=8.31434
1120            NUT=0
1121      C
1122      C   CALC. GAMMA FOR THE UNBURNT ELEMENTS....
1123      C
1124            NNFUEL=100.-(NNO2+NN2)
1125            TT=T1/100.
1126            CPG(5)=37.432+0.020102*(TT**1.5)-178.57*(TT**(-1.5))
1127           -+236.88*(TT**(-2))
1128            CPG(6)=39.060-512.79*(TT**(-1.5))+1072.7*(TT**(-2))
1129           --820.4*(TT**(-3))
1130            CPG(11)=-672.87+439.74*(TT**0.25)-24.875*(TT**0.75)+323.88*
1131           -(TT**(-0.5))
1132            CPG(13)=-4.042+30.46*TT-1.571*(TT**2.)+0.03171*(TT**3.)
1133            CPG(12)=8.3143*(-0.72+0.09285*T1-5.05E-05*(T1**2.)+1.068E-08*
1134           -(T1**3))
1135            CP=(NNO2*CPG(5)+NN2*CPG(6)+NNFUEL*CPG(KFUEL))/100.
1136            CV=CP-RMOL
1137            GAMU=CP/CV
1138      C
1139            POW1=(GAMU-1.)/GAMU
1140            POW2=1./GAMU
1141            TT2=T1*((P2/P1)**POW1)
1142       20 CALL GAM(TT2,T1,GAMU)
1143            POW1=(GAMU-1.0)/GAMU
1144            T2=T1*((P2/P1)**POW1)
1145            IF(DABS(TT2-T2).LE.1.0) GOTO 10
1146            NUT=NUT+1
1147            IF(NUT.GT.20) STOP
1148            TT2=T2
1149            GOTO 20
1150       10 POW2=1.0/GAMU
1151            TU2=T2
1152            VSU2=VSU1*((P1/P2)**POW2)
1153      C
```

```
1154      C   CALC. ENTHALPY OF REACTANTS AT GIVEN TEMP.
1155            DH(1)=((3.096*T2+0.00273*(T2**2)-7.885E-07*(T2**3)
1156           1+8.66E-11*(T2**4))-1145.0)*RMOL
1157            DH(3)=((3.743*T2+5.656E-04*(T2**2)+4.952E-08*(T2**3)
1158           1-1.818E-11*(T2**4))-1167.0)*RMOL
1159            DH(5)=((3.253*T2+6.524E-04*(T2**2)-1.495E-07*(T2**3)
1160           1+1.539E-11*(T2**4))-1024.0)*RMOL
1161            DH(6)=((3.344*T2+2.943E-04*(T2**2)+1.953E-09*(T2**3)
1162           1-6.575E-12*(T2**4))-1023.0)*RMOL
1163            DH(11)=((1.935*T2+4.965E-03*(T2**2.)-1.244E-06*(T2**3.)
1164           1+1.625E-10*(T2**4.)-8.586E-15*(T2**5.))-985.9)*RMOL
1165            DH(12)=((-0.72*T2+4.643E-02*(T2**2.)-1.684E-05*(T2**3.)
1166           1+2.67E-09*(T2**4.))-3484.0)*RMOL
1167            DH(13)=((1.137*T2+1.455E-02*(T2**2.)-2.959E-06*(T2**3.)
1168           1)-1552.9)*RMOL
1169            UUU(1)=-3.93522E05
1170            UUU(3)=-2.41827E05
1171      C   CALC. TOTAL ENERGY OF MIXTURE (KJ/KMOL FUEL)....
1172            ENGY=(NCH*(HF1+DH(KFUEL)-RMOL*T2)+NO2*(DH(5)-RMOL*T2)
1173           -+N*(DH(6)-RMOL*T2)+NRCO2*(UUU(1)+DH(1)-RMOL*T2)+NRH2O*
1174           -(UUU(3)+DH(3)-RMOL*T2))
1175      C   CONVERT TO KJ/KMOL MIXTURE...
1176            ENGY=ENGY/NMIX
1177      C   CONVERT TO KJ/KG MIXTURE...
1178            EU2=ENGY/MWMIX
1179      C   CALC. AVERAGE UNBURNT TEMP. AND PRESS.
1180            PU=(P1+P2)/2.
1181            TU=(T1+T2)/2.
1182      C
1183      C   CALCULATE LAMINAR BURNING VELOCITY:
1184      C
1185      C   METGHALCHI & KECK'S EQN.S FOR PROPANE(13), OCTANE(12),
1186      C   AND INDOLINE(14)......
1187      C
1188            IF(KFUEL.EQ.11) GOTO 501
1189            FI=1./AF
1190            IF(FI.GT.0.95) GOTO 87
1191      C     DATA SUO(13),SUO(12),SUO(14)/23.20DO,19.25DO,19.15DO/
1192      C     DATA ALPHA(13),ALPHA(12),ALPHA(14)/2.27DO,2.36DO,2.27DO/
1193      C     DATA BETA(13),BETA(12),BETA(14)/-0.23DO,-0.22DO,-0.17DO/
1194            GOTO 89
1195         87 IF(FI.GT.1.05) GOTO 88
1196      C     DATA SUO(13),SUO(12),SUO(14)/31.90DO,27.00DO,25.21DO/
1197      C     DATA ALPHA(13),ALPHA(12),ALPHA(14)/2.13DO,2.26DO,2.19DO/
1198      C     DATA BETA(13),BETA(12),BETA(14)/-0.17DO,-0.18DO,-0.13DO/
1199            GOTO 89
1200         88 CONTINUE
1201      C     DATA SUO(13),SUO(12),SUO(14)/33.80DO,27.63DO,28.14DO/
1202      C     DATA ALPHA(13),ALPHA(12),ALPHA(14)/2.06DO,2.03DO,2.02DO/
1203      C     DATA BETA(13),BETA(12),BETA(14)/-0.17DO,-0.11DO,-0.087DO/
1204         89 TBVEL=SUO(KFUEL)*((TU/298.)**ALPHA(KFUEL))*
1205           -((PU/100.)**BETA(KFUEL))
1206            GOTO 510
1207      C
1208      C   ANDREWS AND BRADLEYS EQUATION FOR METHANE(11)...
1209      C
1210      C     PBAR1=PU/100.
1211      C     TBVEL=(10.0+0.000371*(TU**2.)*(PBAR1**(-0.5)))
```

```
1212    C
1213    C  RYAN AND LESTZ'S EQN. FOR METHANE(11)...
1214    C
1215    C 501 B1=9655.5
1216    C      B2=-0.623
1217    C      B3=-2144.5/TU
1218    C      TBVEL=B1*((PU/100.)**B2)*DEXP(B3)
1219    C      GOTO 510
1220    C
1221    C  AGRAWAL AND GUPTAS EQUATION FOR METHANE...
1222    C
1223      501 PBAR1=PU/100.0
1224          C4=-418.0+1287.0/AF-1196.0/(AF**2)+360.0/(AF**3)-15.0*AF*
1225         -DLOG10(PBAR1)
1226          POW3=1.68*DSQRT(AF)
1227          IF(AF.GT.1.) GOTO 65
1228          POW3=1.68/DSQRT(AF)
1229       65 TBVEL=C4*((TU/300.0)**POW3)
1230    C
1231    C  DIVIDE BY 100 TO CONVERT FROM CM/S TO M/S...
1232    C
1233      510 TBVEL=TBVEL/100.
1234    C
1235          IF(IPRINT.EQ.0) GOTO 225
1236    C-----------------------------------------------------
1237          WRITE(9,100) TBVEL,VSU2,EU2,PU,TU,P2,T2
1238      100 FORMAT(1H ,'TBV,VSU2,EU2,PU,TU,P2,T2 =',7E12.4)
1239    C-----------------------------------------------------
1240      225 RETURN
1241          END
1242    C
1243    C
1244    C  SUBROUTINE GAM   THIS CALCULATES THE AVERAGE RATIO OF SPECIFIC
1245    C  ==============   HEATS (GAMMA) OF AN UNBURNED GAS MIXTURE
1246    C                   BETWEEN TWO GIVEN TEMPERATURES.
1247    C
1248          SUBROUTINE GAM(T2,T1,GAMU)
1249    C
1250          COMMON /AREA1/ NCH,NO2,K,L,M,N,KFUEL
1251          COMMON /AREA2/ MOLFL,NMIX,HF1,NNO2,NN2,NNFUEL,KOM
1252    C
1253          REAL*8 T2,T1,NNO2,NN2,NNFUEL,GAMU,TI,CPA(14),A1,A2,R1,R2,S1,S2,
1254         -C1,C2,D1,D2,E1,E2,RMOL,CPAV,TT,NCH,NO2,K,L,M,N,MOLFL,NMIX,HF1
1255    C
1256    C  CALC. VALUES OF CP FOR THE COMBUSTIBLE MIXTURE;
1257    C  5=O2, 6=N2, 11=CH4, 12=C8H18, 13=C3H8, 14=INDOLINE...
1258    C
1259          RMOL=8.31434
1260          TT=T2/100.
1261          TI=T1/100.0
1262    C
1263          A1=(37.432*TT+8.041E-03*(TT**2.5)+357.14/DSQRT(TT)-236.88/TT)
1264          A2=(37.432*TI+8.041E-03*(TI**2.5)+357.14/DSQRT(TI)-236.88/TI)
1265          CPA(5)=(NNO2/(T2-T1))*(A1-A2)
1266    C
1267          R1=(39.06*TT+1025.58/DSQRT(TT)-1072.7/TT+410.2/(TT**2))
1268          R2=(39.06*TI+1025.58/DSQRT(TI)-1072.7/TI+410.2/(TI**2))
1269          CPA(6)=(NN2/(T2-T1))*(R1-R2)
```

143.

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1270      C
1271              S1=-672.87*TT+351.8*(TT**1.25)-14.214*(TT**1.75)+647.76
1272           -*DSQRT(TT)
1273              S2=-672.87*TI+351.8*(TI**1.25)-14.214*(TI**1.75)+647.76
1274           -*DSQRT(TI)
1275              CPA(11)=(NNFUEL/(T2-T1))*(S1-S2)
1276      C
1277              C1=(-4.042*TT+15.23*(TT**2)-0.5237*(TT**3)+7.9275E-03*(TT**4))
1278              C2=(-4.042*TI+15.23*(TI**2)-0.5237*(TI**3)+7.9275E-03*(TI**4))
1279              CPA(13)=(NNFUEL/(T2-T1))*(C1-C2)
1280      C
1281              TT=TT*100.
1282              TI=TI*100.
1283      C
1284              D1=RMOL*(-0.72*TT+4.643E-02*(TT**2)-1.684E-05*(TT**3)+2.67E-09*
1285           -(TT**4))
1286              D2=RMOL*(-0.72*TI+4.643E-02*(TI**2)-1.684E-05*(TI**3)+2.67E-09*
1287           -(TI**4))
1288              CPA(12)=(NNFUEL*0.01/(T2-T1))*(D1-D2)
1289      C
1290              E1=RMOL*(-0.72*TT+4.643E-02*(TT**2)-1.684E-05*(TT**3)+2.67E-09*
1291           -(TT**4))
1292              E2=RMOL*(-0.72*TI+4.643E-02*(TI**2)-1.684E-05*(TI**3)+2.67E-09*
1293           -(TI**4))
1294              CPA(14)=(NNFUEL*0.01/(T2-T1))*(E1-E2)
1295      C
1296      C CALC. CP, GAMMA, AND HENCE PRESSURE(P) AT TEMP. T(J) ASSUMING
1297      C ISENTROPIC COMPRESSION.....
1298
1299              CPAV=CPA(5)+CPA(6)+CPA(KFUEL)
1300              GAMU=CPAV/(CPAV-RMOL)
1301              RETURN
1302              END
1303      C
1304      C
1305      C SUBROUTINE COMP   THIS CALCULATES THE SPECIFIC ENERGY OF THE
1306      C ==============    UNBURNED MIXTURE.
1307      C
1308              SUBROUTINE COMP(T2,ENGY2,NRCO2,NRH2O)
1309      C
1310              COMMON /AREA1/ NCH,NO2,K,L,M,N,KFUEL
1311              COMMON /AREA2/ MOLFL,NMIX,HF1,NNO2,NN2,NNFUEL,KOM
1312      C
1313              REAL*8 P1,V1,T1,P2,V2,T2,NCH,NO2,N,ENGY1,ENGY2,DH(14),RMOL,
1314           -REM,REM1,TT1,REM2,TT2,HF1,MOLFL,DLF1,K,L,M,NMIX,NNO2,NN2,NNFUEL
1315           -,UUU(10),T2OLD,NRCO2,NRH2O
1316      C
1317              RMOL=8.31434
1318      C
1319              DH(1)=((3.096*T2+0.00273*(T2**2)-7.885E-07*(T2**3)
1320           1+8.66E-11*(T2**4))-1145.0)*RMOL
1321              DH(3)=((3.743*T2+5.656E-04*(T2**2)+4.952E-08*(T2**3)
1322           1-1.818E-11*(T2**4))-1167.0)*RMOL
1323              DH(5)=((3.253*T2+6.524E-04*(T2**2)-1.495E-07*(T2**3)
1324           1+1.539E-11*(T2**4))-1024.0)*RMOL
1325              DH(6)=((3.344*T2+2.943E-04*(T2**2)+1.953E-09*(T2**3)
1326           1-6.575E-12*(T2**4))-1023.0)*RMOL
1327              DH(11)=((1.935*T2+4.965E-03*(T2**2.)-1.244E-06*(T2**3.)
```

```
1328            1+1.625E-10*(T2**4.)-8.586E-15*(T2**5.))-985.9)*RMOL
1329            DH(12)=((-O.72*T2+4.643E-02*(T2**2.)-1.684E-05*(T2**3.)
1330            1+2.67E-09*(T2**4.))-3484.O)*RMOL
1331            DH(13)=((1.137*T2+1.455E-02*(T2**2.)-2.959E-06*(T2**3.)
1332            1)-1552.9)*RMOL
1333            UUU(1)=-3.93522E05
1334            UUU(3)=-2.41827E05
1335      C  CALC. TOTAL ENERGY OF MIXTURE (KJ)....
1336            ENGY2=MOLFL*(NCH*(HF1+DH(KFUEL)-RMOL*T2)+NO2*(DH(5)-RMOL*T2)
1337            -+N*(DH(6)-RMOL*T2)+NRCO2*(UUU(1)+DH(1)-RMOL*T2)+NRH2O*
1338            -(UUU(3)+DH(3)-RMOL*T2))
1339      C
1340            RETURN
1341            END
1342      C
1343      C
1344      C  SUBROUTINE EXP   THIS CALCULATES THE TEMP. AND CONCENTRATION OF
1345      C  ============== THE PRODUCTS OF COMBUSTION DURING THE EXPANSION
1346      C                   STROKE.
1347      C
1348            SUBROUTINE EXP(P1,V1,T1,P2,V2,T2,NNN,CC,SUMXS,ENGY1,ENGY2,
1349            -ATOT,DTIME,MTOT,MWBMIX)
1350      C
1351            COMMON /AREA1/ NCH,NO2,K,L,M,N,KFUEL
1352            COMMON /AREA2/ MOLFL,NMIX,HF1,NNO2,NN2,NNFUEL,KOM
1353            COMMON /AREA3/ AREAB,HTEXP,MPV,HTFCN,TWALL,VISC,THCOND
1354            COMMON /AREA4/ NDISS,IPRINT
1355      C
1356            REAL*8 P1,V1,T1,P2,V2,T2,SUMXS,K,L,N,M,NMIX,NM1,TT1,P,EPROD,
1357            -CC(10),X(10),ENGY1,ENGY2,MOLFL,REM1,REM2,TT2,TT3,TT3OLD,NNM1,
1358            -NNM3,REM3,NCH,NO2,HF1,NNO2,NN2,NNFUEL,NNM2,EB2,VSB2,BORE
1359            -,AREAB,ATOT,MPV,HTFCN,TWALL,PDV,DQ,HTCOEF,VISC,THCOND,HTEXP
1360            -,DQMEAS,DTIME,GAMMA,MWBMIX,MTOT
1361      C
1362            BORE=3.25*0.0254
1363            NUT=O
1364            NN=O
1365      C
1366            T2=(MWBMIX*P2*V2)/(MTOT*8.31434)
1367      C
1368 .          CALL ENERGY(T2,P2,EPROD,SUMXS,NNN,CC,X,EB2,VSB2,GAMMA,MWBMIX)
1369      C
1370            ENGY2=EPROD*MOLFL
1371            HTCOEF=(THCOND/BORE)*((MPV*BORE/(VSB2*VISC))**HTEXP)/1000.O
1372            DQ=HTCOEF*ATOT*(T2-TWALL)*HTFCN*DTIME
1373            PDV=((P1+P2)/2.0)*(V2-V1)
1374            DQMEAS=ENGY2-ENGY1+PDV
1375      C
1376            PISEN=((V1/V2)**GAMMA)*P1
1377      C
1378            IF(IPRINT.EO.O) GOTO 4
1379      C-----------------------------------------------------------
1380            WRITE(9,409) ENGY1,ENGY2,PDV,DQ,DQMEAS,PISEN
1381        409 FORMAT(1H ,'ENGY1,ENGY2,PDV,DQ,DQMEAS ',6E12.4)
1382      C-----------------------------------------------------------
1383        4  CONTINUE
1384      C
1385            RETURN
```

```
1386            END
1387      C
1388      C  SUBROUTINE SMOOTH   THIS READS IN THE ENSEMBLED PRESSURE VALUES
1389      C  =================   AND SMOOTHS THEM USING MTS LIBRARY ROUTINES
1390      C
1391            SUBROUTINE SMOOTH(POUT,SCONST,IPRNTS)
1392      C
1393            IMPLICIT REAL*8(A-H,O-W)
1394      C
1395            DIMENSION  PIN(180), DPDTH(180), TOL(180), ANGLE(180), PD1(180)
1396            DIMENSION  PD2(180), W(2000),XIPIN(200), POUT(180), D2PDTH(180)
1397      C
1398      C
1399            SVAL=5.0
1400            CONST1=SCONST
1401            CONST2=SCONST
1402            IBEG=60
1403            IEND=120
1404      C
1405      C  READ IN PRESSURE DATA...
1406      C
1407            READ(4,20)(PIN(K),K=1,180)
1408       20   FORMAT(F12.4)
1409      C
1410      C     DO 600 IJ=1,190
1411      C     WRITE(9,601) IPIN(IJ)
1412      C 601 FORMAT(1H ,I10)
1413      C 600 CONTINUE
1414      C
1415            DO 12 IJ=1,180
1416            ANGLE(IJ)=DFLOAT(IJ)
1417       12   CONTINUE
1418      C
1419      C  CALCULATE dP/dTHETA AT EACH DATA POINT...
1420      C
1421      490   DO 5 J=2,179
1422        5   DPDTH(J)=(PIN(J+1)-PIN(J-1))/2.0D0
1423            DPDTH(1)=0.0
1424            DPDTH(180)=DPDTH(179)
1425      C
1426      C
1427      C  CALCULATE d2P/d(THETA)**2 AT EACH DATA POINT...
1428      C
1429      491   DO 6 J=2,179
1430        6   D2PDTH(J)=(DPDTH(J+1)-DPDTH(J-1))/2.0D0
1431            D2PDTH(1)=0.0
1432            D2PDTH(180)=D2PDTH(179)
1433      C
1434      C
1435      C  CALCULATE STANDARD DEVIATION OF THE SLOPE AT EACH CRANK ANGLE
1436      C  BASED ON VARIATION OVER RANGE OF 3 DEGREES EITHER SIDE...
1437      C
1438      492 DO 15 IT=4,177
1439            JS=IT-3
1440            JF=IT+3
1441            AV=0.0
1442            DO 16 J=JS,JF
1443       16   AV=AV+D2PDTH(J)
```

```
1444      C
1445          AV=AV/7.0
1446      C
1447          SA=0.0
1448          DO 17 J=JS,JF
1449       17 SA=SA+DABS(D2PDTH(J)-AV)**2
1450          SD=DSQRT(SA/6)
1451          IF(IT.LT.IBEG.OR.IT.GT.IEND) GOTO 431
1452          TOL(IT)=SD*CONST2+0.0001
1453          GOTO 15
1454      431 TOL(IT)=SD*CONST1+0.0001
1455       15 CONTINUE
1456      C
1457          DO 18 IT=1,3
1458       18 TOL(IT)=TOL(4)
1459      C
1460          DO 19 IT=178,180
1461       19 TOL(IT)=TOL(177)
1462      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
1463      C     DO 88 IT=1,180
1464      C     WRITE(9,87) TOL(IT)
1465      C  87 FORMAT(1H ,F12.5)
1466      C  88 CONTINUE
1467      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
1468      C
1469      C  CALL LIBRARY CURVE FITTING ROUTINES...
1470      C
1471      493 CALL DSPLFT(ANGLE,PIN,TOL,SVAL,180,W,&100)
1472          CALL DSPLN(ANGLE,POUT,PD1,PD2,180,&100)
1473      C
1474          GOTO 92
1475      100 WRITE(9,101)
1476      101 FORMAT(1H ,'ERROR IN CURVE FITTING ROUTINE')
1477          STOP1
1478      C
1479       92 IF(IPRNTS.EQ.0) GOTO 933
1480          DO 45 JK=1,180
1481          WRITE(9,602) PIN(JK),POUT(JK)
1482      602 FORMAT(1H ,2F12.5)
1483       45 CONTINUE
1484      C
1485      933 RETURN
1486          END
1487          SUBROUTINE BLKRD(CA,RF,VF,AFF,AWP,NDIM)
1488          REAL*8 RF(100),VF(100),AFF(100),AWP(100),D1,D2,D3
1489          INTEGER NREC,CA,NDIM
1490          NREC=4 + CA*82
1491          NDIM=79
1492          IF (CA .GE. 3) NDIM=80
1493          IF (CA .GE. 3)NREC=4+246+(CA-3)*83
1493.5        IF (CA .GE. 34)NDIM=81
1493.7        IF (CA .GE.34)NREC=4+(CA-34)*84 + 246 +2573
1493.8        IF(CA .EQ. 45) NDIM=82
1493.9        IF (CA .EQ. 45)NREC=3663
1496          NREC=NREC*1000
1497          FIND(7'NREC)
1498          DO 2 J=1,NDIM
1499          READ(7,1) RF(J),VF(J),D1,AFF(J),D2,AWP(J),D3
```

```
1500      1         FORMAT(2(F12.10,2X),F12.9,2X,2(F12.10,2X,F12.9,2X))
1501      2         CONTINUE
1502                RETURN
1503                END
1504                SUBROUTINE GEOM(NDIM,H,VOLB,RF,VF,AFF,AWP,RAD,AFRNT,APER,CA)
1505                REAL*8 RF(100),VF(100),AFF(100),AWP(100),RAD,AFRNT,APER,VOLB
1506                REAL*8 H,VINT,V1,V2,NONDIM
1507                INTEGER CA,NDIM
1508                J=0
1508.5             H=H+0.059
1509               V1=0.
1509.5             V2=0.
1510               J=2
1510.5             FIX=3.14*(.041**2*H +.021**2*.0339)
1511      1         IF (VOLB .LE. VF(J)*FIX) GO TO 2
1512                J=J+1
1513                GO TO 1
1514      2         V1=VF(J-1)*FIX
1514.5             V2=VF(J)*FIX
1515               VINT=(VOLB-V1)/(V2 -V1)
1516               L=J-1
1519               RAD=(RF(L) +VINT*(RF(J)-RF(L)))*3.25/2 *0.0254
1520               AFRNT=(AFF(L)+VINT*(AFF(J)-AFF(L)))*2*3.141593*1.625**2
1521               AFRNT=AFRNT*(.0254**2)
1522               NONDIM=2*3.141593*(1.625*H + 0.83*1.337+1.625**2)
1523               APER=(AWP(L)+VINT*(AWP(J)-AWP(L)))*NONDIM*0.0254**2
1524               RETURN
1525               END
1526               SUBROUTINE INPUTS(JFLG,KFUEL,T1,SPEED,COMPR,AF,
1527     1 SPKAD,HTFCN,HTEXP,F,PRO2,PRH2O,PRN2,NDISS,PDCA,
1528     1 TWALL,PINLET,AIRFLO,IGNDEL,SCONST,IPRNTS,PAMB,CUPD,CUPH,HC)
1529               IMPLICIT REAL*8(A-H,O-Z)
1530               INTEGER NCODE,JFLG,NAN,NREP
1530.5             REAL*8 IGNDEL
1531               IF (JFLG .NE. 0) GO TO 99
1532      1         WRITE(6,2)
1533      2         FORMAT(' ','TYPE OF FUEL: 11=CH4 , 12=C8H18 , 13=C3H8')
1534               CALL FREAD('GUSER','I:',KFUEL)
1535               IF (JFLG .NE. 0) GO TO 99
1536      3         WRITE(6,4)
1537      4         FORMAT(' ','TEMPERATURE AT START OF COMBUSTION= ?')
1538               CALL FREAD('GUSER','R:',T1)
1539               IF (JFLG .NE.0) GO TO 99
1540      5         WRITE(6,6)
1541      6         FORMAT(' ','ENGINE SPEED = ?')
1542               CALL FREAD('GUSER','R:',RPM)
1543               IF (JFLG .NE. 0) GO TO 99
1544      7         WRITE(6,8)
1545      8         FORMAT(' ','COMPRESSION RATIO = ?')
1546               CALL FREAD('GUSER','R:',COMPR)
1547               IF (JFLG.NE. 0) GO TO 99
1548      9         WRITE(6,10)
1549     10         FORMAT(' ','AIR TO FUEL RATIO = ?')
1550               CALL FREAD('GUSER','R:',AF)
1551               IF (JFLG .NE. 0) GO TO 99
1552     11         WRITE(6,12)
1553     12         FORMAT(' ','SPARK ADVANCE (DEG. BTDC) = ?')
1554               CALL FREAD('GUSER','R:',SPKAD)
```

