HIGH PRESSURE INJECTION OF NATURAL GAS FOR DIESEL ENGINE FUELING

by

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ABSTRACT

The high velocity unsteady methane jet emerging from a suddenly-opened conical poppet type nozzle is investigated, with the objective of characterising the penetration rate and the jet distribution under different injection conditions. The results are to be utilised in the development and optimization of a prototype injector for late-cycle injection of natural gas in a diesel engine.

Transient underexpanded turbulent jets of methane were visualized utilising schlieren and shadowgraph photography. The methane injections were principally performed in ambient air, with lateral visualization of the jet. Axial visualization of the methane injected into a pressurized cylinder was also executed. Pressure ratios between 1.5 and 8 were utilised to generate the jets. The Reynolds number of the jets covered a range between $7 \times 10^3$ to $5.6 \times 10^4$.

The steady-state turbulent conical sheet jet originating from the conical poppet nozzle is characterised using an integral approach in conjunction with published empirical results. A model of the transient conical sheet jet is developed, in which the transient jet is described as a quasi-steady jet feeding a moving vortex structure. The model is found to predict similar penetration rates as the ones observed experimentally for different conditions, except in the early moments of the injection where the proposed modelling does not describe adequately the initial jet behaviour.

The penetration of the methane jet is found to be proportional to the square root of the time and initial velocity, and to the $1/4$ power of the methane to air density ratio (taken at ambient conditions), the upstream to ambient pressure and the product of the poppet lift by the seat radius. The jet penetration is also dependent on the ratio of methane to air densities at standard temperature and pressure, the poppet angle and the injection duration. The conical sheet penetration is shown to be approximately half of that of round holes, given the same flow area.
Observations of the jet revealed that the conical sheet jet has a distinct curvature towards the inside of the sheet, resulting in the jet collapsing under the nozzle for poppet angles greater than approximately 20°. When the injector is positioned near a top wall, the jet exhibits a bistable behaviour, either collapsing under the poppet or clinging to the top wall.

The immediate effect of the jet collapsing and clinging to the top wall is a reduction in mixing between the gas and the air and a slower penetration rate. Both these conditions are undesirable for an optimum combustion of the methane in a diesel environment. It is deduced that with the current conical poppet nozzle design the distribution of the gas within the chamber is inadequate and the penetration rate of the jet is insufficient.

Conical sheet interruptions at the nozzle is investigated as a potential solution for the clinging and collapsing problems. It is found that interruptions can successfully prevent both phenomena. In addition, proper interruption arrangement generates jets of a different type that are propagating significantly faster than the conical sheet jet.
RÉSUMÉ

Le jet transitoire de méthane débouchant à haute vitesse d’une fine fente annulaire conique soudainement ouverte est étudié, avec pour objectif la caractérisation du taux de pénétration et de la distribution du méthane injecté sous diverses conditions d’injection. L’orifice annulaire est obtenu par le déplacement d’une tige à bout conique à l’extrémité d’un cylindre concentrique à la tige. Les résultats de l’étude serviront au développement et à l’optimisation d’un injecteur prototype pour injection de gaz naturel en fin de compression dans un moteur diésel.

Des jets turbulents transitoires ont été visualisés au moyen des techniques schlieren et shadowgraph. Le méthane a été injecté dans l’air ambiant dans la majorité des expériences, le jet étant visualisé latéralement. Des vues axiales du jet de méthane injecté dans un cylindre sous pression ont aussi été obtenues. Des rapports de pression entre 1.5 et 8 ont été utilisés pour générer l’écoulement. Le nombre de Reynolds des jets observés varient entre 7x10³ et 5.6x10⁶.

Le jet turbulent sous forme de nappe conique s’écoulant en condition permanente de l’orifice annulaire conique a été analysé au moyen des équations intégrales décrivant le jet et en adaptant des résultats empiriques trouvés dans la littérature. Un modèle du jet transitoire a été développé, dans lequel le jet transitoire est représenté par un jet à écoulement quasi-permanent fournissant masse et momentum à un vortex s’éloignant de l’orifice. Le modèle prédit des taux de pénétration similaires à ceux observés expérimentalement, sauf dans les premiers moments du jet où le modèle surestime la pénétration.

Les résultats indiquent que la pénétration du jet de méthane est directement proportionnelle à la racine carrée du temps et de la vitesse initiale, à la puissance 1/4 du rapport de pression et du rapport de densité (entre le méthane et l’air aux conditions ambiantes), et à la puissance 1/4 du produit entre le rayon de l’orifice annulaire et le déplacement de la tige à bout conique. La
La pénétration dépend aussi de l'angle de la partie conique, du rapport de densité entre le méthane et l'air aux conditions standard, et de la durée de l'injection. La pénétration de la nappe conique de méthane est approximativement la moitié de la pénétration de jets débouchant d'orifices circulaires ayant la même surface d'écoulement que l’orifice annulaire conique.

Les photographies du jet de méthane révèlent une courbure de la nappe conique, dans la direction du dessous de la nappe. Pour des angles de la partie conique supérieurs à approximativement 20°, cette courbure conduit à l'effondrement de la nappe qui s'agglomère en un jet quasi-circulaire. Quand l'orifice de l'injecteur est placé juste sous une paroi supérieure (comme c'est le cas dans le moteur), la nappe de méthane affiche un comportement bi-stable; elle adhère à cette paroi ou s'effondre sous l'injecteur selon, entre autre, de l'angle de la partie conique et le rapport de pression.

L'implication directe de cet effondrement ou de cette adhésion à la paroi supérieure est une réduction du mélange entre le méthane et l'air et un taux de pénétration plus lent. Ces deux conditions ne sont pas avantageuses pour une combustion efficace du méthane dans un environnement diésel. Il est déduit des résultats obtenus que le design actuel de l’orifice entraîne une pénétration et une distribution inadéquates du méthane dans la chambre de combustion.

L'interruption de la nappe de méthane à l’orifice a été étudié brièvement en tant que solution potentielle aux problèmes mentionnés. Les résultats indiquent que l'effondrement du jet et l'adhésion à la paroi supérieure peuvent être prévenus. De plus, un bon arrangement des interruptions change le type de jet s'écoulant de l’orifice et entraîne une pénétration significativement supérieure à celle de la nappe continue.
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LIST OF SYMBOLS

a  Constant in Tollmien’s solution.
A  Area.
Ae  Effective area.
An  Nozzle area.
Aps  Pseudo-area for underexpansion.
Cd  Nozzle discharge coefficient.
Cd  Drag coefficient of vortex.
d  Effective diameter (to take into account the difference in density).
d0  Diameter of the orifice.
dsps  Pseudo-diameter for underexpansion.
D  Diameter of combustion chamber.
FBV  Body forces.
FD  Drag force.
Fsz  Surface forces.
H  Distance between the top and bottom wall in the combustion chamber.
k  Specific heat ratio.
kx  n=1,2,3... Various constants.
l  Poppet lift.
l  Effective lift.
leq  Equivalent lift.
lps  Pseudo-lift for underexpansion.
L  \((R, leq)^{1/2}\).
\( m_{av} \) Mass of air within the vortex.

\( m_{gw} \) Mass of second gas within the vortex.

\( m_{v} \) Mass of the vortex structure.

\( M \) Mach number.

\( M_{v} \) Vortex integral momentum.

\( P \) Pressure.

\( P_{a} \) Pressure of the ambient air or pressure of the air in the combustion chamber.

\( P_{e} \) Pressure in the jet at the end of the expansion.

\( P_{o} \) Upstream pressure of the injected gas.

\( Q_{e} \) Mass flow at end of expansion.

\( Q_{n} \) Mass flow at nozzle.

\( r \) Radial position normal to the jet axis.

\( r_{c} \) Radius of the inviscid core.

\( r_{e} \) Radius where the steady state jet velocity = vortex velocity.

\( r_{eq} \) Equivalent radius.

\( r_{o} \) Radius of the orifice.

\( r_{ps} \) Pseudo-radius for underexpansion.

\( r_{1/2} \) Radial position where the velocity is half the axial velocity \( U_{m} \).

\( r_{1}, r_{2} \) Radial penetration on left and right side of the injector in flow visualization pictures.

\( R \) Radius of jet at a position \( z \).

\( R_{a} \) Air gas constant.

\( R_{o} \) Injected gas constant.

\( R_{s} \) Poppet seat radius.

\( R_{v} \) Radius of the vortex.
Re_t  Turbulent Reynolds number.
Re_v  Reynolds number of the vortex.
t  Time.
t_c  Time between valve closing signal and actuation

\( t_i \)  Injection duration.

T  Temperature at a point \((z,r)\).

\( T_a \)  Temperature of the ambient air or of the air in the combustion chamber.

\( T_e \)  Temperature of the injected gas at the end of expansion.

\( T_m \)  Temperature on the axis of the jet at a position \(z\).

\( T_n \)  Static temperature of the injected gas at the nozzle.

\( T_o \)  Stagnation temperature of the injected gas.

U  Velocity at a position \((r,z)\) in the steady-state jet.

\( U_c \)  Velocity of vortex centre.

\( U_e \)  Velocity of the jet at the end of expansion.

\( U_m \)  Velocity on the axis of the steady-state jet.

\( U_n \)  Velocity of the jet at the nozzle exit.

\( U_o \)  Velocity of the jet at the nozzle exit.

\( U_i \)  Velocity of the front of the vortex (tip velocity).

\( U_v \)  Velocity of the vortex at its back plane.

\( V_v \)  Volume of the vortex.

\( y_1, y_2 \)  Average axial penetration (downward) on left and right side of the injector on flow visualization pictures.

z  Position along the jet axis, from virtual origin.

\( z' \)  Position along the jet axis, from nozzle.
Length of the potential core region.

Position of the virtual origin relative to the orifice.

Position of the jet tip, also define as penetration of the jet.

Position of the back of the vortex structure.

**GREEK LETTERS**

$\alpha$  Concentration by volume. In velocity profile $\alpha=\ln(2)$.

$\alpha_v$  Volume concentration in the vortex.

$\beta$  Poppet seat angle and jet axis angle.

$\xi = \frac{r}{r_{1/2}}$

$\eta$  Non-dimensional radius $r/R$.

$\mu$  Viscosity.

$\mu_t$  Turbulent viscosity.

$\nu_t$  Turbulent kinematic viscosity.

$\xi$  Non-dimensional radius $r/r_{1/2}$.

$\rho$  Density.

$\rho_a$  Density of the ambient air or of the air in the combustion chamber.

$\rho_e$  Density of the injected gas at the end of expansion.

$\rho_s$  Density of the injected gas at same temperature and pressure as $\rho_a$.

$\rho_j$  Density at a point $(z,r)$ in the jet.

$\rho_n$  Density of the injected gas at the nozzle.

$\rho_o$  Stagnation density of the injected gas.

$\rho_v$  Vortex density.

$\tau_s$  Shear stress.
\( \chi \)  Concentration by mass.
\( \chi_{ax} \)  Axial mass concentration.
\( \chi_v \)  Mass concentration of the second gas within the vortex.

ABBREVIATIONS

CCD  Charge coupled devices.
CNG  Compressed Natural gas.
DDC  Detroit Diesel Corporation.
PM   Particulate Matter.
PR   Pressure ratio.
PW   Pulse width.
TA   Turbocharged Aftercooled.
TDC  Top Dead Centre.
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1 INTRODUCTION

1.1 GLOBAL PROJECT

The importance of using the earth’s resources efficiently and responsibly has become evident. Alarming levels of pollutants in American and European urban areas, general atmospheric pollution and global warming are direct consequences of our massive use of fossil fuels for transportation and industrial processes. In an effort to ameliorate urban air quality and to reduce general atmospheric pollution, the EPA (Environmental Protection Agency) in the United States established the Clean Air Act Amendments (CAAA). The CAAA sets regulations that target, among other sources of pollution, passenger cars, buses and trucks.

The majority of passenger cars are powered by internal combustion gasoline engines which produce nitrogen oxides (NOx), carbon dioxide (CO2), carbon monoxide (CO) and unburned or partially burned hydrocarbons (HC). Buses and trucks have been traditionally powered by diesel engines, because of their greater durability and thermal efficiencies. Diesel exhaust is characterized by similar concentrations of NOx as that of gasoline engines, slightly lower unburned hydrocarbon content and small amounts of CO and CO2. However, diesel engines are a major source of particulate matter (PM) emissions. Typically, between 0.2% and 0.5% of the fuel mass is emitted as particulates Heywood [1988]; these are composed primarily of soot with some absorbed hydrocarbons. Both diesel and gasoline fuels contain small amounts of sulphur, which is oxidized during the combustion and forms sulphur dioxide (SO2). Diesel contains more sulphur than gasoline, but the sulphur content in both fuels has been reduced significantly in the recent years. All of the above mentioned pollutants have separate and

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1 In this thesis, the year of the referenced publication is in brackets. The full references can be found in alphabetical order at the end of the thesis.
Recognizing the impact of diesel exhausts in urban areas, the EPA has set stringent requirements on emissions from urban buses and heavy-duty trucks. The new regulations call for a reduction of 90% in particulate matter and 15% in nitrogen oxides for urban buses between the years 1990 and 1994, bringing PM at the 0.05 g/bhp-hr and NO\textsubscript{x} at 5.0 g/bhp-hr. Both requirements are difficult to obtain simultaneously even with the latest diesel technology. Together with a tight time schedule, these requirements have placed the diesel engine manufacturers in a difficult situation. Table 1.1 summarizes emission standards for buses and trucks.

<table>
<thead>
<tr>
<th>YEAR</th>
<th>URBAN BUSES HEAVY-DUTY ENGINE EMISSION STANDARDS (g/bhp-hr measured during EPA heavy-duty engine test)</th>
<th>HEAVY-DUTY TRUCK ENGINE EMISSION STANDARDS (g/bhp-hr measured during EPA heavy-duty engine test)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NO\textsubscript{x}</td>
<td>HC</td>
</tr>
<tr>
<td>1990</td>
<td>6.0</td>
<td>1.3</td>
</tr>
<tr>
<td>1991</td>
<td>5.0</td>
<td>1.3</td>
</tr>
<tr>
<td>1993</td>
<td>5.0</td>
<td>1.3</td>
</tr>
<tr>
<td>1994</td>
<td>5.0</td>
<td>1.3</td>
</tr>
<tr>
<td>1998</td>
<td>4.0\textsuperscript{2}</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Table 1.1 - Emissions standards for trucks and buses. Reproduced from Detroit Diesel Information Update. \textsuperscript{1}PM was previously set at 0.1 for 1991, and latter delayed to 1993. California has somewhat stricter standards and kept the 0.1 standard for 1991. \textsuperscript{2}Proposed standards.

Different strategies are being pursued in order to find a solution. Improving diesel engine design and electronic control, and using particulate traps are some of the alternatives. Electronic control of the injection already significantly improves emission characteristics, but further improvements are required to meet the 1993 standards. Particulate traps have been developed and are being field tested with success, but their reliability and cost is a concern. So
far they have yet to satisfy the 290 000 miles life requirement. The other major alternative is to use an alternative fuel. Both methanol and natural gas are being tested extensively as alternative fuels for diesel engines.

Methanol engines have been developed and field tested, and have met the standards both for NO\textsubscript{x} and PM. Methanol is derived either from coal or natural gas, making its conversion cost and therefore its purchase cost relatively high. As a consequence of its corrosive characteristics, most of the fuel system original components must be replaced by more resistant materials, making methanol a less attractive fuel for retrofit. Finally, methanol combustion produces aldehydes which are pollutants as of yet not regulated pollutants. All of these factors deter the usage of methanol.

Natural gas has a longer history than methanol as an internal combustion engine fuel, and has now been used in gasoline engines for a number of years. Natural gas can be stored in gaseous form (compressed natural gas : CNG) or in liquified form (liquified natural gas : LNG). Because of its availability, low cost and potential for clean burning, natural gas is a promising alternative fuel. However its utilisation in diesel engine presents some challenges\textsuperscript{2}.

Different methods to implement the use of natural gas in diesel engines have been investigated. Dual-fuel conversion can be performed, in which the percentage of diesel and natural gas admitted in the chamber can either be fixed or variable. Ignition in dual-fuel engines is ensured by the diesel fuel. Because the auto-ignition temperature of natural gas is higher than that of conventional diesel liquid fuel, the ignition must be assisted by spark plugs or glow plugs for dedicated use of natural gas in a diesel engine.

\textsuperscript{2} At Detroit Diesel, the biggest manufacturer of diesel engine in North America, efforts were first directed to the methanol engine. Recent efforts are directed to the development of a natural gas-fuelled diesel engine.
To introduce the natural gas into the cylinder, one of the first methods to be used was natural fumigation, where the gas is pre-mixed with the air before the intake. Part-load operation with natural fumigation in a diesel engine is characterised by poor combustion due to lean mixtures (there is no throttling in a conventional diesel engine). As an attempt to obtain some stratification of the fuel in the intake air, timed port injection of the gas at low pressure near the intake valve is being investigated. Stratification refers to the combustible mixture being localised in the upper part of the cylinder, and is preventing the deterioration of the combustion at low load (since full mixing of the natural gas with the full charge of air results in a mixture too weak for complete combustion). To date, timed port injection has not fully overcome the problem associated with the natural fumigation. Reduction in compression ratio, throttling and relatively large diesel proportion are needed to obtain acceptable part load combustion, with the overall effect of reduced efficiency.

A third approach being investigated is the late-cycle direct injection of natural gas into the combustion chamber. Late-cycle refers to the injection of the gas near the end of the compression stroke. Full stratification can be obtained with this method, providing therefore good combustibility over the complete operating range. A small amount of pilot diesel fuel is injected with the gas to provide ignition. Successful conversion of large diesel engines to direct injection of natural gas has been accomplished Miyake et al.; Einang [1983]; Wakenell [1987]. In all cases good efficiency, power rating, stable operation and low emissions were obtained, with pilot diesel fuel quantity as low as 5% (operation was acceptable down to 2%, but thermal efficiency decreased at this level).

A project to convert a Detroit Diesel 6V-92 turbocharged and after-cooled (TA) diesel
engine\(^3\) to late-cycle electronically controlled direct injection of natural gas is currently underway at the department of Mechanical Engineering at UBC. The project consists of the design and development of an injector for natural gas. Ignition is ensured by injecting a small proportion of diesel fuel with the natural gas through the same orifice, while in previous research the pilot fuel and the natural gas were injected through separate orifices. Injecting both fuels through the same orifice permits gas blast atomization of the diesel fuel, and limits the modification necessary for the conversion. The aim is to develop a dual-fuel injector that will replace the existing diesel injector and will therefore be easily implemented in existing engines. In order to inject the natural gas late in the cycle, high pressure is required. Consequently, an intensifier is being developed to bring the natural gas to the required pressure. The objective is to meet or exceed the thermal efficiency of a diesel fueled engine while reducing emissions.

1.2 BRIEF REVIEW OF DIESEL INJECTION

The success of this project is intimately related to the quality of the gas injection. In order to establish requirements for the gas injection, a brief review of the conventional compression ignition engine process is necessary. Diesel fuel is injected through small holes at high velocity in the combustion chamber late in the compression stroke. The liquid fuel undergoes atomization as it is injected, vaporizes and mixes with the hot air in the combustion chamber. The properly mixed portion ignites shortly after the beginning of the injection since the pressure and temperature are above the fuel ignition point. The combustion causes an increase in pressure and temperature that accelerates evaporation and ignition of the incoming fuel. The process of atomization, evaporation, mixing and ignition continues until the end of the

\(^3\) Approximately 95% of the urban buses in North-America are powered by Detroit Diesel two-strokes engines.
The high initial velocity is necessary for two reasons. First it is largely responsible for
the atomization, in conjunction with very small injection holes (0.1 to 1 mm, a fairly large L/D
ratio is also required). Second it gives the fuel the necessary momentum to traverse the
combustion chamber in the available time, ensuring adequate air utilization. High initial velocity
is attained by providing a large pressure difference between the fuel supply and the combustion
chamber. Typically, the cylinder pressure is in the range of 50 to 100 atm. Fuel injection
pressures between 200 and 2000 atm are employed depending on the engine type. For the
Detroit Diesel turbocharged 6V-92 engine, cylinder pressure of 100 to 120 atm are common.
Injection pressure of the liquid fuel can be as high as 2000 atm.

The combustion can be separated into different stages. There is first an ignition delay,
the time between injection and ignition. This delay results from the processes that the fuel must
undergo (atomization, evaporation, mixing), and is of the order of 3 to 10 crank angle degrees
depending on engine operating conditions. Some of the fuel injected during this delay period
mixes with air within combustibility limits, resulting in a rapid combustion phase (corresponding
to a peak in heat release). When all the premixed fuel accumulated during the ignition delay
period is burned, the combustion becomes dependent on the incoming fuel. This is the mixing-
controlled combustion phase, in which the rate of burning is essentially dependent on the rate at
which the mixture becomes available for combustion. Approximately 75% of the fuel is burned
in this phase. Combustion continues late into the expansion stroke, and some of the unburned
fuel may burn in a late combustion phase. The mixing-controlled aspect of diesel combustion
indicates that the combustion is directly related to the characteristics of the jet of fuel injected.

Heywood [1988] points out some relevant characteristics of the compression ignition
engine while describing its process. First, because the fuel is not compressed with the air during
the compression stroke, there is no knocking limit to diesel engines. Higher compression ratio can be used, increasing the efficiency of the cycle. Second, since the combustion timing is controlled by the injection timing, the delay between injection and combustion must be repeatable and short. Third, the torque is controlled by the amount of fuel injected, consequently the need for throttling is eliminated, leading to increased mechanical efficiency. Fourth, there may be a problem with air utilization at high load leading to formation of soot that cannot be burned before exhaust. The excessive amount of smoke limits the relative air fuel ratio to about 1.2, where the relative air fuel ratio is the actual air/fuel ratio over the stoichiometric air/fuel ratio.

Diesel combustion depends on different physical processes, of which the proper diffusion of the fuel in the chamber is still the most important one:

"The major problem in diesel combustion chamber design is to achieve sufficiently rapid mixing between the injected fuel and the air in the cylinder to complete combustion in the appropriate crank angle interval close to top-centre" (Heywood p.492)

1.3 PROTOTYPE INJECTOR

A prototype injector for high pressure injection of natural gas with pilot diesel was designed and patented by P.G. Hill, K.B. Hodgins from the Department of Mechanical Engineering at UBC, and R.J. Pierik, a former graduate student and research engineer in the department. The prototype injector is intended to replace the existing diesel injector in the series 60 and 71 Detroit Diesel engines without modifications to the engine itself. Figure 1.1 is a schematic of the natural gas injection system. Timing and fuel quantity are controlled electronically by a modified Detroit Diesel Electronic Control (DDEC) system. The electronic control closes a supply/return valve in the diesel lines towards the end of the compression stroke. The diesel in the injector is then compressed by a cam-actuated plunger, forcing the poppet valve to open once the pressure is high enough to counteract the spring. When a sufficient amount of
Figure 1.1 Schematic of natural gas injector with pilot diesel fuel
gas and pilot fuel have been admitted into the cylinder, the supply/return valve opens, and
injection stops. A controllable throttle regulates the percentage of pilot fuel admitted in the
combustion chamber with the natural gas. The pilot fuel is gas-blast atomized by the natural gas
flow at the nozzle. In order to provide high pressure natural gas at all times, an intensifier brings
the stored natural gas to the required injection pressure. The intensifier is driven by an accessory
shaft of the engine.

Details of the tip of the injector can be found in Figure 1.2. The poppet valve and its
conical tip are not a conventional design for diesel engines, where small holes are normally used
to inject and atomize the diesel fuel. The conical poppet design results in an axisymmetric conical
sheet jet rather than a number of round jets. This design was chosen for several reasons: 
1) Because of its lower density, the total volume of natural gas per injection is greater than the corresponding volume of diesel. A larger orifice size is then necessary to allow the natural gas in the chamber within the time available. The conical shape provides more area to inject the gas. A small lift permits the design to keep good atomization characteristics.

2) Machining and manufacturing costs may be reduced significantly with this design, reducing total cost of the conversion.

3) It is easier with this design than with the conventional pintle nozzle design to ensure choking at the nozzle itself, providing better control on the gas injection.

4) The design permits mixing the gas and the pilot fuel immediately before the nozzle; this would have been difficult with pintle type design.

5) Sealing is a major challenge in the design of a high pressure gas injector, and the conical tip design may be easier to manufacture with appropriate sealing characteristics.

1.4 LATE-CYCLE HIGH PRESSURE GAS INJECTION: UNKNOWNS AND PROBLEMS

A prototype injector was designed and manufactured to gain knowledge and experience regarding the implementation of the conversion. However numerous questions are unexplored and unanswered. The following paragraphs underline some of these questions.

The injector is the most important part of the diesel engine. The injection dictates the quality of the combustion, and therefore of the fuel conversion efficiency, and has definite effects on emissions characteristics. Although there is a reasonably good knowledge of the characteristics of diesel injection, very little has been done on the direct injection of gases into combustion chambers. In order to use natural gas successfully, it is of primary importance to
correlate the injector design and the operating parameters to injection and combustion characteristics. Injector design influences the injection by the shape, angle and diameter of its nozzle and by the lift of the poppet. Operating parameters includes the length of injection, upstream pressure and temperature, and chamber pressure and temperature. Another important factor is the shape of the combustion chamber. These parameters are illustrated in Figure 1.3.

Following the review of diesel injection in the previous section, we can now identify some important considerations for the gaseous injection. While the gas starts mixing immediately as it exits the nozzle, the pilot fuel must atomize, evaporate and mix with the air before it ignites, resulting in an ignition delay. This delay must be reproducible to ensure proper ignition timing; therefore the gas velocity must be kept constant. This is done by ensuring choking conditions...
at the nozzle. A high gas velocity is required for atomization of the pilot fuel and to ensure sufficient diffusion of the gas in the chamber in the short time available. While under-penetration causes problems with air utilization, over-penetration in low-swirl chamber causes impingement of the fuel on the wall, lowering mixing rate and increasing unburned species in the vicinity of the wall. Penetration of the gas as a function of time or crank angle is unknown and must be investigated. The penetration depends on the geometry of the injector tip, the initial momentum of the jet and the conditions in the combustion chamber. The initial momentum is related to the upstream gas condition and the nozzle flow area. For best air utilization, the jet must be properly distributed in the chamber. This distribution is mainly dependent on the nozzle geometry. Since the poppet geometry is not a conventional one, and no information was found
on gas flow from such a nozzle, diffusion for this specific shape must be characterised.

Because of the simultaneous presence of liquid fuel, droplets and evaporated diesel fuel in a jet of natural gas, the auto-ignition is not fully understood. The length and repeatability of the ignition delay are two unknowns.

Other unknowns which must be investigated experimentally are operation variables such as timing and fuel quantity for different engine operation conditions experimentally. Finally, detailed information regarding turbulence intensity, turbulence enhancement, and localised species formation have provided a better understanding of mixing rates and pollutants formation in diesel engine, and could be investigated for natural gas fueling.

