CAVITATION AND ENTRAINMENT IN A DOWNCOMER ENTRANCE

by

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We accept this thesis as conforming
to the required standard

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Two-phase instabilities have been observed at a downcomer entrance in an experimental rig that drains near-saturated Freon-11 from a vessel. The regimes have been characterized using dimensionless parameters describing the pool depth, downcomer flowrate and the subcooling at the liquid interface in the pool.

The two primary mechanisms involved in the instability were entrainment and cavitation. The entrainment regimes observed in this study can be correlated with the previously documented occurrence of air-water incipient drawdown. Drawdown was observed at higher pool depths than expected (for a given flowrate) when vapour bubbles were present at the entrance. Cavitation, the mechanism responsible for bubble formation and growth, has been found to be very susceptible to the presence of nucleation sites and to the amount of subcooling at the pool interface.

Severe instability may occur at a flowrate where the local velocity at the entrance is equal to the rise velocity of a particular vapour bubble. Due to the generation of vapour through entrainment and cavitation, bubbles conglomerate at the entrance, with the vapour having no mechanism for escape. Some segregation occurs, with small bubbles discharging downwards and
large bubbles rising upwards.

Downcomer entrance geometry was varied as an independent parameter. In general, the observed regimes in the re-entrant and sharp-edged geometries were similar. The flow regimes in the rounded geometry were unique due to the effect of the streamlined curvature reducing cavitation at the entrance.
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**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>( B )</td>
<td>calibrated y-intercept (see Ch. III, p. 30)</td>
</tr>
<tr>
<td>( D )</td>
<td>downcomer inside diameter (m)</td>
</tr>
<tr>
<td>( Fr )</td>
<td>Froude number (dimensionless flowrate) ( \sqrt{\frac{V(gD)}{gD}} )</td>
</tr>
<tr>
<td>( \Delta Fr^* )</td>
<td>Froude number peak-to-peak fluctuation expressed as a percentage of the mean Froude number</td>
</tr>
<tr>
<td>( H )</td>
<td>chamber pool depth above the top of the entrance (m)</td>
</tr>
<tr>
<td>( H/D )</td>
<td>dimensionless pool depth</td>
</tr>
<tr>
<td>( K )</td>
<td>linear calibration constant (see Ch. III, p. 30)</td>
</tr>
<tr>
<td>( N )</td>
<td>number of data points</td>
</tr>
<tr>
<td>( P_{ch} )</td>
<td>chamber pressure (Pa)</td>
</tr>
<tr>
<td>( P_V )</td>
<td>chamber pressure signal voltage</td>
</tr>
<tr>
<td>( P_{Sat} )</td>
<td>saturation pressure at temperature ( T_{ch} ) (Pa)</td>
</tr>
<tr>
<td>( Q )</td>
<td>siphon loop flowrate (litres/s)</td>
</tr>
<tr>
<td>( Q_V )</td>
<td>siphon loop flowrate signal voltage</td>
</tr>
<tr>
<td>( SC )</td>
<td>dimensionless subcooling ( \frac{P_{ch} - P_{Sat}}{\rho g D} )</td>
</tr>
<tr>
<td>( SC_{AVG} )</td>
<td>average value of subcooling</td>
</tr>
<tr>
<td>( SD )</td>
<td>standard deviation</td>
</tr>
<tr>
<td>( T_{ch} )</td>
<td>chamber temperature (°C)</td>
</tr>
<tr>
<td>( T_V )</td>
<td>chamber temperature signal voltage</td>
</tr>
</tbody>
</table>
\( V \) \hspace{1cm} \text{average liquid phase velocity in the tube (m/s)}

\( V_n \) \hspace{1cm} \text{valve number \"n\" as shown on Figure 4}

\( g \) \hspace{1cm} \text{gravitational acceleration (m/s}^2\text{)}

\( \rho \) \hspace{1cm} \text{liquid density (kg/m}^3\text{)}

**Abbreviations**

\( \text{rd} \) \hspace{1cm} \text{rounded entrance}

\( \text{re} \) \hspace{1cm} \text{re-entrant entrance}

\( \text{shp} \) \hspace{1cm} \text{sharp-edged entrance}

\( \text{CPD} \) \hspace{1cm} \text{critical pool depth}

\( \text{ID} \) \hspace{1cm} \text{incipient drawdown}

\( \text{OCB} \) \hspace{1cm} \text{onset of cavitation bubbles}
I. INTRODUCTION

1.1 Preliminary Remarks

Much effort has been devoted in the last forty years to the study of two-phase flow regimes and their relationship to heat and mass transfer phenomena. Such previous work has been an integral part of the development of sophisticated power generation and process industry technologies, where two-phase flows occur frequently.

The present study is concerned with the liquid-vapour flow of a one-component fluid, near saturation temperature and pressure. The liquid drains from a vessel through an entrance into a vertical tube or "downcomer". An example of this type of flow is shown in Figure 1. The liquid is draining from the chamber into a region of increasing hydrostatic pressure, but in the direction of decreasing piezometric pressure. Other common examples of this type of near-saturated flow are in package boiler installations and in several types of evaporators used in industry.