147.

```
55              IF (JFLG .NE. O) GO TO 99
56       13     WRITE(6,14)
57       14     FORMAT(' ','HEAT TRANSFER MULTIPLIER = ?')
58              CALL FREAD('GUSER','R:',HTFCN)
59              IF (JFLG .NE. O) GO TO 99
60       15     WRITE(6,16)
61       16     FORMAT(' ','HEAT TRANSFER EXPONENT = ?')
62              CALL FREAD('GUSER','R:',HTEXP)
63              IF (JFLG .NE. O) GO TO 99
63.5     57     WRITE(6,58)
63.7     58     FORMAT(' ','RESIDUAL GAS FRACTION = ?')
63.8            CALL FREAD('GUSER','R:',F)
63.9            IF (JFLG .NE. O) GO TO 99
63.95    59     WRITE(6,60)
63.97    60     FORMAT(' ','RESIDUAL FRACTION CO2 (%)= ?')
63.98           CALL FREAD('GUSER','R:',PRCO2)
63.99           IF (JFLG .NE. O) GO TO 99
64       17     WRITE(6,18)
65       18     FORMAT(' ','RESIDUAL FRACTION O2  (%) =?')
66              CALL FREAD('GUSER','R:',PRO2)
67              IF (JFLG .NE. O) GO TO 99
68       19     WRITE(6,20)
69       20     FORMAT(' ','RESIDUAL FRACTION H2O (%) = ?')
70              CALL FREAD('GUSER','R:',PRH2O)
71              IF (JFLG .NE. O) GO TO 99
72       21     WRITE(6,22)
73       22     FORMAT(' ','REDISUAL FRACTION N2 (%) = ?')
74              CALL FREAD('GUSER','R:',PRN2)
75              IF (JFLG .NE. O)GO TO 99
76       23     WRITE(6,24)
77       24     FORMAT(' ','FULL DISSOCIATION (O), OR PARTIAL ?')
78              CALL FREAD('GUSER','I:',NDISS)
79              IF (JFLG .NE. O) GO TO 99
80       25     WRITE(6,26)
81       26     FORMAT(' ','CRANK ANGLE ITERATION INCREMENT = ?')
82              CALL FREAD('GUSER','R:',PDCA)
83              IF (JFLG .NE. O) GO TO 99
84       27     WRITE(6,28)
85       28     FORMAT(' ','CYLINDER WALL TEMPERATURE =?')
86              CALL FREAD('GUSER','R:',TWALL)
87              IF (JFLG .NE. O) GO TO 99
88       29     WRITE(6,30)
89       30     FORMAT(' ','INLET PRESSURE (PASCALS) = ?')
90              CALL FREAD('GUSER','R:',PINLET)
91              IF (JFLG .NE. O) GO TO 99
92       31     WRITE(6,32)
93       32     FORMAT(' ','AIR MASS FLOW RATE (G/S) = ?')
94              CALL FREAD('GUSER','R:',AIRFLO)
95              IF (JFLG .NE. O) GO TO 99
96       33     WRITE(6,34)
97       34     FORMAT(' ','IGNITION DELAY TIME (CA DEG) = ?')
98              CALL FREAD('GUSER','I:',IGNDEL)
99              IF (JFLG.NE.O) GO TO 99
00       35     WRITE(6,36)
01       36     FORMAT(' ','SMOOTHING ROUTINE CONST. SCONST = ?')
02              CALL FREAD('GUSER','R:',SCONST)
03              IF (JFLG.NE.O) GO TO 99
04       37     WRITE(6,38)
```

```
    38      FORMAT(' ','DO YOU WANT INTERMEDIATE RESULTS   Y=1, N=0?')
            CALL FREAD('GUSER','I:',IPRNTS)
            IF (JFLG.NE.0) GO TO 99
    39      WRITE(6,40)
    40      FORMAT(' ','AMBIENT PRESSURE (KPA) ?')
            CALL FREAD('GUSER','R:',PAMB)
            IF (JFLG.NE. 0) GO TO 99
    41      WRITE(6,42)
    42      FORMAT(' ','PISTON CUP DIAMETER (M) ?')
            CALL FREAD('GUSER','R:',CUPD)
            IF (JFLG .NE. 0) GO TO 99
    43      WRITE(6,44)
    44      FORMAT(' ','PISTON CUP DEPTH (M)?')
            CALL FREAD('GUSER','R:',CUPH)
            IF (JFLG .NE. 0) GO TO 99
    45      WRITE(6,46)
    46      FORMAT(' ','CLEARANCE HEIGHT (M) ?')
            CALL FREAD('GUSER','R:',HC)
    99      WRITE(6,100)
    100     FORMAT(' ','DO YOU WISH TO CHANGE ANY INPUTS (1=YES,0=NO) ?')
            CALL FREAD('GUSER','I:',JFLG)
            IF (JFLG.EQ. 0) GO TO 104
    101     WRITE(6,102)
    102     FORMAT(' ','ENTER THE NUMBER CODE OF THE INPUT (1,2,3,...)')
            CALL FREAD('GUSER','I:',NCODE)
            GO TO (1,3,5,7,9,11,13,15,17,19,21,23,25,27,29,31,33,35,
           137,39,41,43,45,57,59),NCODE
    104     WRITE(6,103)
    103     FORMAT(' ','DO YOU WANT TO SAVE THIS DATA (0=YES,1=NO) ?')
            CALL FREAD('GUSER','I:',NREP)
            IF (NREP .EQ. 1 ) RETURN
            CALL OUTPUT(JFLG,KFUEL,T1,RPM,COMPR,AF,
           1 SPKAD,HTFCN,HTEXP,F,PRCO2,PRO2,PRH2O,PRN2,NDISS,PDCA,
           1 TWALL,PINLET,AIRFLO,IGNDEL,SCONST,IPRNTS,PAMB,CUPD,CUPH,HC)
            RETURN
            END
            SUBROUTINE OUTPUT(JFLG,KFUEL,T1,RPM,COMPR,AF,
           1 SPKAD,HTFCN,HTEXP,F,PRCO2,PRO2,PRH2O,PRN2,NDISS,PDCA,
           1 TWALL,PINLET,AIRFLO,IGNDEL,SCONST,IPRNTS,PAMB,CUPD,CUPH,HC)
            IMPLICIT REAL*8(A-H,O-Z)
            REAL*8 IGNDEL
            WRITE(8,47) KFUEL,T1,RPM,COMPR,AF,SPKAD,HTFCN,HTEXP
    47      FORMAT(I3,2F7.1,3F6.2,F6.3,F5.2)
            WRITE(8,46) F,PRO2,PRCO2,PRH2O,PRN2,NDISS,PDCA,TWALL
    46      FORMAT(5F7.3,I3,F6.2,F7.1)
            WRITE(8,2) PINLET,AIRFLO,IGNDEL,SCONST,IPRNTS,PAMB
            WRITE(8,22) CUPD,CUPH,HC
    22      FORMAT(3F8.3)
    2       FORMAT(F6.1,3F6.2,I3,F6.2)
            RETURN
            END
```

APPENDIX F - PROPERTIES OF B.C. NATURAL GAS

Composition (Volume %)

Methane	94.00
Ethane	3.30
Propane	1.00
Iso-butane	0.15
N-butane	0.20
Iso-pentane	0.02
N-pentane	0.02
Nitrogen	1.00
Carbon Dioxide	0.30
Hexane	0.01

Water Content: 3 to   lbs/million cubic feet

This composition may be conveniently approximated by the following composition:

	% Volume	Volume Fraction		Molecular Weight		Mass kg/kmol
Methane CH4	94.00	0.940	*	16.040	=	15.078
Ethane C2H6	3.30	0.033	*	30.070	=	0.992
Propane C3H8	1.00	0.010	*	44.097	=	0.441
Butane C4H10	0.40	0.004	*	58.124	=	0.232
Nitrogen	1.00	0.010	*	28.013	=	0.280
Carbon Dioxide	0.30	0.003	*	44.010	=	0.132
	100.00	1.000			M=	17.156

It therefore follows that the average molecular weight is 17.156 and the gas constant $= \frac{R}{M} = \frac{8.3143}{17.156} = 0.4846$.

Hence, density = P/(Z*R*T) = 21.1°C at 1 atm (101.3 kPa). Generally, density at 1 atm = 209/T(°K) kg/m.

Viscosity

The viscosity of the natural gas at 0°C may be obtained from the following:

$$\mu_{mix} = \frac{\sum y_i * u_i * (M_i)^{1/2}}{\sum y_i * (M_i)^{1/2}}$$ where y_i = molecule fraction

M_i = molecule weight

given:

μ_{CH_4} = 102.6 micropoise at 0°C.

$\mu_{C_2H_6}$ = 84.8 micropoise at 0°C.

$\mu_{C_3H_3}$ = 75.0 micropoise at 0°C.

μ_{CO_2} = 139.0 micropoise at 0°C.

μ_{N_2} = 166.0 micropoise at 0°C.

Estimating μ as 75.0 for C4H10 as well as C3H8 and including the mole fraction of the former with the latter, the calculation becomes:

	Viscosity	y_i	m_i	$(m_i)^{1/2}$	$y_i*(m_i)^{1/2}$	$y_i\mu_i(m_i)^{1/2}$
CH4	102.6	0.940	16.040	4.005	3.765	386.29
C2H6	84.8	0.033	30.070	5.484	0.181	15.35
C3H8	75.0	0.014	48.105	6.936	0.097	7.28
CO2	139.0	0.003	44.010	6.634	0.020	2.78
N2	166.0	0.010	28.013	5.293	0.053	8.80
					4.116	420.50

with the result

$$\mu_{mix} = \frac{420.5}{4.116} = 102.16 \text{ } \mu poise \text{ at } 0°C.$$

The viscosity of natural gas at other temperatures can be obtained from,

$$N.G.\mu = 9.879*T^{3/2}/(T + 163.17)$$

Therefore viscosity of N.G. at 70°F (21.1°C) = 108.96 μpoise.

Higher and Lower Heating Values

	mass kg/kmol	mass (%)		HHV (kJ/kg)		
CH4	15.078	0.879	*	55496	=	48781
C2H6	0.992	0.058	*	51875	=	3008
C3H8	0.441	0.026	*	50343	=	1309
C4H10	0.232	0.013	*	49500	=	644
CO2+N2	0.412	0.024	*	0	=	0
	17.156	1.000				53742

Therefore the Higher Heating Value of B.C. Natural Gas is 53,742 kJ/kg at 25°C.

The Lower Heating Value is given by,

	mass (%)		LHV		
CH4	0.879	*	50010	=	43959
C2H6	0.058	*	47484	=	2754
C3H8	0.026	*	46353	=	1205
C4H10	0.013	*	45714	=	640
CO2+N2	0.024	*	0	=	0
	1.000				48558

Therefore the Lower Heating Value of B.C. Natural Gas is 48,558 kJ/kg at 25°C.

TABLE I

Engine Specifications

Engine	C.F.R.
Displacement	611.7 C.C.
Bore	82.55 mm
Stroke	114.30 mm
Compression Ratio	11.3
Con-rod Length	254.00 mm
Intake Valves	Diam. 35 mm Opening Angle 10 A.T.D.C. Closing Angle 34 A.B.D.C.
Exhaust Valve	Diam. Opening Angle 40 B.B.D.C. Closing Angle 15 A.T.D.C.
Spark Plug	Champion W18

TABLE II

Hot Wire Probe and Anemometer Specifications

Probe	TSI Model 1226
Wire Material	Platimum-Iridium
Wire Diameter	6.3 μm
Wire Length	1.25 mm
Wire Temperature Coefficient of Resistance	0.0009 /°C
Anemometer	Disa Model 55M
Top Resistance	50 Ω
Cable Resistance	0.214 Ω

TOP
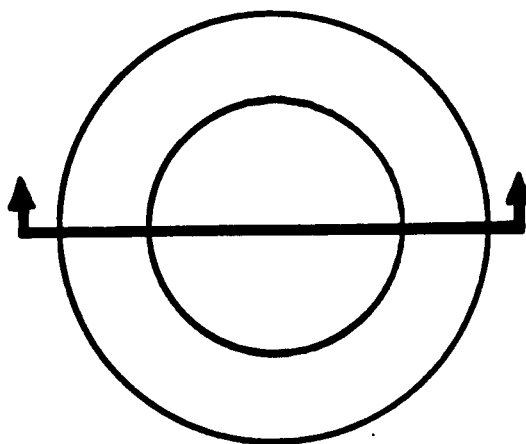
SECTION
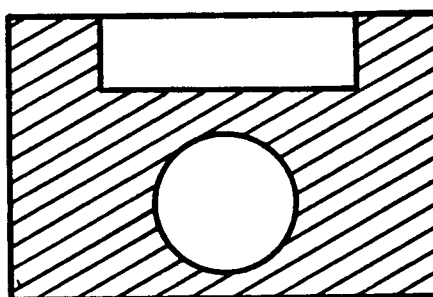
Fig. 1.1 The squish combustion chamber

PISTON A
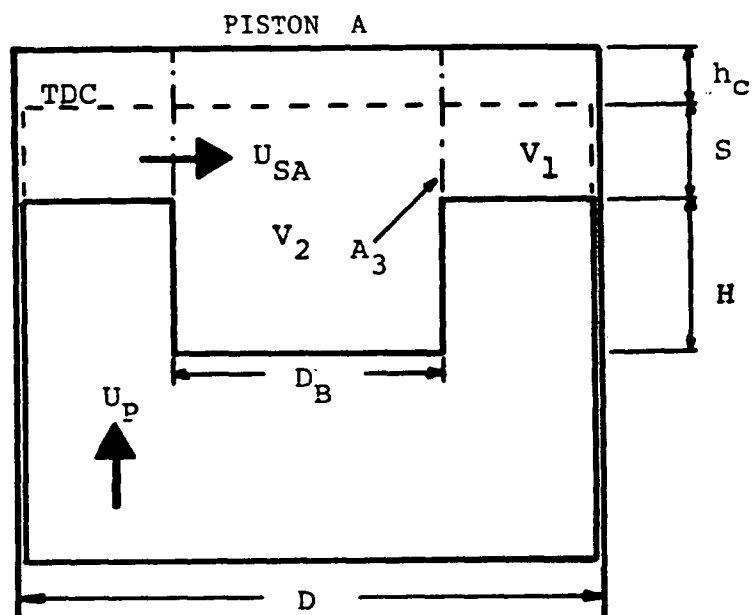
$$A_1 = \Pi/4 \ (D^2 - D_B^2)$$
$$A_2 = \Pi/4 \ D_B^2$$
$$A_3 = \Pi \ D_B(h_c + S)$$
$$\%\text{SQUISH} = A_1/(A_1 + A_2)$$
$$V_1 = A_1(h_c + S)$$
$$V_2 = A_2(h_c + S + H)$$

Fig. 3.1   The standard squish chamber

PISTON   B
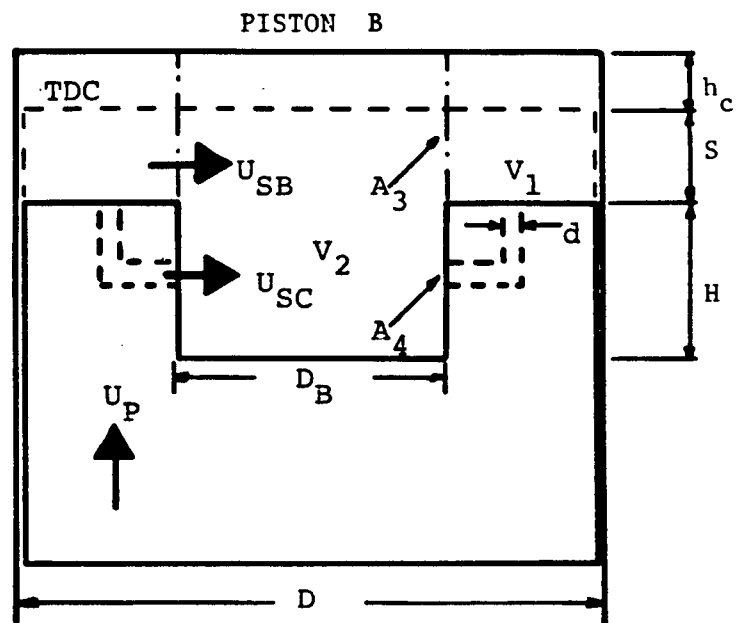
$$A_1 = \pi/4 \ (D^2 - D_B^2)$$
$$A_2 = \pi/4 \ D_B^2$$
$$A_3 = \pi \ D_B (h_c + S)$$
$$A_4 = \pi/4 \ d^2$$
$$\%SQUISH = A_1/(A_1 + A_2)$$
$$V_1 = A_1 \ (h_c + S)$$
$$V_2 = A_2 \ (h_c + S + H)$$