1.5 RESEARCH AND DEVELOPMENT STRATEGY

An experimental assessment of all the unknowns mentioned in the previous section is an enormous task. It was decided to limit experimental work, and to utilize computer simulation to characterize as much as possible the natural gas injection and combustion. The following efforts were therefore undertaken:

- Extensive testing of the prototype injector in a fully instrumented one cylinder Detroit Diesel 71 series research engine. The task can be divided in two categories. First, the instrumentation must be adequate and reliable. Second, the prototype injector must be tested. These efforts have already led to modification of the injector for better sealing and reliability. Research will follow on a turbocharged 6V-92 Detroit Diesel engine.

- Analysis and flow visualization of the turbulent transient gas jet is being done and is the subject of this particular project and thesis. Analytical work should provide a good understanding of the jet diffusion mechanism, while indicating important variables and their respective effects on the jet. Potential scaling factors will also be examined. Flow
visualization will provide diffusion characteristics of the jet, and show evidence of the effects of parameters variation.

- Computer simulation using a modified TEACH code will provide some information about the effects of the piston motion on the jet dispersion and will provide further insight as to the distribution of natural gas within the chamber. This is the subject of a separate project.

- More elaborate and complete simulation will be done using the KIVA code and should provide detailed information about velocity profile, concentration profile, turbulence intensity, species location and concentration, ignition characteristics and combustion characteristics as a function of crank angle. Both computer models and flow visualization will provide information necessary to accelerate the design process of the injector, reducing costly experimental development.

1.6 OBJECTIVE AND ORGANISATION OF THIS THESIS

The project being the subject of this thesis was launched because of the need for an experimental investigation of the injection. Computer models can not provide exact simulation of the injector tip and need to be verified by experimental data. Flow visualization was chosen as the experimental method, since it provides a concrete representation of the injection of natural gas from a conical nozzle poppet not available in the literature, and since it provides the necessary information to investigate the effects of most parameters. Flow visualization has been used widely in diesel injection research.

Only the cold gas flow has been studied in this investigation. It is assumed that the gas flow dictates the pilot fuel diffusion and that the combustion does not significantly affect the flow distribution and penetration. This is a reasonable assumption since diesel combustion is a
mixing-controlled combustion. The effect of the moving piston on the jet will not be investigated in this project.

The objective of this work is to obtain knowledge about the cold gas injection from the prototype injector, investigating in particular the penetration characteristics and the effect of the nozzle tip geometry on the diffusion of the gas. The effects of lift, pressure ratio and injection length on the gas diffusion will be investigated through a parametric study. An analytical description of the conical sheet jet, based on previous work done on transient jets, will be presented and provides understanding and scaling for the flow visualization results. The results of this work will be discussed, with the main goal of identifying important characteristics for natural gas injection and potential improvements for the existing prototype injector.

The analytical investigation of the gas diffusion from a conical nozzle design will be presented in the two first chapters. A brief review of previous work done on transient diesel fuel sprays will be done as an introduction, and will lead to a more detailed analysis of transient jets, since it is the driving mechanism of fuel injection. In order to develop a model for transient jets, the velocity and concentration distribution in the steady-state jet must be known. The properties of the steady conical sheet jet are estimated in chapter 2, following previous work done on the turbulent round free jet. Then a model for the transient turbulent conical sheet jet will be presented in chapter 3. The relevant literature is reviewed as each case is examined. The experimental apparatus and procedure will be described in detail in chapter 4. Results of flow visualization will be presented and discussed in chapter 5. Finally, the potential implications of these results for the global project and potential improvements will be addressed in the conclusions.

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4 In this thesis a conical nozzle describes the type of nozzle illustrated in Figures 1.2 and 1.3. The type of jet emerging from this conical nozzle will be referred as a conical sheet jet.
2 STEADY-STATE TURBULENT CONICAL SHEET JET

The mechanism of the injection of fuel into a combustion chamber is that of a transient turbulent jet. In a mixing-controlled combustion, the attributes of this transient jet dictate the quality of the combustion. In turn this transient jet is influenced by its surroundings (air motion in the cylinder, piston shape) and by its thermodynamics (evaporation, heat transfer, combustion). In spite of these influences, the investigation of the transient jet itself has always been a first step in diesel injection research. One of the first and most fundamental aspects of transient jets to be considered in diesel research is the penetration rate of the fuel spray. The penetration rate is defined as the position of the tip of the jet relative to the nozzle as a function of time. The study of the penetration rate does not provide a complete characterisation of the jet, but it establishes a basic requirement of the injection, that is the appropriate diffusion of the fuel through the combustion chamber. Considerable work, both analytical and experimental, has been done on diesel spray penetration. In most cases, simplified theoretical expressions that agree well with experimental data can be established. These expressions are based on turbulent jet knowledge and a particular expression will be reviewed briefly in the first part of this chapter. This review shall however serve more as an introduction, since in order to apply a similar theory to a turbulent conical sheet jet, the characteristics of this type of jet must be first examined.

The steady-state round free turbulent jet will be reviewed, and a similar characterisation of the steady-state turbulent conical sheet jet will be presented. First, the incompressible jet of air into air case will be examined, then the analysis will be extended to consider the injection of a different gas into air. Underexpansion will also be discussed. The appropriate literature concerning each case will be reviewed as the case is presented.
2.1 DIESEL FUEL SPRAY PENETRATION

The literature on diesel fuel spray penetration is vast and dates back as far as 1937 with the work of Schweitzer on oil sprays. Many empirical correlations have been established over the years to predict penetration of the fuel spray tip in a quiescent chamber as a function of time. The model proposed by Dent [1971] has been shown to best correlate experimental data by Hay and Jones [1972]. The penetration prediction developed by Dent is based on the work of Forstall and Shapiro [1950] on mixing of coaxial gas jets. The velocity decay for a steady-state round jet in their analysis has the following form:

\[ \frac{U_m}{U_0} = \frac{z_c/d_o}{z/d_0} \]  

(2.1)

when the secondary fluid velocity is null. \( U_o \) and \( U_m \) are respectively the initial jet velocity and the velocity on the axis of the jet, \( d_o \) is the diameter of the orifice, \( z \) is the distance along the jet axis and \( z_c \) is the length of the potential core region. A top hat initial velocity profile is assumed. The parameters are illustrated in Figure 2.1. The potential core length was found to be

\[ z_c = 4d_o \]  

(2.2)

A correction must be made to Equation 2.1 to account for density differences between the injected fuel and the surrounding medium. It has been found by Thring and Newby [1952] that the density difference can be treated using an effective diameter \( d_e \) instead of the actual diameter \( d_o \). The effective diameter is the size of the orifice that would yield, given a different injected fluid density, the same momentum as if air was injected:

\[ d_e = d_o \left[ \frac{\rho_g}{\rho_a} \right]^{1/2} \]  

(2.3)

where \( \rho_g \) is the gas or fuel density and \( \rho_a \) is the air density, both taken at ambient temperature and pressure. Equation 2.1 can then be rewritten

and the potential core length becomes \( z_c = 4d_e \). Substituting \( z_c \) into Equation 2.4, the velocity
\[
\frac{U_m}{U_o} = \frac{z_c}{d_e} \cdot \frac{z}{d_e} \quad (2.4)
\]
decay becomes
\[
\frac{U_m}{U_o} = \frac{4d_e}{z} \quad (2.5)
\]
The position \( z=0 \) is a virtual origin situated in recess of the actual orifice. The jet can be thought as originating from a point source. Replacing \( U_m = \frac{dz}{dt} \), where \( z \) is the position of the tip of the jet, in Equation 2.5 and integrating with the initial condition \( z=0 \) at \( t=0 \), the transient nature of the jet can be described by
\[
z_t = [8U_o t d_e]^{1/2} \quad (2.6)
\]
The validity of the substitution is questionable, since it implies that the tip of the jet is travelling with the same velocity as the steady jet. However, it seems to be a good approximation for liquid fuel injection. From the Bernoulli equation for incompressible fluids:
\[
U_o = \frac{C_d}{2} \frac{\Delta P}{\rho_g} \quad (2.7)
\]
where \( \Delta P = P_o - P_i \). \( P_o \) is the upstream pressure and \( P_i \) is the quiescent air pressure. \( C_d \) is the discharge coefficient. Substitution of Equations 2.3 and 2.7 into Equation 2.6, results in
\[
z_t = 3.36 C_d^{1/2} [\frac{\Delta P}{\rho_a}]^{1/2} t d_o \quad (2.8)
\]
A discharge coefficient \( C_d \) of 0.8 is a good approximation for Reynolds number greater than \( 10^4 \) and orifice length-to-diameter ratio between 2 and 4. With this approximation, Equation 2.8 reduces to
\[
z_t = 3.01 [\frac{\Delta P}{\rho_a}]^{1/2} t d_o \quad (2.9)
\]
Equation 2.9 assumed that the density of the fuel and the air were at the same temperature. In cases where the temperature in the chamber is high, the equation must be modified. Assuming
that the injected fluid is at an ambient temperature of 298 K, Equation 2.9 becomes

$$ z_e = 3.01 \left[ \left( \frac{\Delta P}{\rho_a} \right)^{1/2} \right]^{1/2} \left( \frac{298}{T_a} \right)^{1/4} $$

where $T_a$ is the temperature in the chamber. Equations 2.9 and 2.10 give the penetration in meters when SI units are used for pressure, density and diameter. Dent shows that the above equations correlate well with experimental data on cold and hot bomb studies of jet penetration for temperature $T_a$ from ambient to 800 K, orifice sizes from 0.25 mm to 0.7 mm and upstream pressures in the range 100 to 500 atm.

Apparently, this model is a reasonable approximation for the penetration of round transient liquid fuel jets. It should be possible to establish a priori a similar relation for the conical sheet jet. Unfortunately, there is no known relationship for the velocity decay of a jet emerging from a conical nozzle design. The velocity decay must first be established, using integral equations.

It must be mentioned that more recent work has been done on fuel spray penetration from round orifices, but most of these recent studies consider more complex effects, such as swirl, piston movement and combustion chamber design. Those effects are certainly important, but are a step ahead of the present work.

2.2 INCOMPRESSIBLE STEADY-STATE TURBULENT ROUND FREE JET

The injection of natural gas into a combustion chamber is considered to be a compressible transient turbulent jet involving two different gases (natural gas and air). Because choking conditions are to be maintained at the nozzle, an upstream to cylinder pressure ratio larger than the critical pressure ratio will be required, and underexpansion could occur. Furthermore the conical geometry of the prototype injector tip (Figure 1.2) is not one commonly described in the literature. The majority of the knowledge regarding turbulent jets concerns basic incompressible
steady-state jets of air into air, but there are a number of fundamental considerations and a number of approximations can be used to extend the analysis to compressible, underexpanded transient turbulent jets. Starting from the simplest case, the appropriate papers will be reviewed, and the corresponding analysis applied to the round free jet first, for which experimental evidence is available. Then the analysis will be extended to the case of a conical sheet jet of gas.

Figure 2.1 illustrates a round free jet and its principal parameters. The jet can be separated into three main region. The initial region is characterised by a central inviscid core of length $z_o$ in which the velocity is uniform and equal to the orifice velocity $U_o$. This core is surrounded by a free shear layer where the exchange of mass and heat with the surroundings begins. At the end of the central core, a region of transition occurs before the fully developed part of the jet. In this last region, the jet behaves as if it originates from a point source, located at a distance $z_o$ from the orifice. The jet in the fully developed region has the property of self-similarity, meaning that the non-dimensional velocity profile is independent of the distance $z$ along the axis. The similarity concept is conveniently expressed as:

$$\frac{U}{U_m} = f(\eta) \quad \eta = \frac{r}{R}$$

(2.11)

where $U$ is the velocity at a position $(r,z)$, $U_m$ the velocity on the axis $(0,z)$, and $R$ is the radius of the jet at the position $z$. There are different approximations of the velocity profile. The velocity profile suggested by Schlichting is often used:

$$f(\eta) = \frac{U}{U_m} = (1 - \eta^{1.5})^2$$

(2.12)

But the definition of the radius of the jet $R$ at a position $z$ is not definite, so that the profile due to Warren (Witze [1980]) will be employed in this analysis:
\[ f(\xi) = \frac{U}{U_m} = e^{-\frac{\xi^2}{\alpha}} \quad \xi = \frac{r}{r_{1/2}} \quad \alpha = \ln 2 \quad (2.13) \]

where \( r_{1/2} \) is the radius where the velocity is half of the axial velocity \( U_m \). This profile is valid only in the fully developed part of the jet.

Figure 2.1 Characteristic structure and parameters of a round free jet.

A quantitative description of an incompressible round free jet can be found in the literature (Abramovich [1963] and Witze [1980]). The half radius \( r_{1/2} \) and the axial velocity \( U_m \) of the jet can be expressed as a function of the axial distance \( z \). The following assumptions must be made for this analysis:

- In the fully developed region, the jet possesses the property of self-similarity. The transition region extends to approximately 20 diameters.

- The pressure is constant throughout the jet and the surroundings. As long as the
surrounding medium is large in comparison to the size of the jet, and that the initial velocity is low, the pressure uniformity is an experimentally observed fact.

- The density is uniform in the jet, requiring that the injected fluid be the same as the fluid in the surroundings, and that compressible effects are very small in the cases of gases, requiring low initial velocity.

- The initial velocity profile is square. Alternatively, the initial momentum can be corrected by the discharge coefficient $C_d$.

With these assumptions, the conservation of momentum is expressed as:

$$\pi C_d \rho_r^2 U^2 = 2\pi \int_0^\infty \rho U^2 r dr = 2\pi \rho U_m^2 r_{1/2}^2 \int_0^\infty f^2(\xi) \xi d\xi$$

(2.14)

Since the velocity profile is independent of $z$, the integral is a constant. It follows that

$$r_{1/2}^2 U_m^2 = \text{constant}$$

(2.15)

The increase of $r_{1/2}$ as a function of $z$ can be obtained from the momentum integral equation applied to a control volume located inside the steady-state jet, as illustrated in Figure 2.2, and is expressed as:

$$F_{sz} + F_{BV} = \int_{CS} U \rho U d\bar{A}$$

(2.16)

where $F_{sz}$ are the surface forces and $F_{BV}$ are the body forces in the $z$ direction. In the case of a jet of air into air, the body force term can be neglected since convection is dominant in the jet.

The surface forces are shear induced only, the pressure gradient being assumed null. The shear stress is expressed as a function of the turbulent viscosity:

$$\tau_s = \mu_t \frac{\partial U}{\partial r} \bigg|_{r_{1/2}} = \rho v_t \frac{\partial U}{\partial r} \bigg|_{r_{1/2}} = \rho v_t \frac{U_m}{r_{1/2}} f'(1)$$

(2.17)

in which $v_t$ is the turbulent viscosity. The right hand side of Equation 2.16 can be separated into two terms. The first is the momentum flux through the normal surfaces of the control volume.
The second is the momentum at the half-radius, equal to the product of the mass flow through the lateral surface by the velocity at $r_{1/2}$, $U_m/2$. The momentum integral equation is then:

$$
\frac{\partial}{\partial Z} \left[ 2\pi r_{1/2}^2 U_m \rho \int_0^{1/2} f^2(\xi) \xi \, d\xi \right] \, dz - \frac{U_m}{2} \frac{\partial}{\partial Z} \left[ 2\pi \rho U_m r_{1/2}^2 \int_0^{1/2} f(\xi) \xi \, d\xi \right] \, dz
= 2\pi \rho U_m r_{1/2} f'(1) \, dz
$$

The self-similarity property states that the profile $f(\xi)$ is independent of $z$. Consequently, the first integral in the left-hand side of Equation 2.18 is a constant. According to Equation 2.15, the remaining part of that term is also a constant. The equation simplifies then to

$$
\frac{\partial}{\partial Z} (r_{1/2}) = \frac{-2\nu f'(1)}{U_m r_{1/2} \int_0^{1/2} f(\xi) \xi \, d\xi}
$$

General empirical knowledge on turbulent round free jets states that the radius or the half radius of the jet is directly proportional to the axial distance. To reflect that fact, a turbulent Reynolds number $Re_t$ is defined as

Figure 2.2  Control volume for momentum integral equation.
Equation 2.19 can now be integrated and yields

\[ \frac{I \frac{1}{2}}{R e} = \frac{2 f'(1)}{f(\xi)} \frac{z}{k_1} Re \]

where \( k_1 \) is a constant dependent on the velocity profile, and \( Re \) is found experimentally. With Warren's velocity profile (Equation 2.13), \( k_1 = 3.84 \). The half-radius \( r_{\frac{1}{2}} \) is now expressed as a function of \( z \). To obtain an evaluation of \( U_m \), Equation 2.21 can be replaced in the momentum conservation Equation 2.14:

\[ U_m = \sqrt{\frac{C_d r_o^2 U_o^2}{2 \int_{1/2}^{z} f^2(\xi) \xi d\xi}} \]

The distance \( z \) is actually the distance from the virtual origin of the jet. The relation between \( z \) and \( z' \), the actual distance from the nozzle orifice, is

\[ z = z' + z_o \]

where \( z_o \) is the position of the virtual origin relatively to the orifice, and can be seen in Figure 2.1. Setting \( Re = 45 \) to match Warren empirical constant (Witze [1980]) and assuming a square velocity profile \( (C_d = 1) \), the following expressions are obtained for the half radius and the axial velocity as a function of \( z \):
\[ \frac{U_m}{U_o} = \frac{k_2}{(z'+z_o)/r_o} = \frac{13.8}{(z'+z_o)/r_o} \]  \hspace{1cm} (2.24)

where \( k_2 \) is a decay constant

\[ r_{1/2} = 0.085 (z'+z_o) \]  \hspace{1cm} (2.25)

This solution agrees very well with Tollmien's solution (Abramovich [1963]), Equation 2.26, for which experimental evidence is available. In section 2.1, the solution of Forstall and Shapiro was characterised by the same decay equation, but with a constant of 8 instead of 13.8.

\[ \frac{U_m}{U_o} = \frac{0.96}{a(z'+z_o)/r_o} \quad \text{(Tollmien)} \]  \hspace{1cm} (2.26)

The constant \( a \) in Tollmien's solution was found to be dependent on the initial velocity profile. Typical experimental values are 0.066 for a uniform velocity profile, while values of 0.07 and 0.076 have been reported for initial velocity profiles not completely uniform. The corresponding values for the decay constant in Equation 2.24 are given in Table 2.1. In his analysis, Witze [1980] takes into account the velocity profile in the core region, and obtains a similar relation for the velocity decay:

\[ \frac{U_m}{U_o} = \frac{14.27}{z/r_o + 1.77} \quad \text{(Witze)} \]  \hspace{1cm} (2.27)

According to these relationships, the core length (obtained when \( U_m = U_o \)) is found to be approximately 12 to 14 times the orifice radius. As for the virtual origin, it is dependent on the nozzle configuration. As an example, good agreement between Tollmien's solution and experiments were found when the virtual origin was set back about 4 times the orifice radius.

The general form of Equation 2.24 indicates that results should be properly scaled when the velocity and the axial distance are non-dimensionalized with the orifice velocity and the orifice radius.
constant $a$ in Tollmien's Equation 2.26  

<table>
<thead>
<tr>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>0.066</td>
</tr>
<tr>
<td>0.07</td>
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<tr>
<td>0.076</td>
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decay constant $k_2$ in Equation 2.24

<table>
<thead>
<tr>
<th>Value</th>
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<tbody>
<tr>
<td>14.6</td>
</tr>
<tr>
<td>13.7</td>
</tr>
<tr>
<td>12.6</td>
</tr>
</tbody>
</table>

Table 2.1 - Corresponding values of the decay constant in Equation 2.24 for experimentally encountered values for constant $a$ in Tollmien's solution.

2.3 INCOMPRESSIBLE STEADY-STATE TURBULENT CONICAL SHEET JET

The velocity decay and the spreading of a turbulent round free jet were obtained using the momentum integral equations and assuming a Gaussian velocity profile in the jet. Presumably, the velocity decay and the spreading of a turbulent conical sheet jet could be obtained following the same procedure if the velocity profile is known. Unfortunately, experimental data concerning the velocity profile in such a jet are not available. However for small jet axis angles, it will be assumed that the velocity profile within the jet is Gaussian. Figure 2.3 illustrates the conical poppet design and the main parameters of a conical sheet jet.

Making the assumptions stated in the previous section, the conservation of momentum equation can be written as:

$$
\rho C_d A U_0^2 = 2 \int_0^\infty \rho U \bar{U} \cdot d\bar{A}
$$

(2.28)

$$
= 2 \int_0^\infty \rho U^2 2\pi [z \cos(\beta) + r \sin(\beta)] dr
$$

The term $r \sin(\beta)$ is small compare to $z \cos(\beta)$ since the angle is assumed to be small, leading to

$$
\rho C_d A U_0^2 = 2 \int_0^\infty \rho U^2 2\pi z \cos(\beta) \, dr
$$

(2.29)

$$
= 4\pi \rho U^2 r_{1/2} z \cos(\beta) \int_0^\infty f^2(\xi) \, d\xi
$$

Since the velocity profile is a constant, Equation 2.29 leads to
The momentum integral equation can be applied inside the jet, to a similar control volume (extending to $r_{1/2}$) as for the round free jet (Figure 2.2). The area of the top and bottom of the sheet are in fact different, but with the small angle assumption, that difference can be neglected\(^1\).

The shear stress is similar to the one expressed in Equation 2.17. The momentum integral equation is

\[ U_{m}^2 z r_{1/2} = \text{constant} \]  

\(^{1}\text{By actually comparing the areas at any position } z\text{, it is possible to show that for an angle of 10 degrees, the top area is 3\% larger. For 20 and 30 degrees, the top areas are respectively 5\% and 9 \% larger.}\)
\[
\frac{\partial}{\partial Z} \left[ 2 \int_{0}^{Z_{1/2}} \rho U^2 dA \right] - \frac{U_m}{2} \frac{\partial}{\partial Z} \left[ 2 \int_{0}^{Z_{1/2}} U \rho dA \right] = \tau_f dA
\]

\[
\frac{\partial}{\partial Z} \left[ 4 \pi Z R_{1/2}^2 \cos(\beta) \rho \int_{0}^{1} f^2(\xi) d\xi \right] dz
\]

- \frac{U_m}{2} \frac{\partial}{\partial Z} \left[ 4 \pi \rho Z \cos(\beta) U_m R_{1/2} \int_{0}^{1} f(\xi) d\xi \right] dz

\[
= 4 \pi \rho Z \cos(\beta) v_t \frac{U_m}{R_{1/2}} f'(1) dz
\]

The velocity profile is constant, and considering Equation 2.30, the first term on the left-hand side is zero. Rearranging and substituting for the turbulent Reynolds number, yields

\[
\frac{\partial}{\partial Z} [z U_m R_{1/2}] = \frac{-2 z v_t f'(1)}{-2 z U_m f'(1)} = \frac{-2 z U_m f'(1)}{R e t \int_{0}^{1} f(\xi) d\xi}
\]

Dividing by \(z U_m^2 R_{1/2}\) = constant (Equation 2.30), results in

\[
\frac{1}{z U_m} \frac{\partial}{\partial Z} \left[ \frac{1}{U_m} \right] = \frac{-2 f'(1)}{R e t \int_{0}^{1} f(\xi) d\xi (z U_m^2 R_{1/2})}
\]

Substituting the transformation

\[
\frac{1}{U_m} \frac{\partial}{\partial Z} \left( \frac{1}{U_m} \right) = \frac{1}{2z} \frac{\partial}{\partial Z} \left( \frac{1}{U_m^2} \right) = \frac{\partial}{\partial Z^2} \left[ \frac{1}{U_m^3} \right]
\]

we obtain

\[
\frac{\partial}{\partial Z^2} \left[ \frac{1}{U_m^2} \right] = \frac{-2 f'(1)}{R e t \int_{0}^{1} f(\xi) d\xi (U_m^2 z R_{1/2})}
\]

Multiplying by \(z U_m^2 R_{1/2}\) = constant, we finally get

\[
\frac{\partial}{\partial Z^2} [z R_{1/2}] = \frac{-2 f'(1)}{R e t \int_{0}^{1} f(\xi) d\xi}
\]

Once integrated and substituting the actual distance from the nozzle, Equation 2.36 yields
\[ x_{1/2} = \frac{-2f'(1)}{Re_t} \int_0^1 f(\xi) \, d\xi = \frac{k_1}{Re_t} (z' + z_o) \tag{2.37} \]

and with Warren's velocity profile, \( k_1 = 1.7114 \). Replacing \( r_{1/2} \) in Equation 2.28 we obtain an expression for the velocity decay of the conical sheet jet:

\[
U_m = \sqrt{\frac{\rho C_d A U_0^2}{4 \pi \rho \cos(\beta) \int_0^1 f^2(\xi) \, d\xi}} \left( \frac{1}{l_{1/2} Z} \right) \tag{2.38}
\]

Referring to Figure 2.4, the area at the nozzle is

\[
A = 2\pi R l \cos(\beta) \\
\text{and } R = R_s - \frac{1}{2} \cos(\beta) \sin(\beta) \tag{2.39}
\]

where \( R_s \) is the seat radius. In cases where the angle is small and when the lift is small compare to the seat radius, Equation 2.39 reduces to

\[
A = 2\pi R_s l \cos(\beta) \tag{2.40}
\]

In the case of the prototype injector, the lift is approximately 0.1 mm compared to a seat radius of 3.4 mm. Equation 2.40 will be utilised to approximate the area at the nozzle. Replacing the area in Equation 2.38 yields

\[
U_m = \sqrt{\frac{C_d R_s A U_0^2 Re_t \int_0^1 f(\xi) \, d\xi}{-4 f'(1) \int_0^1 f^2(\xi) \, d\xi}} \left( \frac{1}{(z' + z_o)} \right) \tag{2.41}
\]

Rearranging and saying \( C_d = 1 \),
\[
\frac{U_m}{U_o} = \sqrt{\frac{\int_0^1 f(\xi) d\xi}{-4 f'(1) \int_0^\infty f^2(\xi) d\xi}} \frac{\sqrt{Re_e}}{\frac{(z' + z_o)}{\sqrt{R_s I}}} = \frac{k_2}{(z' + z_o) \sqrt{R_s I}}
\]

(2.42)

where \( k_2 = k(Re)^{1/2} \) and \( k = 0.623 \) for Warren's velocity profile. Apparently, the results for the conical sheet jet should scale when the axial distance is non-dimensionalized with the square root of \( R_s l \) (seat radius multiplied by lift).