When vapour phase is present, the resulting tube flowrate turns out to be much less (and the frictional head loss much greater) than that predicted in the conventional single-phase analysis.

The existence of this type of instability has been
hinted at several times in the literature, for example by Simpson \[1\], but it seems that it has not been visualized or systematically studied. Simpson made a vague, and it seems misleading postulate as to the mechanisms involved, suggesting certain design guidelines be followed to minimize the effect of the instability. In essence he stated that one should avoid Froude numbers from 0.31 to 1.0 in vertical two-phase pipe flow. In the past this guideline has been used by engineers in industry. However, very inconsistent results have been obtained, particularly in flows with near-saturated liquids. Often trial and error solutions have been attempted in efforts to control the instability (for example air-injection into the downcomer) without any basic understanding of the flow regimes involved.

1.2 Review Of The Terminology

1.2.1 Dimensionless Parameters

In characterizing two-phase flow regimes, dimensionless parameters are sometimes used to describe the flow of one fluid under a particular set of conditions. Then, using the principle of dynamic similarity, this description can be applied to other
fluids and other sets of conditions.

In liquid flow with a liquid-vapour interface, the Froude number (abbreviated Fr) is a significant dimensionless group. In pipe flow it is usually defined as the square root of the ratio of inertial to buoyancy forces, given by

\[ Fr(\text{liquid}) = V(gD)^{-\frac{1}{2}} \left( \frac{\rho}{\rho - \rho_v} \right)^{\frac{1}{2}} \]

Here \( V \) is the average liquid velocity in the tube, \( D \) is the tube diameter, \( g \) is gravitational acceleration, and \( \rho \) and \( \rho_v \) are the respective liquid and vapour densities. Since at low pressures, the vapour density is negligible when compared to that of the liquid, this term simplifies to

\[ Fr = V(gD)^{-\frac{1}{2}} = "\text{dimensionless flowrate}" \]

It is assumed that when the principle of dynamic similarity of Froude numbers is applied to other fluids and sets of conditions, other forces on the fluid such as those involved with surface tension and viscosity, are small relative to inertial and buoyancy forces.

The pool depth \( H \), defined as the vertical distance from the vapour-liquid interface in the chamber to the
top of the downcomer entrance, is another important parameter. It is a measure of the suppression of vapour formation at the downcomer entrance due to hydrostatic pressure effects. \( H \) can be non-dimensionalized by dividing by the tube diameter \( D \), to give

\[
H/D = \text{"dimensionless pool depth"}
\]

The third dimensionless parameter used in this project describes the magnitude of liquid subcooling in the chamber. The subcooling number, defined here as

\[
SC = (P_{ch} - P_{sat})/\rho g D = \text{"dimensionless subcooling"}
\]

is the difference between the chamber pressure \( P_{ch} \) and saturation pressure \( P_{sat} \) of the liquid in the chamber (at the chamber temperature \( T_{ch} \)), non-dimensionalized by dividing by \( \rho g D \). The suitability of non-dimensionalizing by \( \rho g D \) will have to be examined in the future with experimental studies using several other tube diameters.

APPENDIX A contains a brief dimensional analysis used to justify the use of these dimensionless groups.
1.2.2 Descriptive Terms

Three terms used in the hydraulic study of downcomers, with the definitions in the context used in the present study are:

1. "flow instability" - a spontaneous occurrence of rapidly changing two-phase flow regimes in a tube, accompanied by fluctuations in the tube flowrate.

For a more general definition of two-phase flow instabilities, the reader is referred to a review done on this subject by Bergles [2].

2. "cavitation" - vapour-filled bubble formation and collapse in a liquid caused by dynamic (flow-induced) pressure reduction in an adiabatic flow.

Knapp [3] has defined the term "incipient" cavitation as the stage of cavitation that is barely perceptible as the liquid pressure is lowered, with "desinent" cavitation describing the stage where the cavitation disappears with increasing pressure. Theoretically cavitation occurs when the normal stresses on an infinitesimal particle of liquid are reduced to
the vapour pressure of the liquid (at the particle temperature). The presence of surface tension forces, boundary layers, turbulence, undissolved gas and dust particles (which act as nucleation sites), distort the requirement of zero net normal stress at a point in the liquid. Since bubble formation and collapse are time-dependent phenomena, the time a liquid particle remains trapped in a low pressure eddy will be an important factor in determining if and to what extent cavitation will occur. In the absence of any nucleation sites, the formation of vapour after pressure reduction is delayed due to the existence of a "thermodynamically metastable" state.

3. "incipient drawdown" - the point of incipient entrainment.