Fig. 3.2   The squish-jet chamber
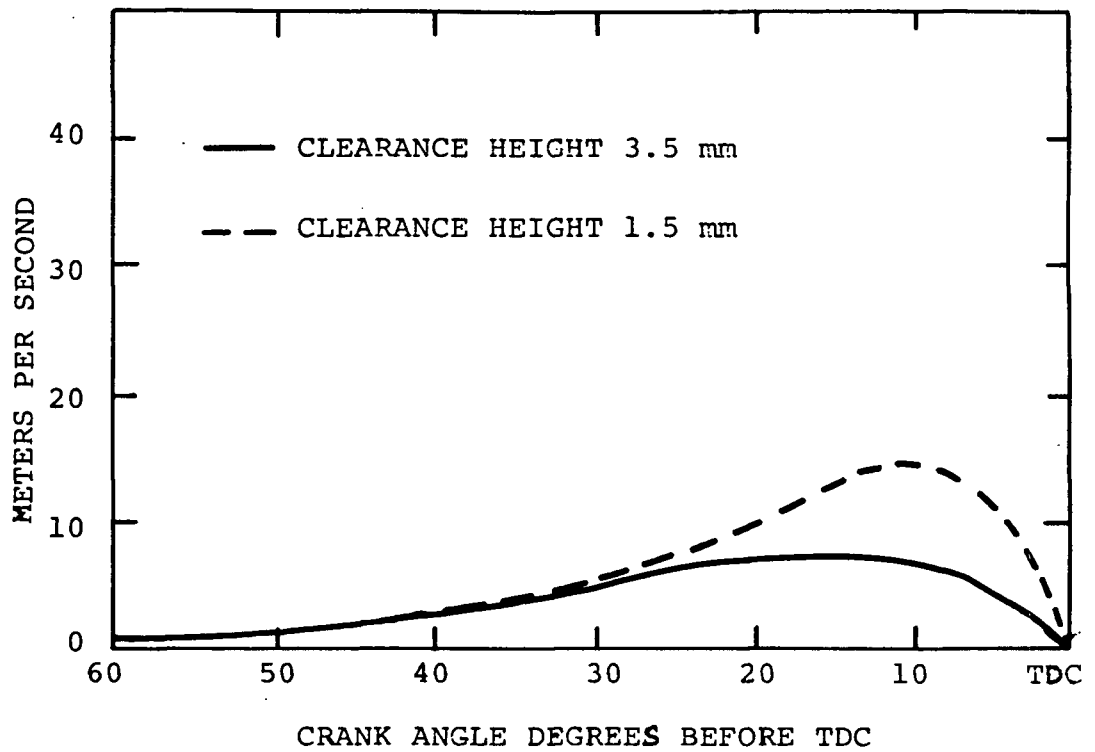
Fig. 3.3 The effect of clearance height on squish velocity
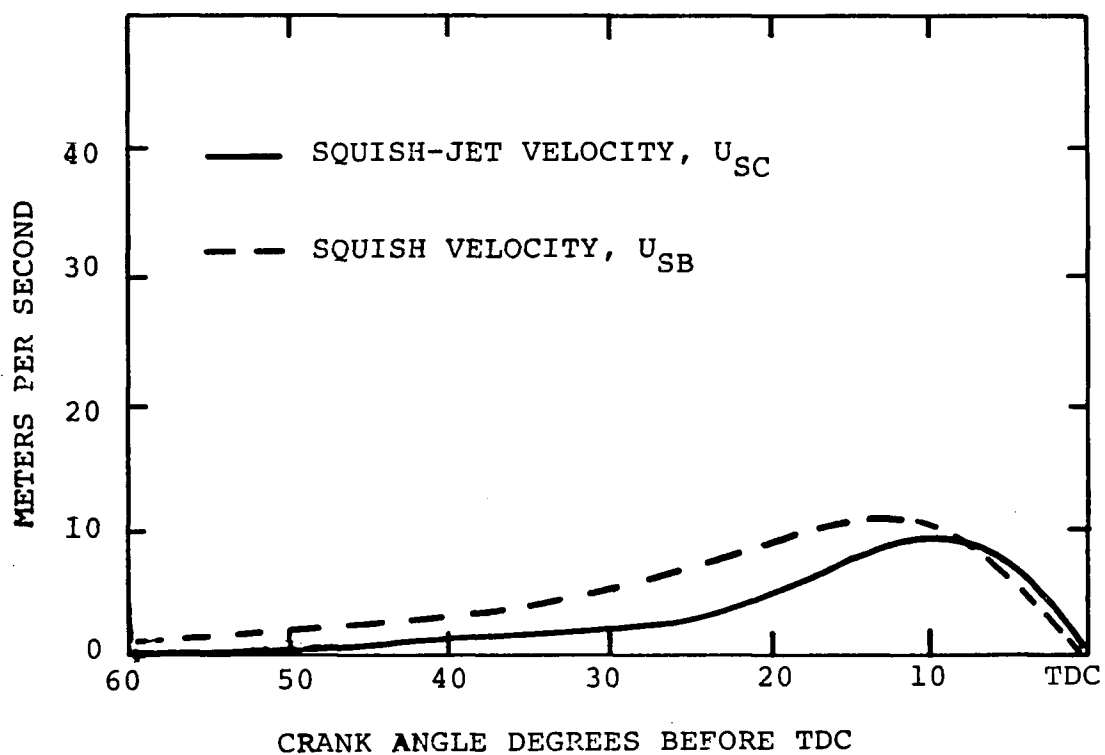
Fig. 3.4   The effect of the squish-jet design on squish velocity
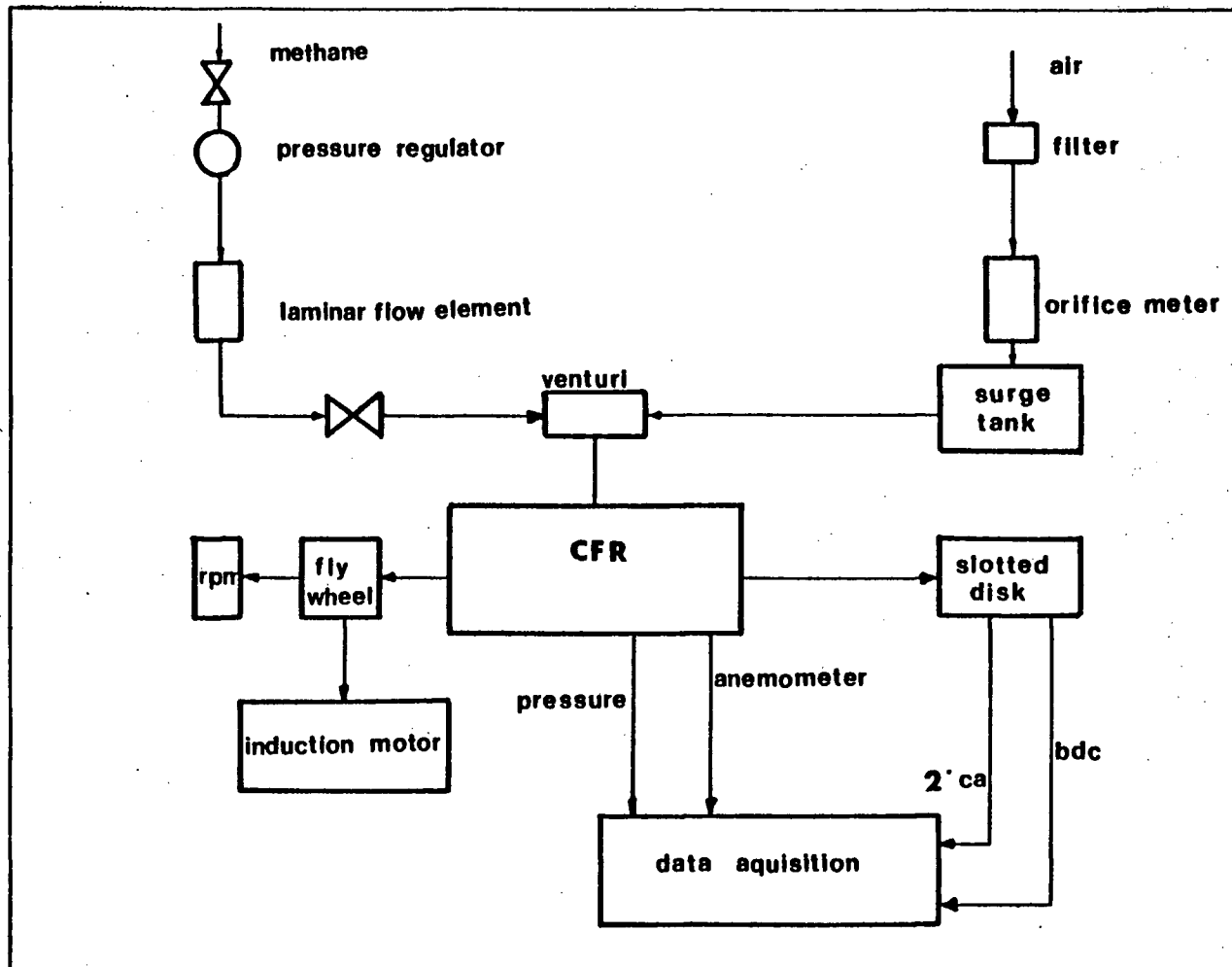
Fig. 4.1 Schematic of experimental setup and instrumentation

Fig. 4.2   The C.F.R. engine

34 mm RADIUS
MILL 0.030"

0.390

TYPICAL
0.187 RADIUS

0.250

0.600

A

B

1.337

C

1.500

2.500

3.250
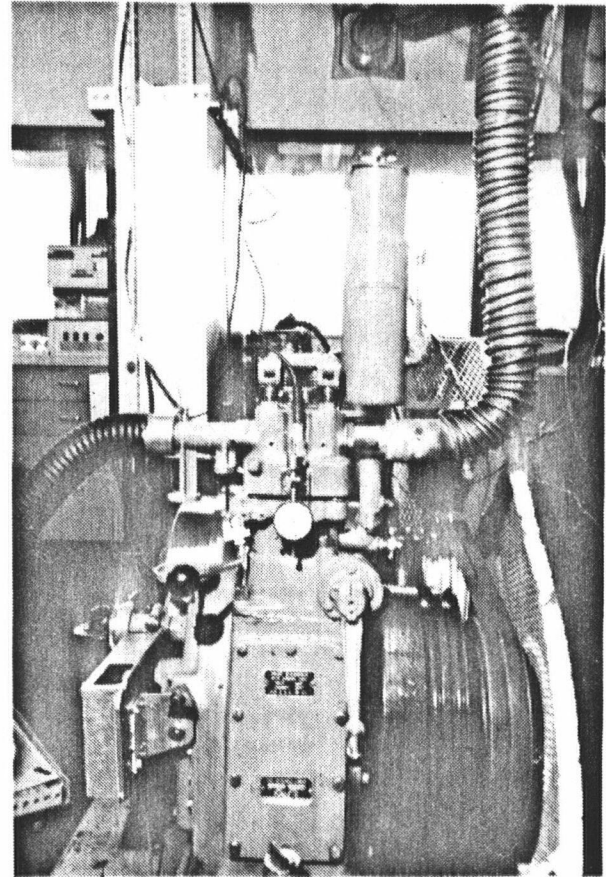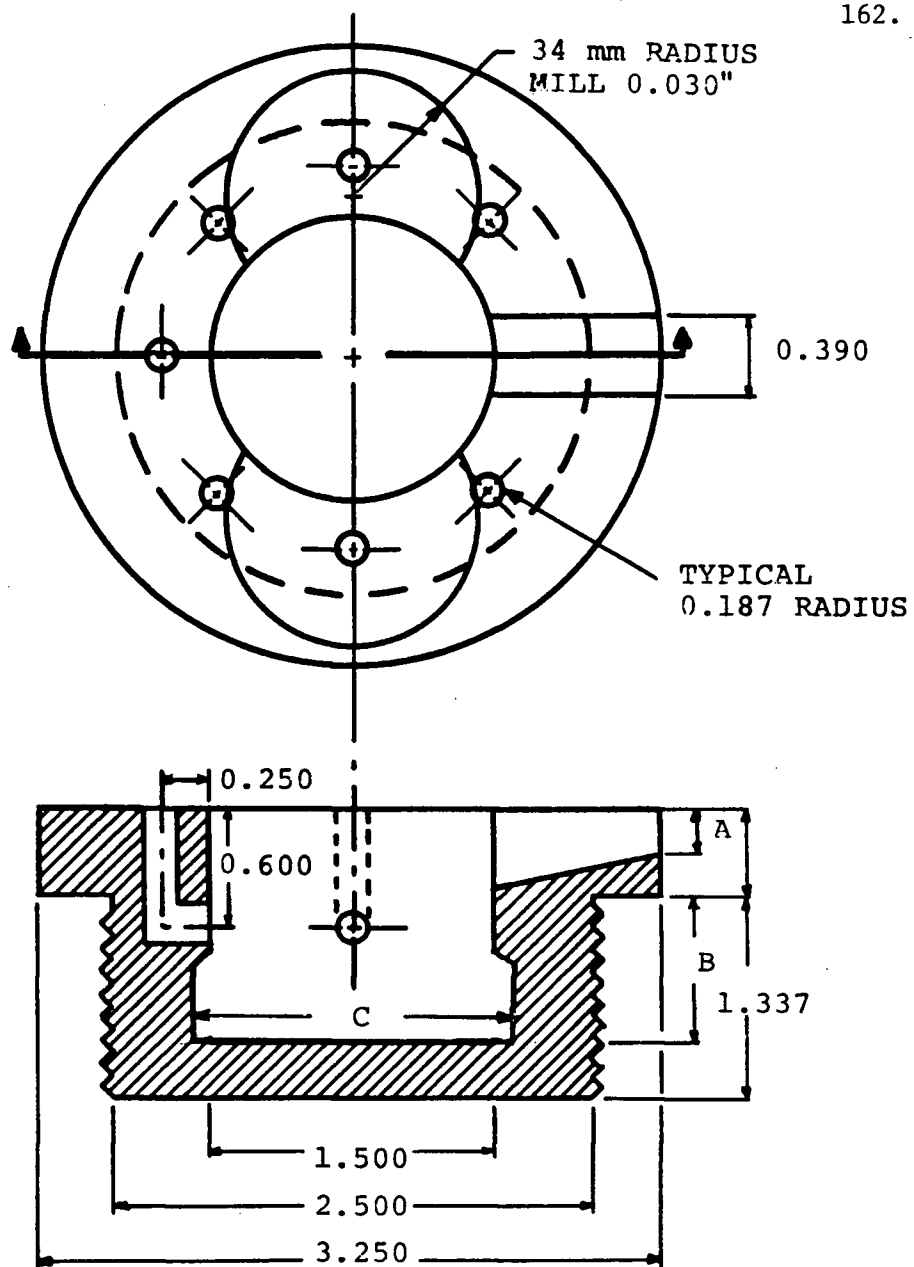
Piston A, Case 1   A=0.354 B=0.947 C=1.819
Piston B, Case 1   A=0.354 B=0.947 C=1.739
Piston A, Case 2   A=0.354 B=0.931 C=1.500
Piston B, Case 2   A=0.354 B=0.889 C=1.500

Piston A - exclude the 7 holes
Case 2   - do not mill recess for valves

Fig. 4.3 The squish piston inserts
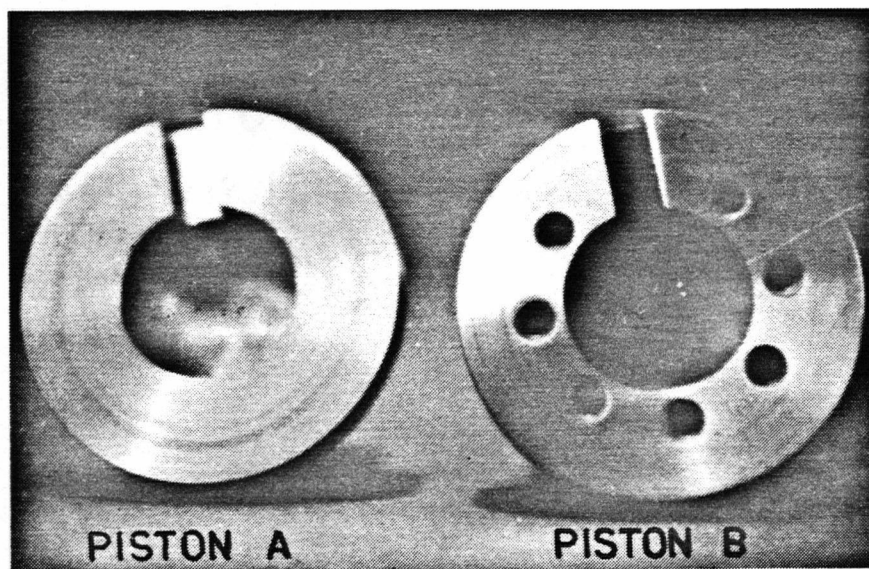
Fig. 4.4   Photograph of squish piston inserts

TOP

SPARK (FIRED)
PRESSURE
TRANSDUCER (MOTORED)

SIDE

HOT WIRE PROBE
(MOTORED)
PRESSURE TRANSDUCER
(FIRED)
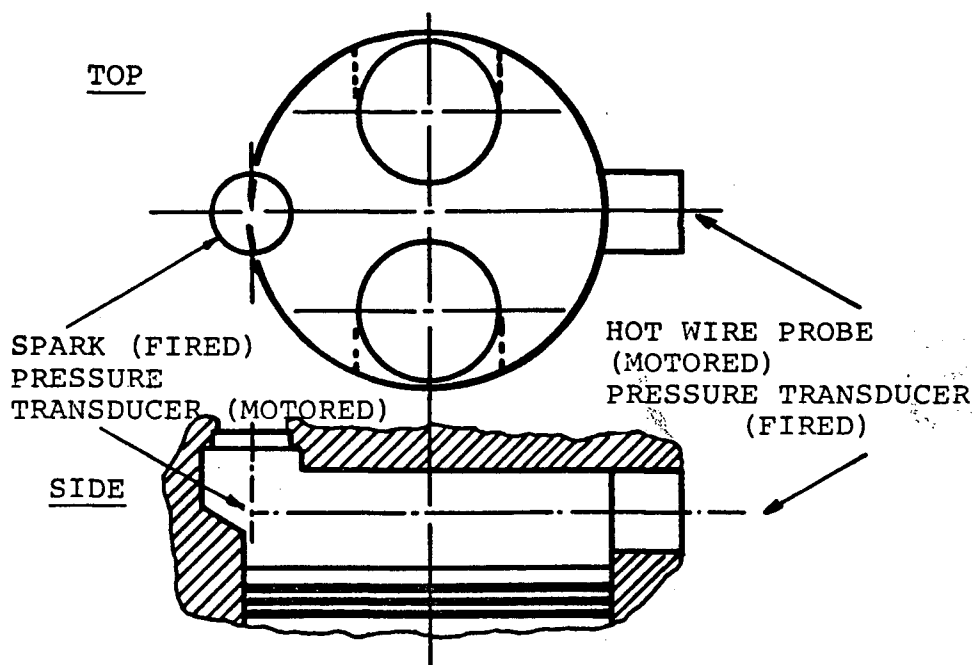
Fig. 4.5 Top and side view of C.F.R. combustion chamber
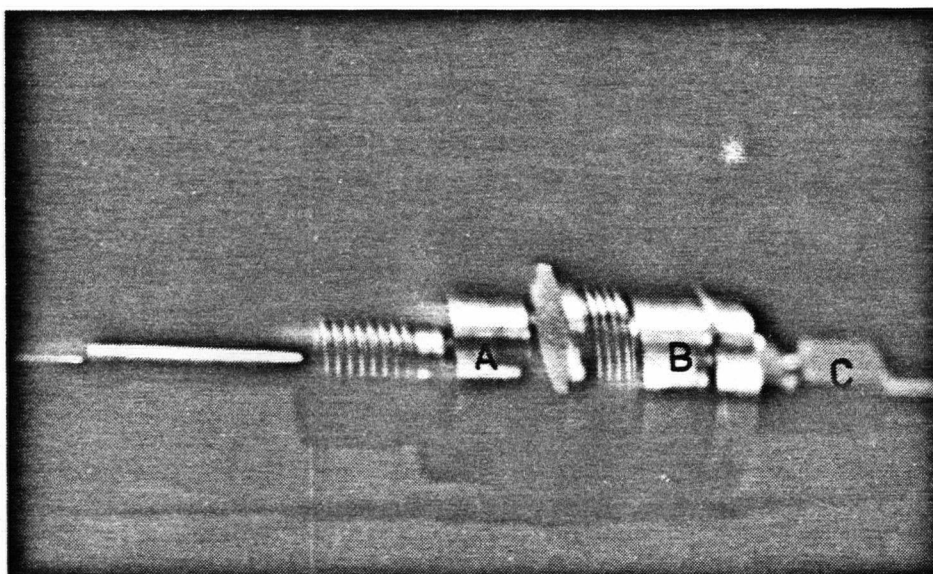
Fig. 4.6 Fitting for hot wire probe
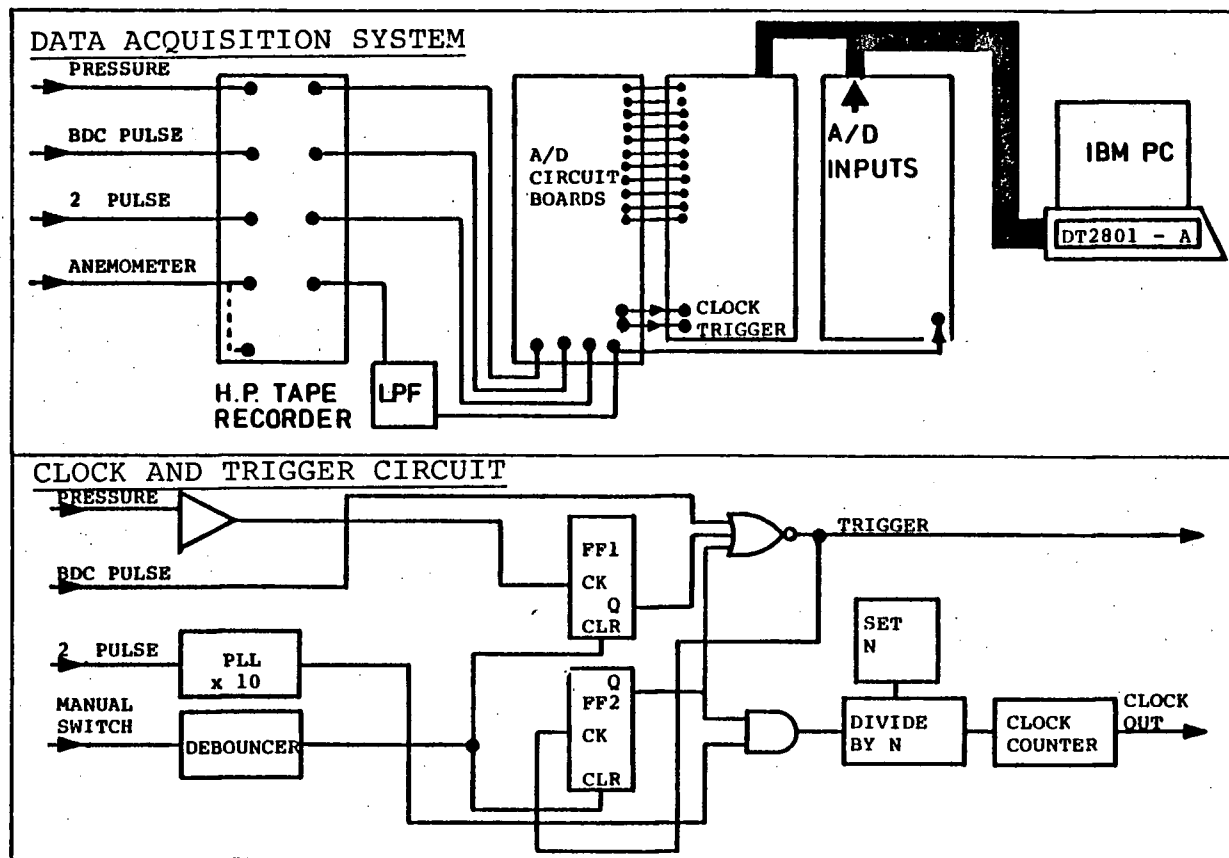
Fig. 4.7   Schematic of data acquisition
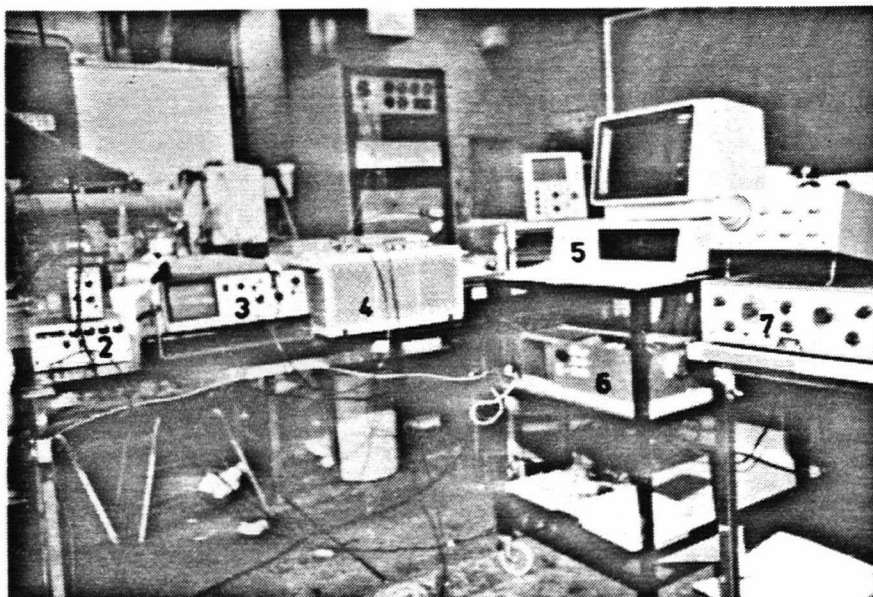
1 - Charge Amplifier for Pressure Signal