The turbulent Reynolds number for a conical sheet jet is unknown. Its value is estimated by assuming that the conical sheet jet will have the same spreading angle as the round free jet and as the plane jet. For these two jets, the angle between the jet axis and the surface of the jet (spreading angle) is approximately the same and is equal to roughly 13 degrees. For the round free jet, \( Re \) is approximately 45. For the plane jet, \( Re \) is lower, in the range 15-20 (Abramovich [1963]). Since the velocity profiles are the same for each jet, the increase of the half-radius \( r_{1/2} \) with \( z \) should be the same. For the round free jet, \( r_{1/2} = 0.085 z \). To yield the same constant for the conical sheet jet, the turbulent Reynolds number must be approximately 20 (from Equation 2.37). With this turbulent Reynolds number, the velocity decay given by Equation 2.42 becomes

\[
\frac{U_m}{U_o} = \frac{2.8}{z' + z_o} \quad \text{with } Re_e = 20
\]

(2.43)

Equation 2.43 indicates that the velocity decay is not dependent on the jet angle. However, this is only true because of the area approximation in Equation 2.40. The velocity decay was computed for different cases, with the exact value of the area, and is plotted in Figure 2.5. The scaling established on the area approximation is seen to be appropriate.

In typical diesel injectors, the fuel is admitted through a number of small holes placed on the circumference of the tip. The performance of the conical poppet design relative to a series
of circular holes can be readily evaluated by comparing the axial velocity decay of the jets emerging from each of these nozzles. The velocity decay for the turbulent conical sheet jet is compared to the one of the turbulent round free jet in Figure 2.6. The comparison is based on an equivalence between the conical nozzle area and the combined area of 7 holes (number of holes chosen because the Detroit Diesel injectors for the 71 series have 7 holes). The actual comparison is performed between the jet from the conical poppet nozzle and the jet from one of the 7 holes. The initial velocity is the same in the two cases. The velocity decay of the conical sheet jet occurs more rapidly then for the round free jet, that is a disadvantage since it will correspond to a lower penetration rate of the jet. The initial core length is shorter, as expected for a source with a smaller transverse scale. For the same total area, the jet from the conical
Figure 2.6 Velocity decays of the round jet and the conical sheet jet from Equations 2.24 and 2.43. \( Re = 20 \) for the conical sheet jet, and \( Re = 45 \) for the round jet.

poppet design will travel slower through the combustion chamber than the jets from 7 holes.

So far we have discussed the simplest case of a low speed jet of air into air. In the following section the injection of a gas with a different density will be discussed.

2.4 COMPRESSIBLE TURBULENT ROUND FREE JET OF METHANE INTO AIR

Choking is required at the nozzle to ensure high velocities and reproducibility. Above a Mach number of about 0.3, compressibility effects are no longer negligible. Nozzle conditions must be modified to account for these compressibility effects. First the Mach number is computed from one-dimensional isentropic gas dynamics. The temperature, the density and the velocity at the nozzle exit can be obtained from the Mach number.
The specific heat ratio $k$ was taken as 1.35 for methane. In the immediate surrounding outside the nozzle, velocities are high and compressibility effects are also present. The density profile in this area will differ from the incompressible case. However experimental results show that the velocity profile still possesses the property of similarity (Abramovich [1963]). For the present analysis the details of the jet in the immediate surrounding of the nozzle ($z < 10(R_\text{eq})^{1/2}$) are not required and will not be considered.

The observation of the momentum conservation equation underlines the challenge of treating an incoming gas of a different density in air.

$$\pi C_d \rho_j r_j^2 U_o^2 = 2 \pi U_m r_1^2 \int_0^m \rho_j f^2(\xi) \, \xi \, d\xi$$

where $\rho_j$ is the density at a point $(r,z)$ anywhere in the jet. While the velocity profile at any axial distance $z$ remains Gaussian, the density is now a function of the axial distance and of the radius. At a point $j(z,r)$ in the incompressible part of the jet (i.e. not near the nozzle), the density of the mixture depends on the local concentration of the incoming gas. Assuming that air and methane behave as ideal gases, it can be shown that at a point $j$ in the jet
\[ \rho_j = \alpha \rho_g + (1 - \alpha) \rho_a \]
\[
\rho_j = \frac{\rho_a}{\chi \left( \frac{\rho_a}{\rho_g} - 1 \right) + 1} \quad (2.49)
\]

where \( \alpha \) is the concentration by volume of the injected gas at a point \((z,r)\) and \( \chi \) is the concentration by mass. The subscripts \( a \) and \( g \) refer respectively to the ambient gas and to the injected gas. The densities of the air and the injected gas are taken at the same temperature and pressure. The concentration by mass within a jet is known to possess also the property of self similarity (Abramovich [1963]). The Taylor theory of turbulence for axisymmetric jets predicts that the concentration and the temperature profile are related to the velocity profile in the following manner:

\[
\frac{X}{X_m} = \frac{\Delta T}{\Delta T_m} = \sqrt{\frac{U}{U_m}} \quad (2.50)
\]

where \( X \) is concentration by mass, \( \Delta T = T_a - T \) and \( \Delta T_m = T_a - T_m \).

This relationship is well validated by numerous experimental data (Abramovich [1963]). The respective velocity, concentration and temperature profiles are plotted in Figure 2.7 according to Equations 2.13 and 2.50. The difference between the velocity profiles and the concentration profile is due to the faster diffusion of the mass relative to the momentum.

The conservation of
momentum equation is obtained by replacing the density by its relation to the mass fraction concentration, and by making the necessary transformation to take into account the concentration profile.

\[ \pi C_d \rho_n r_o^2 U_o^2 = 2\pi U_m^2 r_{1/2}^2 \rho_a \int_0^\infty \frac{f^2(\xi) \xi d\xi}{\chi_m G(\xi) \left( \frac{\rho_a}{\rho_g} - 1 \right) + 1} \]  \hspace{1cm} (2.51)

where \( g(\xi) = \chi/\chi_m \) and \( \chi_m \) is the axial concentration. Since we now have a new variable, the mass conservation equation is also required:

\[ \pi C_d \rho_n r_o^2 U_o = 2\pi \int_0^\infty \alpha \rho_g U_r d\xi = 2\pi U_m^2 r_{1/2}^2 \int_0^\infty \alpha \rho_g f(\xi) \xi d\xi \]  \hspace{1cm} (2.52)

The volume fraction is related to the mass fraction by

\[ \alpha = \frac{\rho_a}{\rho_g} \frac{\chi}{\chi \left( \frac{\rho_a}{\rho_g} - 1 \right) + 1} \]  \hspace{1cm} (2.53)

Replacing Equation 2.53 in Equation 2.51 yields

\[ \pi C_d \rho_n r_o^2 U_o = 2\pi U_m \chi_m r_{1/2}^2 \rho_a \int_0^\infty \frac{g(\xi) f(\xi) \xi d\xi}{\chi_m G(\xi) \left( \frac{\rho_a}{\rho_g} - 1 \right) + 1} \]  \hspace{1cm} (2.54)

When treating the incompressible jet of air into air, the momentum integral equation was used to obtain the half radius of the jet \( r_{1/2} \). Unfortunately, because the integral in Equations 2.51 and 2.52 are no longer independent of \( z \), the momentum integral becomes intractable for binary mixtures. Consequently empirical information is utilised to pursue this analysis. A good source of information is found in a paper written by a group from the British Gas Corporation (Birch, Brown, Dodson and Thomas [1978]), in which the turbulent concentration field of a methane jet is examined. The decay of the axial concentration was shown experimentally to closely follow the following relationship:
where \( d_e \) is the effective diameter, presented in section 2.1. For a round orifice, the effective diameter is

\[
\frac{x_m}{x_0} = \frac{k_3 d_e}{z + z_o}
\]

(2.55)

where \( d_o \) is the actual diameter of the orifice. The decay constant \( k_3 \) takes values between 4 and 6 in the literature. The group from the British Gas Corporation found that a value of \( k_3 \) of 4 matches well the experiments in the far field \((z>25d)\), while in the near field region \((10d<z<30d)\) a value of 4.7 fits better the results. The virtual origin was found to be \(-5.8d_o\).

Since the concentration decay is well predicted by Equation 2.53, it can serve as the third equation needed to complete the analysis of the round free jet of methane into air. The solution of the system of equations is no longer explicit but simple to solve by iteration. The integrals can be evaluated explicitly. The following steps were performed to obtain the solution:

for \( 0 < z < 50 \text{ mm} \)

1 - compute axial concentration according to Equation 2.55 and with \( k_3 = 4 \),

2 - guess the axial velocity \( U_m' \),

3 - compute the half radius \( r_{1/2} \) from mass conservation 2.54,

4 - compute the axial velocity \( U_m \) from momentum conservation 2.51,

5 - repeat steps 3 and 4 until the difference between \( U_m' \) and \( U_m \) is small.

Equation 2.55 indicates that the concentration decay for different cases will be scaled when the axial distance is non-dimensionalized with the effective diameter. Figure 2.8 shows that this is an appropriate scaling also for the velocity decay. In Figure 2.8, results are scaled with the effective radius that is half the effective diameter. The obtained velocity decay can be fitted with a decay equation similar to 2.24 and a decay constant of 11.2; this contrasts with a
velocity decay constant of 13.8 for the incompressible jet of air into air. The half-radius $r_{1/2}$ is found to be approximately $0.11(z+z_0)$, while a value of $0.085(z+z_0)$ was obtained for the incompressible case.

Figure 2.8 Velocity and concentration decay for the round free jet of methane into air.

So far no mention was made of the buoyancy forces that occur when a jet of different density is injected into air. At a certain distance away from the nozzle, where velocities are small, buoyant effects will become important. However, within the time scale relevant to engine operation, buoyancy effects could not be observed experimentally.

2.5 COMPRESSIBLE TURBULENT CONICAL SHEET JET OF METHANE INTO AIR

The previous discussion about compressible effects is applicable for the turbulent conical
sheet jet. The same treatment for the density can be applied, assuming that the concentration profile is equal to the square root of the velocity profile, as for the round free jet. The momentum and mass conservation equations for a conical sheet are then written

\[ \rho_n C_d A_n \frac{U_0^2}{4 \pi U_m x_1/2 \cos (\beta)} \rho_a \int_0^\infty \frac{a^2 (\xi) \, d\xi}{\chi_n g(\xi) \left( \frac{\rho_a}{\rho_g} - 1 \right) + 1} \] 

(2.57)

\[ \rho_n C_d A_n \frac{U_0}{4 \pi U_m x_1/2 \cos (\beta)} \rho_a \int_0^\infty \frac{g(\xi) f(\xi) \, d\xi}{\chi_n g(\xi) \left( \frac{\rho_a}{\rho_g} - 1 \right) + 1} \] 

(2.58)

In the previous section, experimental results from the British Gas Corporation were utilised to obtain the concentration decay of a binary mixture for a round free jet. For the conical sheet jet, such data are not available. Since concentration and velocity decay take a similar form for the round free jet, it is assumed that it is also true for the conical sheet. According to this assumption, the equation for the concentration decay would take the form

\[ \frac{\chi_m}{\chi_0} = \frac{k_4}{Z + Z_0} \sqrt{\left( R_s - 1 \right)_e} \] 

(2.59)

where the subscript \( \epsilon \) denotes the use of an effective area used to consider the difference in density between the incoming gas and the ambient. We can derive the effective area from the equivalent momentum concept of Thring and Newby, and replacing for the approximate area at the conical poppet nozzle (Equation 2.40):
\[ A_0 \rho_g U_0^2 = A_e \rho_a U_0^2 \]

\[ A_e = A_0 \frac{\rho_g}{\rho_a} \]

\[ 2\pi (R_e l_e) \cos(\beta) = 2\pi (R_s l) \cos(\beta) \frac{\rho_g}{\rho_a} \]

\[ (R_s l) = (R_e l_e) \frac{\rho_g}{\rho_a} \]

To get the equivalent momentum, changing only one of these two dimensions \((R_s, l)\) is sufficient. In our case the seat radius is fixed and it is more convenient to define an effective lift:

\[ l_e = l \left( \frac{\rho_g}{\rho_a} \right) \]

Equation 2.59 then takes the following form

\[ \frac{\chi_{\infty}}{\chi_0} = \frac{k_4}{z' + z_0} \sqrt{\frac{R_s}{l_e}} \]

The constant \(k_4\) is unknown, but it can be evaluated by assuming again that the spreading angle is similar to the one of a round free jet of methane into air. The solution of the system of equation was obtained for different values of \(k_4\) until one was found that yielded \(r_{1/2} \approx 0.11(z + z_0)\). A concentration decay constant \(k_4 = 2.14\) was found. With this constant, a velocity decay constant of 2.5 is obtained, while for the incompressible conical sheet jet of air into air, the velocity decay constant is 2.8. It is important to note that decay constants vary throughout the literature, and that the values proposed here are intended to be approximations.

There are three equations and three unknowns to express as a function of the axial distance \(z\). The integral in Equations 2.57 and 2.58 must be solved numerically. The solution remains simple and follows the following steps:

for \(0 < z < 50 \text{ mm}\)
1 - compute axial concentration from Equation 2.62,

2 - numerical integration in Equation 2.57,

3 - numerical integration in Equation 2.58,

4 - guess a value of the axial velocity $U_m'$,

5 - compute $r_{1/2}$ from mass conservation Equation 2.58,

6 - compute $U_m$ from momentum conservation Equation 2.57,

7 - repeat steps 5 and 6 until the difference between $U_m'$ and $U_m$ is small.

The concentration decay should be properly scaled when the axial distance is non-dimensionalized with $(R_sI')^{1/2}$. Figure 2.9 shows that this scaling is also appropriate for the velocity decay. The data plotted in Figure 2.8 were computed without making the approximation for the nozzle area (Equation 2.40).

![Figure 2.9 Velocity and concentration decay for the conical sheet jet. The concentration and velocity decay constants are 2.2 and 2.6 respectively.](image)
2.6 UNDEREXPANDED ROUND FREE JET

At this point it is unknown at which pressure ratio the natural gas injection will take place in the engine. Choking is necessary at the nozzle so that repeatable injection velocity and mass flow can be obtained. For natural gas flowing through a converging nozzle, choking occurs when the pressure ratio across the nozzle is greater than 1.86. To increase the penetration rate, pressure ratio greater than the critical one might be required. When the pressure ratio is greater than 1.86, the jet is not fully expanded at the nozzle, and expansion occurs outside the nozzle. Also, because the geometry of the nozzle is similar to a converging-diverging nozzle, supersonic velocities could occur at the nozzle exit. In both cases, the jet is underexpanded. The mechanism of the complex expansion process is well summarized in a paper by Ewan and Moodie [1986] and briefly in the next paragraph (see Figure 2.10).

Figure 2.10 Principal characteristics of the expansion process for an underexpanded jet.

When choking conditions are reached (M=1), further increase in upstream pressure forces the exit plane pressure to increase. As a result the jet expands outside the nozzle, where it accelerates. Expansion waves originate around the expansion point. They propagate in the high
velocity expansion region and are reflected as compression waves when they meet the outer layer. The coalescence of these compression waves results in a barrel shape shock surrounding the immediate surrounding of the supersonic region, and expanding for a few diameters. The barrel shock ends up in the axial direction as a normal shock (Mach disk) and subsequent reflected shocks. If the underexpansion is large, this process is repeated a number of times.

This complex problem has however been treated simply and successfully for a round free jet by at least two groups Moodie and Ewan [1986] and Birch, Brown, Dodson and Swaffield [1984]. The immediate effect of the underexpansion can be seen on the flow visualization pictures presented in the first of these papers. The jet increases in diameter suddenly as it expands outside the nozzle. It is possible to retain the analysis for correctly expanded jets described in the previous sections by defining a pseudo-diameter larger than the actual diameter. The underexpanded jet behaves therefore as if it is a correctly expanded jet emerging from a larger orifice. This concept is only valid of course at a certain distance away from the nozzle, where the jet is known to have little memory of its origin, but barrel lengths are shown to be no more than 3 diameters at pressure ratios up to 10.

The pseudo-diameter can be obtained from the assumption that the mass flow is conserved throughout the expansion, meaning that the mixing is negligible during the expansion process. Figure 2.11 illustrates an

**Figure 2.11** Schematic expansion with pseudo-diameter.
underexpanded jet and the parameters used in the analysis. It must be underlined that the representation in Figure 2.11 is a simplified illustration to describe the pseudo-diameter concept.

The mass flow at the orifice and at the pseudo-diameter are given respectively by

\[ Q_n = \frac{\pi}{4} C_d d_o^2 \rho_n U_n \]
\[ Q_e = \frac{\pi}{4} d_{ps}^2 \rho_e U_e \]

Because \( Q_n = Q_e \), the pseudo-diameter can be related to the real diameter by the following relationship:

\[ \left( \frac{d_{ps}}{d_o} \right)^2 = C_d \frac{U_n \rho_n}{U_e \rho_e} \]

The velocity is sonic both at the nozzle and at the pseudo-diameter. We can relate the conditions at the nozzle to the upstream conditions using compressible isentropic flow relationships and ideal perfect gas law.

\[ \left( \frac{d_{ps}}{d_o} \right)^2 = C_d \frac{\sqrt{T_n}}{\sqrt{T_e}} \frac{\rho_o}{\rho_e} \left( \frac{2}{k+1} \right)^{\frac{1}{k-1}} \]
\[ = C_d \frac{\sqrt{T_n}}{\sqrt{T_e}} \frac{P_o}{P_e} \left( \frac{T_e}{T_o} \right)^{\frac{2}{k+1}} \left( \frac{2}{k+1} \right)^{\frac{1}{k-1}} \]
\[ T_o = T_n \left( \frac{k+1}{2} \right) \text{ and } P_e = P_a \text{ so that} \]

\[ \left( \frac{d_{ps}}{d_o} \right)^2 = C_d \left( \frac{T_e}{T_n} \right)^{1/2} \left( \frac{P_o}{P_a} \right) \left( \frac{2}{k+1} \right)^{\frac{k}{k-1}} \]

In Birch et al., the temperature at end of expansion \( T_e \) and the temperature in the reservoir are assumed to be equal to the ambient temperature. Here it is preferred to assume that temperatures are similar at the nozzle and in the plane of the pseudo diameter, since the conditions are sonic at both locations. Ewans shows that for an upstream pressure of 20 atm the nozzle \( T_n = .85 \ T_o \) and at the pseudo diameter \( T_e = 0.8 \) to \( 0.9 \ T_o \), justifying this assumption. We therefore obtain
for natural gas

\[
\left( \frac{d_{ps}}{d_0} \right)^2 = C_d \left( \frac{P_o}{P_a} \right) \left( \frac{2}{k+1} \right)^{\frac{k}{k-1}}
\]

that reduces to

\[
d_{ps} = d_0 \sqrt{0.537 C_d \left( \frac{P_o}{P_a} \right)}
\]

Based on the different assumption for the temperature, Birch et al. obtained the same relation but with a constant of 0.582 instead of 0.537. This difference does not change the validity of their results, since the coefficient \(C_d\) is somehow empirical. Their experiments show very well that the axial concentration decay for underexpanded jets behaves just like a correctly expanded jet when scaled with the pseudo-diameter. The experimental evidence of that the pseudo-diameter can be used successfully to describe underexpanded jets shall be used in this research to apply our previous analysis to underexpanded jets. The concept can readily be applied to the round free jet analysis done in section 2.5. The radius must be replaced by the pseudo-radius, half the pseudo-diameter, before computing the results if the pressure ratio is greater than 1.86. Different cases were computed, and results are plotted in Figure 2.12. The concentration and velocity decay collapse when the axial distance is scaled with the following equivalent radius:

\[
x_{eq} = x_{ps} \left( \frac{\rho g}{\rho_a} \right)^{\frac{1}{2}} = \left[ x_o \left( \frac{\rho g}{\rho_a} \right)^{\frac{1}{2}} \right] \sqrt{0.537 C_d \frac{P_o}{P_a}}
\]

2.7 UNDEREXPANDED CONICAL SHEET JET

The same idea is exploited for the turbulent conical sheet jet thin sheet. An expression can be obtained for a pseudo-lift to replace the actual lift if the jet is underexpanded. We find that
Figure 2.12 Velocity and concentration decay for underexpanded round free jet of methane.

$$A_{ps} = 0.537 \pi \frac{C_d}{P_o/P_a}$$

$$2\pi (R_s l)_{ps} \cos(\beta) = 0.537 (2) \pi R_s l \cos(\beta) \frac{C_d}{P_o/P_a}$$

$$(R_s l)_{ps} = 0.537 R_s l C_d \frac{P_o}{P_a}$$

A change in the lift only is sufficient to provide equivalent mass flow, so that Equation 2.70 can be written

$$l_{ps} = 0.537 l C_d \frac{P_o}{P_a}$$

Scaling should then be provided by the equivalent lift
\[ l_{eq} = l_{ps} \left( \frac{\rho_g}{\rho_a} \right) \]

\[ l_{eq} = 0.537 \cdot l C_d \left( \frac{P_g}{\rho_a} \right) \left( \frac{P_o}{P_a} \right) \]

The pseudo-lift \( l_{ps} \) is replaced in the calculation of the conical sheet jet velocity and concentration decays when the pressure ratio is greater than 1.86. Again when different cases are computed, they collapse on a unique curve if the axial distance is non-dimensionalized with the square root of the \( R_s l_{eq} \) (Figure 2.13).

Figure 2.13  Velocity and concentration decay for underexpanded conical sheet jet.
3 TRANSIENT TURBULENT JET

J.S. Turner in 1962 modelled a starting plume as a steady buoyant plume feeding a vortex structure. His model was inspired by the observation of thermal plumes. Flow visualization of the early stages of impulsively started jets Batchelor [1967] revealed the formation of a vortex "mushroom" or "ball", suggesting that a model similar to the one used by Turner could be utilized for transient jets. Abramovich and Solan [1973] exploited that idea, and modelled a starting laminar jet as a quasi-steady state jet feeding a vortex structure. Witze [1980] applied the same model to a turbulent round free jet. The model predictions for the penetration of the jet compare very well with experimental measurements in the papers by Abramovich and Solan [1973] and Witze [1980]. In this section, the transient model will be presented first for a turbulent round free jet of air into air. Then the model will be adapted to take into account the injection of a different gas into air. Finally, the possibility of building such a model for the transient turbulent conical sheet jet will be examined.

3.1 INCOMPRESSIBLE TRANSIENT TURBULENT ROUND FREE JET

The transient model for the starting jet from a round orifice is illustrated in Figure 3.1. The jet is modelled as the combination of a quasi-steady turbulent jet feeding a spherical vortex structure. In the quasi-steady state region, the velocity profile is the one of the steady-state jet, described in chapter 2. The vortex structure is considered as a whole. It is modelled as a sphere of radius $R_\sigma$, possessing mass and momentum, travelling away from the nozzle in the z direction. The location, mass and momentum of the vortex change with time. The momentum of the structure is reduced by a drag force and by the need to accelerate the surrounding fluid.

There is a plane i at the back of the vortex where mass and momentum are being fed to
Figure 3.1 Proposed transient jet model.

the vortex structure by the quasi-steady jet. The plane is at a distance $z_v$ from the orifice. The position of the tip, also defined as the penetration, is $z_t$. Assuming that the back plane is close to the surface of the sphere at the axis, the relation between $z_t$ and $z_v$ is

$$z_t = z_v + 2R_v$$  \hspace{1cm} (3.1)

The velocity $U_v$ is the velocity of the back of the vortex structure, at the plane $i$. Because the vortex is expanding, the velocity at the centre of the vortex $U_c$ and the tip velocity $U_t$ differ from $U_v$, but are related by

$$U_c = U_v + \frac{dR_v}{dt} \hspace{1cm} U_t = U_v + 2 \frac{dR_v}{dt}$$  \hspace{1cm} (3.2)

At a point $(z_v, r)$ on the back plane $i$, there is exchange of momentum from the jet to the vortex only if the velocity in the jet $U(z_v, r)$ is greater than the velocity of the vortex $U_v$. The radius $r_v$,
is the radius in the plane $i$ where $U(z_r i_e) = U_v$.

Given that the velocity profile in the steady state jet is known, the location, mass and momentum of the vortex as a function of time can be calculated. For the incompressible jet, the following assumptions are made:

1) The vortex structure is modelled as a whole. It is assumed that the density is uniform in the structure and that its internal velocity field has no influence on its mean velocity.

2) The vortex receives mass from the jet only. It is assumed that no mixing takes place between the surface of the vortex and the surrounding fluid.

3) The expansion of the vortex is small compared to its velocity. The momentum of the jet can then be approximated by the product of the mass of the vortex and $U_v$.

The internal structure of the vortex is believed to have some effects on the penetration of the jet (McGregor [1974], Middelton [1975]), but these effects are small, and would add greatly to the difficulty of this analysis. Also, while most of the mass is fed by the jet, some surrounding gas will be entrained on the surface of the vortex. However, the good predictions reported in the literature suggest that the effects of assumptions 1) and 2) are secondary. The purpose of the third assumption is to simplify the calculation, but if the expansion $dR_v/dt$ was found to be significant compared to $U_v$, it could be taken into account.

In the steady-state part of the jet, the axial velocity is

\[
\frac{U_m}{U_o} = \frac{13.8}{(z+z_o)}
\]

and the velocity at a radius $r$ is
\[ U = U_m e^{-\ln(2) \frac{(r-r_c)^2}{(r_{1/2}-r_c)^2}} \]  

(3.4)

where \( r_c \) is the radius of the inviscid core, which is taken into account for the transient model.

In the inviscid core of length \( z_c \), the axial velocity is equal to the initial velocity. The radius \( r_c \) is evaluated by assuming that the central core vanishes linearly with the axial distance \( z \). When \( z \) is greater than \( z_c \), \( r_c = 0 \). At the interface between the steady state jet and the vortex, plane \( i \), we can write

\[ U_v = \frac{dz_v}{dt} \]  

(3.5)

For an incompressible jet of air into air, the density is uniform in the jet and in the vortex, and the rate of change in volume can be written:

\[ \frac{dV_v}{dt} = 2\pi \int_0^{r_e} (U-U_v) r dr \]  

(3.6)

where \( V_v \) is the volume of the vortex, and \( r_e \) is illustrated in Figure 3.1. The momentum change is

\[ \frac{dM_v}{dt} = 2\pi \int_0^{r_e} \rho_s (U-U_v) U r dr - \frac{f_{\text{accel.of \ fluid}}}{\text{surrounding}} - F_D \]  

(3.7)

where \( M_v \) is the momentum of the vortex and \( F_D \) is the drag force. The momentum loss due to the acceleration of the surrounding fluid is equal to the change in momentum of a virtual mass of surrounding fluid, where the virtual mass is the product of a fraction of the displaced volume by the density of the surrounding fluid (Milne-Thomson [1968]). For an accelerating sphere, the fraction is 1/2. The momentum change equation then becomes

\[ \frac{dM_v}{dt} = 2\pi \int_0^{r_e} \rho_s (U-U_v) U r dr - \frac{1}{2}\rho_s \frac{d(U_v V_v)}{dt} - F_D \]  

(3.8)

Equation 3.8 can be expressed as a function of \( U_v \) only by performing the following transformation:
replacing Equation 3.6 and 3.9 in Equation 3.8 yields

\[
\frac{dU_v}{dt} = \frac{4 \pi}{3 V_r} \int_0^{r_e} (U-U_v) U r dr - \frac{U_v}{V_r} \int_0^{r_e} (U-U_v) r dr - \frac{2}{3} \frac{F_d}{V_r \rho_a}
\]

(3.10)

The drag force is

\[
F_D = C_D \left( \frac{1}{2} \rho_a U_v^2 \right) \left( \pi R_v^2 \right)
\]

(3.11)

where \( C_D \) is the drag coefficient, and can be approximated by the drag coefficient of a sphere in a turbulent flow. Its value can be determined according to the Reynolds number of the vortex structure defined as \( \text{Re}_v = 2 \frac{U_v R_v}{v} \). Equations 3.5, 3.6 and 3.10 can be solved by successive iterations. The initial conditions are:

\[
z_v = z_o, \quad U_v = U_o, \quad V_v = \frac{4}{3} \pi r_o^3 \quad \text{at} \quad t = 0
\]

(3.12)

For given initial conditions, a solution for the system of equations is obtained in the following manner:

1) increment the time,

2) guess the vortex velocity \( U_v \) (the previous velocity is a good guess),

3) calculate \( z_v \) from 3.5,

4) calculate \( r_{1/2} \) and \( U_m \) for the steady state region at \( z = z_v \),

5) calculate the radius \( r_e \) where \( U(r_e, z_v) = U_v \). This radius is evaluated from Equation 3.4, replacing \( U \) by \( U_v \). After rearrangement:

\[
r_e = r_c + (r_{1/2} - r_c) \sqrt{-\ln \left( \frac{U_v}{U_m} \right) / \ln(2)}
\]

(3.13)

6) Integrate Equation 3.6 and obtain the vortex volume \( V_v \),

7) integrate Equation 3.10 and obtain a new vortex velocity \( U_v \) from the momentum
8) If the new value \( U_v \) differs from the guessed value repeat steps 3) to 7), otherwise increment time and repeat.