2 - Anemometer Bridge Unit

3 - Digital Oscilloscope

4 - Hewlett Packard Tape Recorder

5 - I.B.M. Microcomputer

6 - Data Acquisition Circuitry

7 - Bandpass Filter

Fig. 4.8 Photograph of data acquisition system
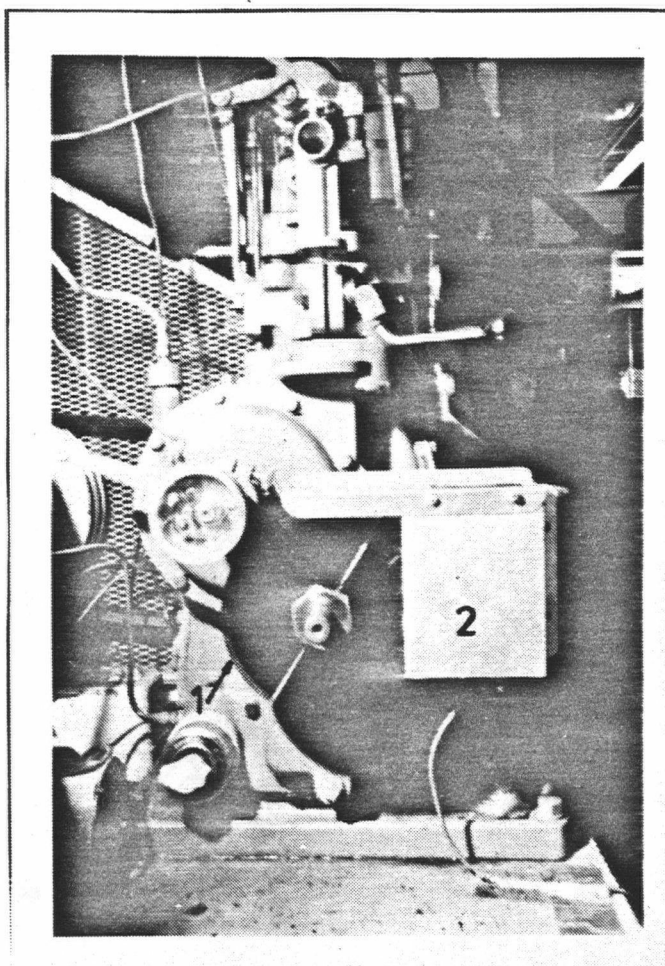
1 - Slotted Wheel

2 - Optical Pickup and Trigger Circuitry

Fig. 4.9 Photograph of optical trigger system

TOP
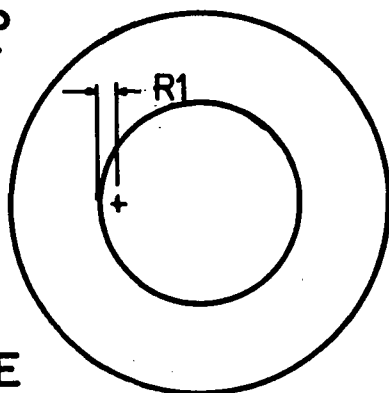
SIDE
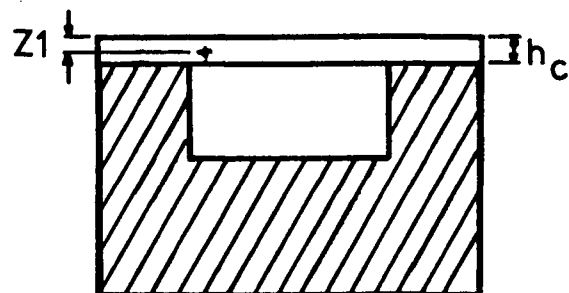
Piston	h_c	Z_1	R_1
A,B	3.5	2.0	10.0
A,B	1.5	2.0	10.0
A	2.5	2.0	10.0
FLAT	10.7	2.0	10.0
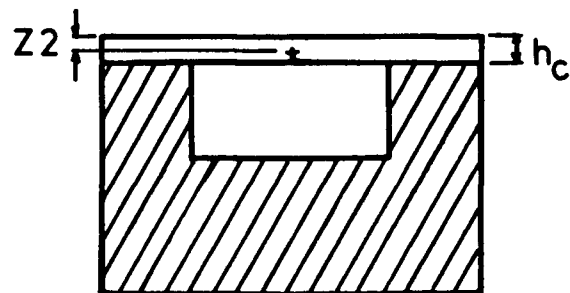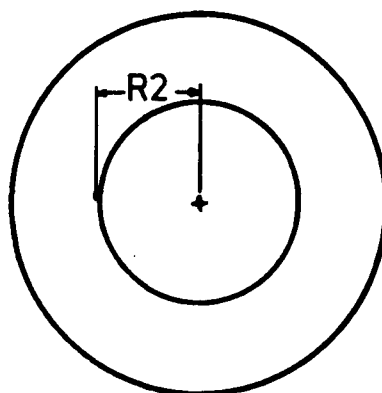
Piston	h_c	Z_2	R_2
A,B	3.5	2.0	23.0
A,B	1.5	2.0	23.0
A	2.5	2.0	23.0
FLAT	10.7	2.0	23.0
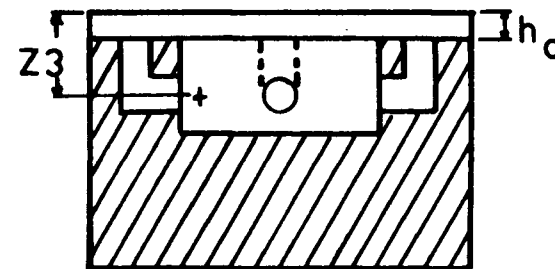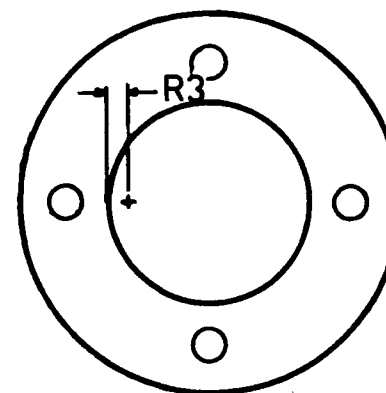
Piston	h_c	Z_3	R_3
B	1.5	16.0	5.0