A solution was obtained for the round free jet of air into air and the results are compared with the data of Witze that can be found in a paper by Kuo and Bracco [1982]. The comparison is illustrated in Figure 3.2, and it can be seen that the model represents the data well. A constant drag coefficient \( C_D \) of 0.5 was used in the comparison computations. Witze matches the data better by utilizing a drag coefficient proportional to the velocity and size of the ball at a given time. The vortex expansion rate \( dR/dt \) was found to be in the worst case less than 5% of the velocity \( U_v \), indicating that assumption 3 is reasonable.

Figure 3.2 Comparison between computed case and Witze experiments. Case 1: \( U_o = 53 \) m/s. Case 2: \( U_o = 103 \) m/s. In both case the diameter of the orifice is 1.2 mm.

As shown briefly in section 2.1 on diesel sprays, and also shown in the literature, the tip penetration is proportional to the square root of time. This proportionality is illustrated in Figure
3.3 where the penetration for two different cases is plotted against the square root of time. The penetration is scaled by the orifice radius, while the time is scaled by \( r_o / U_o \). The proportionality to \( t^{1/2} \) is evident except in the early moments of the jet. The two cases are seen to collapse to a common curve, but that result is true only if the drag coefficient is independent of the vortex velocity and size.

Numerical simulation of the turbulent jet performed by Kuo and Bracco [1982] shows that the jet penetration is mildly dependent on the Reynolds number. They suggest that for the turbulent jet, the tip penetration should be scaled using \( r_o \cdot \text{Re}^{0.03} \), and that the time be scaled with \( r_o \cdot \text{Re}^{0.03} / U_o \). Witze's experimental data are shown to be well scaled with that Reynolds number dependency. Another interesting characteristic of the transient jet is illustrated in Figure 3.4 where the tip velocity and the axial velocity of the steady state are plotted as a function of the axial distance. It can be seen that the vortex head velocity is about half the steady-state velocity at any given point.

In the literature; the model is analyzed for a jet of air into air. In the following section, the model is extended to a round free jet of methane into air.

3.2 TRANSIENT TURBULENT ROUND FREE JET OF METHANE INTO AIR

When a gas with a different density is injected into air, the model must be modified to take into account the fact that the rate of change of the vortex mass depends on the extent of the mixing between the gas and the air in the jet. The vortex is now composed of a mixture of two gases of different densities. Its mass depends on the respective amount of each gas. There is therefore an extra variable required to describe the vortex structure. The methane content\(^1\) of

\(^1\) To keep the analysis applicable to any gas, it should be called the secondary gas content. Methane content is utilised for clarity.
Figure 3.3 Proportionality between tip penetration and the square root of time.

Figure 3.4 Comparison between the tip velocity and the steady-state axial velocity. $U_o = 53 \text{ m/s}$, $d_o = 1.2 \text{ mm}$.

the vortex $m_{v}$ is defined, as the mass of methane present in the vortex at a given time.
The same assumptions as in section 3.1 are made, adding the following one:

- The mixture of gas in the vortex is uniform.

With this assumption, the mass concentration of the vortex \( \chi_v \), can be defined as

\[
\chi_v = \frac{m_{gv}}{m_{gv} + m_{av}} = \frac{m_{gv}}{m_v}
\]  

(3.14)

where \( m_{av} \) is the mass of air in the vortex and \( m_v \) is the total mass of the vortex. Similarly the vortex density can be defined, and is related to the concentration by:

\[
\rho_v = \frac{\rho_a}{\chi_v (\frac{\rho_a}{\rho_g} - 1) + 1}
\]  

(3.15)

There are now four equations: i) the change in position, ii) the change in total vortex mass, iii) the change in methane content and iv) the change in momentum.

i) The change in position of the vortex is

\[
U_v = \frac{dz_v}{dt}
\]  

(3.16)

ii) The change in mass is expressed by

\[
\frac{dm_v}{dt} = 2\pi \int_0^r \rho (U - U_v) r dr
\]  

(3.17)

where \( \rho \) is the density at a radius \( r \) and at position \( z_c \) in the steady-state section. The density is related to the mass concentration:

\[
\rho = \frac{\rho_a}{\chi (\frac{\rho_a}{\rho_g} - 1) + 1}
\]  

(3.18)

and the concentration in the steady state part is given by:

\[
\chi = \chi_m e^{-\frac{\ln(2)}{2} \frac{(r-r_c)^2}{(r_{1/2}-r_c)^2}} \quad \text{and} \quad \chi_m = \frac{4}{(z+z_o)}
\]  

\[
T_{eq}
\]  

(3.19)

The velocity \( U \) is obtained from Equation 3.4. The velocity \( U_m \) is obtained from the steady-state
solution. It is convenient for the transient case to express the axial velocity decay in the steady-state jet with an equation similar to 3.3. The decay constant can be obtained by fitting the results of the steady-state calculation.

iii) The change in methane mass content:

\[
\frac{dm_{gV}}{dt} = 2\pi \int_0^{r_e} \alpha \rho_g (U - U_v) r dr
\]  

where \( \alpha \) is the volume concentration of methane at the back plane of the vortex at a radius \( r \).

Recalling Equation 2.53 for the relationship between the volume and mass fraction, Equation 3.20 yields

\[
\frac{dm_{gV}}{dt} = 2\pi \rho_a \int_0^{r_e} \frac{\chi (U - U_v) r dr}{\chi (\frac{\rho_a}{\rho_g} - 1) + 1}
\]  

iv) The change in momentum:

\[
\frac{dM_v}{dt} = 2\pi \int_0^{r_e} \rho (U - U_v) U r dr - \frac{1}{2} \rho_a \frac{d(U_V V_v)}{dt} - F_D
\]  

A different transformation than for the previous case is performed here since the density of the vortex differs from the ambient density and changes with time:

\[
\frac{dM_v}{dt} = \frac{d(U_V V_v)}{dt} = \rho_v \frac{d(U_V V_v)}{dt} + U_V V_v \frac{d\rho_v}{dt}
\]  

this can be rearranged to

\[
\frac{d(U_V V_v)}{dt} = \frac{1}{\rho_v} \left[ \frac{dM_v}{dt} - U_V V_v \frac{d\rho_v}{dt} \right]
\]  

Using Equation 3.24 in the momentum equation 3.22, replacing the density with Equation 3.18 and rearranging yields

\[
(1 + \frac{1}{2} \frac{\rho_a}{\rho_v}) \frac{dM_v}{dt} = 2\pi \rho_a \int_0^{r_e} \frac{(U - U_v) U r dr}{\chi (\frac{\rho_a}{\rho_g} - 1) + 1} + \frac{1}{2} \rho_a U_V V_v \frac{d\rho_v}{dt} - F_D
\]  

The density change is obtained by differentiating Equation 3.15:
The solution of Equations 3.16, 3.17, 3.21 and 3.25 provides the location, total mass, methane content and momentum of the vortex as a function of time. The volume and the radius of the vortex can be inferred from its mass and density, and the velocity from its momentum and mass. The initial conditions are the following

\[ z_v = z_o, \quad ρ_v = ρ_n, \quad m_v = ρ_n \frac{4}{3} πr_p^3, \quad m_{\text{gas}} = m_v, \quad M_v = m_v U_o \quad \text{at} \quad t = 0 \quad (3.28) \]

where \( ρ_n \) is the density of the gas at the nozzle, and \( r_p \) is the pseudo-radius so that underexpansion can be considered if applicable. The solution of the system of equations follows similar steps to the ones outlined in section 3.1. More details regarding the non-dimensional solution of a transient jet of methane into air are given in section 3.3.2.

The solution for the penetration of a round free jet of methane was obtained using the same drag coefficient as for the air jet. Results are illustrated in Figure 3.5, where the penetration of the methane jet is compared with the penetration of an air jet with a same orifice size and a same initial velocity. The methane jet penetration is slower then the air jet, since the initial momentum of the methane jet is almost 50% smaller than the one of the air jet. The circles on Figure 3.5 are representatives of the vortex size, and are obtained by plotting the

\[ \frac{dp_v}{dt} = \frac{ρ_a (1 - \frac{ρ_a}{ρ_g})}{[ρ_v (\frac{ρ_a}{ρ_g} - 1) + 1]^2} \frac{dρ_v}{dt} \quad (3.26) \]

\[ \frac{dp_v}{dt} = \frac{ρ_a (1 - \frac{ρ_a}{ρ_g})}{[ρ_v (\frac{ρ_a}{ρ_g} - 1) + 1]^2} \frac{dm_{\text{gas}}}{dt} = \frac{dm_v}{dt} \quad (3.27) \]
penetration at the back plane $z$, as well as the tip penetration $z_t$.

Figure 3.5 Penetrations of the air jet and of the methane jet. $U_0 = 256.8$ m/s and $r_e = 0.6$ mm. The pressure ratio is smaller for the methane jet.

Unfortunately, there are no experimental data to verify the validity of the model. However the comparison with the jet of air into air indicates that the model is reasonable. Compressibility effects are partially taken into account; the gas expansion in the nozzle is considered, but the local compressibility effects in the area close to the nozzle exit are not considered. By using the solution for the steady-state jet of methane, underexpanded jets can also be taken into account in the solution of the transient jet.

3.3 TRANSIENT CONICAL SHEET JET OF METHANE INTO AIR

Exploiting the same idea, the conical sheet jet can be modelled as a quasi steady-state
conical sheet jet feeding a vortex structure. The model is illustrated in Figure 3.6. The vortex structure has a toroidal shape. The assumptions are identical to the one stated in the previous sections. For the steady-state section of the jet, the velocity and concentration profiles are the ones developed in chapter 2. The change in location, in total mass, in methane content and in momentum of the vortex structure at the back plane of the torus can be expressed in forms similar to those derived for the round free jet of methane into air.

Figure 3.6 Model for the transient conical sheet jet.

i) The change in location:

\[ U_v = \frac{dz_v}{dt} \]  

(3.29)

ii) The rate of change in total mass:
\[
\frac{dm_v}{dt} = 2 \int_0^{r_e} \rho (U-U_v) 2\pi z_v \cos(\beta) \, dr \\
= 4\pi z_v \cos(\beta) \rho a \int_0^{r_e} \frac{(U-U_v)}{\chi \left(\frac{\rho_a}{\rho_g} - 1\right) + 1} \, dr \\
\tag{3.30}
\]

The concentration and velocity decays are obtained from the steady-state solution.

iii) The rate of change in methane content:

\[
\frac{dm_{\text{gas}}}{dt} = 4\pi z_v \cos(\beta) \rho_a \int_0^{r_e} \frac{\chi (U-U_v) \, dr}{\chi \left(\frac{\rho_a}{\rho_g} - 1\right) + 1} \\
\tag{3.31}
\]

iv) The change in momentum:

\[
\frac{dM_v}{dt} = 4\pi z_v \cos(\beta) \rho_a \int_0^{r_e} \frac{(U-U_v) U \, dr}{\chi \left(\frac{\rho_a}{\rho_g} - 1\right) + 1} \text{ accel. of surrounding fluid} - F_d \\
\tag{3.32}
\]

The acceleration of the surrounding fluid can be approximated by the case of an accelerating cylinder, for which it is given by

\[
\rho_a \frac{d(U_v V_v)}{dt} \\
\tag{3.33}
\]

Replacing in Equation 3.32 and utilizing the substitution given by Equation 3.24, the change in momentum is

\[
(1 + \frac{\rho_a}{\rho_v}) \frac{dM_v}{dt} = 4\pi z_v \cos(\beta) \rho_a \int_0^{r_e} \frac{(U-U_v) U \, dr}{\chi \left(\frac{\rho_a}{\rho_g} - 1\right) + 1} + \frac{\rho_a U_v V_v \frac{d\rho_v}{dt}}{\rho_v} - F_d \\
\tag{3.34}
\]

The change in density is given by Equation 3.27. The drag force is proportional to the frontal area:
\[ F_D = C_D \left( \frac{1}{2} \rho_a U_{v'} \right) \left( 4\pi (z_v + R_v) \cos (\beta) R_v \right) \]  

where \( R_v \) is the radius of the torus. \( C_D \) can be approximated by the drag coefficient of a cylinder, that is equal to one if the vortex Reynolds number \( \text{Re}_v \) is greater than \( 10^3 \). The volume of the torus is given by

\[ V_v = 2\pi^2 (z_v + R_v) \cos (\beta) R_v^2 \]

and the initial conditions are

\[ z_v = z_{0v}, \quad U_v = U_{0v}, \quad V_v = 2\pi^2 \left( z_v + \frac{1}{2} \frac{l_{ps}}{2} \right) \cos (\beta) \left( \frac{l_{ps}}{2} \right)^2, \]

\[ m_v = p_v V_v, \quad m_{gv} = m_v, \quad M_v = m_v U_v \] at \( t = 0 \)

where \( l_{ps} \) is the lift corrected for underexpansion if applicable. The solution is discussed in section 3.3.1. The penetration of the conical sheet jet is readily compared with the penetration of a round jet in Figure 3.7. The pressure ratio in both cases is 2, and the size of the round orifices was chosen so it would yield \( 1/7^{th} \) of the total area of the conical nozzle (since the Detroit Diesel 71-series injectors have 7 holes). The tip penetration of the conical sheet is compared with the tip penetration of the round jet from one of the 7 holes. It can be seen that penetration is approximately 30% lower for the conical sheet jet.

### 3.3.1 Scaling and Dimensional Analysis

In the analysis of the steady-state conical jet, some scaling factors were obtained. The following equations summarize the conditions in the steady-state part, taken at the back plane of the vortex, at \( z = z_v \).
Figure 3.7 Penetration comparison between a round jet and a conical jet. \( U_o = 422.8 \text{ m/s, } l = 0.1 \text{ mm, } r_o = 0.31 \text{ mm, } C_d = 0.5 \) for round jet, \( C_d = 1 \) for conical jet.

\[
\frac{U}{U_m} = e^{-\ln(2) \left( \frac{r}{r_{1/2}} \right)^2} \quad \text{and} \quad \frac{U_m}{U_o} = \frac{k_1}{\sqrt{R_s l_{eq}}}
\]

\[
\frac{\chi}{\chi_m} = e^{-\frac{1}{2} \ln(2) \left( \frac{r}{r_{1/2}} \right)^2} \quad \text{and} \quad \frac{\chi_m}{\chi} = \frac{k_2}{\sqrt{R_s l_{eq}}}
\]

\[
\frac{r_{1/2}}{\sqrt{R_s l_{eq}}} = k_3 \frac{z_v}{\sqrt{R_s l_{eq}}}
\]

where \( l_{eq} \) is given by

\[
l_{eq} = l C_d \frac{\rho_g}{\rho_a} \quad \text{if } \frac{p_o}{p_a} < 1.86
\]

\[
l_{eq} = 0.537 l C_d \frac{\rho_g p_o}{\rho_a p_a} \quad \text{if } \frac{p_o}{p_a} > 1.86
\]

Also
The term \((R_s l_{eq})^{1/2}\) is seen to be a natural scaling factor having length dimension for the jet emerging from the conical nozzle. The velocity \(U_o\) is the scaling factor for velocities. For the transient case, the time needs to be scaled. For the round free jet, it is shown in the literature that \(r_o/U_o\) is an appropriate time scaling factor for the round free jet (Kuo and Bracco [1982]). Following the same idea, the time can be scaled with \((R_s l_{eq})^{1/2}/U_o\) for the conical sheet jet. Two cases were computed and scaled using these parameters and are illustrated in Figure 3.8, where it is seen that the proposed time scaling factor is adequate. It was shown in section 3.1 that for the round free the jet penetration is proportional to the square root of time. The two cases in Figure 3.8 are plotted in Figure 3.9 where it is seen that the penetration of the conical sheet jet is also directly proportional to the square root of time. In Figure 3.9, the data are also scaled with the proposed scaling parameters.

Utilising the scaling factors and the steady-state Equations 3.38 to 3.42, the equations describing the rate of change of position, mass and momentum of the vortex can be non-dimensionalized. The non-dimensional transient vortex equations are given in appendix A. The following dimensionless parameters are first defined:

\[
\begin{align*}
L &= \sqrt{R_s T_{eq}} , \\
Z_v^* &= \frac{Z_v}{L} , \\
t^* &= \frac{t U_o}{L} , \\
U_v^* &= \frac{U_v}{U_o} \\
E^*_v &= \frac{E_v}{\rho_a L^3} , \\
E_{gv}^* &= \frac{E_{gv}}{\rho_a L^3} , \\
M_v^* &= \frac{M_v}{\rho_a L^3 U_o} , \\
R_v^* &= \frac{R_v}{L}
\end{align*}
\]  

(3.43)

It is found that, given \(\rho_g/\rho_a\), \(\beta\) and the steady-state constants \(k_1, k_2\) and \(k_3\), the change in position, mass, methane content and momentum of the vortex can be expressed as function of the following parameters:
Figure 3.8 Penetration of a conical sheet jet as a function of time. For the case illustrated, \( \text{Re}_i=20 \), \( C_d=0.85 \) and \( C_D=1 \).

Figure 3.9 Penetration of the conical sheet jet as a function of the square root of time. Same cases as in figure 3.8.
The initial conditions can also be stated in dimensionless form:

\[ a t \ t^* = 0 : \ z_v^* = \frac{z_o}{L}, \ R_v^* = \frac{\frac{1}{2} L_{eq}}{L}, \ U_v^* = 1 \] (3.48)

The solution of the system of equations is obtained by solving simultaneously Equation 3.44, 3.45, 3.46 and 3.47. The general method of solution follows these steps:

For \( 0 < t^* < t^*_\text{end} \)

1) \( U_v^* \) is guessed,

2) \( z_v^* \) is obtained from 3.44,

3) \( m_v^* \) is obtained from 3.45,

4) \( m_{gv}^* \) is obtained from 3.46,

5) \( M_v^* \) is obtained from 3.47,

6) \( U_v^* \) is computed from:

\[ U_v^* = \frac{M_v^*}{m_v^*} \] (3.49)

7) if the vortex velocity and the guessed value differ, repeat step 2) to 7), otherwise continue.

8) calculate the radius \( R_v \) from the mass and density of the vortex,

9) calculate the tip penetration from:
The tip penetration of the turbulent conical sheet jet in an unbounded space is seen to be dependent on the following initial parameters:

\[ z_t^* = z_v^* + 2R_v^* \]  \hspace{1cm} (3.50)

10) increment time and repeat.

The turbulent Reynolds number for the conical sheet jet could only be estimated and its value could not be obtained experimentally. Penetration computation for different turbulent Reynolds number were performed in order to establish its effect on the model. The turbulent Reynolds number \( U_{mr} / \nu_t \) is seen in Figure 3.10 to have a small effect on the conical sheet jet penetration rate.

Similarly, the nozzle discharge coefficient is not known accurately, so the sensitivity of the model to its variation has been verified. It is seen in Figure 3.11 that the model is not very sensitive to a change in discharge coefficient.

The drag coefficient of the vortex was approximated by the one of a cylinder given a Reynolds number greater than \( 10^5 \). A drag coefficient 20% larger was tried and showed very small effect on the penetration of the vortex, as seen in Figure 3.12. For all cases, the pressure ratio is 2 and the lift is 0.056 mm.

\[ \frac{z_t}{\sqrt{R_e L_{eq}}} = f\left( \frac{tU_o}{\sqrt{R_e L_{eq}}}, \beta, \frac{\rho_g}{\rho_a} \right) \]  \hspace{1cm} (3.51)

given the steady-state constants \( k_1, k_2 \) and \( k_3 \). The equivalent lift for a nozzle choked at the exit plane is

\[ I_{eq} = 0.537 C_d l \frac{\rho_g P_o}{\rho_a P_a} \]  \hspace{1cm} (3.52)

3.3.2 Model Sensitivity

The turbulent Reynolds number for the conical sheet jet could only be estimated and its value could not be obtained experimentally. Penetration computation for different turbulent Reynolds number were performed in order to establish its effect on the model. The turbulent Reynolds number \( U_{mr} r_{1/2} / \nu_t \) is seen in Figure 3.10 to have a small effect on the conical sheet jet penetration rate.

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Figure 3.10 Effect of turbulent Reynolds number on penetration of the conical sheet jet. The pressure ratio is 2 and the lift is 0.056 mm.

Figure 3.11 Effect of discharge coefficient on conical sheet jet penetration. Pressure ratio of 2 and lift of 0.056 mm.
Figure 3.12 Effect of vortex drag coefficient on the jet penetration. Pressure ratio of 2 and lift of 0.056 mm.
4 EXPERIMENTAL APPARATUS AND PROCEDURE

4.1 DESCRIPTION OF EXPERIMENTAL WORK

The objective of the experimental work was to obtain knowledge about the natural gas injection from the prototype injector, investigating in particular the penetration characteristics and the effects of tip geometry on the gas diffusion. Flow visualization was chosen as the experimental method, providing the qualitative and quantitative information necessary to meet the experimental objectives. Since experimental data regarding the conical sheet jet could not be found in the literature, flow visualization was particularly suited to obtain a first descriptive account of this type of jet\(^1\). It is interesting to note that flow visualization has been widely used in diesel research, and specifically in diesel spray penetration.

There are three methods especially suited to visualize flows involving gas of different densities. All of them are based on the principle that the refraction index in a medium is proportional to its density. The three methods are shadowgraph, schlieren and interferometry photography. Without entering into the details of each method, it can be said that schlieren photography is more sensitive to density change than the shadowgraph method. Interferometry is interesting when actual density measurements are desired, but also requires a more elaborate experimental apparatus. Schlieren photography was the main method employed in this project, but shadowgraph photographs were also taken. More details on the flow visualization method will be given in section 4.3.3.

The visualization of the gas injection in a pressurized cylindrical chamber has limitations.

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\(^1\) Hot wire anemometry was also considered and would be very useful to verify velocity profiles in the steady-state jet. In retrospect, however, it would have been difficult to obtain results without any certain knowledge of the conical sheet. The use of a concentration probe and of laser doppler velocimetry were discarded because of their limits and difficult usage in short duration jets. Laser induced fluorescence was also considered.
Visualization can either be done through the top and bottom of the cylinder, or through side windows. The curvature of the wall diminishes the potential of visualization through side windows; the field of view is limited when conventional optics are utilised, unless the geometry of the chamber can be modified. Alternatively corrective cylindrical lenses can be used. A top view gives only the radial aspect of the flow, withholding valuable information about the unknown flow pattern in the axial direction. For these reasons, it was decided to perform two visualization experiments. First, injection of gas from the prototype injector into atmospheric conditions would be performed, and the jet visualized laterally. Second, the gas would be injected into a cylindrical chamber, and visualization would be done radially. These experiments are illustrated in Figures 4.1 and 4.2.

The first method provides a basis for the penetration characteristics of conical sheet jets, and will supply data to verify the integral model used to predict jet penetration in chapter 3. In addition, it gives qualitative and quantitative information about axial and radial penetration, and about the jet angle. Pressure ratios similar to or larger than the ones used in the engine can be attained, and the effect of pressure ratio variation can be assessed. Geometrical parameters such

![Figure 4.1](image1.png)  
**Figure 4.1** Experimental set 1; flow visualization of jet under atmospheric conditions.

![Figure 4.2](image2.png)  
**Figure 4.2** Experimental set 2; flow visualization of jet within the pressurized chamber.
as the poppet lift and angle, the presence of a top wall, the presence of a bottom and side walls with different spacing from the top wall will also be studied.

In the second set of experiments, the gas injection will be first performed into a cylindrical chamber at atmospheric pressure, permitting to study the effects of the pressure rise and of the cylinder walls on the jet penetration. The pressure rise is caused by the injection of gas into a sealed cylinder. The jet penetration can be compared to results obtained in the first set of experiments. The initial pressure in the cylinder will be increased, while keeping the same pressure ratios as the one previously used, in order to investigate the Reynolds number effect. However, it was decided to limit the pressure in the cylinder to a fraction of the engine cylinder pressure, reducing the time, the technical difficulties and the experimental cost. It should be mentioned that the early stages of injection will be hidden by the presence of the injector itself (see Figure 4.2).

The effect of the swirl and of the piston motion on the jet diffusion have not been studied experimentally as a consequence of both technical and time constraints. As mentioned previously, combustion, and the pressure rise associated with it, will not be studied experimentally in this particular project.

Each component and aspects of the experimental set-up and procedure are described in more details in the following sections, but first similarity questions are discussed.

4.2 SIMILARITY

In this section the relation between the flow visualization experimental conditions and the engine conditions is examined. As mentioned in the first section of this chapter, the conditions of the experiments will not match all conditions of the injection in a diesel engine. In order to establish the consequences of this incomplete similarity, the major parameters on which the jet
penetration depends are identified. From the observation of these parameters, the relationship between the experiment and the engine condition can be assessed.

Figure 4.3 Principal parameters relevant to similarity.

Figure 4.3 illustrates the major parameters for the injection of gas into a combustion chamber. The parameters can be divided into two distinct groups. The first one contains the parameters directly related to the penetration of the free turbulent conical sheet jet (unbounded). The second group contains the geometrical parameters regarding the combustion chamber.