All dimensions in millimeters

Fig. 5.1 Hot wire probe locations

SIDE

TOP

$\alpha = 0^{\circ}$

SIDE

TOP

$\alpha = 90^{\circ}$
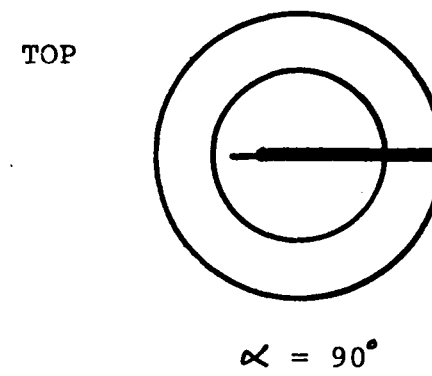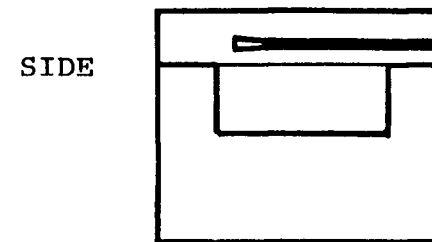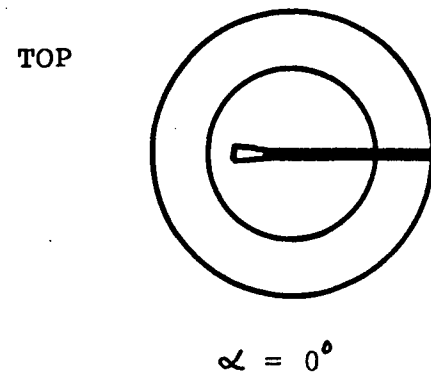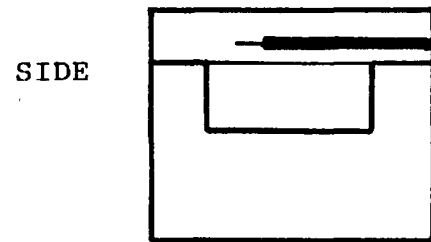
Fig. 5.2   Hot wire probe orientation
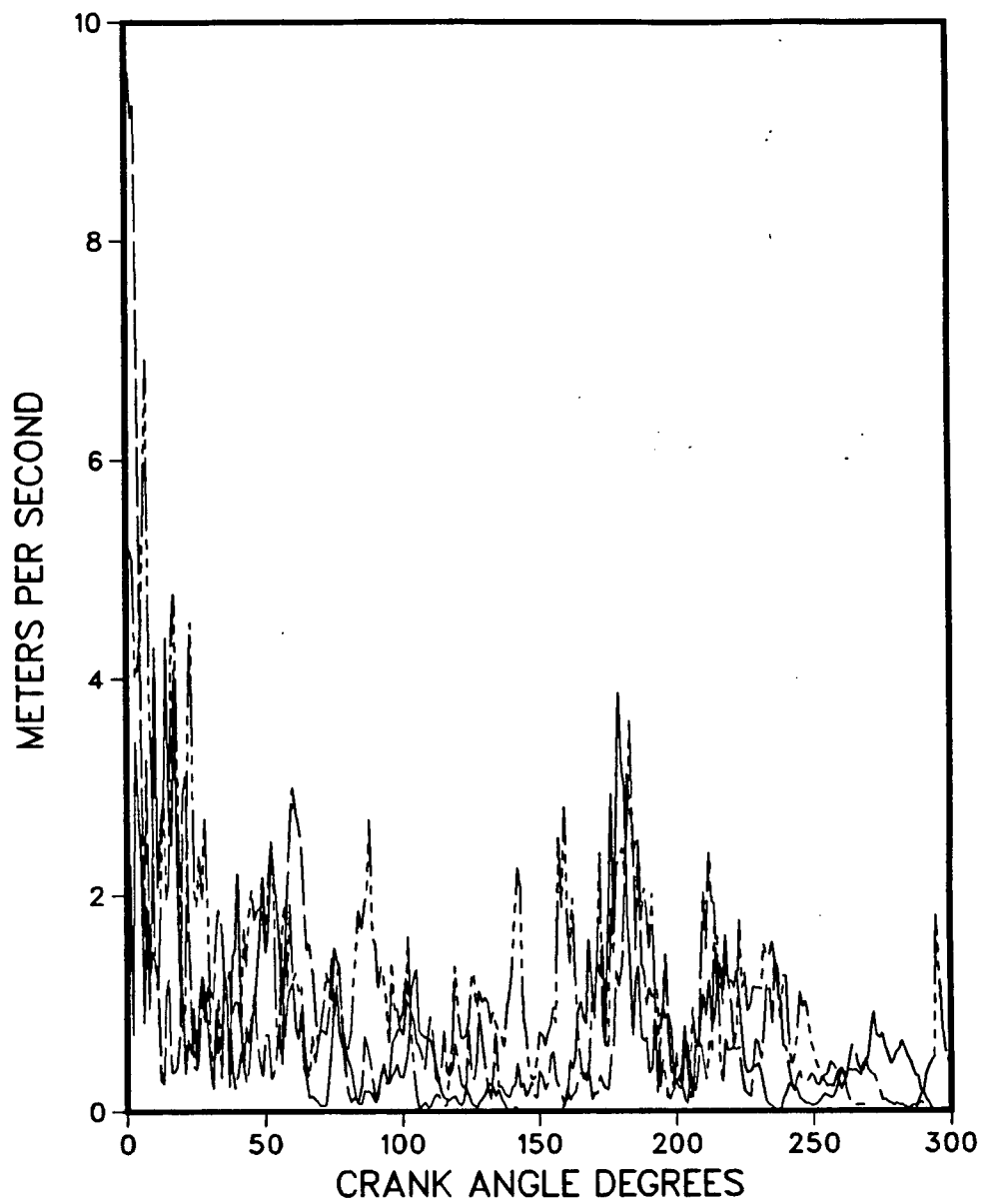
Fig. 7.1 Three consecutive instantaneous velocity records
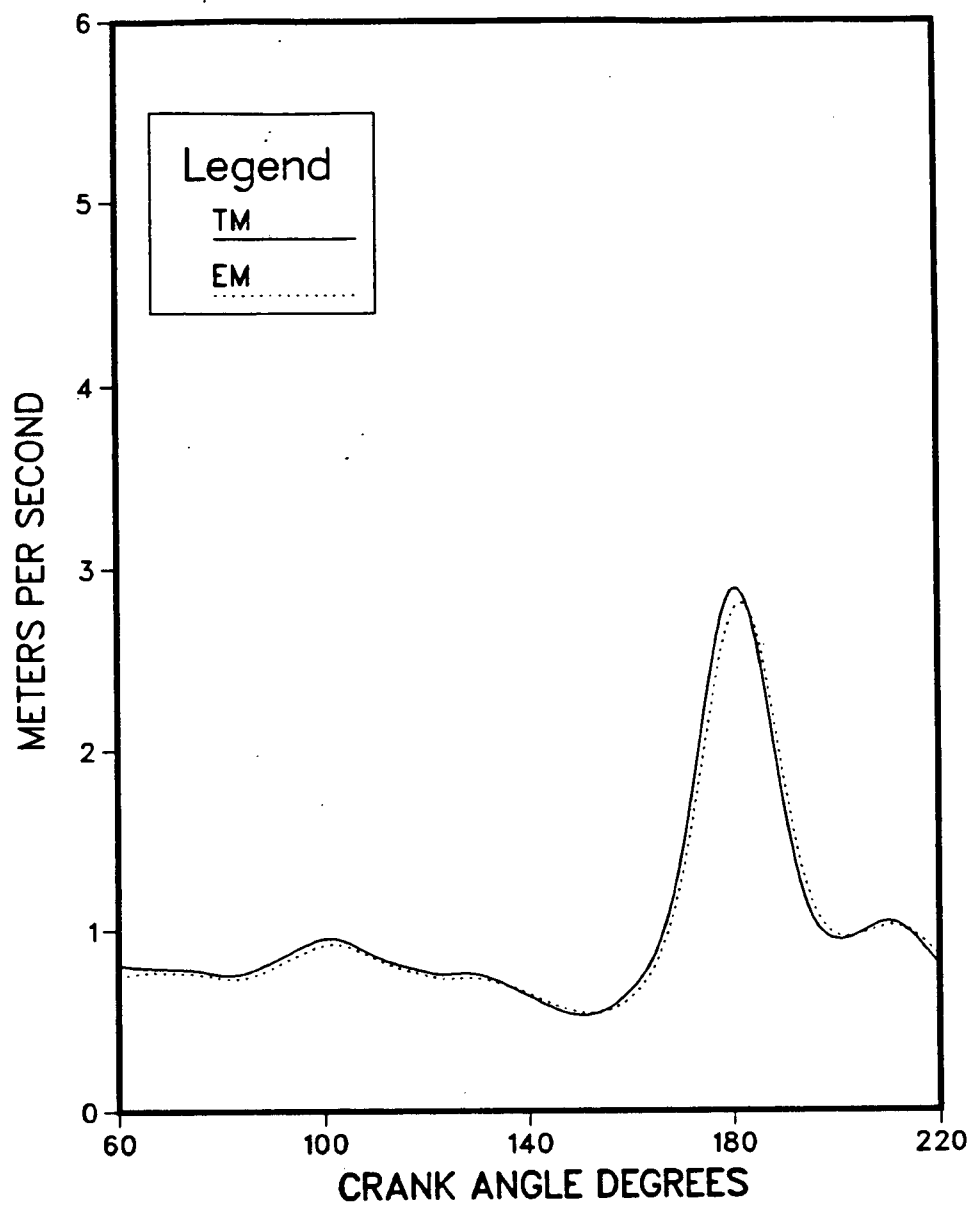
Fig. 7.2 Comparison of time averaged and ensemble averaged
mean velocity
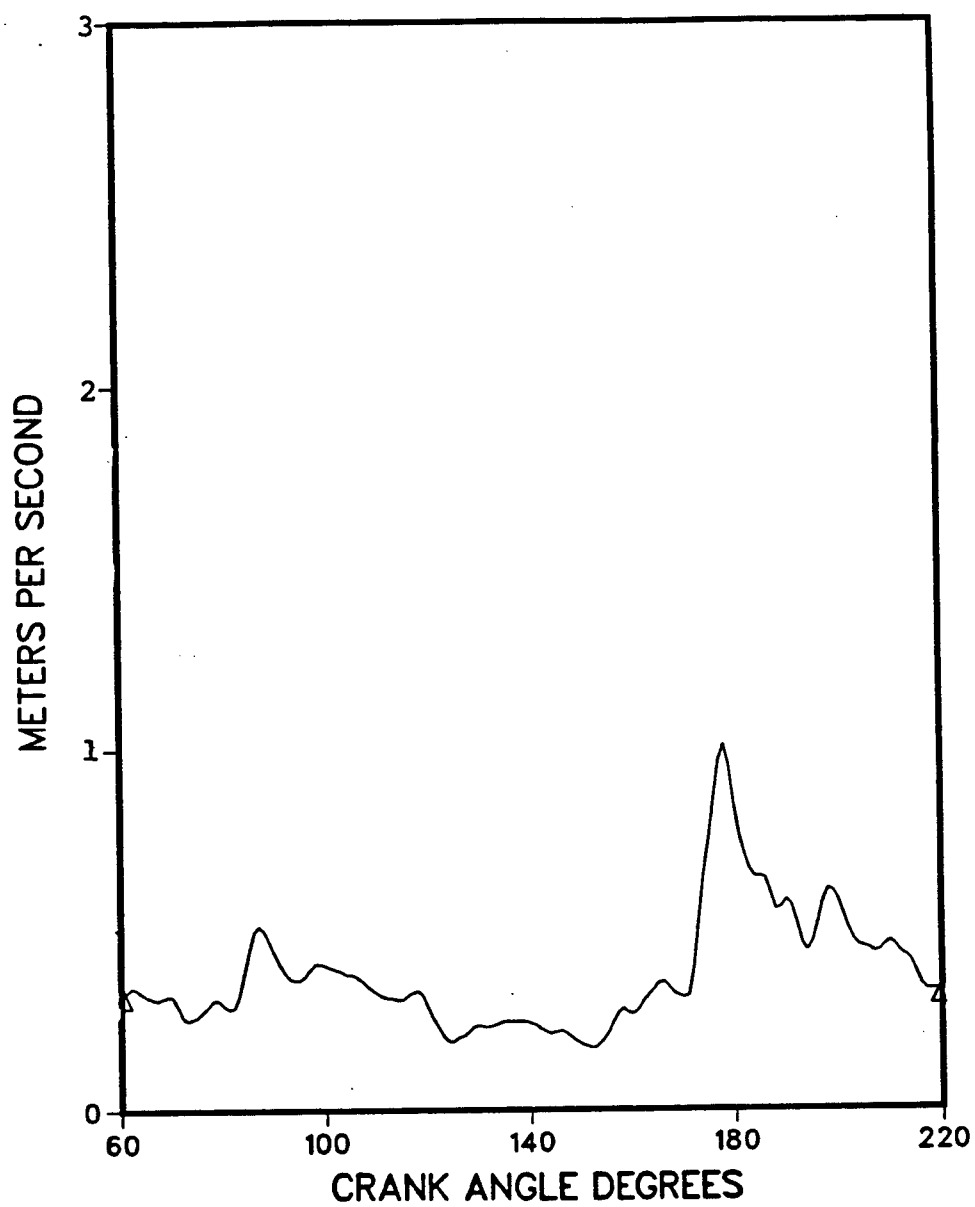
Fig. 7.3 Cyclic variation of the mean velocity
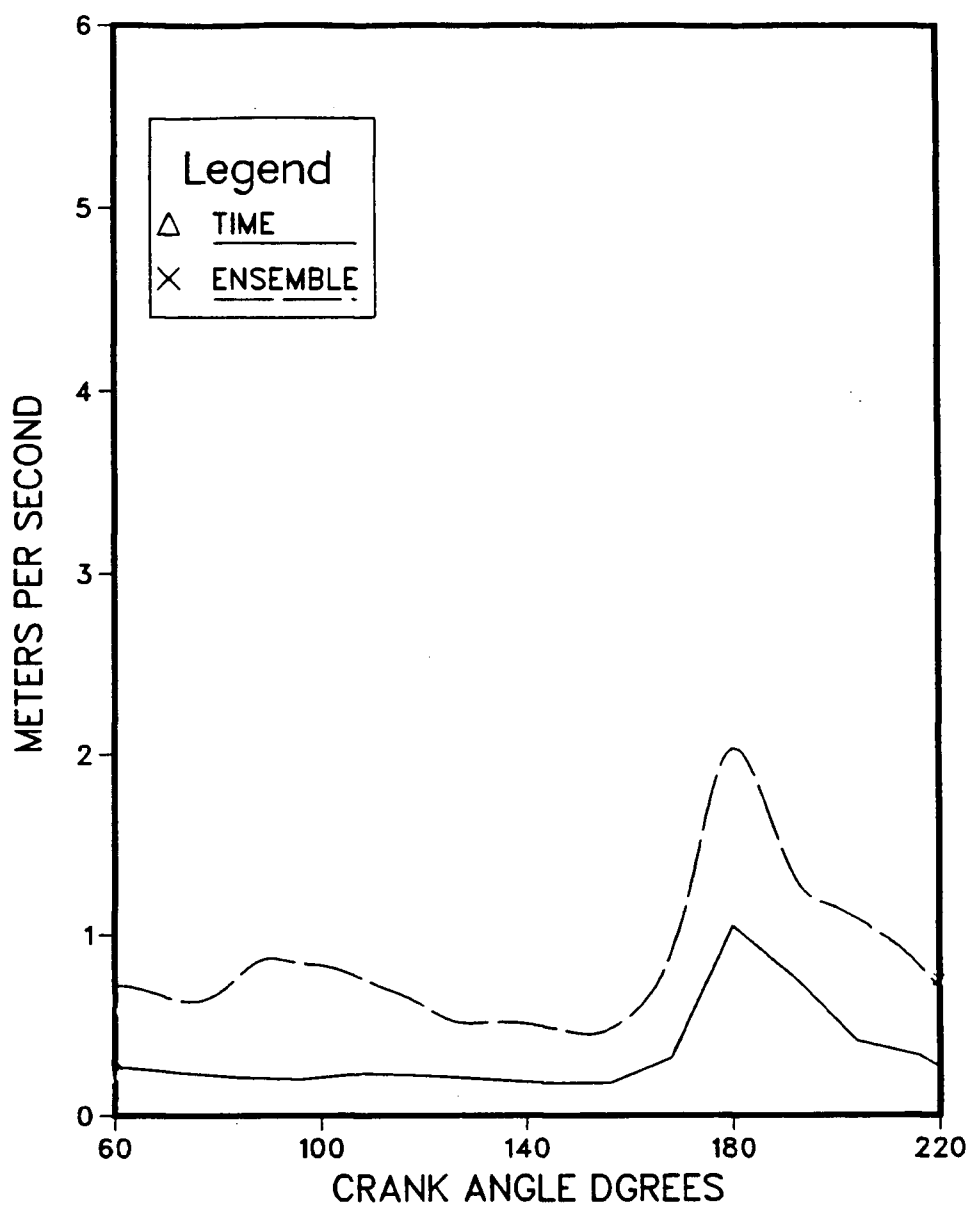
Fig. 7.4 Comparison of time and ensemble averaging techniques
for the evaluation of turbulence intensity
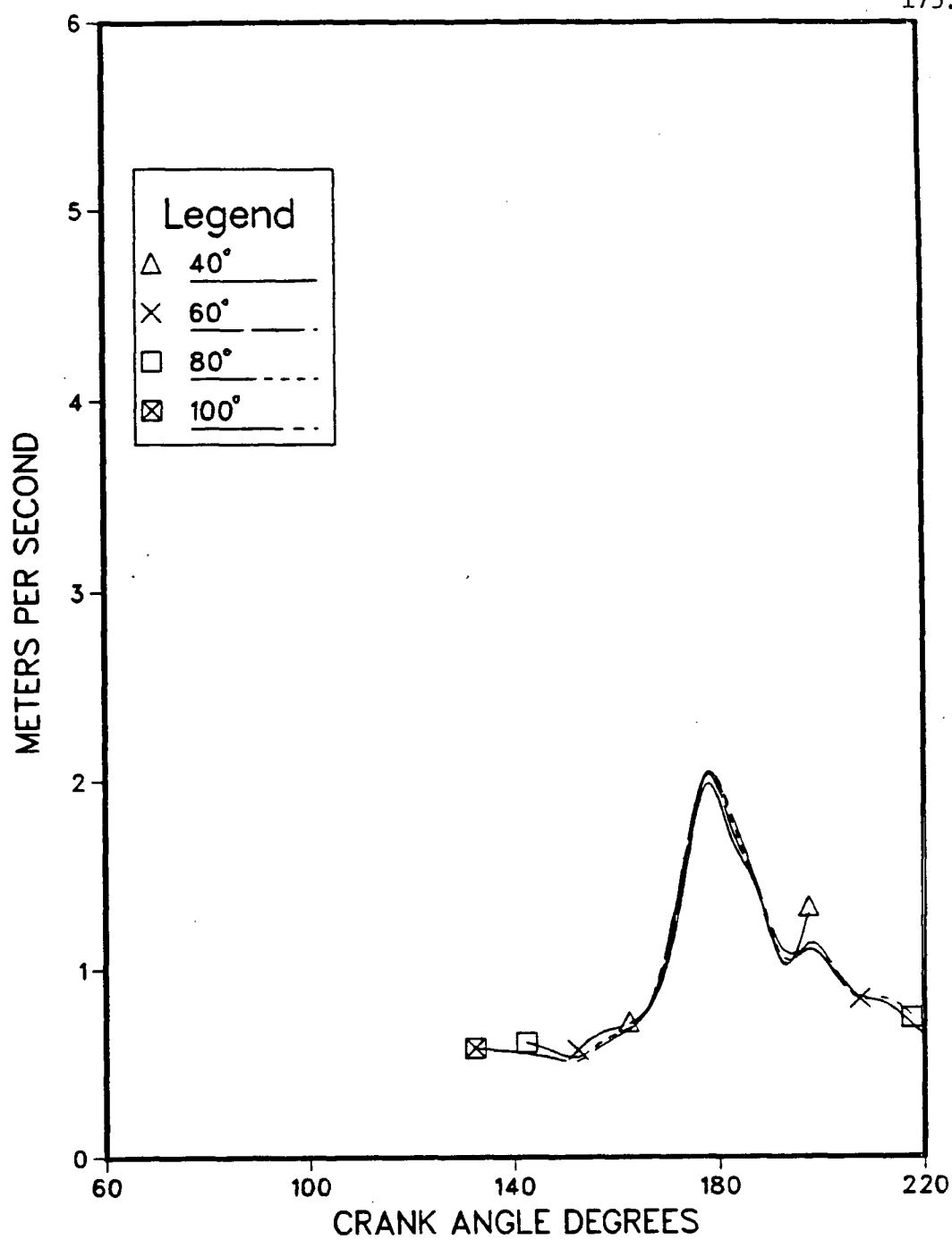
Fig. 7.5   Turbulence intensity evaluated with Lancaster's
nonstationary technique
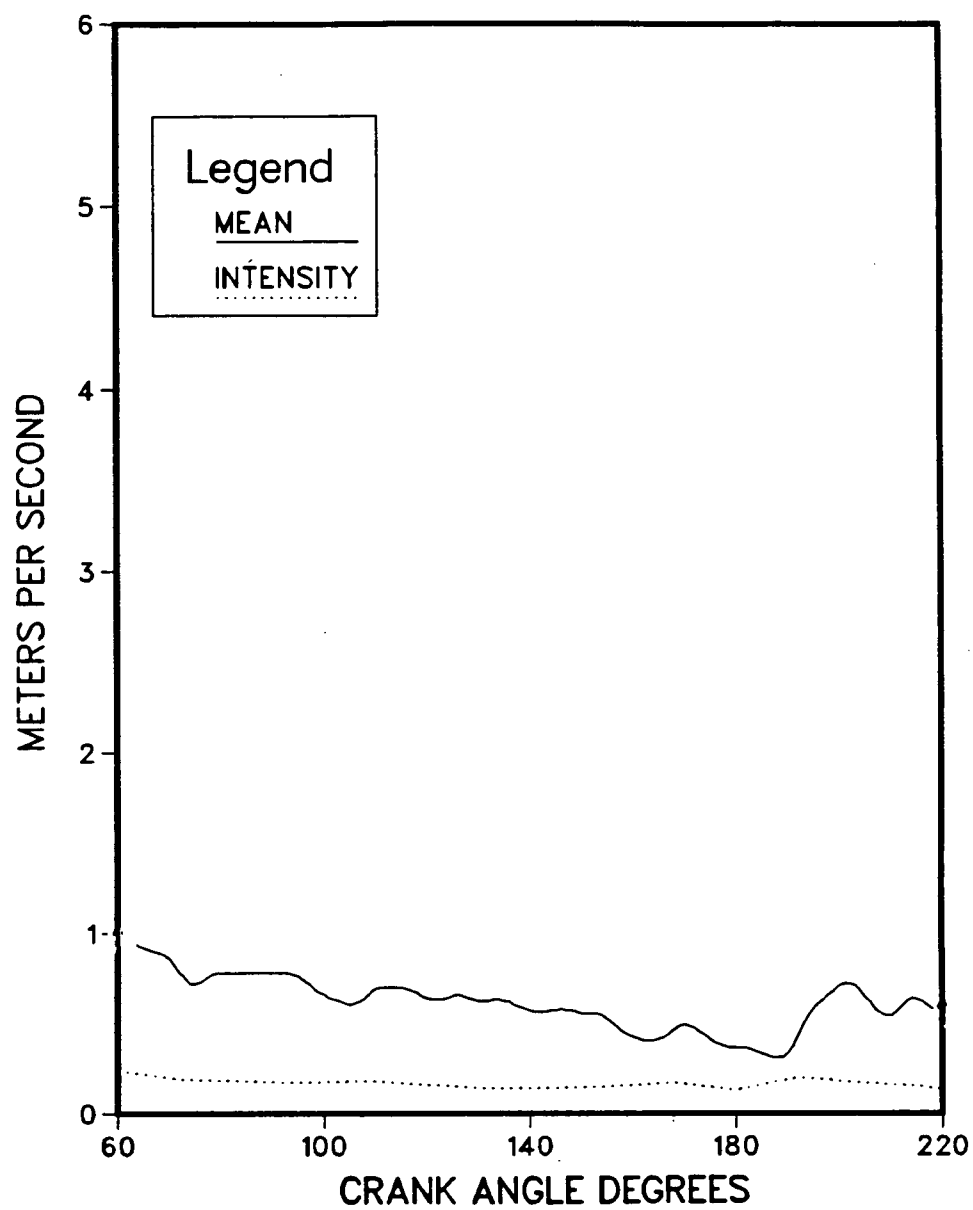
Fig. 7.6 Mean velocity and turbulence intensity for Piston A;
h_c = 3.5 mm; probe at cup edge
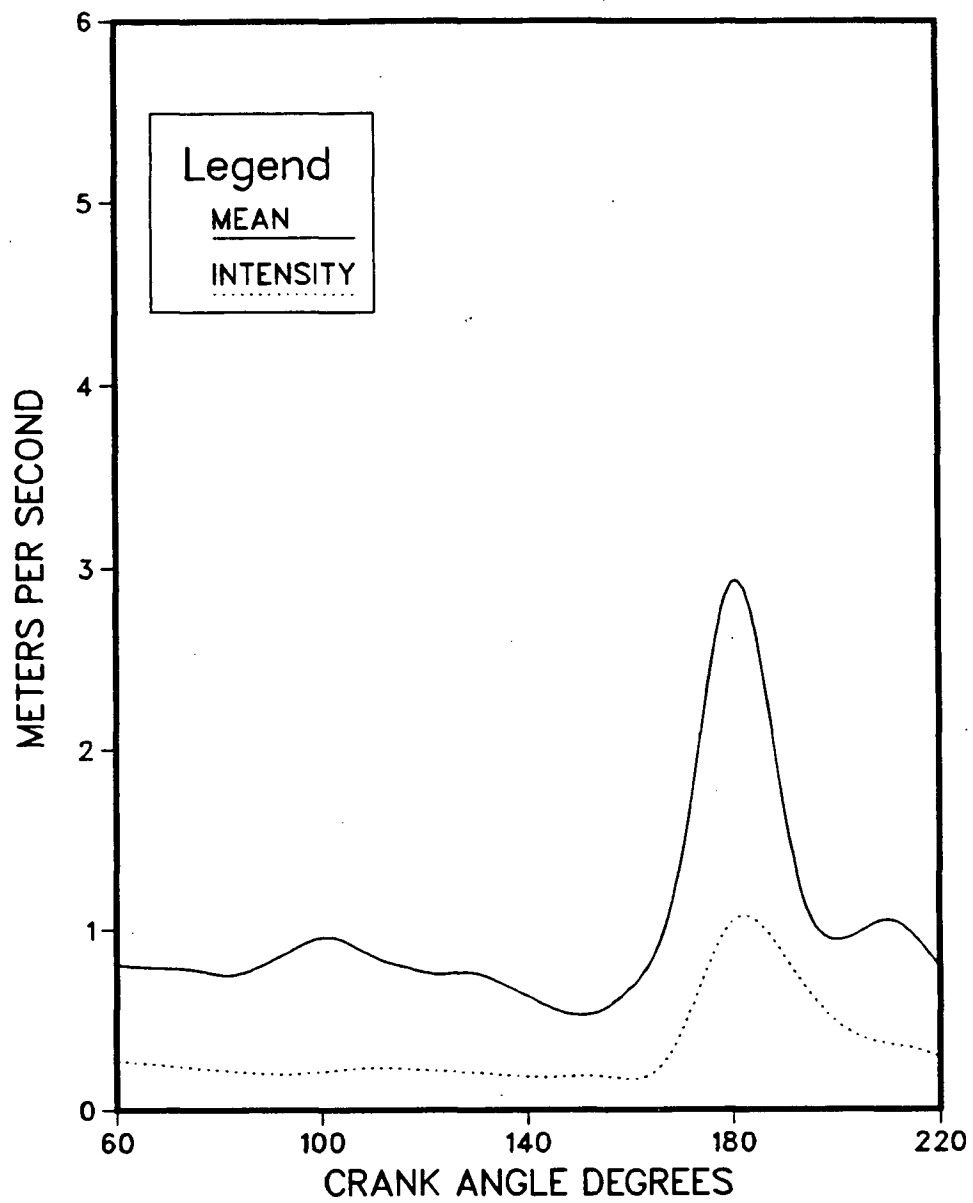
Fig. 7.7   Mean velocity and turbulence intensity for Piston A;
h_c = 1.5 mm; probe at cup edge
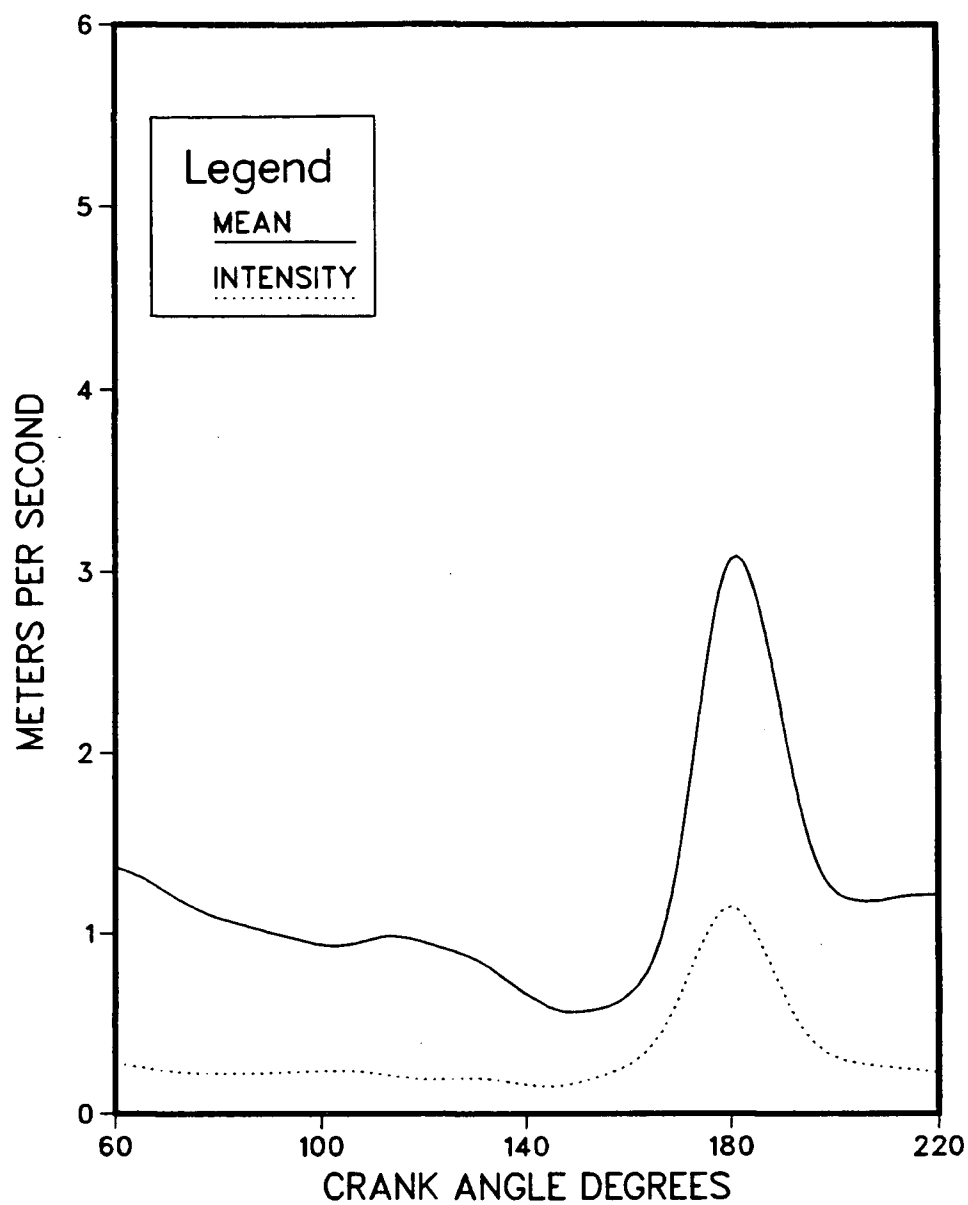
Fig. 7.8 Mean velocity and turbulence intensity for Piston A;
h_c = 1.5 mm; probe at chamber center
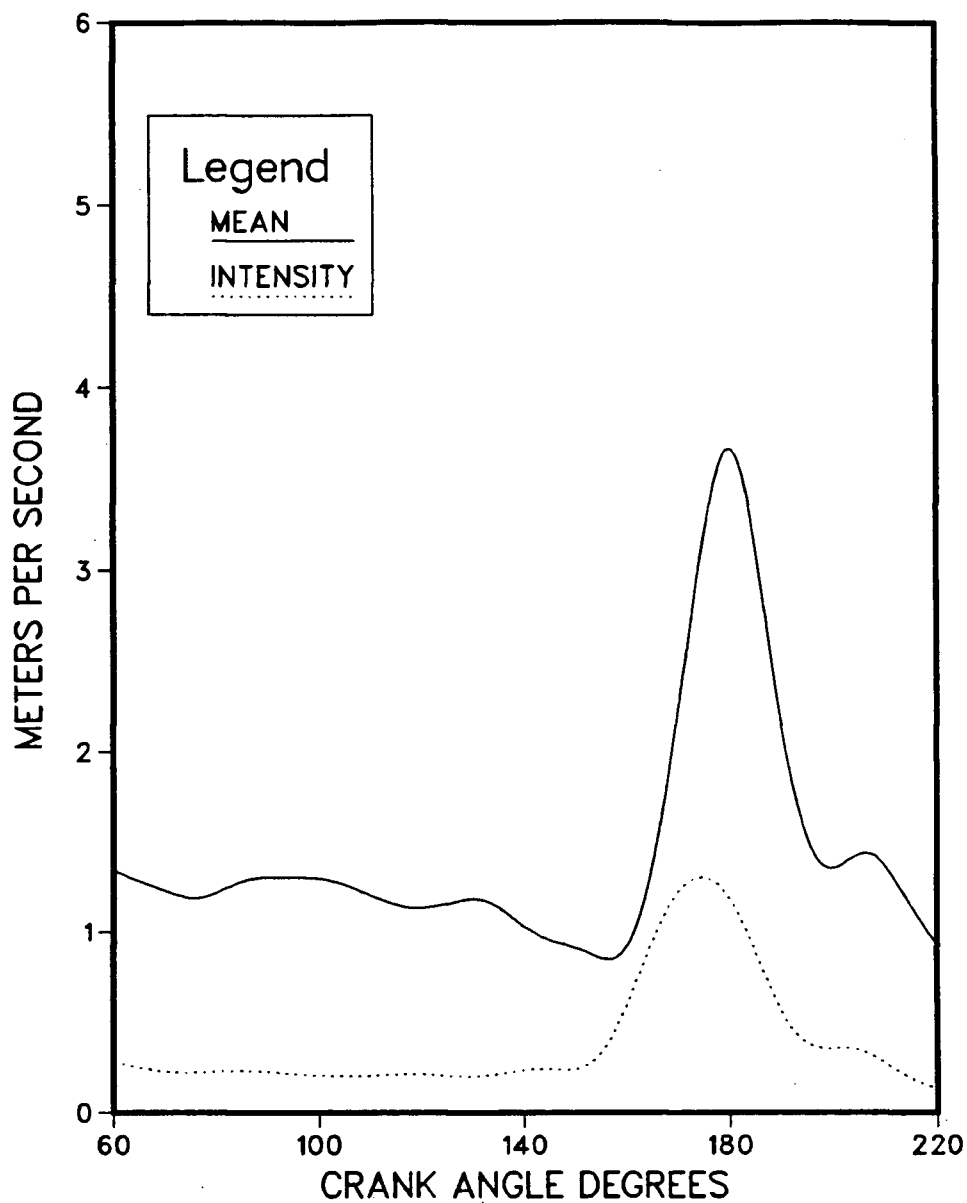