The parameters regarding the conical sheet were identified in chapter 3 and are summarized here:
The equivalent radius \( l_{eq} \) is

\[
\frac{z_t}{\sqrt{R_{eq}^2}} = f \left( \frac{t U_o}{\sqrt{R_{eq}^2}}, \frac{\rho_g}{\rho_a}, \beta \right)
\]

(4.1)

The equivalent radius \( l_{eq} \) is

\[
l_{eq} = 0.537 C_d l \left( \frac{\rho_g}{\rho_a} \right) \left( \frac{P_0}{P_a} \right)
\]

(4.2)

when \( P_j/P_a \) is greater than 1.86. In the density ratio \( \rho_g/\rho_a \), the densities of air and methane are taken at the same temperature and pressure. The penetration is also dependent on two other parameters that were not considered in the model. First is the Reynolds number of the flow at the nozzle, which for large enough values was assumed to have little effect on the jet penetration. Second is the injection duration \( t \), that was not modelled in the previous chapter. The Reynolds number is already dimensionless. The injection duration can take the same scaling as the time.

\[
\frac{z_t}{\sqrt{R_{eq}^2}} = f \left( \frac{t U_o}{\sqrt{R_{eq}^2}}, \frac{\rho_g}{\rho_a}, \beta, \frac{t U_o}{\sqrt{R_{eq}^2}}, \frac{\rho_n U_o l}{\mu} \right)
\]

(4.3)

Methane will be injected in the flow visualization experiments, so that the ratio \( \rho_g/\rho_a \) is roughly the same as in the engine (where natural gas is utilised). Different poppet angles \( \beta \) were manufactured to match the ones proposed for usage in the engine. The seat radius \( R_s \) of the poppet is the same for the injector used in the flow visualization experiments and the one used in the engine. Then if \( U_o, l_{eq}, Re \) and \( t \) are the same for the flow visualization experiments and for the engine, the penetration of the conical jet should be the same.

1) For a choked flow at the nozzle, and assuming that in both cases the temperature of the gas before injection is ambient, the initial velocity \( U_o \) will be the same.

2) The equivalent lift must be the same. The methane to air density ratio is practically
the same as the natural gas to air density ratio. The pressure ratio can also be matched. Then, given that the nominal lift can be matched, the equivalent lift will be the same.

3) The injection time $t_i$ in the flow visualization will be shown to be longer than the one in the engine. Nevertheless, the effect of the injection duration on the jet penetration will be investigated experimentally and is discussed in section 4.3.1.

4) Finally the Reynolds number will differ in the engine because the upstream pressure is higher\(^2\). With a pressure ratio of 2, and a lift of 0.1 mm, the Reynolds number in the engine is in the order of $5 \times 10^5$, while in the rig, allowing for correction to the lift because of underexpansion, the Reynolds number for a pressure ratio of 3.5 is approximately $4 \times 10^4$. Roughly, the Reynolds number in the rig is 10 times lower than in the engine. Fortunately, turbulent jets are moderately dependent on the Reynolds number. In Kuo and Bracco [19821, the turbulent round free jet is found to be dependent on $Re^{0.053}$. This dependency would cause small differences between the atmospheric rig and the engine conditions. The effect of the Reynolds number was investigated experimentally to determine the extent of the Reynolds number dependency for the turbulent conical sheet jet.

The second set of parameters includes the height and diameter of the chamber at a given point. These parameters can be non-dimensionalized with $(R_s \ l_{eq})^{1/2}$. The penetration then depends on the following parameters:

\(^2\) The lift could in principle be increased to increase the Reynolds number. However there is a point where the lift can no longer be increased while conserving choked flow conditions at the nozzle.
The diameter of the cylindrical chamber that will be used in the second set of flow visualization experiments is the same as the engine chamber (series 71). The height can be adjusted. The offset from the top wall could also have been considered, but its effect is more qualitative than quantitative. In the experiments, the offset will be kept the same as in the engine. The piston shape is another factor not included in the list of parameters. A piston shape was modelled for utilization in the atmospheric rig.

In summary, the experiments relate to the engine conditions in the following manner: for both sets of experiments, the penetration should be similar to the one occurring in the engine if the equivalent lift (nominal lift, pressure ratio and density ratio) and the initial velocity are matched and if the effects the Reynolds number is small. Because the injection duration is longer in the flow visualization experiments, the penetration would be similar only during the time of the injection. The similitude between the penetration in the engine and the one in the atmospheric experiments depends also on the magnitude of the sealed cylinder effect.
4.3 DESCRIPTION OF APPARATUS

4.3.1 Injection System And Control

In the engine the injector is actuated with a cam, that is not ideal for a flow visualization rig. Since only one injection at a time is needed, a simpler actuation mechanism can be used. A pneumatic actuation system was chosen because it is simple and clean. Also, compressed air is readily available, and there are some compact fast-acting valves for compressed air. The injector and the actuator are illustrated in Figure 4.4.

The pneumatic actuator was designed so that it would replace the upper part of the prototype injector. The body and internal parts of the prototype injector used for the engine experiments were used in the flow visualization experiments. High pressure air is allowed into the upper chamber by a fast-acting 3-way solenoid valve, causing the main plunger to force the poppet down via an intermediate rod. When power to the solenoid valve stops, the air in the upper chamber escapes by a vent port which opens when the valve closes, and the return spring closes the poppet. The high speed valve is a 3-way Servojet HSV 3000, with an opening time of 2 ms. The valve is operated from a controller board, which provides power to the solenoid when a trigger signal is input to the board. A line from the computer parallel port is used as the trigger signal. The power is supplied by a 12V, 4 amperes regulated power supply. Compressed air regulated at 3.45 MPag (500 psig) is used to actuate the plunger, ensuring quick opening. Since the actuating pressure is smaller than in the engine, the return spring was changed for one with an appropriate spring constant. Methane was used as an injected gas. Since a very small quantity is being injected during each injection, and since the time between each injection is relatively long (15 - 30 seconds), the methane is released directly into the air. A solenoid shut-off valve was placed in the gas line, and the switch kept accessible to immediately shut off the gas in case of a leak at the nozzle.
Figure 4.4 Pneumatic actuator and prototype injector.
The displacement of the poppet is limited by the seat under the poppet cap (see Figure 4.4). The poppet cap is screwed onto the poppet stem, allowing the lift to be varied by the extent to which the cap is screwed on the stem\(^3\). The actual lift of the poppet could be measured with a dial displacement meter with an accuracy of 0.006 mm (0.25 thousandth of an inch). The dial meter was placed under the poppet, and measurement was taken with the poppet kept open. The adjustment is better made when the injector is disassembled. To verify that lift values and characteristic times of the poppet lift were repeatable, the trace of the lift was obtained using a non-contact magnetic displacement sensor (proximitor). With the appropriate power supply, the

\[^3\] This is true only of the first version of the prototype injector. The newest versions have a fixed lift and a different design to limit the lift.
sensor outputs a signal proportional to the displacement. The calibration of the sensor is 200 mV/thousandth of an inch (7874 mV/mm). Calibration was double-checked with the values obtained by the dial displacement gage and found to be in good agreement. The output signal from the proximitor was recorded on a Nicolet 3071 oscilloscope, and then transferred to an 286 AT computer for further analysis. The signal sent to the high speed valve triggered the acquisition on the scope so that the delay between the signal and the poppet opening would be known. Figure 4.6 shows a typical lift trace.

Preliminary results indicated that the lift was increasing due to a slow unscrewing of the poppet cap as injections were performed. This problem was solved and subsequently the lift was found to be repeatable. The delay between the trigger pulse to the high speed valve and the beginning of opening is of approximately 5 ms. The duration of opening is in the order of 1 ms, the poppet being fully open just before 6 ms. The effects of pressure ratio, actuation pressure and pulse width to the high speed valve were analyzed with the proximitor, and the results are reported in Table 4.1.

The results are characterized by some scattering, partially due to the noise and the vibration of the injection system rendering difficult the precise identification of the time of the observed parameters. According to these results, the delay between the trigger signal to the high speed valve and the beginning of opening is fairly constant at 4.6 ± 0.1 ms when the actuation pressure is 3.45 MPag. Remarkably the duration of the opening process is not very sensitive to change in upstream pressure or nominal lift. The scattered data renders it difficult to ascertain definite effects when these parameters are changed. The length of the opening is approximately 1.25 ± 0.1 ms., but a careful examination of the lift traces shows that in fact 90% of the opening (starting at 10% of total lift and ending at total lift) is done in approximately 0.62 ms. This difference is caused by a slow rise in the early stage of pressurization, and can be seen in Figure
Figure 4.6 Lift trace obtained from a proximiter. In this case, the pressure ratio was 1 and the pulse width 5 ms.

4.6. A minimum pulse width of 4 ms is required to obtain a full opening of the poppet. Increasing the pulse width results in a proportional increase of the total length of injection. An increase of 1 ms roughly increases the total length by about 3.5 ms. The actuation pressure has a very definite effect on the transient characteristics of the opening. Smaller actuation pressure increases significantly the length of the opening, and if too low, does not provide a complete opening of the poppet. An actuation pressure of 3.45 MPag (500 psig) was judged to be adequate, yielding complete opening at each trial in a reasonably short time. When the injector is operated in the engine, the pressure build-up to open the poppet is much greater (30000 psig, 202.7 MPag), but the return spring is also much stronger. At this stage, the exact opening time of the poppet in the engine is unknown, but is estimated to be 0.1 ms. The length of injection
Table 4.1 AP : actuation pressure (MPag), PR : pressure ratio, PW : pulse width (ms), NL : nominal lift (thou), BO : beginning of opening (ms, 1% of NL), EO : end of opening (ms, top of 1st peak), CL : closure (ms, 10% of NL), OD : duration of opening (ms, EO-BO), TL : total length of opening (ms, CL-BO). t = 0 ms when signal is sent to high-speed valve.

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Given an engine speed of 1000 RPM, and a injection duration of 13 degrees (idle conditions), the injection length is approximately 2.2 ms. For an engine speed of 2000 RPM and a duration of 15 degrees, the injection length is 1.25 ms.
the jet starts later than the actual opening. The longer total opening will however prevent an accurate study of the deceleration rate of the jet once its feeding stops.

An important consideration linked with the lift is choking. To maintain constant operation, the flow must be choked at the nozzle. To obtain choking, the upstream pressure to ambient pressure ratio must be greater than the critical pressure ratio. Also, the area at the nozzle must be smaller than the smallest orifice size in the CNG port. Since ports in the injector have large lengths compared to their diameters, friction choking can occur. According to approximate calculations using one-dimensional isentropic flow with friction described in appendix C, the maximum lift yielding choking at the nozzle for the version of the prototype injector employed is 0.089 mm (0.0035").

4.3.2 Atmospheric Injection Rig And Cylindrical Chamber

As discussed in section 4.1, two separate sets of experiments were conducted. The first one was a lateral visualization of an injection in an atmospheric pressure, while the second one was the axial visualization of the injection in a pressurized chamber (Figures 4.1 and 4.2). In this section the two arrangements required for these two experiments are described.

The first set up is a simple adjustable holder for the injector, and is illustrated in Figure 4.7. The threaded rods allow the positioning of the top or bottom wall, either for the purpose of flow visualization or for observing wall effects. Configuration #1 is used for a free injection, without any constraint on the flow. Configuration #2 positions the injector tip just below the top wall, as in the engine. The offset is 1.6 mm. Walls of different heights were used to simulate wall effects, and a model of the piston bowl could be placed under the injector. The second set up consists of a cylindrical chamber with the same inside diameter as the bore diameter in the series 71 engine, 4.25 inches or 108 mm. The cylinder was designed by Paul Walsh, another
graduate student in the Department of Mechanical Engineering. Figure 4.8 illustrates the cylinder and its adjustable support for the flow visualization system. The aluminium walls are 6.35 mm thick (1/4"), and the quartz are 12.7 mm thick (1/2"). According to manufacturer specifications, the quartz windows can withstand a pressure of approximately 450 KPa. The cylinder is sealed by 3 gaskets, one on each side of the top quartz, and the third one on the inside part of the bottom quartz. An o-ring seal ensures sealing between the injector and the top quartz. Different height spacers were manufactured to give the possibility of varying the distance between the two quartz.

Two ports permits charging and scavenging of the chamber (scavenging is the evacuation of the gas mixture in the chamber after injection). Each port is connected to a solenoid valve.
INSIDE DIAMETER : 4.25", 10.8 cm
SPACING BETWEEN QUARTZ : VARIABLE
MAXIMUM INSIDE PRESSURE : 400 KPa
LENGTH OF CYLINDER : 6", 15.24 cm

INJECTOR HOLDER

QUARTZ WINDOWS

SPACER

Figure 4.8 Cylindrical chamber with top and bottom quartz for flow visualization.

Before injection, the input valve opens and fills the chamber with air at the regulated pressure, while the output valve is kept closed. After the injection, the output valve is opened first, then the input valve is opened. Scavenging occurs for few seconds, and then the output valve is closed so that the cylinder is pressurized for the next injection. The air in the chamber must settle down for a few seconds before the next injection.

4.3.3 Flow Visualization Set Up

Schlieren photography is based on the proportionality between the refractive index and the density. A ray of light is deflected when it passes through a medium in which the density is changing in a direction normal to its path. The bending is associated with the light travelling at a different speed in a different refractive index medium, and the refractive index being
proportional to the density. The natural gas injection can be visualized using a schlieren method because there is a density gradient associated with the mixing of gases with different densities. In a typical schlieren apparatus, the test section is illuminated by a parallel beam of light, obtained by placing a light source at the focal point of a lens or concave mirror. A second lens or mirror produces an image of the source at its focal plane. A schematic of a typical schlieren system is illustrated in Figure 4.9.

If there is a density gradient in the test section, some of the light rays will be deflected, and will generate another image of the source. If at this point the image is projected on a screen, shadowgraph visualization is obtained. If a focusing lens is placed between the image and the screen, the image and the disturbed image are superimposed, and the disturbance is not apparent. The Toepler method renders the disturbance visible by reducing the intensity of the undisturbed source image, utilizing a knife-edge. Because the disturbed image is not affected in the same way by the knife edge, zones of illumination and shadings will appear corresponding to the zones of density change in the test section. The orientation of the knife-edge determines the density gradient orientation that will be observed.

The setup used to visualize the methane injection is illustrated in Figure 4.10. Two schlieren mirrors with a diameter of 304 mm (12 inches) and a focal length of 2.4385 meters (8 feet) were available in the department. Their size is more appropriate for wind tunnel experiments, and not required for this experiment where the area of interest lies in a diameter in the order of 127 mm (5 inches). Given the cost of optical equipment, the setup was adapted to their size. The distance between the mirrors should be approximately 2 times their focal length. One mirror was placed at the extremity of a 3.66 m (12 feet) long table, while a smaller table with adjustable height and a sliding top surface allowing front and back movement of the mirror was designed and built to accommodate the second one. A 200 watts mercury arc lamp was
LS : LIGHT SOURCE  
M1, M2 : SCHLIEREN MIRRORS  
TS : TEST SECTION  
KE : KNIFE EDGE  
FL : FOCUSING LENS  
P : SCREEN OR PHOTOGRAPHIC PLATE

Figure 4.9 Beam deflection in a typical schlieren configuration.

used as a continuous light source, producing a bright white light with radiation in the ultra-violet region. The light that was not directed to the apparatus was blocked by a metallic curtain that acts as a shield for the UV. The dimensions of the arc is estimated to 2.5x1.3 mm (Holder and North [1963]). The light from the source is condensed by a lens, generating a slightly magnified image of the source at its focal point. In its current configuration, the magnification is around 1.2, yielding an image width of 1.2x1.3 mm = 1.56 mm = 0.0615 inch = 1/16th of an inch. A circular pin-hole of 1/16" diameter was placed at the focal point of the schlieren mirror (M1 in Figure 4.10). The test section (apparatus 1 or 2 discussed in the previous section) is placed at the focal point of the second mirror (M2 in Figure 4.10). Originally a circular knife-edge was used since there was no preferred direction for the density gradient. An adjustable plate with
different size holes was designed and tried, but the manufacturing of sharp circular orifices was not of good enough quality, and visualization was unclear. Straight knife-edge were found simpler to use, and the single gradient orientation was not found to be a handicap in visualizing the flow. The knife-edge and the pin-hole were positioned in the 3 directions by precision adjustable holders. The light-source, the lenses, the pin-hole and the knife-edge were all supported by optical sliding holders, while the mirrors were self-supported and provided adjustment in rotation and inclination. Some of the lenses used were not in perfect condition and, combined with stains on the light source glass tube, resulted in a background not perfectly clear or uniform. Nevertheless the jet appears very clearly in contrast to the background.

S : LIGHT SOURCE - MERCURY ARC LAMP 200 W  
CL : CONDENSING LENS φ = 114,3 mm (4.5''), FL = 101,6 mm 4''  
PH : PIN HOLE φ = 1,5875 mm (1/16'')  
KE : KNIFE EDGE, HORIZONTAL OR VERTICAL  
FL : FOCUSING LENS φ = 88,9 mm (3.5''), FL = 139,7 mm (5.5'')  
M1, M2 : SCHLIEREN MIRRORS φ = 304,8 mm (12''), FL = 2,44 m (8')  
TS : TEST SECTION  
CAM : CAMERA  
θ = 7.5°

Figure 4.10 Principal dimensions of the schlieren apparatus.
4.3.4 Picture Acquisition

High speed photography would be ideal for the visualization of a transient jet. In the absence of funds to purchase a high speed video camera, a single shot camera was purchased. The history of the jet was obtained by varying the timing between the injection of the jet and the time of exposure. Since continuous light sources were available in the department, a shuttered camera was acquired. The camera purchased is a black and white CCD video camera, with an electronic shutter speed of 1/10000th of a second. This shutter speed was judged acceptable for this application, recognizing however that at the early stages of the injection the image of the jet would most likely be blurred. The principal characteristics of the camera are:

- High resolution; 968 (V) x 493 (H) array,
- Low light sensitivity: 0.5 lux,
- Adjustable shutter speed in step from 1/60 to 1/10000th of a second,
- Standard 75Ω video signal output,
- Price with power supply and cables: approximately $2500,
- Distributed in Richmond B.C. by Infrascan.

Charge coupled devices (CCD) are arrays of photosensitive pixels that are very efficient photon collectors compared to regular photographic emulsions (CCD detect up to 70% of incoming photons, compared to 1% for photographic films). As a result, they are very sensitive even in low light or short exposure time conditions. Solid-state cameras (CCD) usually produce a standard video signal, carrying the video information at a rate of 30 frames per second. In the standard interlace mode, each frame is composed of two fields, the first carrying the video information of all odd lines, while the second carries the even lines. For each field, every pixel is charged to the extent of light received. When it is time to regenerate, the pixels are "emptied" and their charge converted to a 8 bit digital signal. For black and white cameras, this means that
each pixel detects a grey level in the range 0 (black) to 255 (white). The digital signal is then converted to a video signal. CCD cameras are especially well suited for image digitization, and many areas of science now use solid-state cameras in conjunction with image digitization systems. This option is very attractive because it permits automatic image analysis and processing and eliminates film processing time and costs.

An Imaging Technology PC-based frame grabber board for image digitization was purchased from the same distributor. It was installed in a PC-AT, and the output of the camera was directly input to the frame grabber board. The board reconverts the video signal to digital information and reconstructs an image of 512x512 pixels, each of 256 shades of grey. The acquired pictures were recorded on standard 3.5" high density computer disks. A library of subroutines controlling the board and permitting image processing and analysis was also purchased.

The time between the moment the signal is sent to the actuator valve and the moment the picture is taken is controlled by monitoring the synchronization pulses of the video signal. The video signal contains vertical blanks; a portion of the signal that carries no video information and that marks the end of a field and the beginning of the following one. The vertical blank status is extracted from the video signal by the frame grabber board, and its value (0 or 1) placed in a special register. This register can be accessed and the value of the vertical blank monitored by a computer program. Another indicator in the same register (a register is composed of eight bits and each bit or group of bit is assign specific information), is the odd/even status and indicates if the current field is the first (odd) or second (even) field of a frame. Figure 4.11 illustrates these two indicators.

5 By comparison, the human eye can detect approximately 30 levels of grey.
to : time between valve actuation and exposition
tc : time between valve closing signal and actuation, could be after $t=33.33$ ms
tc - to : pulse width of signal sent to valve

*The image acquired during that time is the 0.1 ms exposition of the array*

**Figure 4.11** Vertical blank and odd/even status indicators used in triggering control.

The frame grabber board also contains control registers that allow one to decide what the board will do next. For example, the registers can be set so that the image from the camera is displayed live, or they can be set so that the image will be frozen or "grabbed". Freezing the picture at a specific moment is the goal that must be achieved. When the control register is set to freeze a picture, the board waits for the beginning of the next frame before capturing it. The timing is then obtained the following way: knowing that acquisition will only occur at the beginning of a frame, corresponding to a rise on the vertical blank status and a low on the odd/even status, the injection signal will be sent at a given time before the acquisition. The vertical blank and the odd/even status indicators are monitored and as soon as a new frame begins, the control register is set so that the next frame will be captured. A counter is established
between that moment and the beginning of the next frame. Each frame takes $1/30^{th}$ of a second (33.33 ms) to complete. The counter is utilised to control the time at which the opening and closing signals are sent to the high speed valve before the picture is taken. On the 16 MHz 286 PC-AT, there are 1849 counts in 33.33 ms, including the two outputs command to the valve. Therefore it is possible to control the opening and the closing with an accuracy of 18 microseconds. In practice, the count number is not always 1849 because of other tasks the computer co-processor must do during the counting (verify state of other registers, increment time etc...). However the value the counter reaches is known and cases in which the counter did not reach 1849 are rejected. The timing was verified with a Nicolet 3071 digital oscilloscope, and the error on the timing was found to be in the order of 0.05%, except when very short times were required, where the error could be as much as 2% (when a delay of 0.25 ms was requested, a repeated value of .256 ms was obtained on the scope). The timing control was judged to be adequate for the experiment. The program written to control the acquisition first requests the desired time for exposition after the opening signal to the valve, then the desired length of the opening signal. A key must be pressed to initiate the above procedure. If the count is right, then the picture can be saved for further processing; otherwise the operation is repeated.

One problem was discovered when the first flow visualization images were obtained. Both fields of the captured frame had been exposed for $1/10000^{th}$ of a second, resulting in two pictures being superimposed, one at the desired time, and one $1/60^{th}$ of a second later. According to the manufacturer specifications, a non-interlaced mode can be set, but proper functioning in that mode could not be obtained. As a result, the second field had to be erased by removing every other line. The resulting image suffered from being only half the resolution anticipated. To somewhat mend this problem, a reconstruction program was written; this will be discussed in the next section. Reconstruction was performed immediately before saving the pictures.
The system described above was found to be very practical. Results from adjusting the schlieren system or from different cases were immediately seen, offering a distinct advantage on regular photography. Automatic processing of the picture was also found to be a useful tool when consistent quantification of a large number of images must be performed. Of course, it is not high speed photography, and it is expected that irregularity in the jet will cause the time history data to be a bit scattered. Repeatability will be investigated in the next chapter. Other disadvantages are the large memory space required by each picture, and the limitations in producing good quality hard copies of the picture.

Figure 4.12 and Table 4.2 summarize the experimental set up.

4.4 PICTURE ANALYSIS

Beside general qualitative observation of the picture, the penetration of the jet in time must be obtained and compared with the analytical prediction. A program was written to automatically calculate the penetration length from the digitized picture. Automatic processing ensures greater consistency than a manual approach, and also reduces the time required for analysis.

The picture is composed of 512x512 pixels, each with an integer value between 0 and 255 corresponding to a grey level. The value of each pixel can be accessed, modified and replaced, allowing for two categories of processing: image enhancement and image analysis. Image enhancement permits one to improve the visual aspect of some characteristics of the image.
1 Prototype injector with pneumatic actuator (fig. 3.X). Compressed air at 500 psig is admitted in actuator by high speed valve (HSV 3000, Servojet). Usual lift is .004" or 0.1 mm. 90% of poppet opening occurs in 0.6 ms. Total duration is in the order of 15 ms. Delay between trigger to HSV and poppet opening is 5 ms.

2 Control board for the HSV, power from power supply (4) is allow to valve when trigger is received from computer.

3 Trigger signal taken on parallel port of computer (5V)

4 Regulated 12V power supply, 4 Amps.

5 Test rig, either straight support or cylinder (Figures 3.7 and 3.8)

6 Compressed air and regulator

7 Compressed methane and regulator

8 Emergency shut-off valve, powered from power supply, manual switch near computer

**INJECTION SYSTEM AND CONTROL**

<p>| | |</p>
<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Prototype injector with pneumatic actuator (fig. 3.X). Compressed air at 500 psig is admitted in actuator by high speed valve (HSV 3000, Servojet). Usual lift is .004&quot; or 0.1 mm. 90% of poppet opening occurs in 0.6 ms. Total duration is in the order of 15 ms. Delay between trigger to HSV and poppet opening is 5 ms.</td>
</tr>
<tr>
<td>2</td>
<td>Control board for the HSV, power from power supply (4) is allow to valve when trigger is received from computer.</td>
</tr>
<tr>
<td>3</td>
<td>Trigger signal taken on parallel port of computer (5V)</td>
</tr>
<tr>
<td>4</td>
<td>Regulated 12V power supply, 4 Amps.</td>
</tr>
<tr>
<td>5</td>
<td>Test rig, either straight support or cylinder (Figures 3.7 and 3.8)</td>
</tr>
<tr>
<td>6</td>
<td>Compressed air and regulator</td>
</tr>
<tr>
<td>7</td>
<td>Compressed methane and regulator</td>
</tr>
<tr>
<td>8</td>
<td>Emergency shut-off valve, powered from power supply, manual switch near computer</td>
</tr>
</tbody>
</table>
Table 4.2 Summary of experimental set up and equipment.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>1st Concave Mirror, 12&quot; diameter, 8' focal length</td>
</tr>
<tr>
<td>10</td>
<td>2nd Concave mirror, 12&quot; diameter, 8' focal length</td>
</tr>
<tr>
<td>11</td>
<td>Adjustable support table</td>
</tr>
<tr>
<td>12</td>
<td>200 Watt continuous wave mercury arc lamp</td>
</tr>
<tr>
<td>13</td>
<td>Condenser lens, 4.5&quot; diameter, 9&quot; focal length</td>
</tr>
<tr>
<td>14</td>
<td>3-axis adjustable pin hole, 1/16&quot; diameter</td>
</tr>
<tr>
<td>15</td>
<td>3-axis adjustable knife-edge</td>
</tr>
<tr>
<td>16</td>
<td>Focusing lens</td>
</tr>
<tr>
<td>17</td>
<td>Pulnix TM-745 high resolution CCD shutter camera. 768x493 pixels array. 1/10000th of a second shutter speed.</td>
</tr>
<tr>
<td>18</td>
<td>Shutter control SC-745 for camera. Choice of manually selectable shutter speed from 1/60th to 1/10000th of a second.</td>
</tr>
<tr>
<td>19</td>
<td>Power supply 12P-02 for Pulnix camera and power cable K25-12V</td>
</tr>
<tr>
<td>20</td>
<td>Imaging Technology PCVISION Plus board, with ITEX PCplus subroutine library</td>
</tr>
<tr>
<td>21</td>
<td>80286 PC AT Computer from ANO.</td>
</tr>
</tbody>
</table>

Image analysis extracts from the image some specific quantity.