Fig. 7.9 Mean velocity and turbulence intensity for Piston A;
h_c = 1.5 mm; probe at cup edge; θ = 90°
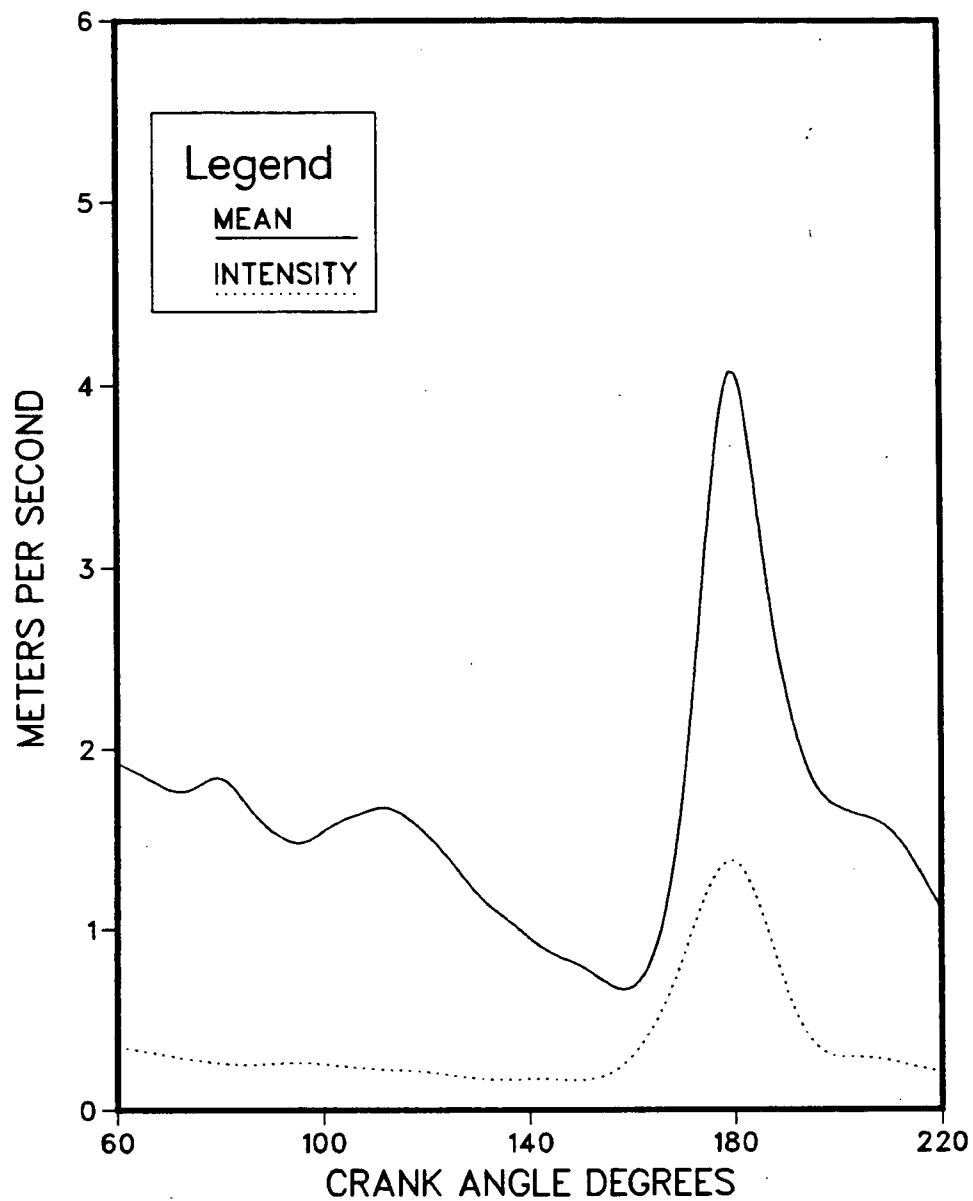
Fig. 7.10   Mean velocity and turbulence intensity for Piston A; h_c = 1.5 mm; probe at chamber center; θ = 90°
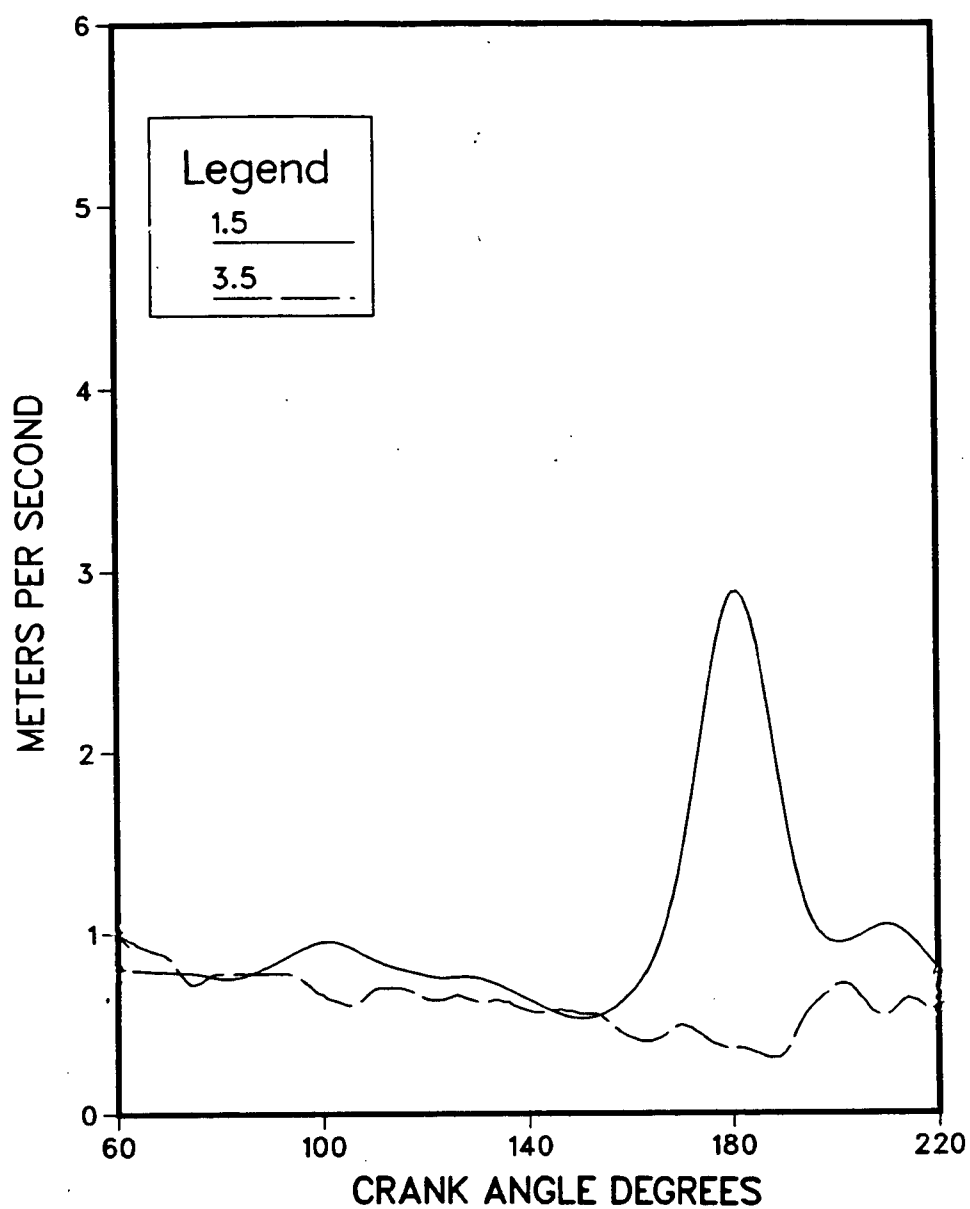
Fig. 7.11 Comparison of mean velocity traces for Piston A;
h_c = 3.5 and 1.5 mm; probe at cup edge
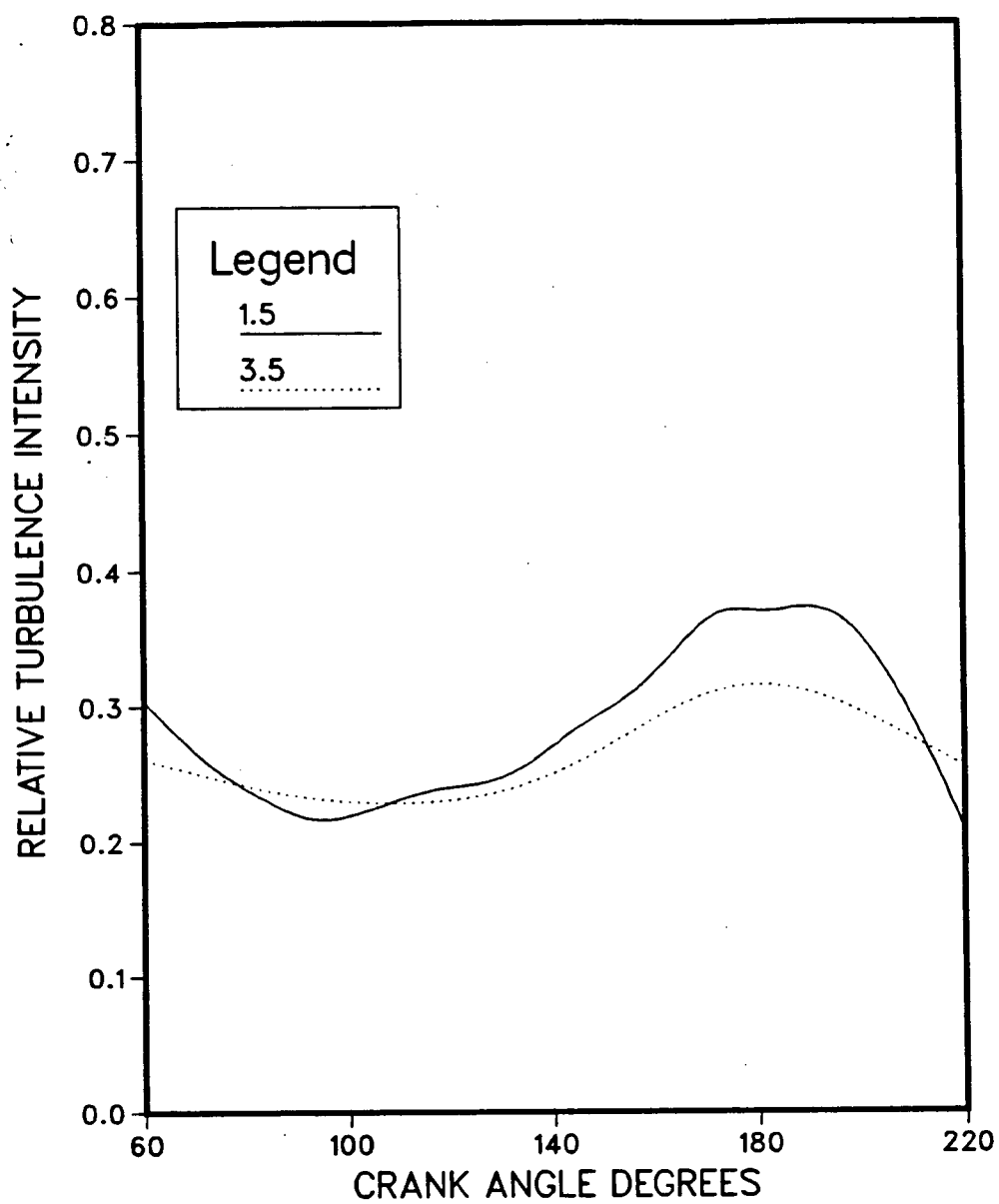
Fig. 7.12 Comparison of relative turbulence intensities for Piston A; $h_c = 3.5$ and 1.5 mm; probe at cup edge
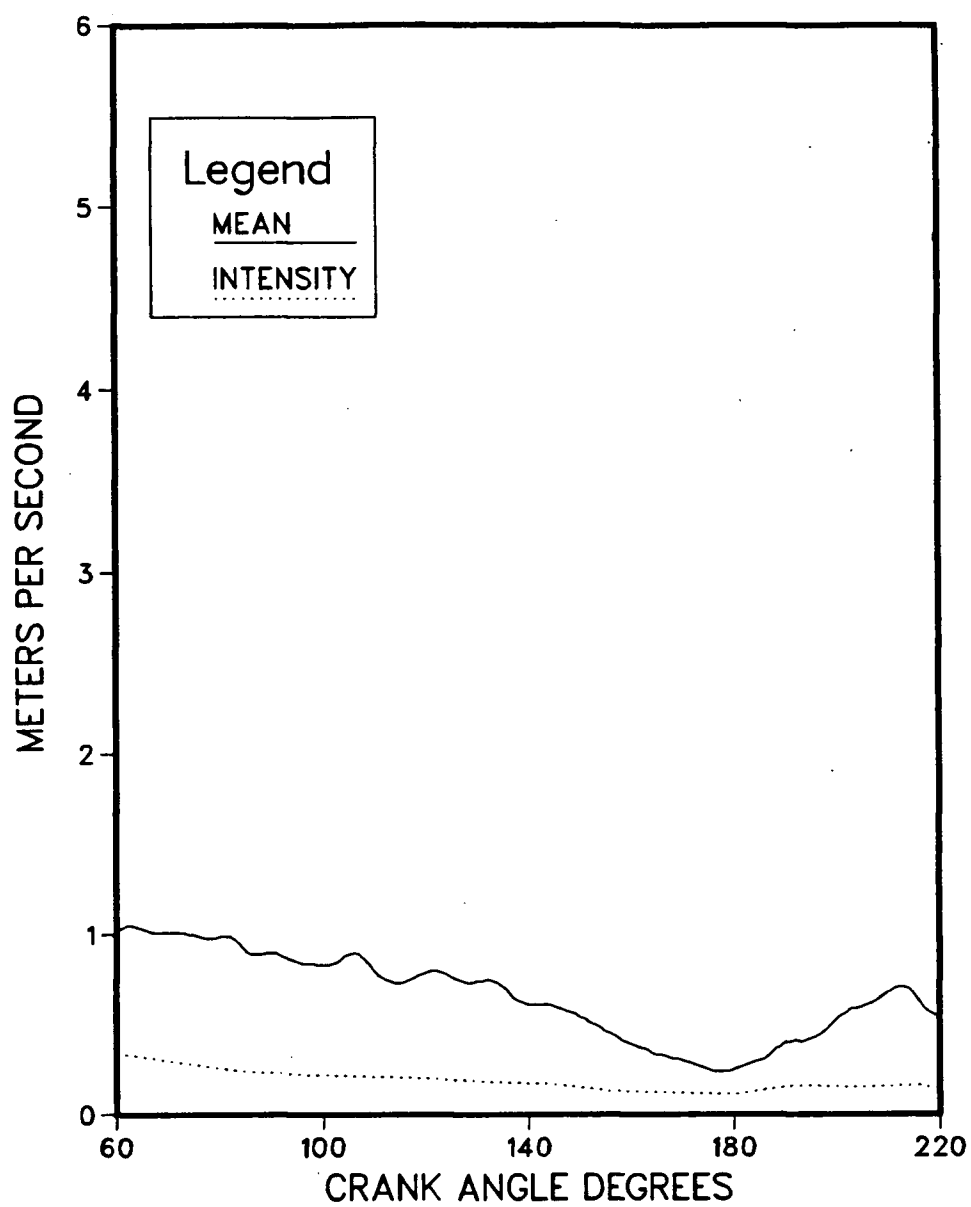
Fig. 7.13 Mean velocity and turbulence intensity for Piston B; h_c = 3.5 mm; probe at cup edge
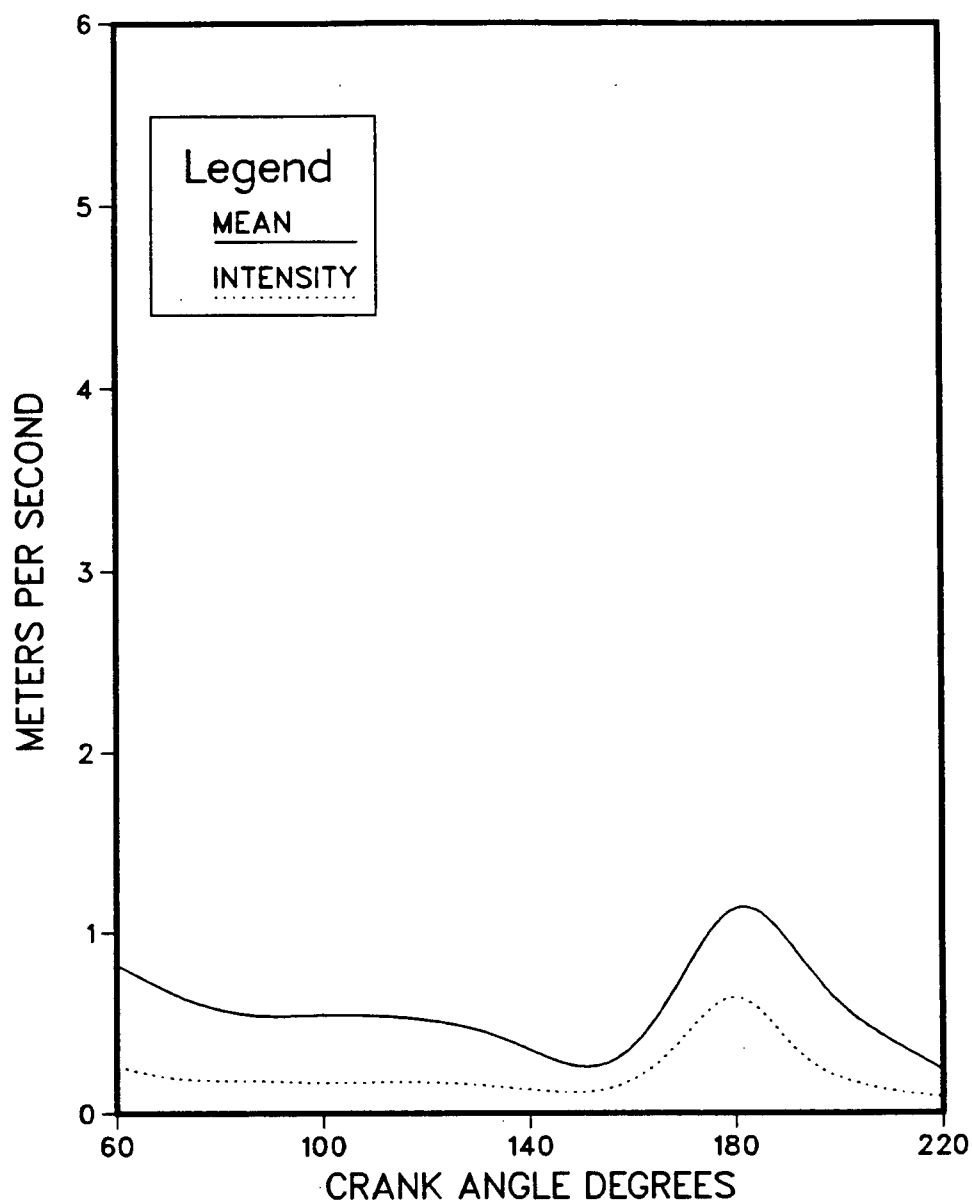
Fig. 7.14 Mean velocity and turbulence intensity for Piston B;
h_c = 1.5 mm; probe at cup edge
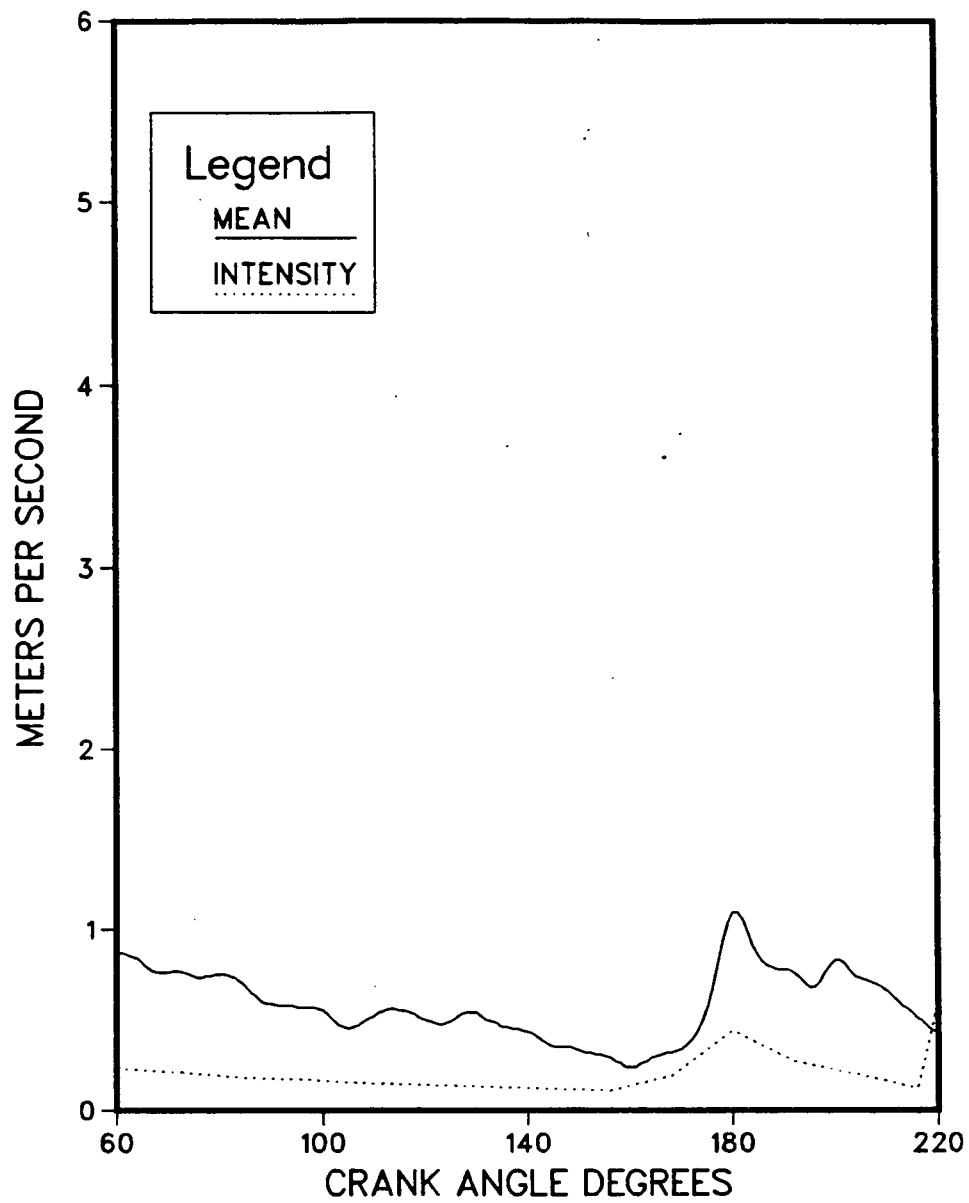
Fig. 7.15 Mean velocity and turbulence intensity for Piston B; h_c = 1.5 mm; probe at chamber center
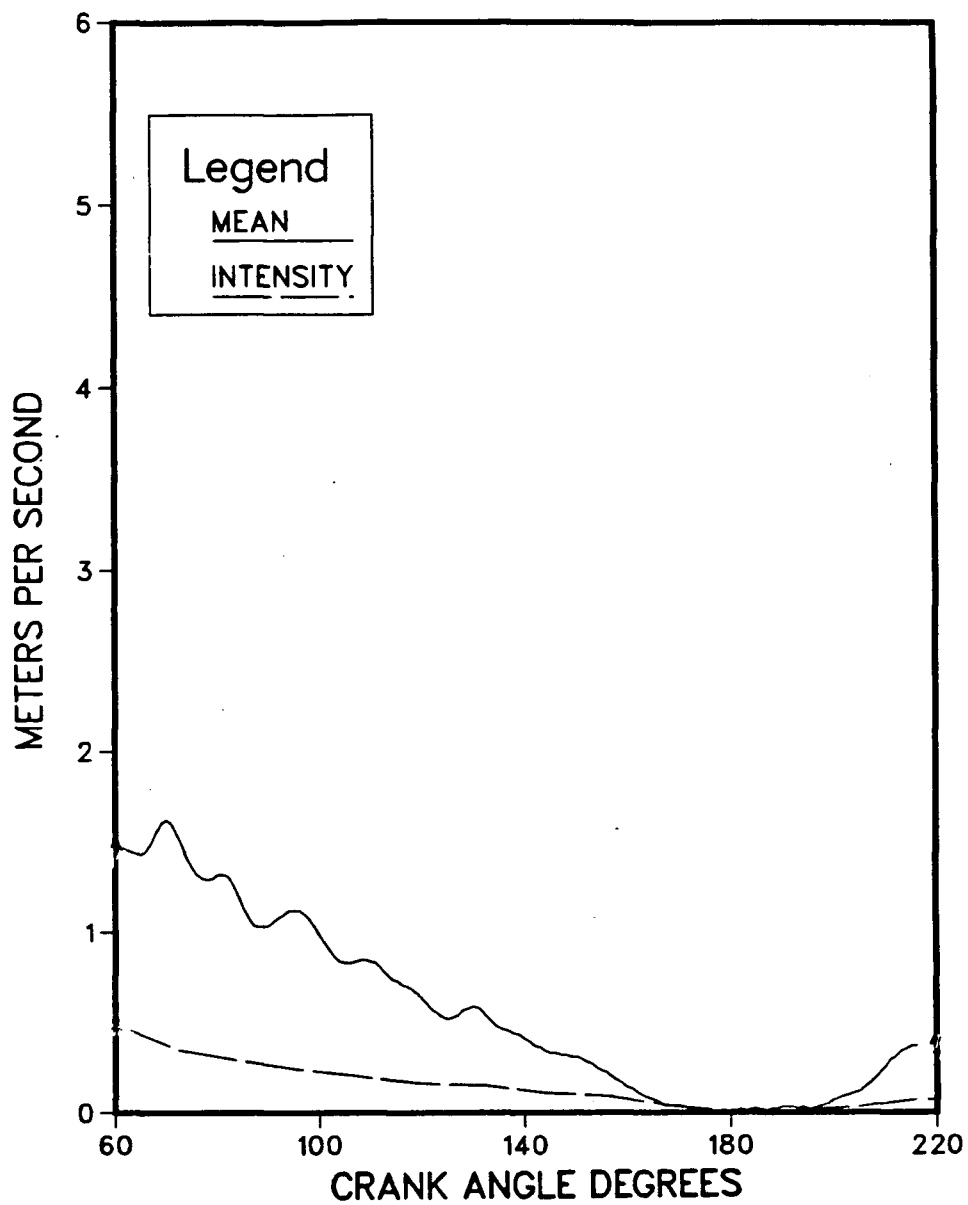
Fig. 7.16 Mean velocity and turbulence intensity for Piston B;
h_c = 1.5 mm; probe inside cup
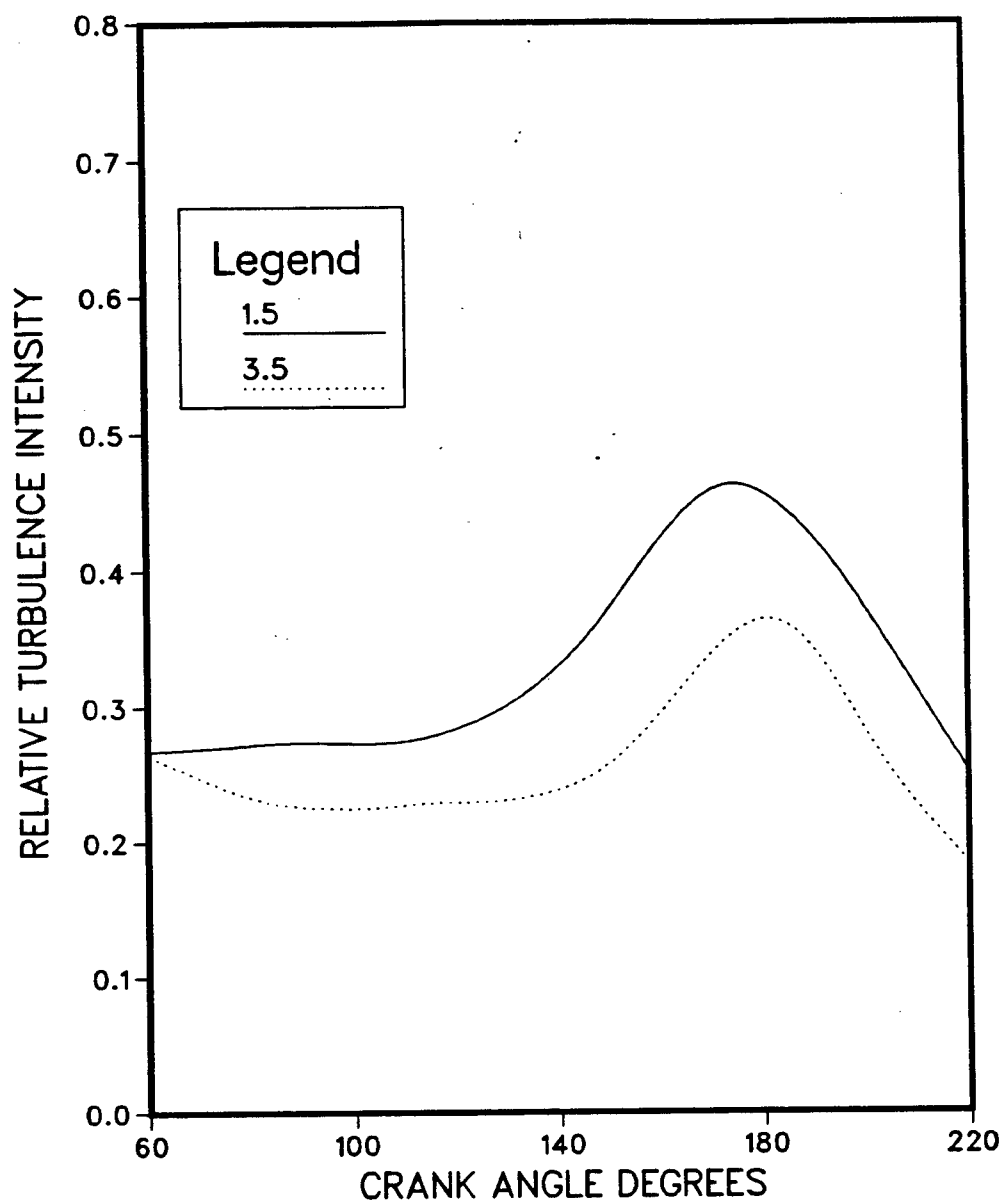
Fig. 7.17 Comparison of relative turbulence intensities for Piston B; h_c = 3.5 and 1.5 mm; probe at cup edge
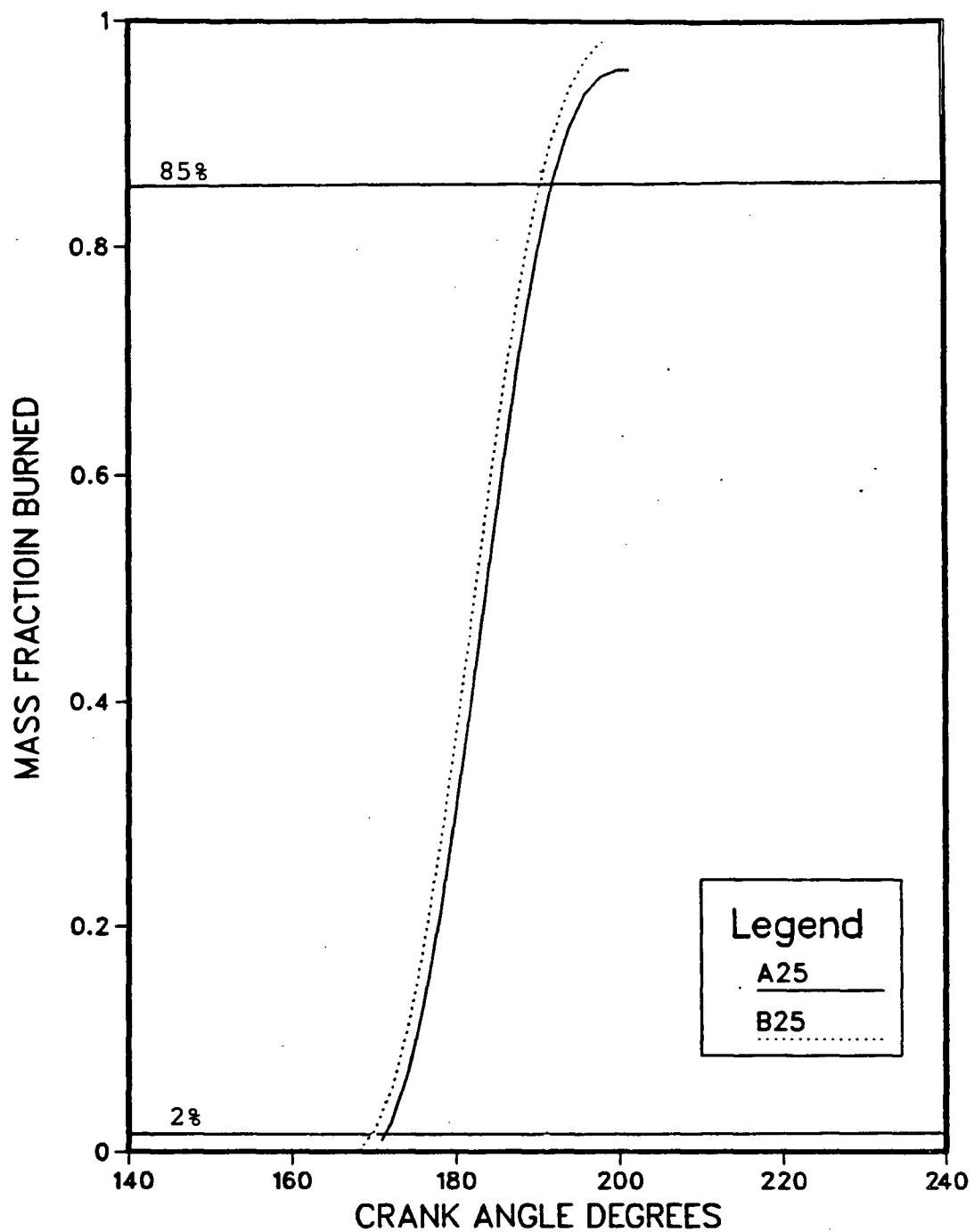
Fig. 7.28   Comparison of mass fraction burn curves for Pistons
A and B at a spark timing of 25° BTDC