The first processing performed on the image obtained from the flow visualization is image reconstruction. As previously discussed in the last section, every other line had to be erased because two pictures were superimposed. The image can be improved by giving the erased pixels a value based on its immediate neighbours. Although complex algorithms exist that consider the values and the gradients associated with a large number of

Figure 4.13 Rows of pixel. The row i must be reconstructed
pixels in the neighbourhood of the pixel to reconstruct, it was decided to use a very simple algorithm, mainly because the long processing time associated with a complex algorithm appeared unjustified by the accuracy gain. The algorithm employed is the following one: given a row $i$ of pixel to reconstruct (see Figure 4.13), the pixel at position $i,j$ is given by the value:

$$\text{pix}(i,j) = \frac{1}{2} [\text{pix}(i-1,j) + \text{pix}(i+1,j)]$$

(4.5)

The quality of the reconstruction was verified by comparing the reconstructed image of a deliberately altered image with the original. Subtracting these two images revealed the situations where the reconstruction is not perfect. In general it was found that the reconstruction was very good, except in areas containing sharp curved edges.

Once the image is reconstructed, the contour can be found. The following steps, illustrated in Figure 4.14, outline the principle:

1- Subtract from the image to analyze an image of the background. The area corresponding to the jet is isolated, minus a low level background difference due to noise, vibration and air movement.

2- Threshold the resulting image. The threshold will give a value of zero (black) to all pixels that are less than a fixed value, and 255 (white) to all the others. The threshold value is typically fixed to 8 or 3%. The resulting image is a white jet on a black background.

3- Scan the image and detect edges, recording the coordinates.

Once the coordinates of the edges are known, the radial penetrations $r_1$ and $r_2$ and the

---

6 The algorithm that was used to find the contour of the jet is different than the usual edge-detection algorithms usually employed. The method described was preferred because it identified only the edges of interest by contrast to all edges present inside and outside the jet, resulting in a simpler algorithm required to obtain the contour coordinates.
axial penetrations $y_1$ and $y_2$ are computed (illustrated in Figure 4.15). Their real dimension is obtained from previously-defined scaling factors. The penetration $y_1$ and $y_2$ are taken as averages. The apparent angle of the jet can also obtained. It is called the apparent angle because it does not necessarily correspond to the axis of the conical sheet jet. It is more an indication of the travel tendency of the jet. Also a general penetration can be obtained from $r$ and $y$ such as $p = (r^2+y^2)^{1/2}$. This will however overestimate slightly the actual penetration. Radial and axial penetrations are illustrated schematically in Figure 4.15. A manual measurement subroutine was also written so that measurement between two points indicated with the mouse could be obtained.

The accuracy of the method was evaluated by taking picture of objects of known dimensions and comparing the value obtained with the automatic measurement program. It was
found that the automatic program overestimated slightly the size in a manner proportional to the threshold value. The phenomena is caused by the presence of a small region of shade immediately surrounding the objects. This region of shade is small, but is considered "the object", by the program. With a threshold value of 3%, the error on different dimensions is of the order of 0.8 mm. For a threshold of 8%, the error drops to 0.6 mm. Manual measurements (pointing the edges of the object with the mouse on the digitized picture) yielded dimensions within 0.4 mm of the real values. It must however be said that the measurement depends on the scaling, that is done manually by pointing the edges of a well defined object of known dimension in the picture. The overall uncertainty on the measurement of the jet penetration is in all cases less then 1 mm.

4.5 EXPERIMENTAL CASES AND PROCEDURE

The experimental cases were chosen so that they would provide sufficient information regarding the effect of a given parameters. As previously discussed, the parameters to study are:

• pressure ratio,

• tip geometry : includes angle and lift,

• environment : includes effect of top wall, bottom wall at different distances from the top wall, and sealed cylinder,

• duration of injection,
Reynolds number.

The effect of these parameters will be determined by looking at the penetration rate of the jet and at its distribution. Table 4.3 lists the main experiments to be performed. The injection in a free environment (experiments #1, 9 and 13) will permit to verify the validity of the model proposed in chapter 3. The angle effect can be studied by comparing cases 1, 9 and 13. Cases 1, 2 and 3 should reveal the effects of varying the lift. The duration of the injection on the penetration will be observed in case 8. Many cases provide information about the effects of top wall, bottom plate and sealed cylinder. The repeatability of the injection is investigated in case 4. Finally, the Reynolds number effect will be observed in cases 16, 17, 18.

Once the set-up is installed to study specific parameters, the light source is turned on and allowed to warm-up for few minutes. The desired pressure ratio is adjusted and pictures of the jet are taken at different times following the trigger signal to the high speed valve. The first picture taken is always the one of the undisturbed background, and must be retaken every time a new configuration is used, or the schlieren system is adjusted. The pictures that are accepted (count is right, and no major irregularities) are reconstructed and saved. Once all the required pictures for a given configuration and pressure ratio are done, the latter can be modified and a

<table>
<thead>
<tr>
<th>#</th>
<th>environment</th>
<th>lift (mm)</th>
<th>β</th>
<th>PR</th>
<th>PW (ms)</th>
<th>times (ms)</th>
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<tbody>
<tr>
<td>1</td>
<td>free</td>
<td>0.056</td>
<td>10</td>
<td>1.5, 2, 5</td>
<td>5</td>
<td>.25, .5, .75, 1, 1.5, 2, 3, 5, 10</td>
</tr>
<tr>
<td>2</td>
<td>free</td>
<td>0.081</td>
<td>10</td>
<td>2, 5</td>
<td>5</td>
<td>.25, .5, .75, 1, 1.5, 2, 3, 5, 10</td>
</tr>
<tr>
<td>3</td>
<td>free</td>
<td>0.15, 0.2</td>
<td>10</td>
<td>2, 2.64, 3.43, 5</td>
<td>5</td>
<td>.25, .5, .75, 1, 1.5, 2, 3, 5, 10</td>
</tr>
<tr>
<td>4</td>
<td>repeatability</td>
<td>0.056</td>
<td>10</td>
<td>1.7,5</td>
<td>5</td>
<td>1, 3</td>
</tr>
</tbody>
</table>
Table 4.3 List of experiments performed.

| 5 | top wall | 0.056, 0.2 | 10 | 2, 2.64, 3.43 | 5 | 0.5, 0.75, 1, 1.5, 2, 3, 5, 10 |
| 6 | top and bottom wall H=17.8 mm, 7.95 mm, 14.25 mm | 0.056 | 10 | 2, 5 | 5 | 1, 2, 3, 5, 10 |
| 7 | interrupted jet | 0.056 | 10 | 2, 5 | 5 | 1, 2, 3, 5, 10 |
| 8 | free | 0.056 | 10 | 2 | 5, 6 | 1, 3, 5, 10, 11, 12, 13, 14, 15, 16, 17, 18 |
| 9 | free | 0.081 | 30 | 2, 5 | 5 | 0.25, 0.5, 0.75, 1, 1.5, 2, 3, 5, 10 |
| 10 | top wall | 0.081 | 30 | 5 | 5 | 1, 2, 3, 5, 10 |
| 11 | top and bottom wall H=17.8 mm, 7.95 mm | 0.081 | 30 | 5 | 5 | 1, 2, 3, 5, 10 |
| 12 | top and bottom wall + interruptions | 0.081 | 30 | 2.5 | 5 | 1, 2, 3, 5, 10 |
| 13 | free | 0.056, 0.2 | 20 | 2, 2.64, 5 | 5 | 1, 2, 3, 5, 10 |
| 14 | top wall | 0.056 | 20 | 2.5 | 5 | 1, 2, 3, 5, 10 |
| 15 | top and bottom walls, H = 38.1 mm, 14.25 mm | 0.056 | 20 | 5 | 5 | 1, 2, 3, 5, 10 |
| 16 | in-cylinder Pa = 1atm (not pressurized) | 0.2 | 10 | 2.64, 3.43 | 5 | 1, 2, 3, 5, 10 |
| 17 | in-cylinder Pa = 2, 3 and 3.7 atm | 0.2 | 10 | 2.64 | 5 | 1, 2, 3, 5, 10 |
| 18 | in-cylinder Pa = 2.85 atm | 0.2 | 10 | 3.43 | 5 | 1, 2, 3, 5, 10 |

new set of picture taken. When all the pressure ratios required for the given configuration are done, the easiest parameter to modified is changed, and the process is repeated.
5 RESULTS

The results regarding the parameters studied with the flow visualization and with the model are presented in the following discussion. A conical sheet jet is first examined, and the reproducibility is discussed. In section 5.1, the penetration rate of a conical sheet jet in an unbounded space is discussed, comparing experimental results with the model developed in chapter 3. The effects of the upstream pressure, lift and poppet angle on the free jet and the scaling of the results are also addressed. In the second section, the effects of the environment on the jet are discussed. In section 5.3, the implications of the results for engine operation are examined.

Figure 5.1 Schlieren photography of the free conical jet sheet at 4 different times. The lift is 0.056 mm, the upstream (tank) to atmospheric pressure ratio is 5, and the poppet angle is 10 degrees.

Figure 5.1 illustrates a typical jet progression in atmospheric conditions without wall
constraints. For the case illustrated the upstream pressure, the lift and the poppet angle are respectively 506.7 kPa (5 atm), 0.056 mm and 10 degrees. The schlieren was obtained with a horizontal knife edge. In the jet, intense zones of black or white indicate large density differences with the surrounding. The abrupt change between the black zone and the white zone in the vicinity of the nozzle indicates a change in density gradient sign, also identifying a maximum density at that junction. Schlieren photography is sensitive to all planes normal to the light beam, rending difficult the density analysis of a two-dimensional representation of a three-dimensional jet. The axis visible at the junction of the black and white zone is not necessarily the axis of the jet, defined as the location where the velocity and the methane content are maximal at any normal plane away from the nozzle. The schlieren of the three-dimensional jet should yield a visible axis lower then the actual axis of the jet. The visible axis angle in Figure 5.1 is approximately 25 degrees, comparatively with the poppet angle of 10 degrees.

The jet in Figure 5.1 is not evenly distributed on either side of the axis, whether the visible axis or the real axis is considered. The jet is seen to develop more on the bottom side of the conical sheet. In Figure 5.4, in which the jet from the same nozzle is seen but with a lower pressure ratio, the jet appears bent in the last frame. With larger angle poppets, this phenomenon causes dramatic effects on the jet, as it is discussed in section 5.1.5. The jet distribution differs then from the geometry of the transient conical sheet model proposed in chapter 3. The observed curvature is attributed to the lower pressure associated with air entrainment taking place in the enclosed area formed by the conical sheet, and is discussed in section 5.1.5.

The jet is also seen to propagate further and with a slightly different angle on the right side. This difference is attributed to an unequal opening of the poppet. For this reason, measurements on both sides of the injector were always taken.
The Reynolds number of the jet, defined as \( \rho_u U_0 L / \nu \), is approximately 7000 in Figure 5.1. In the engine the Reynolds number is an order of magnitude higher. Reynolds number dependency is discussed in section 5.2.5 and shown to be small. Results obtained from the injection of gas in atmospheric conditions should then be representative of the jet behaviour at higher Reynolds number.

The four frames illustrated in picture 5.1 are single shots from different injections, and consequently the first question to be addressed is the reproducibility of the experiments. Keeping the conditions constant, several pictures of the jet at the same time after the beginning of the injection were taken. This reproducibility experiment was done for two different cases and details of the results are reported in appendix B. For the first case investigated, 8 injections with the 10° angle poppet were photographed, with an upstream pressure of 1.7 atm and 1 ms after the beginning of injection. The average penetration\(^1\) of the jet was 11.5 mm on the left side and 12.6 mm on the right side. The standard deviation was 0.4 mm (3.5%), with a maximum deviation from the average of 0.7 mm (6.1%). For the second case, 9 injections from the same poppet were photographed, this time with an upstream pressure of 5 atm, and 3 ms after the beginning of injection. The average penetration for this second case was 29.9 mm on the left and 35.1 mm on the right. The standard deviation was 0.9 mm (3%), with a maximum deviation from the average of 1.7 mm (5.7%). The standard deviation indicates that in most cases the penetration is reproducible to within 1 mm. While penetration data will show a definite trend, the variation from injection to injection results in a source of uncertainty on the measurements greater than the uncertainty attributed to the measurement procedure discussed in chapter 4.

\(^1\) The penetration of the jet is taken as the distance between the nozzle and the far-most point reached by the jet radially (left or right) and downward.
5.1 FREE PENETRATION OF THE CONICAL SHEET JET

5.1.1 Comparison Between Model and Experiment

The model does not take into account the jet curvature observed in Figure 5.1. However, for the 10° angle poppet, the jet distribution is still reasonably close to the one utilised in the model. Figure 5.2 compares the penetration predicted by the model described in chapter 3 with results obtained experimentally, for the 10° angle poppet, a lift of 0.056 mm and three different upstream pressures. The experimental penetration values are measured from schlieren photographs. In the model, the discharge coefficient is set to 0.85, the turbulent Reynolds number to 20 and the drag coefficient to 1 if the Reynolds number of the vortex is greater than 10^3. In addition, the conditions at the nozzle are assumed to be those of a choked nozzle. It is seen that the general trend is correct, and that the model response to different pressure ratio corresponds to experimental observations. However, the predicted penetration is significantly larger than the one observed experimentally.

The difference between the model and the experiments can be the consequence of a number of factors. There are numerous assumptions made in the model which could affect significantly its accuracy. The first assumption to consider is the assumed geometry of the jet that differs from the geometry observed experimentally. The geometry of the jet and the mechanism that causes it are only partially known through schlieren photography. Consequently, the model could not be modified to consider this difference. The sensitivity of the model to the turbulent Reynolds number, the discharge coefficient and the drag coefficient is mild as it was shown in section 3.3.3 (Figures 3.10 to 3.12). A realistic change in any of these parameters could not render the model closer to the experimental values.

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2 The modification might be difficult to implement to the simple model.
Figure 5.2 Comparison between the model and experimental results for the penetration of the conical sheet. $\beta = 10^\circ$, $l = 0.056$ mm. In the model $Re = 20$, $C_d = 0.85$ and $C_D = 1$.

In calculating the initial velocity in the model, choking at the nozzle exit was assumed and pressure losses in the injector were neglected. Since the CNG ports in the injector are of small diameter and are relatively long (large L/D), the flow reaches high subsonic Mach number in the smallest passage. An investigation was made to see if the pressure drop is significant through these small passages, and to determine the conditions that cause internal friction choking. Approximate calculations using one dimensional isentropic and adiabatic flow in pipes with friction were conducted and are described in Appendix C.

The calculations are based on the assumption that the upstream pressure remains constant during the injection and that the flow becomes steady in the injector. The latter assumption is acceptable in the case of the flow visualization experiments because the tip reservoir contains less
then 10% of the injected gas mass. The tip reservoir is the annular space surrounding the poppet valve in the tip of the injector, and can be seen in Figure 1.2. The presence of sharp edges between ports of different sizes and potential flow separation were not considered in these calculations. Calculations suggested that, for the gas port dimensions of the test injector employed in the experiments, the maximum lift that can be set without occurrence of internal choking is approximately 0.089 mm. Calculations also showed that combined pressure losses in the gas ports could lead to a pressure drop of 16% for a lift of 0.056 mm, and of 22% for a lift of 0.081 mm. The model was modified to consider a pressure drop according to initial conditions, and new results for the same case are illustrated in Figure 5.3. The details of the modifications are given in Appendix C. The modified model yields a penetration closer to the

![Figure 5.3 Penetration of the conical jet sheet; same conditions as in figure 4.1. The model was adjusted to consider pressure drop inside the injector.](image)

experimental one, but there is still an overestimation in the order of 5% for the higher pressure
ratio and of 20% for the lower pressure ratio. It can be seen that the model predicts a faster propagation in the early moments than the one observed experimentally, especially for the lower pressure cases, suggesting that the modelling of the conical jet is inadequate in the early moments of propagation.

5.1.2 Effect of Pressure Ratio and Lift on Penetration

Figures 5.2 and 5.3 indicate a strong pressure effect. Scaling results presented in chapters 2 and 3 indicate that the penetration $z_t$ and the time $t$ can be scaled with the following factors:

\[
\frac{z_t}{\sqrt{R_s l_{eq}}} = \frac{t U_o}{\sqrt{R_s l_{eq}}} \tag{5.1}
\]

where $R_s$ is the seat radius, $U_o$ the nozzle velocity, and $l_{eq}$ is the equivalent lift given by

\[
l_{eq} = l C_d \frac{p_g}{p_a} \quad \text{if} \quad \frac{P_o}{P_a} < 1.86
\]

or

\[
l_{eq} = 0.537 l C_d \frac{p_g}{p_a} \frac{P_o}{P_a} \quad \text{if} \quad \frac{P_o}{P_a} > 1.86
\]

1.86 is the critical pressure ratio for methane. In chapter 3, the penetration of the modelled conical sheet jet was shown to be directly proportional to the square root of time. This can also be observed experimentally (shown is Figure 5.9). Applying the scaling from Equations 5.1 and 5.2, and assuming a pressure ratio greater than 1.86, the penetration can be expressed as:

\[
\frac{z_t}{\sqrt{t U_o}} = \left( R_s l C_d \frac{p_g}{p_a} \frac{P_o}{P_a} \right)^{1/4} \tag{5.3}
\]

The penetration is directly related to the square root of time, to the square root of the initial velocity, to $(p_g/p_a)^{1/4}$, and to $l^{1/4}$, and to $(P_o/P_a)^{1/4}$ if the jet is underexpanded. If the pressure ratio is under the critical one, an increase in pressure will yield a higher velocity and a higher density ratio. Once the flow is choked at the nozzle, the initial velocity remains constant, and an increase in pressure will yield an increase of $l_{eq}$. In both cases, an increase in pressure ratio
causes an increase in penetration that is observed experimentally.

Jets emerging from nozzles with lifts of 0.056 mm and of 0.081 mm are presented in Figures 5.4 and 5.5 respectively. The pressure ratio is 2 and the poppet angle is 10. Corresponding penetration are plotted in Figure 5.6, along with other cases. For a same pressure ratio, the penetration observed experimentally does not differ significantly for different lifts. The observed jet from the larger lift nozzle has a slightly larger downward penetration, and occupies more space (indicates a larger volume) then the jet from the smaller nozzle. In addition, the jet from the larger lift has a smaller downward curvature.

The model prediction corresponding to the experimental results plotted in Figure 5.6 are presented in Figure 5.7, without correction for the pressure drop inside the injector. The model clearly shows a dependency of the penetration on the lift, that is not reflected by the experimental penetration measurements. The apparent insensitivity of the penetration to the lift in the experiments can be explained in part by the conditions of the flow inside the injector. Two cases must be addressed: i) choking conditions occur at the nozzle and internal friction is considered, ii) the lift is too large and internal choking occurs.

i) When the flow is choked across the nozzle of the injector, an increase in lift also causes an increase in Mach number in the gas ports, leading to a larger pressure drop. The model was corrected for the pressure drop and penetration results obtained with the corrected model are presented in Figure 5.8. In Figure 5.8, the curves for lifts of 0.056 and 0.081 mm were corrected for friction. The difference between the penetration is seen to be significantly smaller than in Figure 5.7.

ii) If the lift is too large, the flow is choked internally. There is a maximum mass flow that can be maintained given the upstream pressure and temperature. An increase in lift while internal choking occurs will cause a lower nozzle velocity and therefore a lower momentum.
Along with internal choking, the flow is also subject to friction, reducing the actual stagnation pressure at the nozzle. In Figure 5.6, the maximum lift is 0.15 mm, lift at which the flow is internally choked. Values for the velocity and the density at the nozzle for the internally choked flow were obtained (Appendix C) and were used in the model. The curve for the lift of 0.15 mm in Figure 5.8 depicts the prediction of the model when it is corrected for internal choking. The corrected model does predict a lower penetration for the larger lift of 0.15 mm than for smaller lift. This is not reflected in the experiments, where the lift is in fact slightly higher for the larger lift. This can be explained by the fact that the flow does not choke instantly as the poppet opens. In the early moments, the flow is choked at the nozzle, resulting in a high initial momentum. This high initial momentum is sufficient to compensate for the subsequent drop in velocity associated with internal choking.

5.1.3 Scaling

The experimental data were scaled according to the factor proposed in Equations 5.1 and 5.2, and the results are reported in Figure 5.9. These scaling factors are calculated from the expected conditions at the nozzle. The real pressure ratio, density ratio and discharge coefficient are not known accurately. The corrections performed to account for internal flow conditions were considered in the scaling parameters. The experimental points are plotted as a function of the square root of time, to which they can be seen to be directly proportional, except in the early moments. It is seen that all cases lie on lines with similar slopes, indicating that the penetration far from the nozzle is scaled appropriately. However, higher pressure cases lie on a line offset from the lower pressure cases. This seems to indicate that the jet development at the beginning of the injection depends on the pressure ratio. It should be noted again that the conditions at the nozzle are known only approximately. The scaling for the model is also indicated in Figure 5.9. The slope of the predicted penetration is similar to that of the experimental one, but is seen
Figure 5.4 Free conical sheet jet from the 10° angle poppet. Pressure ratio of 2 and lift of 0.056 mm.

Figure 5.5 Free conical sheet jet from the 10° angle poppet. Pressure ratio of 2 and lift of 0.081 mm.
Figure 5.6 Variation of the penetration with lift and upstream pressure, according to experiments.

![Graph showing variation of penetration with lift and upstream pressure.](image)

Figure 5.7 Variation of the penetration with lift and pressure ratio as predicted by the model.

![Graph showing variation of penetration with lift and pressure ratio.](image)
Figure 5.8 Variation of the penetration with lift and upstream pressure as predicted by the model corrected for internal flow behaviour.

Figure 5.9 Experimental data and model scaled with the factors given in Equation 5.1. The penetration is plotted as a function of $t^{1/2}$. 
to be shifted towards the left on the graph, indicating again that the difference between the model and the experiments occurs mainly in the early moments of the jet.

5.1.4 Effect of Injection Duration

In the penetration results shown so far, the poppet remained open over the time period the penetration was considered. In the engine, the injection duration is shorter, between 1 and 2 ms depending on operating conditions, and it is of interest to characterise the penetration while the injector is closed. Although the actuation used in the experiments does not permit a duration as short as that which occurs in the engine, it is possible to look at the jet penetration just after the actual closing time of the injector. For pulse widths of 5 ms and 6 ms (the length of the signal sent to high speed valve) the injection durations are approximately 11 ms and 14.5 ms respectively.

Picture 5.10 Free conical sheet jet from 10° angle poppet. Pressure ratio of 2, lift of 0.056 mm. Post-injection penetration.
Pictures were obtained for the jet from a 10° angle poppet before and after the closing of the poppet for both pulse widths. Figure 5.10 shows the jet at different stages for a pulse width of 6 ms. At 16 ms, no jet appears at the nozzle, and the jet penetration does not increase substantially after the end of the injection. The penetration data for two different pulse widths are plotted as a function of $t^{1/2}$ in Figure 5.11. The straight line is a fit to the previously obtained penetration data before the poppet starts to close (at approximately 7 ms for PW=5 ms). The deviation from the proportionality line indicates that the jet quickly slows down once its feeding stops. The scattering of the data is in part due to the difficulty of identifying low density gradient areas characteristic of the jet edges far from its origin. For the same reason, these results are not conclusive regarding the magnitude of the change in penetration rate. For a pulse width of 5 ms, the jet is found to deviate from its original penetration rate before the injection is finished (at approx 11 ms). This is a consequence of the long closing process of the poppet. At 10 ms ($3.1 \text{ ms}^{1/2}$), the penetration is seen to be less than if the poppet was still open.

5.1.5 Effect of Poppet Angle

The distribution of the jet within the chamber must provide good mixing between the gas and the air, and must be such that rich zones of fuel are avoided. The angle at which the jet is injected is a major factor affecting the jet distribution. To relate the distribution to the angle, pictures of injection from poppets with seat angles of 10, 20 and 30 degrees were taken. Different pressure ratios were tried for each angle, since the pressure ratio also has a large effect on the distribution.

The jet distribution for the 10° angle poppet is shown in Figures 5.1, 5.4 and 5.5. Figures 5.12, 5.13, 5.14 and 5.15 were obtained for the 20° and 30° angle poppets at pressure ratios of 2 and 5. The curvature observed for the 10° angle poppet jet radically change the jet distribution.
Figure 5.11 Penetration data plotted versus the square root of time. The deviation from the direct proportionality results from the closing of the poppet.

of the jet from the 20° and 30° angle poppets. Early after its emergence from the nozzle, the jet from the 20° angle poppet bends downward. For a relatively low pressure ratio (2) the jet collapses under the poppet completely and propagates downward. For higher pressure ratio, the jet avoids the collapsing, and propagates radially with a very definite curvature. The phenomena is even more definite for the 30° angle poppet, where the jet collapses very soon under the poppet and propagates directly downward with little radial penetration, even at higher pressure ratio.

It is also observed for the 30° angle jet that the jet takes a preferred orientation after it has completely collapsed (clearly seen on the 10 ms frame in picture 5.13). This phenomena is
Figure 5.12 Free conical sheet jet from 20° angle poppet. Pressure ratio of 2, lift of 0.056 mm.

Figure 5.13 Free conical sheet jet from 20° angle poppet. Pressure ratio of 5, lift of 0.056 mm.
Figure 5.14 Free conical sheet jet from 30° angle poppet. Pressure ratio of 2, lift of 0.081 mm.

Figure 5.15 Free conical sheet jet from 30° angle poppet. Pressure ratio of 5, lift of 0.081 mm.
less accentuated for higher pressure ratio.

The process believed responsible for the observed curvature is described in this paragraph. The conical sheet forms an enclosed space under the poppet. Air entrained by the incoming jet at its inside surface depletes the air in this enclosed space. Consequently, the pressure in the enclosed space is reduced, and air from the surrounding flows in. There is a pressure difference between the top and bottom surfaces of the conical sheet. The curvature of the jet is attributed to the effect of this pressure difference on the sheet. A schematic of the mechanism is illustrated in Figure 5.16. The extent of the curvature is related to the velocity of the jet and to the pressure gradient. Under some combinations of angle and velocities, the jet is brought completely towards the middle and the conical sheet collapses under the poppet.

Gas penetration directly towards the piston is judged unacceptable for engine operation, since it leads to a rich area underneath the poppet and poor overall air utilisation. The question arises if this phenomenon is likely to occur in engine operation. In the flow visualization experiments, piston motion was not investigated; numerical simulation done by Paul Walsh shows that the piston motion has a definite effect on the jet. For the 20° and 30° angle poppets, the jet does not propagates downward to the same extent when the piston goes up. However the jet does propagates downward under the poppet when the piston goes down. In either case, the jet diffusion from the 30° poppet is inadequate. Consequently, the usage of 30° angle poppet of the prototype injector employed in the engine was discontinued, and two other poppets with respective angles...
of 10 and 20 were manufactured.