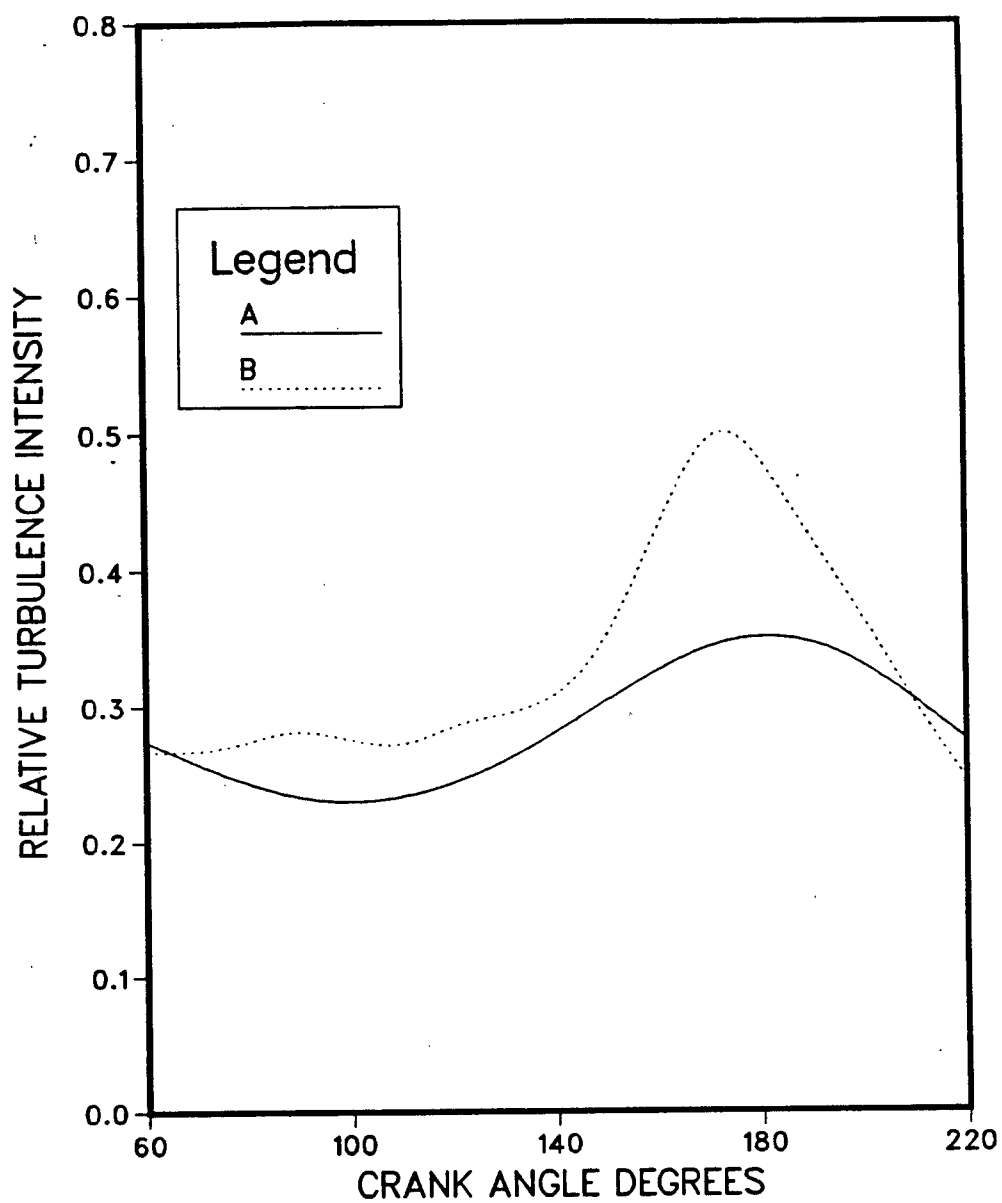
Fig. 7.19 Comparison of relative turbulence intensities for Pistons A and B; h_c = 1.5 mm; probe at cup edge
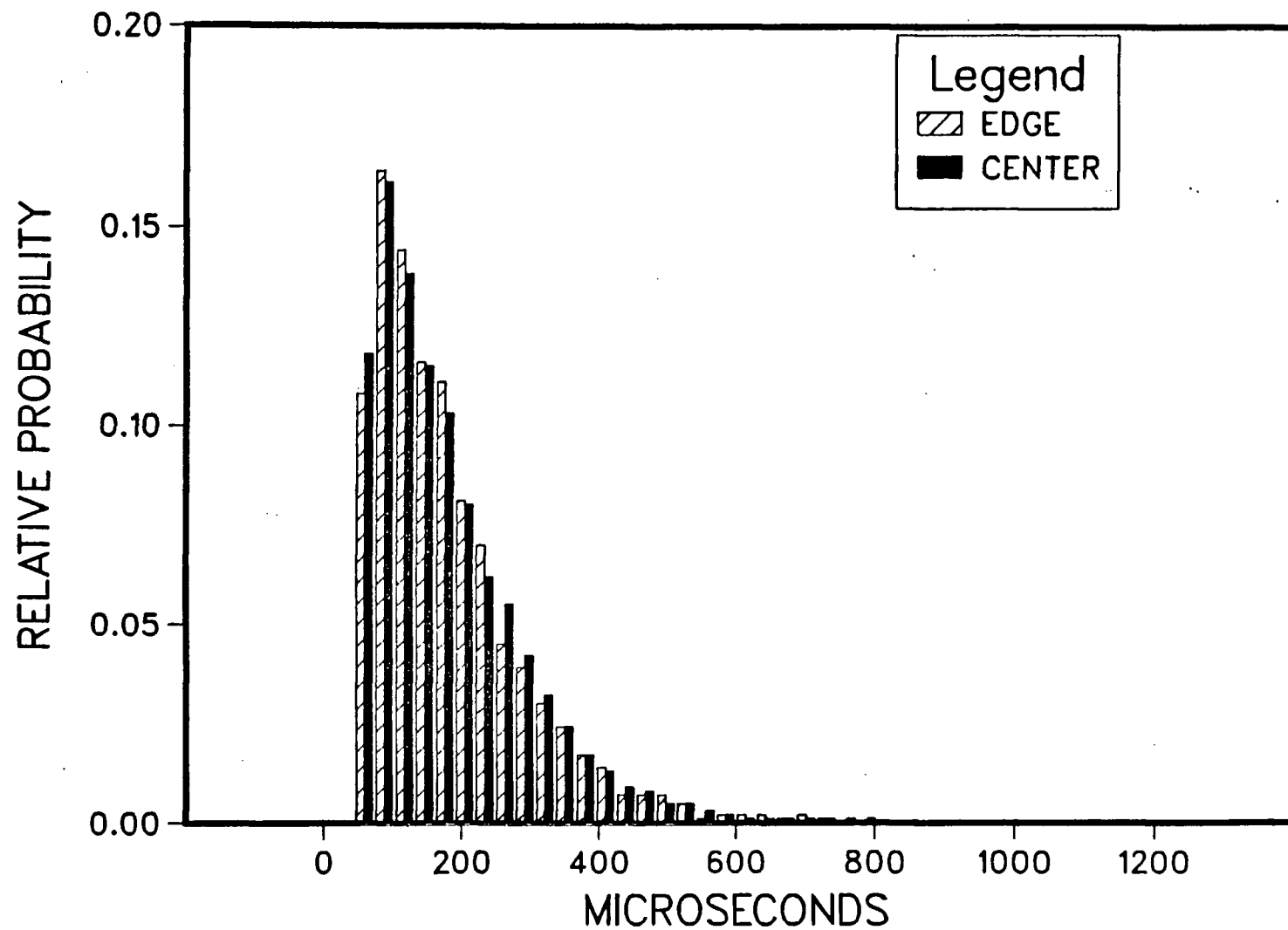
Fig. 7.20 Comparison of the relative probability distributions of small scale turbulence structure for Piston A at the chamber center and at the cup edge
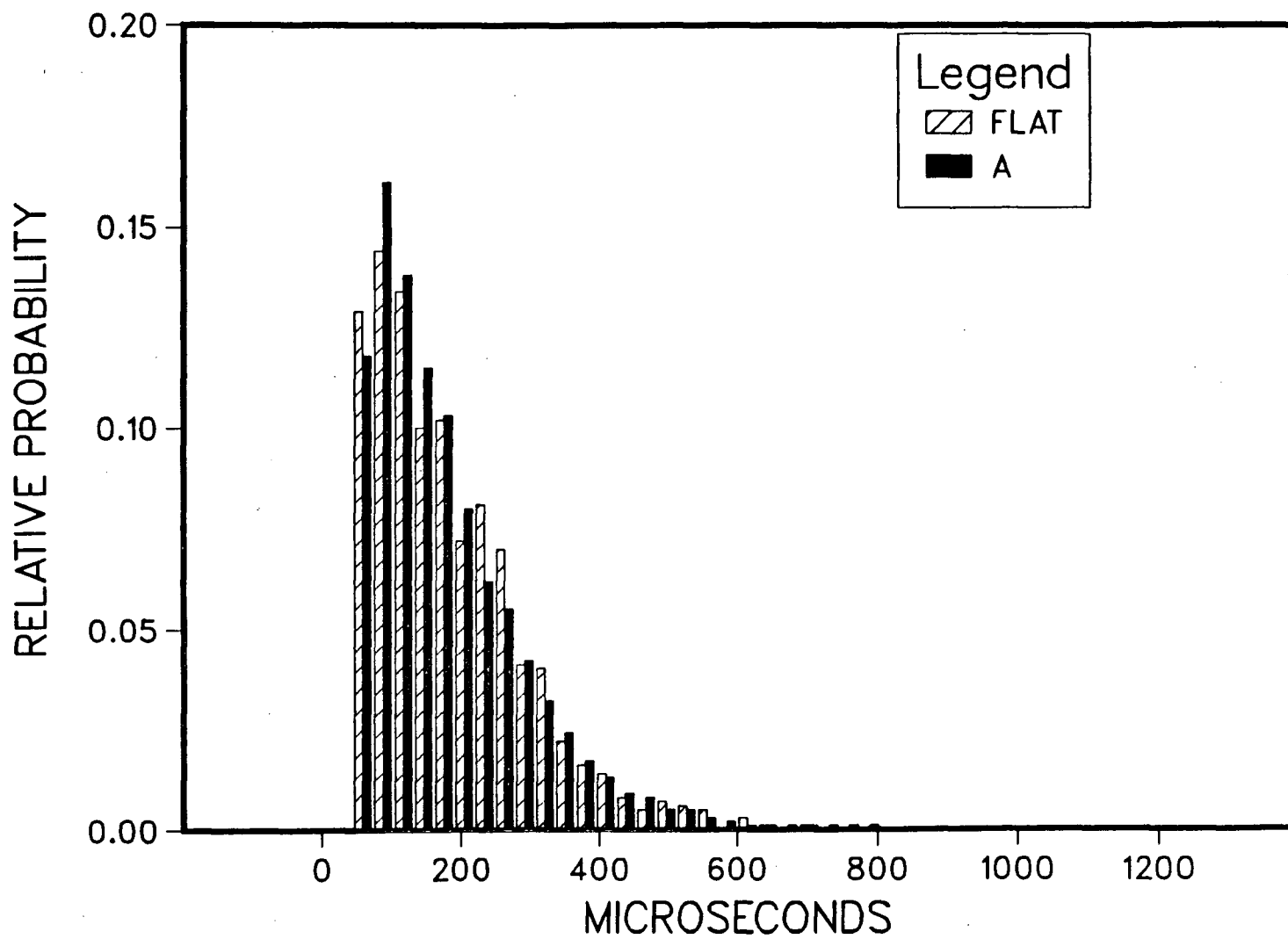
Fig. 7.21 Comparison of relative probability distributions of small scale turbulence structure at the chamber center for Piston A and the flat piston
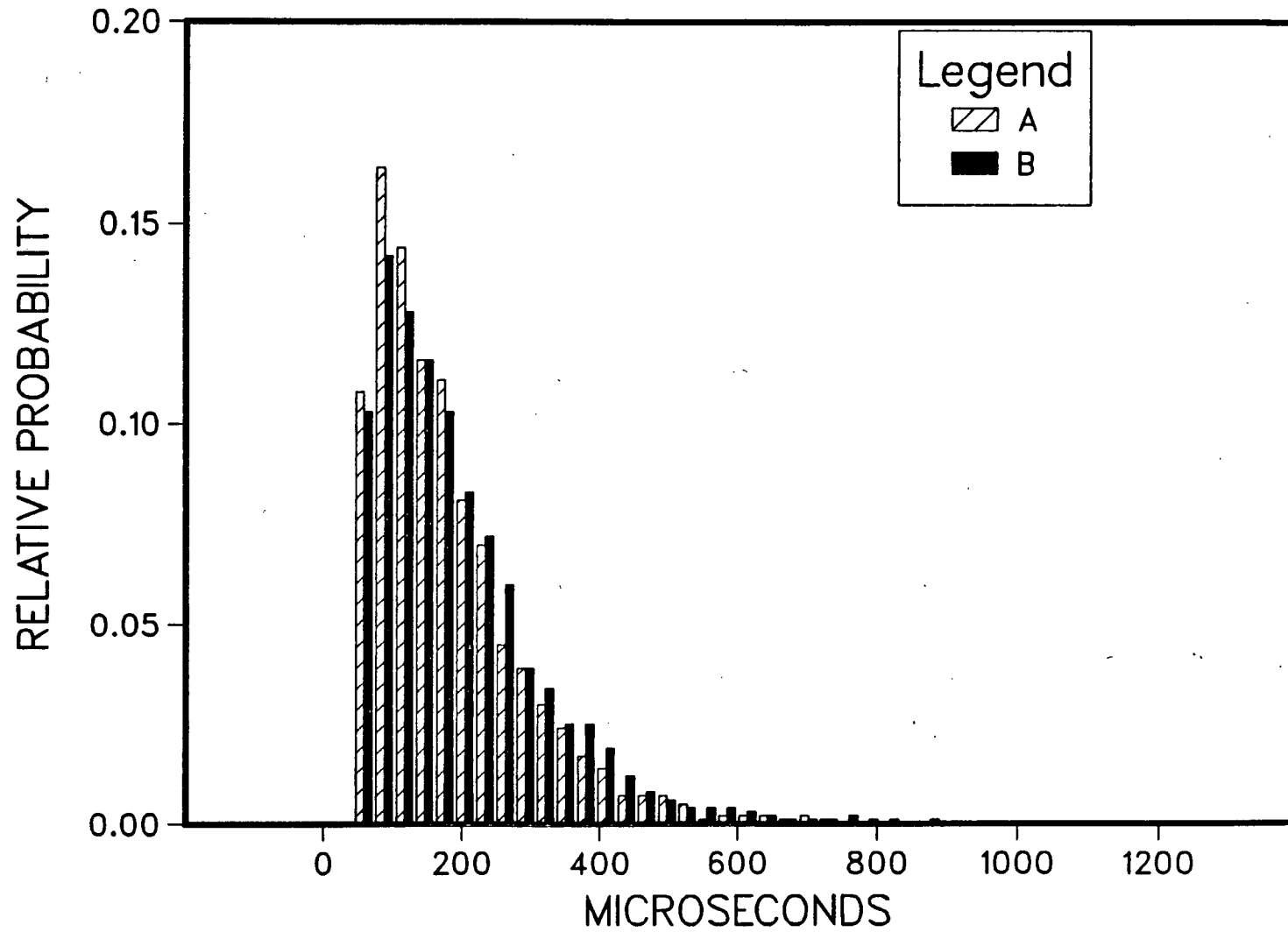
Fig. 7.22 Comparison of relative probability distributions of small scale turbulence structure at the cup edge for Pistons A and B
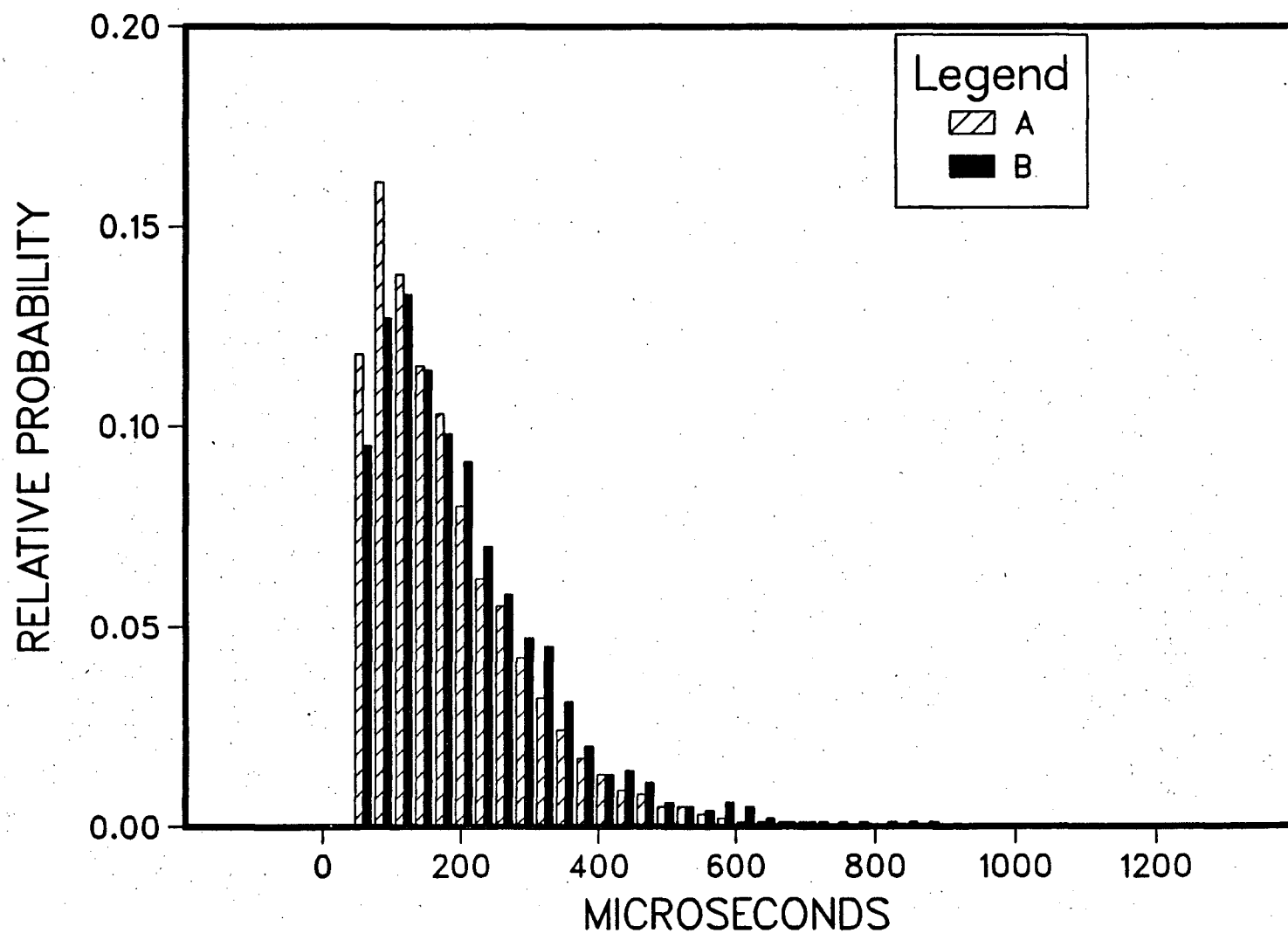
Fig. 7.23   Comparison of relative probability distributions of small scale turbulence
structure at the chamber center for Pistons A and B
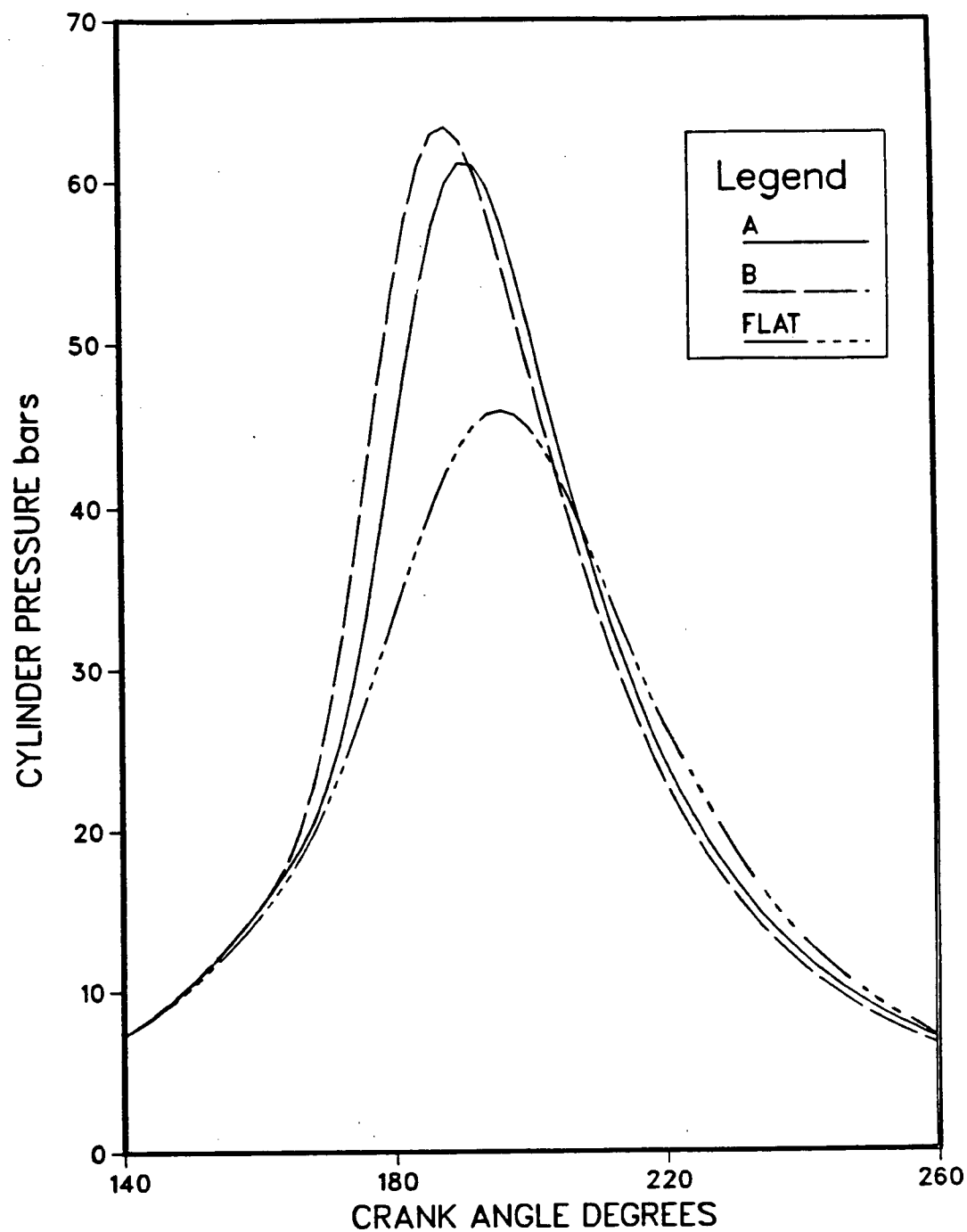
Fig. 7.24 Comparison of pressure history for Pistons A and B
and the flat piston for a spark timing of 30° BTDC
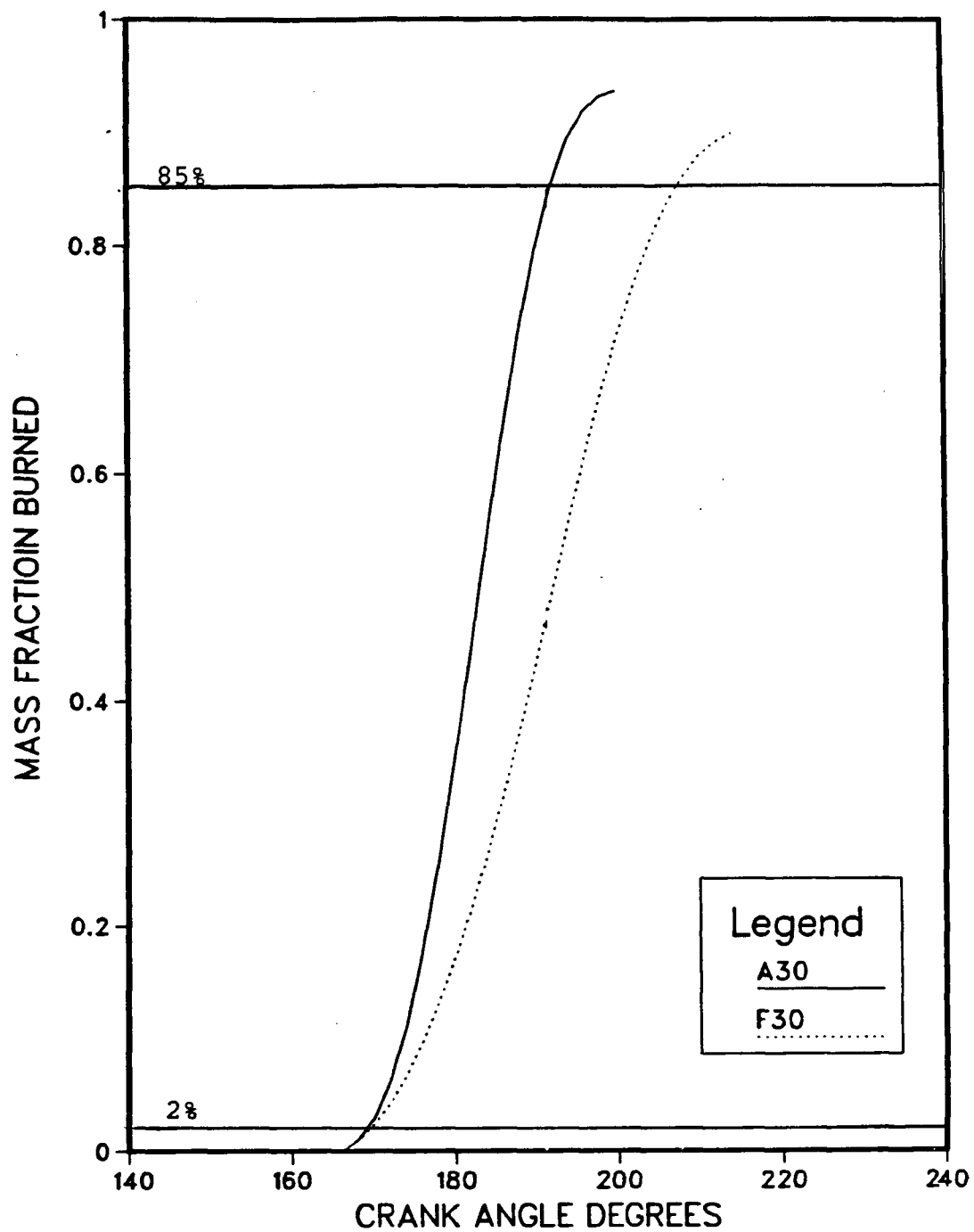
Fig. 7.25 Comparison of mass fraction burn curves for the flat piston and for Piston A at a spark timing of 30° BTDC
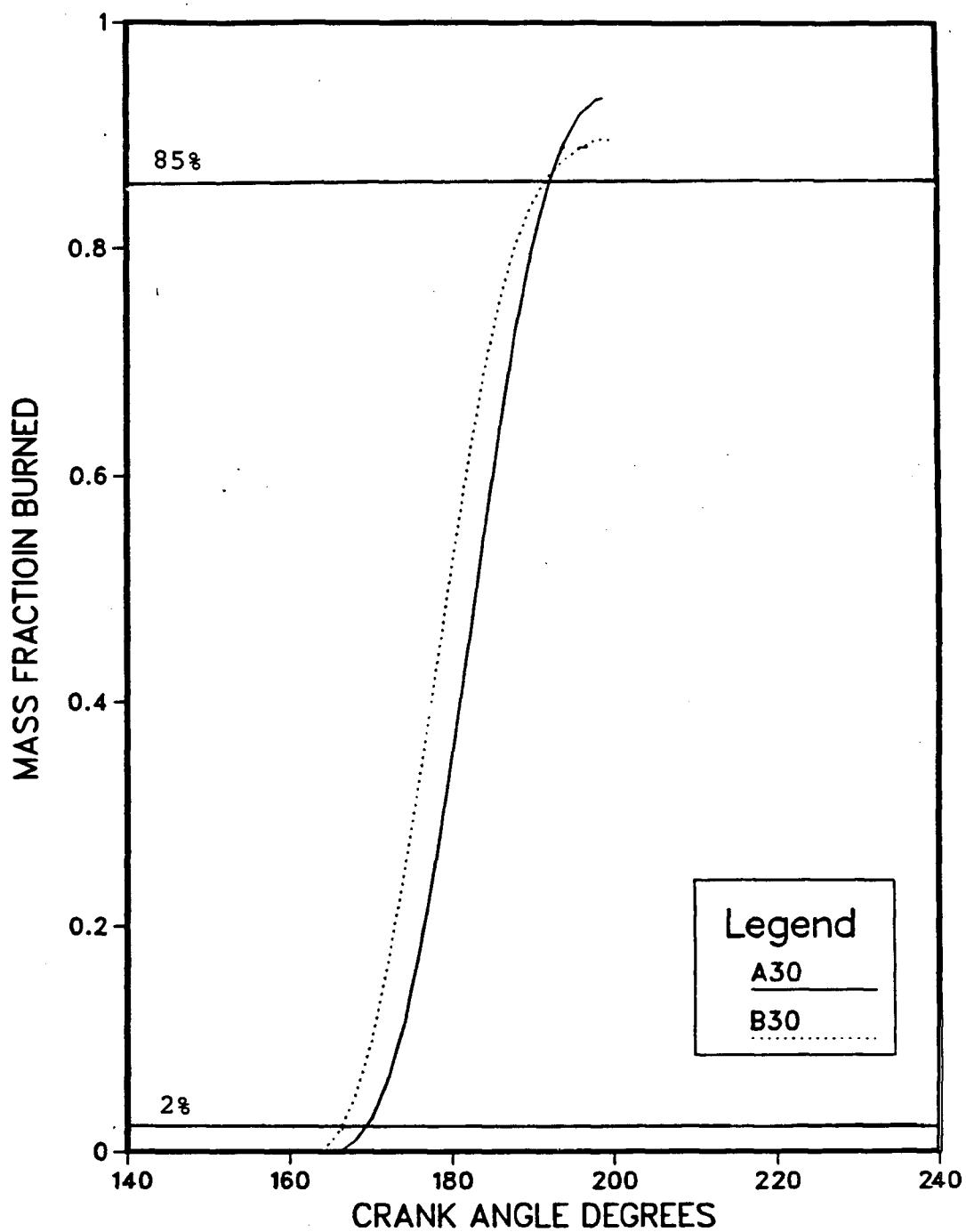
Fig. 7.26 Comparison of mass friction burn curves for Pistons
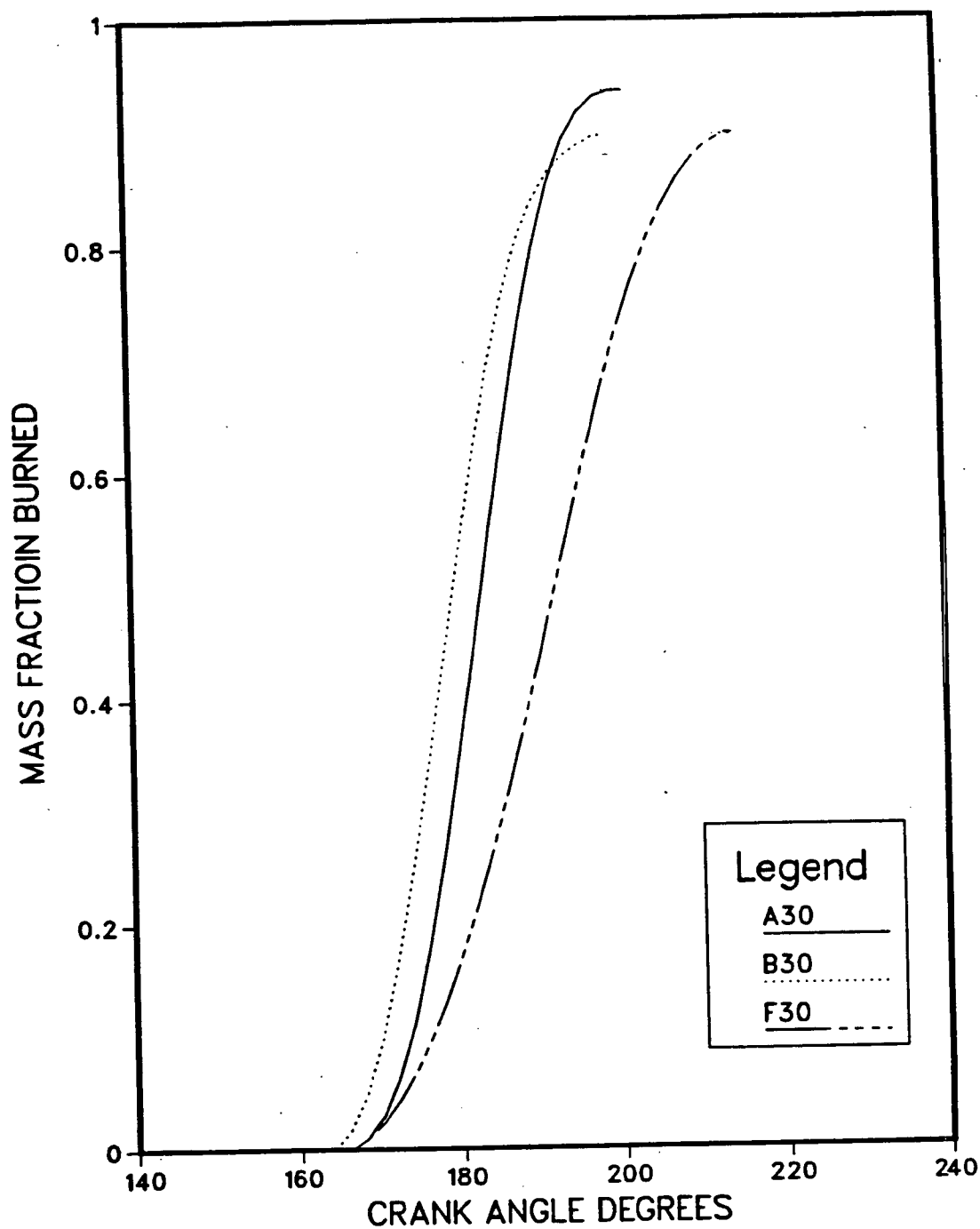A and B at a spark timing of 30° BTDC

Fig. 7.27   Comparison of mass fraction burn curves for all three
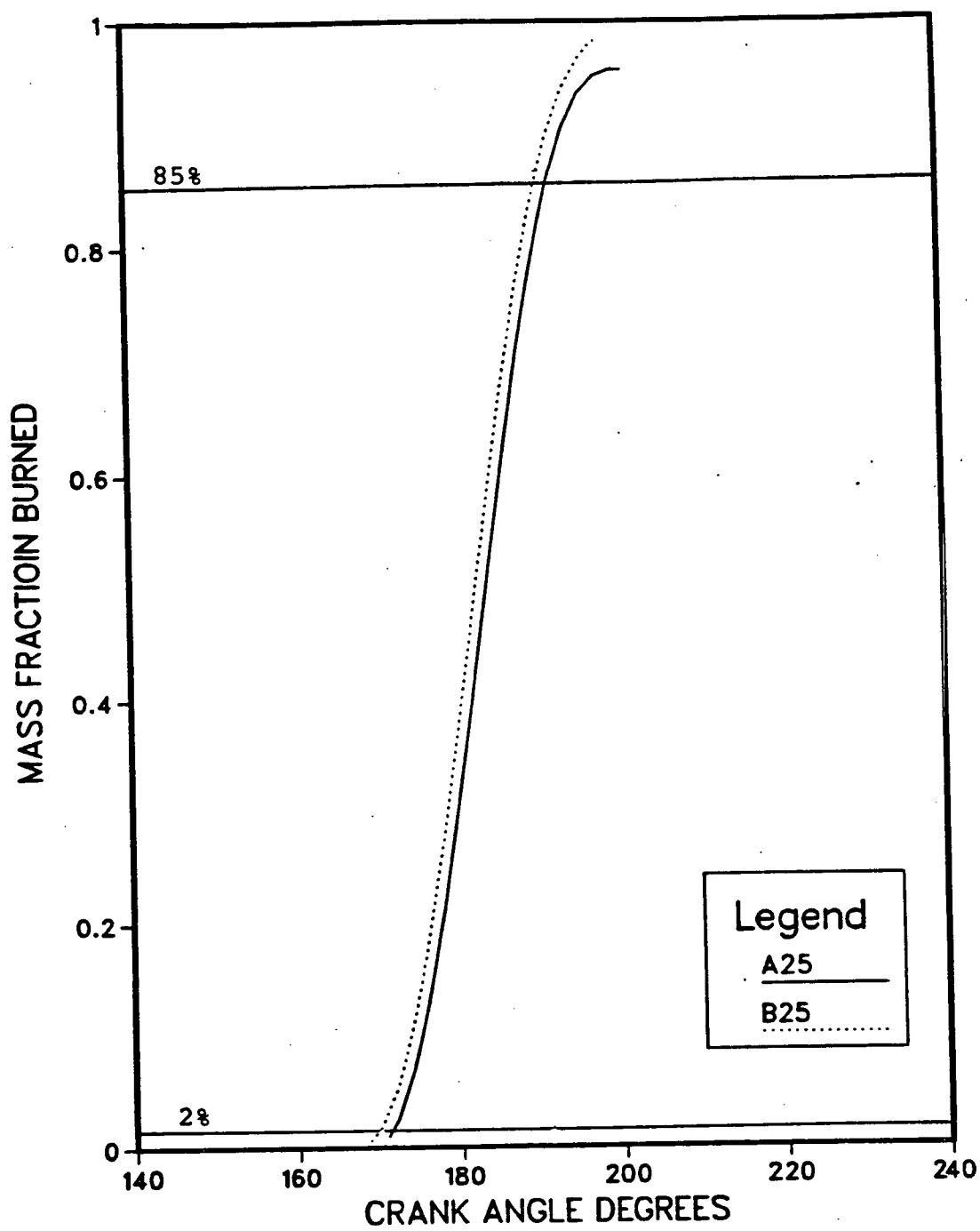pistons at a spark timing of 30° BTDC

Fig. 7.28 Comparison of mass fraction burn curves for Pistons
A and B at a spark timing of 25° BTDC