5.2 EFFECT OF GEOMETRICAL CONSTRAINTS ON JET

5.2.1 Top Wall

In the engine, the nozzle is offset by approximately 1.6 mm from the top wall of the cylinder. This condition was reproduced and it was found that the top wall has a definite effect on the jet behaviour. Figure 5.18 depicts clearly that the jet emerging from the 10° angle poppet clings to the top wall early in its progression, and subsequently propagates along the top wall. The clinging is caused by a similar phenomenon that caused the jet to collapse under the poppet. The air entrainment between the top surface of the jet and the top wall creates a low pressure zone acting on the sheet, forcing the jet to cling to the top wall. The immediate effect of the clinging is to reduce the extent of mixing between the jet and the air. This is clearly seen by comparing the area occupied by the jet in Figure 5.18 with Figure 5.1. The total penetration is slower by about 10% for the jet propagating along the wall as it can be seen on Figure 5.17. For the jet emerging from the 20° angle poppet, a similar phenomena occurs. The jet first propagates downward but is then attracted towards the top wall. The phenomenon is depicted in Figure 5.19. Once it has made contact with the top wall, the jet continues

![Figure 5.17 Penetration comparison between the free jet and the jet propagating along the top wall.](image-url)
Figure 5.18 Effect of the top wall on the conical sheet jet. 10° angle poppet, pressure ratio of 5, lift of 0.056 mm.

Figure 5.19 Effect of the top wall on the conical sheet jet. 20° angle poppet, pressure ratio of 5, lift of 0.056 mm.
its course along it, while the mass of gas initially propagating downward continues to diffuse. For the 30° poppet, the jet is unaffected by the top wall.

5.2.2 Bottom Wall

The bottom wall represents a static piston placed at a distance H from the top wall. Pictures were taken with a bottom wall at different heights H for all 3 poppet angles in order to determine the principal effect of the wall on the jet. Figure 5.21 shows the propagation of the jet from a 10° angle poppet between two plates distant of 14.25 mm. The jet travels along the top wall until its thickness is in the order of the distance H between the two plates. The jet then propagates touching the two walls, permitting mixing with the air only at its tip. Figure 5.20 shows the radial penetration of the jet as a function of time for the 10° angle poppet and for three different heights H. The radial penetration for the case without a bottom wall is also indicated. For the heights observed, the jet propagates radially faster in the beginning and then slows down because of friction on both top and bottom walls. The same phenomena is observed for a

\[ \text{Figure 5.20 Penetration for the 10° angle poppet with bottom wall at three different heights. Pressure ratio of 5. Lift of 0.056 mm.} \]

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3 The jet from the 30° is unaffected by the top wall only if the nozzle is offset from the top wall. When the nozzle is placed flush with the top wall, the jet also clings to the top wall.
pressure ratio of 2. This phenomena indicates that within a certain range, the wall has an effect on the jet even before the jet touches the wall.

The jet emerging from the 20° poppet travels initially downward. When the bottom wall is at 14.25 mm from the top wall, the jet impinges onto the bottom wall to which it clings. The propagation continues radially and soon the jet clings also to the top wall. For the larger distances between top and bottom wall tried, the jet clung to the top wall. The jet from the 20° angle is seen to have two different behaviour depending on the distance of the bottom wall. Either the bottom wall is close and the jet clings initially to it before filling the gap between the two walls, or it clings to the top wall only. For both the 10° and 20° poppet, a distant wall did not have any effects.

For the 30° angle poppet, the jet impinges on the bottom plate, and then propagates radially clinging on the bottom plate, as seen in picture 5.22. When the jet reaches the bottom wall, air no longer access the enclosed area inside the conical sheet. As a result, a recirculation ring is formed under the poppet. This recirculation zone is also associated with a low pressure zone forcing the sheet to curve. Results of computer flow simulation of the above jet by Paul Walsh using a modified TEACH Code are illustrated in Figure 5.23. The recirculation and the curvature of the jet are clearly seen.

The radial penetration rate between the two plates is similar for each poppet angle, except at the beginning of the injection, where radial penetration is slower for jets diffusing towards the bottom wall.

5.2.3 Conical Sheet Jet Interruption

As it has been shown, the conical sheet jet is subject to deviation from its expected course. Either it clings to the top wall, or it propagates toward the piston, reducing greatly the
Figure 5.21 Propagation of the conical sheet from the 10° angle poppet between two walls. \( H = 14.25 \) mm, \( P_j/P_a = 5 \), lift = 0.056 mm.

Figure 5.22 Propagation of the conical sheet jet from the 30° angle poppet between two walls. \( H = 17.1 \) mm, \( P_j/P_a = 5 \), lift = 0.081 mm.
possibility of distribution control. This phenomenon is related to the fact that the continuity the sheet renders it sensitive to the difference in pressure between the top and bottom surface of the sheet. The immediate results of both these phenomena are a lower penetration rate and a smaller spatial distribution, leading to a reduced mixing between the natural gas and the air. In an attempt to correct this situation while still keeping the advantages of the conical poppet design, the sheet was interrupted to allow pressure communication between the top and the bottom of the conical sheet.

The injector is seated within a copper cartridge in the engine head. It is possible to modify this cartridge so that small fences cover the tip of the injector. This concept is illustrated in figure 5.24. An available cartridge was modified so that 4 fences with widths of approximately 2 mm would interrupt the jet as it emerges from the nozzle. It was found that these four fences were sufficient to prevent the jet from the $30^\circ$ angle poppet to collapse.
downward as illustrated in picture 5.26. However four fences were not sufficient to prevent the jet from clinging to the top wall for either the 10° or 20° angle poppets.

To investigate if more interruptions would prevent the clinging of the jet to the top wall, small slices of tape were placed on the tip of the injector so that the jet would be interrupted at regular intervals. As shown in Figure 5.24 Fences for jet interruption. As shown in picture 5.27, 6 fences 2 mm wide are sufficient to prevent clinging to the top wall for the jet from the 10° angle poppet. In Figure 5.27, the 10° poppet jet does however exhibit a definite curvature, suggesting that a low pressure zone is still present under the poppet.

A new phenomenon was observed while investigating jet interruptions. For some interruption configurations, the penetration of the jet is significantly faster than for the conical jet. Picture 5.28 is a shadowgraph photograph of the jet from the 10° poppet from the newest version of the prototype injector4. Frames 1 and 2 represent the full conical jet sheet at times 1 and 3 ms. In frames 3 and 4, the jet is interrupted by two 6 mm wide fences placed perpendicularly to the plane of the picture. The pictures are also respectively at 1 and 3 ms. In this case the penetration after 3 ms is more than double. At first, it was hypothesized that the

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4 The faster penetration occurring when the jet is interrupted was also observed with the older test injector used in most of this experimental work.
flow was internally choked and that a reduction in area at the tip caused the flow to choke at the nozzle. This hypothesis was disproved since an equal reduction in area with a different interruption arrangement did not lead to a higher penetration. To obtain an idea of the behaviour of the interrupted jet, axial visualization of the jet was performed for different interruption arrangements.

Figure 5.29 shows shadowgraphs of the jet for different interruption patterns at time 3 ms. The first frame is that of the uninterrupted jet. Frames 2, 3 and 4 are interrupted jets by 6 fences of 2 mm, 6 fences of 1 mm and 8 fences of 1 mm respectively. The penetration in all cases is larger than for the full jet.

The lateral spreading of each jet is small, indicating that the initial velocity at the nozzle has a small radial component, contrarily to the profile expected for the non-interrupted conical poppet (see illustration 5.25). The jets emerging from the interrupted nozzle resemble more to a series of round jets.

Figure 5.30 depicts different arrangements of 4 interruptions. In the first three frames, the jet is interrupted with 4 small slices of tape respectively of 1, 2 and 3 mm. The forth frame show the jet interrupted with the modified copper cartridge illustrated in Figure 5.24, at the tip of which 4 fences of 2 mm were manufactured. It is seen that for 4 interruptions of 1 mm, the jet is larger and does not penetrates as deeply. Also observed is the fact that the jet is different when interrupted with small pieces of tape and when interrupted with the thicker fences of

Figure 5.25 Hypothesized difference in initial velocity profile for full and interrupted conical jet.
5.26 Interrupted conical jet from 30° poppet. Interruption is performed by 4 fences 2 mm wide at tip of copper cartridge. $P_r/P_a = 5$, lift = 0.081 mm.

Figure 5.26

5.27 Interrupted conical jet from 10° angle poppet. Interruption is performed with 6 fences of 2 mm width. $P_r/P_a = 5$, lift = 0.056 mm.

Figure 5.27
Figure 5.28 Shadowgraph of jet from $10^\circ$ angle poppet (newest injector prototype). Frames 1 and 2 show full conical jet at 1 and 3 ms. Frames 3 and 4 show jet interrupted by two 6 mm wide fences at same times.

Figure 5.29 Shadowgraph of different interruption arrangements. In respective order: full conical sheet, 6x2 mm, 6x1 mm, and 8x1 mm. New prototype, $10^\circ$ poppet.
the copper cartridge.

It is not possible to reach a definite conclusion at this point regarding the ideal number, size and shape of jet interruptions. Nevertheless the following statements results from the observations:

- Interruption successfully prevents the jet from collapsing under the poppet. For the 10° and 20° angle poppets, top wall clinging could be prevented by an appropriate number and size of interruptions. However, the resulting jet can still exhibit a large curvature.

- The width, number and shape of the fences all have an effect on the penetration, most likely by their effect on the initial velocity profile at the injector’s tip.

- There is probably an arrangement that would yield a good gas distribution. It would be
interesting to have a 15° angle poppet and 6 interruptions of 1 or 2 mm. At this point, both the 10° and 20° angle poppet should be tested in the engine with an interruption arrangement of 6 x 1.5 mm. More experiments would be beneficial.

- With adequate arrangement, the penetration is faster than for the continuous sheet. Generally it is observed that if the initial jets resulting from the interruptions are wide, they will exhibit the characteristics of the conical sheet jet and have a slower penetration rate. On the other hand if the jets are narrow, they behave more like round jets and have a larger penetration rate.

The disadvantage of the interruption is a reduction in nozzle area, leading to lower mass flow. However, if internal choking can be avoided, a higher lift can be set to compensate for the reduced area. Interruptions would allow a better control on the jet diffusion.

5.2.4 Enclosed Area Effect

In the second series of experiments, gas was injected in a sealed cylinder. Schlieren photography was difficult to perform, potentially because of the difficulty in aligning the beam of light in a perfectly parallel direction with the cylinder axis. Shadowgraph photography was therefore utilised. Due to its small lift, the test injector initially utilised allowed very little gas into the chamber and axial visualization was difficult to perform. Consequently, the newest prototype injector with a larger lift (0.2 mm) was utilised in order to improve and facilitate visualization. Injections were first performed in atmospheric pressure to investigate the difference in penetration in an enclosed area.

Figure 5.31 compares the total penetration of the free jet, the jet propagating along a top wall and the jet in an enclosed area. All these results were obtained from the newest injector. Because the pressure rises in the sealed cylinder as the gas is injected, the penetration rate should
in principle be smaller than for the jet propagating in constant atmospheric pressure. Also the jet must slow down as it approaches the cylinder wall. Neither of these effects could be observed within the accuracy of the measurements taken, as it is seen in Figure 5.31. The pressure rise in the cylinder due to the injection is small and its effect is likely to be negligible. Insufficient experimental data were obtained from the newest prototype injector to reach conclusions regarding the deceleration of the jet as it approaches the cylinder wall.

![Diagram](image)

**Figure 5.31** Difference in penetration for the free jet, the jet propagating along the top wall and the enclosed jet. Data taken with the new prototype 10° poppet, 0.23 mm lift and pressure ratio of 2.64.

### 5.2.5 Reynolds Number Effect

Turbulent jets are known to be moderately dependent on the Reynolds number. It was
attempted to define the dependency of the conical sheet jet on the Reynolds number, since the Reynolds number is one of the parameter that was not reproduced in the flow visualization experiments. When the gas is injected in atmospheric pressure, the Reynolds number at the nozzle for the new prototype injector is approximately $1.5 \times 10^4$ for a pressure ratio of 2.64. By raising the pressure in the cylinder while keeping the pressure ratio kept constant, the Reynolds number can be increased. Limited by the maximum pressure that the cylinder can withstand, the maximum Reynolds number attained was in the order of $5.6 \times 10^4$. Figure 5.32 is a graph of the penetration obtained for different Reynolds number at the nozzle. The pressure ratio is 2.64, the lift is 0.23 mm and the $10^\circ$ poppet of the new prototype was utilised.

![Graph](image)

**Figure 5.32** Penetration comparison between jets with different Reynolds number. The indicated pressure is the cylinder pressure before injection. $10^\circ$ angle poppet, pressure ratio of 2.64.

It is seen that within the small range of Reynolds number tried, no significant dependency can be observed. In the engine the Reynolds number is in the order of $5 \times 10^5$. For the round free jet, the penetration is found to be dependent to $Re^{0.053}$ (Kuo and Bracco [1982]). Assuming a
similar dependency for the conical sheet jet:

\[ z_t \propto \sqrt{t U_o R e^{0.053} (R_s / \rho_g \rho_a)^{1/4}} \]  

(5.4)

one can see that for a Reynolds number 10 times higher, the penetration would be approximately 5% higher. The injection of gas in the cylinder can be observed in picture 5.33.

**Figure 5.33** Axial shadowgraph visualization of the jet in the cylinder. For the case illustrated, the chamber pressure is 3 atm and the upstream pressure is 7.92 atm.

5.3 EXTENSION OF RESULTS TO ENGINE APPLICATION

Two main objectives have been pursued in this project. The first one was to evaluate the penetration rate of the fuel in the chamber and to see if it is adequate. The second was to get some information about the fuel distribution within the chamber.

5.3.1 Penetration Rate

Assuming that the Reynolds number effect is small, the penetration rate for a flow choked
at the nozzle will take the form indicated in Equation 5.3:

$$z_t = K \sqrt{t \over U_o} \left(0.537 R_s l C_d \frac{P_o P_g}{P_a P_o} \right)^{1/4}$$  \hspace{1cm} (5.5)$$

where $K$ is a constant. The density ratio is approximately 0.55. The initial velocity is the sonic velocity at the nozzle conditions (choked nozzle), and assuming a constant upstream temperature of 300 K, is approximately 422 m/s for natural gas. The discharge coefficient is taken as 0.85. Replacing these values in Equation 5.5 yields

$$z_t = 14.6 K \sqrt{t} \left( R_s l \frac{P_o}{P_a} \right)^{1/4}$$  \hspace{1cm} (5.6)$$

Equation 5.6 is a convenient relationship to approximate the natural gas penetration when injected from a choked conical nozzle. The constant $K$ can be found from experimental data. If the model is utilised, $K$ is found to be approximately 1.8. The experimental penetration data for the 10° angle poppet along the top wall taken from the first prototype injector yields a value of $K$ of 1.6. Because the proportionality between the penetration and the square root of time holds only far from the nozzle, Equation 5.6 overestimates the penetration for $P < 20 (R_s l)^{1/2}$.

It is easier to judge if the natural gas penetration is sufficient by comparing it with diesel fuel penetration. Diesel fuel penetration can be approximated by the following relationship developed in chapter 2 (from DENT [1971]):

$$z_t = 3.01 \left( \frac{\Delta P}{\rho_a} \right)^{1/2} t d_o \left( \frac{298}{T_a} \right)^{1/4}$$  \hspace{1cm} (5.7)$$

The diesel pressure at the nozzle is in the order of 750 atm and the holes diameter are typically between 0.15 to 0.2 mm. The temperature and the density depends on the type of engine. For the Detroit Diesel research engine (series 71) on which preliminary tests are performed, the pressure at the end of compression is 2.5 Mpa and the temperature is approximately 900 K,
yielding an air density of 10 kg/m³. Utilising these values, approximate penetration of the diesel fuel was compared to approximate penetration of the natural gas calculated with Equation 5.8. The lift and seat radius of the newest 10° prototype injector are utilised. Results are plotted in Figure 5.34. Different upstream pressures for both the gas and the diesel are plotted. These results are approximations, and neglect the fact that the injection last only from 1 to 2 ms. Nevertheless, the order of magnitude indicates that natural gas penetration is slower than the diesel one for the present testing conditions. Similar results are obtained for the 6V-92 engine, in which the cylinder pressure can be as high as 100 atm. Approximation of the jet penetration for the conditions prevailing in the 6V-92 are illustrated in Figure 5.35.

Jet penetration can be increased (almost doubled) by proper interruption arrangement or by redesigning the injector tip and utilising circular orifices. The pressure ratio can also be increased, but it is a limited parameter in practice. Before attempting to increase the jet penetration, the combustion characteristics must be taken into consideration, so that flow velocity and burning rates stay compatible.
Figure 5.34 Approximation of the jet penetration for diesel fuel and natural gas. Employed engine conditions are cylinder pressure and temperature of 24 atm and 900 K, diesel holes diameter of 0.15 mm.

Figure 5.35 Approximate penetration for the diesel and natural gas injection for the conditions prevailing in the 6V-92 engine. Employed cylinder pressure and temperature of 100 atm and 900 K.
5.3.2 Pulse Width Effect

The propagation of the jet after the end of the injection could not be fully simulated. However experimental observations indicated that the jet tip slows down immediately as the poppet closes. The jet tip should then be close to the cylinder wall at the moment the poppet closes. For the series 71 engine the cylinder radius is 54 mm. It is seen in Figure 5.34 that the diesel jet tip reaches approximately 45 mm after 1 ms and 65 mm after 2 ms. The natural gas on the other hand reaches 20 mm after 1 ms and 25 mm after 2 ms. Typically in diesel engines, the injection starts between 15 to 20 degrees before TDC (top dead center), and stops at TDC. Most of the fuel is burned at 20 degrees after TDC. Assuming an engine speed of 1200 RPM, the duration of the injection is approximately 2.5 ms, and the time between the starts of the injection and 20 degrees after TDC is approximately 5 ms. When the injector closes, the diesel jet has reached the cylinder wall. For natural gas fueling, the proposed beginning of injection is 25 degrees before TDC. The duration of the injection is similar to that of diesel, 2.5 ms, while the time between the beginning of the injection and 20 degrees after TDC is approximately 6.25 ms. At the time the injector closes, the natural gas jet has barely reached half the distance across the chamber. Because of the slow penetration rate of the conical sheet it would take an injection duration of nearly 8 ms to reach the cylinder wall. It can be concluded that the actual gas penetration is inadequate.

5.3.3 Jet Distribution

The subject of flow distribution has been discussed in many sections of this chapter, and only a summary will be discussed here. While the flow visualization performed did not considered piston motion, swirl and combustion, some characteristics of the gas injection from the conical poppet design were established.
The conical sheet injected near a top wall was shown to have a bi-stable behaviour. It either clings to the top wall or collapses under the poppet. Both phenomena are caused by low pressure zones created by the air entrainment and to the sensitivity of the sheet to a pressure difference between its top and bottom surfaces. Both phenomena reduce greatly the mixing surface between the gas and the air. Along with the slow penetration discussed in the last section, the poor distribution provided by the actual design is likely to result in excessive smoke and non-optimal efficiency.

Sheet interruption has been investigated and showed some potential improvement both in improving the flow distribution and the penetration rate. Appropriate interruption prevents both jet collapse and clinging to the top wall. More research would be required to obtain an optimal interruption arrangement if such a solution is considered.
6 CONCLUSIONS

The objective of this project was to obtain knowledge about the injection of a high velocity gas emerging from a suddenly opened conical poppet type nozzle, investigating in particular the penetration rate and the flow distribution characteristics. The effect of pressure ratio, lift, injection duration and wall constraints on the jet were also to be determined.

Flow visualization of transient sonic methane jets was performed in this project. In most experiments, the jet emerging from the test injector was underexpanded at the nozzle. The Reynolds number of the jets observed ranged from $7 \times 10^3$ to $5.6 \times 10^4$. Visualization was realized with schlieren and shadowgraph techniques, and single-shot images were obtained with a CCD black and white camera at a shutter speed of $1/10000^{th}$ of a second. Images were digitized for recording and further processing. In a first set of experiments, the jet was injected in atmospheric conditions and visualized laterally. Then axial visualization of methane injections in a sealed cylindrical chamber was performed. The jet penetration and general distribution were established from photographs.

The characteristics associated with the incompressible steady-state turbulent conical sheet jet were examined utilising a momentum-integral approach and assuming the similarity of profiles in the jet. For small jet axis angles, an expression for the axial velocity decay of the turbulent conical sheet was obtained. The velocity decay was found to be inversely proportional to the axial distance $z$, as is the case for the round free jet. The turbulent Reynolds number was estimated to be 20 for the conical sheet, while it is approximately 45 for the round free jet. Based on results from selected review papers, the analysis was extended to binary mixtures. Compressibility effects were partially considered. A simple treatment for underexpanded jet was also discussed.
A model of the transient turbulent conical sheet jet was developed. The transient conical jet is modelled as a quasi-steady-state conical sheet feeding a vortex ring. The model is an extension of a similar model for the incompressible transient round jet discussed in the literature. In the quasi-steady-state section of the transient jet, the properties are the one established in the steady-state analysis. The vortex structure is considered as a whole; it is fed mass and momentum by the steady-state jet, and is slowed down by a drag force and the need to accelerate surrounding fluid. The model permits one to obtain the tip penetration, the vortex mass and the vortex velocity as a function of time for a high-velocity turbulent transient conical sheet jet of methane into air. While in principle the model depends on some properties not known accurately - the turbulent Reynolds number, the drag coefficient and the discharge coefficient - its transient nature renders the model quite insensitive to a variation in these parameters.

Before comparing the penetration rate obtained analytically and experimentally, a first conclusion regarding the observed jet geometry must be stated:

- (1) The free conical sheet jet is seen to have a definite curvature of its axis, towards its inside surface, that leads to the collapsing of the jet for large poppet angle. As a result, the geometry of the jet observed experimentally differs from the geometry proposed in the modelling of the transient jet.

When the jet is free from any wall constraints, the jet sheet naturally forms an enclosed area under the poppet. Air entrained by the jet is depleted in this area, causing a lower pressure zone. This lower pressure zone is sufficient to have an effect on the sheet, since its continuity renders it sensitive to pressure. For the 10° angle poppet, the sheet exhibits a definite curvature, causing a downward penetration larger than expected. For the 20° angle poppet, the curvature is severe and causes the jet to collapse under the
poppet, except at higher pressure ratios (5 to 1) where the jet avoids collapsing but is strongly curved. The jet from the 30° angle poppet collapses under all conditions tested.

The difference between the jet geometry for the 10° angle poppet and the modelled geometry was small. Consequently the penetration rate obtained from the model and the one obtained experimentally with the 10° angle poppet could be compared. The following statements can be stated regarding the agreement between the experimental and analytical results:

- The compared penetration rates far from the nozzle are similar.
- The predicted variation in penetration rate for different pressure ratios across the nozzle is consistent with the one observed experimentally. However, the magnitude of the variation observed experimentally is greater than the one predicted, potentially because of pressure effects in the development of the jet.
- Larger variations in penetration rate for different lifts were predicted than the ones observed experimentally, but this difference was explained by non-ideal flow conditions inside the test injector.
- The model predicted that penetration rates in the early stages of the jet propagation are larger than the ones observed experimentally, especially at lower pressure ratios, leading to an overall penetration approximately 15% higher than that observed experimentally for a pressure ratio of 2.

It appears that, in addition to a difference in overall geometry, the development of the highly transient jet as it exits the nozzle is not adequately modelled by the proposed geometry. Nevertheless, the model is consistent in predicting the effect of parametric variation, and gives some insight regarding the mechanism of the jet penetration. Both model and experimental results support to the following conclusions:
(2) The model, to a large extent in accord with experimental observations, shows that the free jet tip penetration of the conical sheet is proportional to:

- the square root of time: $t^{1/2}$,
- the square root of the initial velocity: $U_0^{1/2}$,
- the methane to air density ratio at ambient conditions to the power 1/4: $(\rho_m/\rho_a)^{1/4}$,
- the upstream to ambient pressure ratio to the power 1/4: $(P_0/P_a)^{1/4}$,
- the product of the seat radius by the lift to the power 1/4: $(R_s R_l)^{1/4}$.

The jet penetration is also dependent on:

- the poppet angle: $\beta$,
- the injection duration: $t_i$.

In addition, it was found that the flow conditions inside the test injector were important to consider. Relatively long passages of small diameter in conjunction with high subsonic velocities lead to considerable pressure drop due to friction inside the test injector. Consequently, the pressure just upstream of the nozzle is smaller than expected. Internal friction choking can also occur if the lift is set such that the nozzle area is not significantly smaller than areas of the passages inside the test injector.

Furthermore, the magnitude of the conical sheet jet penetration was found to be significantly less (by about 30%) than that of a series of round jets, given that the total flow area is the same.

(3) An increase in the upstream-to-ambient pressure ratio is always found to cause an increase in jet tip penetration, given that it is caused by an increase in upstream pressure. This penetration increase is both observed experimentally and predicted by the model. If the flow at the nozzle is not choked, an increase in pressure ratio causes an
increase in initial velocity. If the flow is choked at the nozzle, an increase in pressure causes underexpansion to occur. The underexpanded jet behaves as if it originated from a larger source area. An increase in nozzle velocity and area will both result in an increase in jet tip penetration.

(4) The model predicts an increase in penetration if the lift is increased. Experimental observations indicated that the lift has little effect of the jet penetration. It was shown however that the flow behaviour inside the test injector could be held responsible for the lack of effect of the lift variation. If the flow is choked at the nozzle exit, the pressure drop increases when the lift is increased, resulting in a momentum gain much smaller than the one predicted by the model. If the lift is increased too much, internal choking occurs and nozzle velocity diminishes, yielding again a much lower momentum than the predicted one. It is believed that if the injector is designed to limit internal friction, by increasing the size of the gas passages, an increase in lift will yield a larger penetration.

(5) The presence of the top wall was found to have a very significant effect on the conical sheet. A similar phenomenon to that described in the first conclusion occurs when the nozzle is positioned near a top wall for the 10° angle poppet. The air entrained by the jet causes a low pressure zone between the sheet and the wall, provoking the clinging of the jet to the top wall. Clinging to the top wall was also observed for the 20° angle poppet at large pressure ratios. The top wall was found to have no influence on the jet from the 30° angle poppet.
Conclusions (1) and (5) lead to some corollary statements:

- The effect of the angle on the jet is related to the observed jet geometry. For small angles, the jet bends; the larger the angle, the larger the curvature. If the angle is large enough, the jet collapses under the poppet.

- When the nozzle is situated near a top wall, the jet exhibits a bi-stable behaviour associated with the poppet angle. For a given angle, the jet either clings to the top wall or collapses under the poppet, propagating downward. It is not apparent that any intermediate case exists between these two situations. The switching from one case to the other seems to occur in the vicinity of an angle of 20°, since for this angle both behaviours were observed depending on the pressure ratio.

- The effect of the bottom wall was observed for different distances between the top and bottom walls and for different poppet angles. In all cases it was observed that for a small distance (15 mm) the jet rapidly fills the gap between the two walls and subsequently propagates radially, mixing with the air only at its front. The following observations were made for each poppet angle:

  10° poppet: The jet clings to the top wall first and propagates along it. If the walls are separated by a distance larger than the jet thickness (approx. 20 mm), the jet does not reach the bottom wall. Even without contact, the presence of the bottom wall was found to have a small effect on the jet penetration (provided the bottom wall is not too far, in which case it has no effect).

  20° poppet: The jet initially propagates downward. If the bottom wall is near the top wall, the jet clings to the bottom wall first, then fills the space between the two walls. If the bottom wall is further (25 mm) and the pressure ratio is high (5 to 1), the jet will
cling to the top wall first.

30° poppet: The jet propagates towards the bottom wall to which it clings.

The similarity between the experiments performed in this project and the conditions in the engine were discussed in chapter 4 and it was found that all parameters on which the penetration depends could be reproduced experimentally, with the exception of the Reynolds number and of the injection duration. In the literature, it is stated that the penetration increases mildly with an increase in Reynolds number. Some experiments performed in this project looked at the effect of increasing the Reynolds number. This was accomplished by injecting the gas in a pressurised chamber, while maintaining the pressure ratio constant. The higher upstream density results in a higher Reynolds number. The following conclusion can be drawn from these experiments:

- (7) An increase in the Reynolds number from $1.5 \times 10^4$ to $5.6 \times 10^4$ produced no significant change in the penetration rate. Together with results reported in the literature, this result indicates a mild dependence of the turbulent jet on the Reynolds number.

The injection duration in the flow visualization experiments was longer than the one occurring in the engine. However, the penetration of the conical sheet after the injector had closed was observed, and it can be concluded that

- (8) The penetration rate of the jet tip decreases rapidly when the poppet closes. A consequence of this observation is that given a point at a determined distance from the nozzle to be reached by the jet tip within a specified time, the jet tip must have travelled
the majority of this distance before the injector closes.

Conclusions #7 and #8 lead to another corollary statement:

○ If all other parameters are matched (initial velocity, density ratio, pressure ratio, seat radius and lift and poppet angle), during the time the injector is open the penetration rate observed experimentally is similar to that occurring in the engine.

Extending the conclusions and corollaries stated so far to the present use of the prototype injector in the series 71 diesel engine, the following corollaries can be stated:

○ The natural gas jet has reached only half way across the chamber at the time the injector closes. For the series 71 engine, it is evaluated that the natural gas penetration is approximately half of the diesel penetration for typical operating conditions. The natural gas penetration for the present injector and conditions utilised is not sufficient to yield optimal mixing with the surrounding air.

○ The actual flow distribution is inadequate. While the flow distribution cannot be clearly established because the motion of the piston, the swirl and the squish effect were not considered, the jet distribution is limited by its dual behaviour. With the present 10° and 20° angle poppets, clinging to the top wall is likely to occur, resulting in poor mixing near the top wall. Clinging and slow penetration rate would result in an overall poor mixing and in the presence of a rich zone near the top wall, leading to soot formation and non-optimal fuel conversion efficiency. If the jet propagates downward, the same
phenomenon occurs since then a rich zone occurs on the surface of the piston. In both cases, the flow distribution is inadequate.

The continuity of the jet renders it sensitive to the pressure difference across its surfaces, and diffusion cannot be easily controlled. As a potential solution for this problem, jet interruption was investigated as a mean to allow pressure equilibrium between the top and bottom surfaces of the sheet. The following preliminary conclusion were drawn:

- (9) Jet interruption is a successful method to avoid top wall clinging and jet collapsing in most cases. In addition, appropriate jet interruption can provide a jet penetration rate significantly higher (almost double penetration rate was observed in some cases). The number, width and thickness of the interruptions utilised are important parameters to consider.

6.1 RECOMMENDATIONS AND FUTURE WORK

One of the main goals regarding the injection of natural gas into diesel engines is to obtain adequate penetration and distribution of the fuel in the chamber. The actual natural gas penetration is slower mainly because of the chosen nozzle geometry. A series of round orifices could probably yield a similar fuel penetration for the natural gas as for the diesel fuel. The injector tip could be redesigned so that the gas would be introduced through a series of holes. However if the actual design is to be kept, jet interruption is recommended. The optimal number and width of the interruptions could be determined with little more experimental work involving the manufacturing of different interruption arrangements and flow visualization.

Even if the conical nozzle is not retained, the modelling of the conical sheet is an
interesting problem and the results obtained are promising. In order to improve the actual model further experiments could be performed. In this project, the experiments carried out were related to the transient jet. Experimental data concerning the steady-state jet would be useful in verifying the assumptions made regarding the conical sheet jet. Two axis hot wire measurements of the velocity within the conical sheet jet would provide a good experimental basis to establish more accurately the steady-state characteristics.

The flow inside the injector is subject to friction and recirculation, and because the injector tip geometry is complex, the exact nozzle conditions are not known accurately. A special nozzle assembly could be manufactured for the steady-state experimental measurements that would ensure better knowledge of the nozzle conditions.

Regarding the transient conical sheet jet, modelled starting conditions seems to misrepresent the actual starting jet. If light sheet visualization could be performed, requiring some means of rendering the flow visible, the structure of the starting jet, and of the remaining jet, could be established more completely than with schlieren photography.
7 REFERENCES


Einang, P.M., Engja, H., Vestergen, R., Medium speed 4-stroke diesel engine using high pressure gas injection technology.

Einang, P.M., Koren, S., Kvamsdal,R., Hansen, T., Sarsten,A., High-Pressure, Digitally Controlled Injection of Gaseous Fuel in a Diesel Engine, With Special Reference to Boil-Off from LNG Tankers, Proceedings CIM AC Conference, June 1983


Fox, WR.W., McDonald, A.T., Introduction to fluid Mechanics, John Wiley and sons, 1985

Holder, D. W., North, R. J., Schlieren Methods, Publisher: Her Majesty’s Stationary Office, 1964


Midgeley, P., Natural Gas Intensifier/Injector for DDEC - Equipment Diesel Engines, Market Study by Canadian Resourcecan Limited, Vancouver, B. C., December 1989


Saber, A. J., Georgallis, M., Fluid Dynamic Structures Relevant to Fuel Injection and Jet Ignition, December 1989


Shapiro, A. H., The Dynamics and Thermodynamics of Compressible Fluid Flow, The Ronald Press Company


8 APPENDICES

8.1 APPENDIX A - NON-DIMENSIONAL ANALYSIS

The transient turbulent conical sheet jet was modelled in chapter 3 as a quasi-steady-state jet feeding a vortex structure. The equations describing the rate of change of mass, momentum and position of the vortex structure can be non-dimensionalised using the appropriate scaling factors. Equations A.1 to A.5 summarize the steady-state equations, taken at the back plane of the vortex, at \( z = z_v \).

\[
\frac{U}{U_m} = e^{-\alpha t^2} \quad \text{and} \quad \frac{U_m}{U_o} = \frac{k_1}{z_v} \sqrt{\frac{R_{/eq}}{R_{/eq}}}
\]

\[
\frac{X}{X_m} = e^{-\frac{1}{2}\alpha t^2} \quad \text{and} \quad \frac{X_m}{X_v} = \frac{k_2}{z_v} \sqrt{\frac{R_{/eq}}{R_{/eq}}}
\]

\[
\frac{r_{1/2}}{\sqrt{R_{/eq}}} = k_3 \frac{z_v}{\sqrt{R_{/eq}}}
\]

where \( \xi = r/r_{1/2} \) and \( \alpha = \ln(2) \) and \( l_{eq} \) is given by

\[
l_{eq} = l C_d \frac{\rho_g}{\rho_a} \quad \text{if} \quad \frac{P_o}{P_a} < 1.86
\]

\[
l_{eq} = 0.537 l C_d \frac{\rho_g P_o}{\rho_a P_a} \quad \text{if} \quad \frac{P_o}{P_a} > 1.86
\]

Also

\[
\rho = \frac{1}{\rho_a \chi (\frac{\rho_o}{\rho_g} - 1) + 1}
\]
The transient equation for the position, mass, methane content and momentum of the vortex structure (for the conical jet sheet) are given by:

\[ U_v = \frac{dz_v}{dt} \quad (A.6) \]

\[ \frac{dm_v}{dt} = 2 \int_0^{r_e} p(U-U_v)2\pi z_v \cos(\beta) dr \]

\[ = 4\pi z_v \cos(\beta) \rho_a \int_0^{r_e} \frac{(U-U_v)}{\chi(\frac{\rho_a}{\rho_g} - 1) + 1} dr \]

\[ (A.7) \]

\[ \frac{dm_{v'}}{dt} = 4\pi z_v \cos(\beta) \rho_a \int_0^{r_e} \frac{\chi(U-U_v)}{\chi(\frac{\rho_a}{\rho_g} - 1) + 1} dr \]

\[ (A.8) \]

\[ (1 + \frac{\rho_a}{\rho_v}) \frac{dM_v}{dt} = 4\pi z_v \cos(\beta) \rho_a \int_0^{r_e} \frac{(U-U_v)U}{\chi(\frac{\rho_a}{\rho_g} - 1) + 1} dr + \frac{\rho_a U_v V_v}{\rho_v} \frac{d\rho_v}{dt} - F_D \]

\[ (A.9) \]

The drag force is proportional to the frontal area:

\[ F_D = C_D \left( \frac{1}{2} \rho_a U_v \right) (4\pi z_v R_v \cos(\beta) R_v) \quad (A.10) \]

and the change in density is:

\[ \frac{d\rho_v}{dt} = \frac{\rho_a(1 - \frac{\rho_a}{\rho_g})}{\rho_g} \frac{dm_{v'}}{dt} - \frac{m_{v'}}{m_v} \frac{dm_v}{dt} \]

\[ (A.11) \]

The following dimensionless parameters are defined:
The steady-state Equations A.1 to A.5 and the non-dimensional parameters defined in Equation A.11 are replaced in the transient Equations A.6 to A.10 and after rearrangement, the following non-dimensional expression are established:

i) The rate of change of position:

\[
\frac{dz_v^*}{dt^*} = U_v^*
\]

(A.13)

ii) The rate of change in total vortex mass:

\[
\frac{dm_v^*}{dt^*} = 4\pi z_v^* \cos(\beta) \left[ \frac{k_1 e^{-a t^2} - U_v^*}{z_v^*} \right] \int_0^{z_v^*} \frac{d(r)}{\frac{L}{R_{eq}}} - \ln(U_v^* \frac{z_v^*}{k_2})
\]

(A.14)

the radius \( r_c \) can also be non-dimensionalized from Equation 3.13 (neglecting \( r_c \)):

\[
\frac{r_c}{L} = \frac{1}{L} \left[ \ln(U_v^* \frac{z_v^*}{k_2}) \right] - \frac{1}{\ln(2)}
\]

(A.15)

iii) The rate of change in methane content:

\[
\frac{dm_{g,v}^*}{dt^*} = 4\pi z_v^* \cos(\beta) \left[ \frac{k_2 e^{-\frac{1}{2} \alpha t^2} \left[ \frac{k_1 e^{-\frac{1}{2} \alpha t^2} - U_v^*}{z_v^*} \right]}{\frac{L}{R_{eq}}} \right] \int_0^{z_v^*} \frac{d(r)}{\frac{L}{R_{eq}}} - \frac{k_2 e^{-\frac{1}{2} \alpha t^2} \left( \frac{\rho_a}{\rho_g} - 1 \right) + 1}{\frac{z_v^*}{\rho_g}}
\]

(A.16)

iv) The rate of change in momentum:
\[
(1 + \frac{\rho_a}{\rho_v}) \frac{dM_v^*}{dt^*} = 4\pi z_v^* \cos(\beta) \int_0^r \frac{k_1 e^{-\alpha t^2} - U_v^*}{z_v^*} \frac{k_1 e^{-\alpha t^2}}{z_v^*} \frac{k_2 e^{-\frac{1}{2} \alpha t^2}}{z_v^*} \left( \frac{\rho_a}{\rho_v} - 1 \right) + 1
\]
(A.17)

\[
\frac{d(\frac{\rho_v}{\rho_v})}{dt^*} + \frac{\rho_a U_v^* V_v}{\rho_v L^3} \frac{d(z_v)}{dt^*} - 2\pi C_p \cos(\beta)(U_v^*)^2 \frac{(z_v + R_v)(R_v)}{L^2}
\]

It is found that, given \( \rho_v/\rho_a, \beta \) and the steady-state constants \( k_1, k_2 \) and \( k_3 \), the change in position, mass, methane content and momentum of the vortex can be expressed as function of the following parameters:

\[
\frac{dz_v^*}{dt} = f_1(U_v^*)
\]
(A.18)

\[
\frac{dm_v^*}{dt^*} = f_2(z_v^*, U_v^*)
\]
(A.19)

\[
\frac{dm_v^*}{dt^*} = f_3(z_v^*, U_v^*)
\]
(A.20)

\[
\frac{dM_v^*}{dt^*} = f_4(z_v^*, U_v^*, R_v^*)
\]
(A.21)

The initial condition can also be stated in dimensionless form:

\[
\text{at } t^* = 0 : z_v^* = \frac{z_0}{L}, \quad R_v^* = \frac{1}{2} \frac{r_e}{L}, \quad U_v^* = 1
\]
(A.22)

The solution of the system of equation is obtained by solving simultaneously Equation A.18, A.19, A.20 and A.21, according to the following steps:

For \( 0 < t^* < t^*_{\text{end}} \)

1) the term \( U_v^* \) is guessed,
2) \( z_v^* \) is obtained from A.13,

3) \( m_v^* \) is obtained from A.14,

4) \( m_{gv}^* \) is obtained from A.16,

5) \( \rho_v/\rho_a \) is obtained from:

\[
\frac{\rho_v}{\rho_a} = \frac{1}{M_{gv}^* (\frac{\rho_a}{\rho_g} - 1)} + 1
\]

(A.23)

6) \( M_v^* \) is obtained from A.17,

7) \( U_v^* \) is computed from:

\[
U_v^* = \frac{M_v^*}{m_v^*}
\]

(A.24)

8) if the vortex velocity and the guessed value differ, repeat step 2) to 8), otherwise continue.

9) calculate the radius \( R_v \) from:

\[
\left( \frac{R_v}{\sqrt{R_{s_{eq}}}} \right)^3 = 3 \frac{m_v^*}{4\pi} \frac{\rho_v}{\rho_a}
\]

(A.25)

10) calculate the tip penetration:

\[
\frac{z_t}{\sqrt{R_{s_{eq}}} \sqrt{R_{s_{eq}}} \sqrt{R_{s_{eq}}}} = \frac{z_v}{\sqrt{R_{s_{eq}} \sqrt{R_{s_{eq}} \sqrt{R_{s_{eq}}}}} + 2 \frac{R_v}{\sqrt{R_{s_{eq}} \sqrt{R_{s_{eq}} \sqrt{R_{s_{eq}}}}}}}
\]

(A.26)

11) increment time and repeat.
8.2 APPENDIX B - REPEATABILITY STUDY

Because the history of the jet was to be obtained from single shots photographs from different jets at different times, a certain repeatability had to be shown. For two different cases, multiple pictures of different jets at the same time after the beginning of the injection and for the same conditions were obtained. The results of each case are reported in Table B.1 and B.2.

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Table B.1 Repeatability study. Upstream pressure of 173.7 kPa (1.7 atm), 10° angle poppet 0.056 mm lift at time 1 ms. RPL: radial penetration measured on left side, RPR: right radial penetration, APL: left axial penetration, APR: right axial penetration, PL: total penetration measured on left side, PR: right total penetration. Measurements in mm.
It is desired to obtain choking at the nozzle of the injector to maintain good control over the mass of fuel injected. The small diameter of some of the CNG port in the prototype injector along with high Mach number leads to potential friction choking inside the injector. The maximum lift of the poppet that can be achieve without friction choking is calculated in this appendix for different conditions. In addition, the condition that would be found at the nozzle given an internal friction choked flow are evaluated. Another consequence of the small passages and of the high Mach number is the potentially significant pressure drop inside the injector. An approximation of this pressure drop will also be obtained. The goal of these calculations is to
obtain a reasonable approximation of the characteristics of the flow inside the injector.

The injector was modelled as illustrated in Figure C.1. Each section represents a specific section in the injector. The size difference between each section is exaggerated on the figure, but the sharp junctions are present in the injector. The following assumptions will be made:

- the flow in the injector is isentropic and adiabatic,
- only friction choking is considered in the passages, the effect of edges is not considered,
- because the mass of gas in the tip reservoir is in most cases less than 10% of the total mass injected, the flow will be assumed as steady-state. This is not a reasonable assumption in the early stages, but once the flow is developed, it should provide a good understanding of the process and a good estimate of the mass flow.

The different scenario for choking flow in the injector are the following ones:

1) The area at the nozzle is the smallest restriction. In which case friction choking in the inside passages might occur in section B and C and must be verified. Also the pressure drop occurring in the passages and due to friction can be evaluated.

2) The area at the nozzle is no longer the smallest area. Choking is then likely to occur either at the end of section B, or at the end of section C.

Case 1

The nozzle area is the smallest. Given upstream stagnation pressure and temperature and given the downstream pressure, the Mach number is obtained at the nozzle using the following relationship:
**Figure C.1** Model of the methane ports inside the test injector.

\[
M = \sqrt{\frac{2}{k-1} \left( \frac{P_o}{P_a} \right)^{\frac{k-1}{k}}} 
\]

The temperature, density, velocity and mass flow of the gas at the nozzle can be computed from the Mach number:

\[
T_n = \frac{T_o}{1 + \frac{k-1}{2} M^2} 
\]

\[
\rho_n = \frac{\rho_o}{(1 + \frac{k-1}{2} M^2)^{\frac{1}{k-1}}} 
\]
The mass flow at point 3 is the same as at the nozzle. From that mass flow, the Mach number at 3 is computed:

$$U_n = \sqrt{\frac{2k}{k-1} R(T_o - T_n)}$$  \hspace{1cm} (C.4)

$$\frac{\dot{m}}{A_n} = \rho_n U_n \quad \dot{m} = \rho_n U_n A_n$$  \hspace{1cm} (C.5)

The temperature, density, velocity are also computed at 3, using the same equations (C2-C4). The Reynolds number is also calculated at 3. From Shapiro, the following term is evaluated

$$L_1 = \frac{k+1}{2} M_3^2$$  \hspace{1cm} (C.6)

where $f$ is the average friction coefficient, $L_{\text{max}}$ is the maximum length of duct that will handle the initial mass flow without choking. The friction coefficient $f$ can be evaluated from

$$\frac{4f L_{\text{max}}}{D} = 1 - \frac{M^2}{k} + \frac{k+1}{2k} \ln \frac{(k+1)M^2}{2(1+\frac{k-1}{2}M^2)}$$  \hspace{1cm} (C.7)

where $e/D$ is the relative roughness, and for smooth pipe can be taken as 0.000001 (equation taken from Fox and McDonald, Introduction to Fluid Mechanics). The maximum L/D ratio is then obtained, and compared with the actual one. If the actual L/D ratio is larger then the computed one, choking will occur in the injector. The previous computations were performed on a LOTUS spreadsheet. It was found that internal choking occurred at a lift of approximately 0.089 mm. The Mach number and pressure drop for each section is indicated in Table C.1 for lifts of 0.056 and 0.081 mm.
It can be seen that the compounded pressure drop is 16% for a lift of 0.056 mm and 22% for a lift of 0.081 mm. The pressure drop was calculated the following way: For the section B in which the flow is choked, the stagnation pressure change can be readily obtained with

\[ \frac{P_o}{P_o^*} = \frac{1}{M} \left( \frac{2(1 + \frac{k-1}{2} M^2)}{\frac{k+1}{k-1} M} \right)^{\frac{k+1}{k-1}} \]  \hspace{1cm} (C.9)

Where the Mach number at the beginning of the section considered is taken (given the Mach number is one at the end of the section). For the sections where the flow does not choked, the following relationship is utilised:

\[ 4f \frac{L}{D} = (4f \frac{L_{\max}}{D})_{M_b} - (4f \frac{L_{\max}}{D})_{M_e} \]  \hspace{1cm} (C.10)

where \( M_b \) and \( M_e \) are the Mach number at the beginning and at the end of the section considered respectively. The Mach number at the beginning of the section can be found from the mass flow and upstream conditions. The first term is also known. The Mach number at the end of the

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Table C.1 Mach numbers and pressure drop in the injector. Numbers refer to the different sections in Figure C.1. The primed numbers indicated the end of the previous section by opposition to the beginning of the current one. Because the pressure drop does not change significantly with the initial pressure, the initial conditions were not corrected (no iterations).
section can then be calculated from the previous Equation (C.10). The pressure drop in the section is then obtained from

\[ \frac{P_{de}}{P_{di}} = \frac{(P_{de}/P_o^*)}{(P_{di}/P_o^*)} \]  

(C.11)

where the respective pressure drop are calculated from Equation C.9.

**Case 2**

The previous results show that if choking occurs, it will occur at the end of section B. Given Mach = 1 at location 2, we can evaluate the maximum Mach number at the entrance of the port (3) utilizing Equation C.7. Since the friction coefficient depends on the Reynolds number, an iterative process is required to obtain M3. Once the Mach number is obtained at location 3, the mass flow can be obtained, and the Mach number at the nozzle can be calculated. Again pressure differences due to friction can be computed. The pressure drops are used iteratively to modify the initial conditions. Condition at the nozzle are then inferred from the Mach number and from the equation stated previously. Some results for these calculation are reported in Table C.2.

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**Table C.2** Conditions at nozzle when internal friction choking is occurring.

It is seen that the initial velocity is much lower than for a choked nozzle, even if the
increase in lift is only of \( \frac{1}{20} \) of a millimeter. The density however increases moderately.

8.1 PICTURE PROCESSING RESULTS

In the next pages are reproduced the results of the automatic and manual processing of the digitized photographs. The dimensions are in mm. The distances are taken from the nozzle. Some of the indicators are illustrated in Figure 4.15.

Key to abbreviations:

- PYA1 : automatic average downward penetration on left side.
- PYA2 : automatic average downward penetration on right side.
- R1 : automatic radial penetration on left side.
- R2 : automatic radial penetration on right side.
- P1 : automatic estimation of the jet penetration on the left side. Overestimate the penetration.
- P2 : automatic estimation of the jet penetration on the right side. Overestimate the jet penetration.
- P1M : manual measurement (with the mouse) of the jet total penetration on right side.
- P2M : manual measurement of the jet total penetration on the left side.
- TETA1 : automatic measurement of the apparent angle on right side.
- TETA2 : automatic measurement of the apparent angle on left side.
- AREA : automatic evaluation of the two-dimensional area occupied by the jet. Could be converted to the volume assuming the jet is perfectly axisymmetric.
- PYMAX : maximal distance reached downward.
PICTURE PROCESSING RESULTS

1 - 10 DEGREE ANGLE POPPET - FREE JET

### A - LIFT - 0.056 PR - 1.5

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### 2 - 10 DEGREE ANGLE POPPET - FREE JET - REPEATABILITY DATA

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**FILE NAME PREFIX: L4C1**

### 4 - 10 DEGREE ANGLE POPPET - TOP WALL AND BOTTOM PLATE

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### 5 - 10 Degree Angle Poppet - Interrupted Jet and Bottom Plate

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### 7 - 30 Degree Angle Poppet - Free Jet

#### A - Lift = 0.081 Pr = 2

**NOT PROCESSED**

#### B - Lift = 0.081 Pr = 5

**NOT PROCESSED**

### 8 - 30 Degree Angle Poppet - Top Wall

#### A - Lift = 0.081 Pr = 5

**NOT PROCESSED**

### 9 - 30 Degree Angle Poppet - Top Wall and Bottom Plate

#### A - Lift = 0.081 Pr = 5 H = 17.8

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### Table 5: Time and Lift Details

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### Table 6: Time and Lift Details

| 68.7  | 72.8  |

### Table 7: Time and Lift Details

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### Table 8: Time and Lift Details

| B - LIFT = 0.056 | PR = 2 | NOT PROCESSED |

### Table 9: Time and Lift Details

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### C - Lift = 0.056 PR = 5\** H = 7.9**

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### 13 - 20 Degree Angle Poppet - Free Jet

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NOT PROCESSED

B - Lift = 0.056 PR = 2

NOT PROCESSED

C - Lift = 0.1 PR = 5

NOT PROCESSED

### 14 - 20 Degree Angle Poppet New Injector - Top Wall

A - Lift = 0.2 PR = 2.64

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B - Lift = 0.2 PR = 2.64 INT 6X2

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C - Lift = 0.2 PR = 3.43 INT 6X2

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### 15 - 10 Degree Angle Poppet New Injector - Top Wall

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### 16 - 10 Degree Angle Poppet New Injector

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**18 - AXIAL VISUALISATION - 2° DEGREE ANGLE POPPET FREE OR INTERRUPTED**

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**D - LIFT = 0.2 PR = 5 INT 4X2**

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<tr>
<th>TIME (ms)</th>
<th>PYA1</th>
<th>PYA2</th>
<th>R1</th>
<th>R2</th>
<th>P1</th>
<th>P2</th>
<th>PY1</th>
<th>PY2</th>
<th>TETA1</th>
<th>TETA2</th>
<th>AREA</th>
<th>PYMAX</th>
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**FILE NAME PREFIX : Y1C6**

**E - LIFT = 0.2 PR = 5 INT 4X1**

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<th>P1</th>
<th>P2</th>
<th>PY1</th>
<th>PY2</th>
<th>TETA1</th>
<th>TETA2</th>
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<th>PYMAX</th>
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**FILE NAME PREFIX : Y1C7**

**F - LIFT = 0.2 PR = 5 INT 4X2 WITH COPPER CARTRIDGE**

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<th>P1</th>
<th>P2</th>
<th>PY1</th>
<th>PY2</th>
<th>TETA1</th>
<th>TETA2</th>
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**FILE NAME PREFIX : Y1C8**

**G - LIFT = 0.2 PR = 5 INT 6X2**

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<th>R2</th>
<th>P1</th>
<th>P2</th>
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<th>TETA2</th>
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**FILE NAME PREFIX : Y1C9**

**F - LIFT = 0.2 PR = 5 INT 6X1**

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<th>R2</th>
<th>P1</th>
<th>P2</th>
<th>PY1</th>
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<th>TETA2</th>
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**FILE NAME PREFIX : Y1CA**

**G - LIFT = 0.2 PR = 5 INT 6X1**

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<th>R1</th>
<th>R2</th>
<th>P1</th>
<th>P2</th>
<th>PY1</th>
<th>PY2</th>
<th>TETA1</th>
<th>TETA2</th>
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