Consider the "irrotational" downflow (without swirl) of a liquid from a pool, through a vertical drain or downcomer. For each pool depth there exists a critical flowrate at which the liquid interface suddenly breaks down, and a cone-shaped interface forms above the entrance. The stratified gas or vapour above the liquid surface becomes entrained in the liquid at the vertex of the cone.
This critical flowrate, defined as incipient drawdown (abbreviated ID), is illustrated in Figure 2 for the case of air-water flow into a liquid level at or near the tube entrance. With water flowing at very low depths above the entrance (1 or 2 mm), the flowrate is susceptible to surface tension effects. At low pool depths (H/D less than 0.25 as suggested by Souders [4]) the maximum water flow is limited by a circular weir phenomenon (Figure 2a), where the liquid flows down to the liquid level in an annular or falling film regime. For every pool depth, there is a maximum flowrate given by the lower part of the "circular weir" curve on Figure 2. The magnitude of air entrainment is negligible in this regime as any bubbles present in the tube quickly rise upwards. At higher pool depths (H/D greater than 0.25) the maximum flowrate at a given pool depth is governed by incipient drawdown, shown on the upper part of the same curve (Figure 2b). Any attempt to increase the flowrate above values given by the curve (by increasing the chamber pressure Pch) will result in the large scale entrainment of the air from above the interface, with no net increase in the liquid flowrate.

Figure 2 is arrived at based on the assumption that the transition from weir flow to incipient drawdown is continuous, which happens only when the flow is into a liquid level at or near the tube entrance. In this
study the phenomena of weir flow and incipient drawdown are described solely by the term incipient drawdown, with the implication that the curve joining the two phenomena is continuous.

The transition from weir flow to incipient drawdown is not well defined when the liquid level in the tube is much lower than the entrance. An example of water draining from a vessel (under the effects of gravity only) is shown in Figure 3. As the flowrate into the upper chamber is increased the following sequence is observed. Initially a thin film of water runs down the wall of the tube in an annular or weir regime (Figure 3a). Eventually as the pool depth rises, necking occurs at the vena contracta (Figure 3b). As the depth rises further, the vapour core bridges with liquid (Figure 3c). The Froude number does not increase significantly after bridging, and the pool depth diverges from the drawdown curve (Figure 3d). Despite the bridging of the annular air-filled region, annular flow will persist in the tube well below the pool interface. Any mechanism for increasing the flowrate by increasing the pressure in the upper vessel will again be limited by the drawdown curve. At very high flowrates, "flooding" will occur in the tube, irrespective of drawdown (Figures 3e and 3f). During flooding, the liquid film bridges throughout its whole
vertical extent, and the tube flows full for its entire length.

Both bridging (Froude number observed at approximately 0.5 for Freon-11) and flooding (Froude number approximately 2.0 from [1]) phenomena occur above a dimensionless pool depth of 0.25. However, if the liquid level is maintained at the tube entrance independent of flowrate (by lowering the pressure in the upper vessel), a smooth but definite transition without bridging will be observed, as shown previously in Figure 2.

1.3 Review Of Previous Work

A literature search was conducted and it was concluded that no systematic study of this instability could be found. However, various authors have published work on related topics.

1.3.1 Instabilities In Two-Phase Systems

Bergles [2] has published a review of previous work done in this area. This review included both thermal and hydrodynamic instabilities characterized as either static or dynamic, and of a primary, secondary or compound nature. No mention was
made of any cavitation-induced entrance instability.

1.3.2 Cavitation

Oba [5] studied cavitation in water flowing through a horizontal micro-orifice, under prescribed nuclei condition. The effect of orifice diameter on the desinient cavitation number, given by

\[(P_{ch} - P_{sat})/(\rho V^2/2)\]

was investigated.

Lienhard [6] did a similar study varying the magnitude of the orifice-to-pipe-diameter ratio and the ratio of orifice-diameter-to-nucleation-site-spacing in a horizontal submerged orifice. The cavitation number at desinence was correlated to the product of these two ratios.

1.3.3 Incipient Drawdown

Souders [4] experimentally studied incipient drawdown as it related to rotational flow in a fractionation column. The downcomer was modelled under three distinct conditions of fluid head. These were; operating as a circular weir at low depths, operating as
a free running orifice at intermediate depths, and operating as an orifice running full at high depths.

Davidian [7] did experimental work on the development of a non-circulatory waterspout. This phenomenon is essentially incipient drawdown reversed, with the liquid entrained upwards by the flow of a gas into a tube, rather than gas entrained downward by the flow of a liquid. The results seem to agree well with other published air-water incipient drawdown experiments.

Harleman [8] analyzed irrotational incipient drawdown using potential flow, modelling the entrance as a point sink. An experimental study was then performed using two vertically stratified liquids, testing for the critical entrainment point. Re-entrant, sharp-edged and rounded entrance geometries were tested for a 2.54 cm diameter tube.

Kalinske [9] used re-entrant and sharp-edged pipes of various diameters and lengths in a study of incipient drawdown. While draining an air-water mixture from a closed vessel with a metered air inlet, the air entrainment rate at incipient drawdown was measured.

Simpson [1], reviewed previous work done on incipient drawdown. Also reviewed was work done on the dependence of bubble rise velocity on Froude number in vertical pipe flow. Bubble rise velocity is usually
defined in a stagnant pool of liquid and is a function mainly of liquid surface tension, viscosity, bubble size and shape, and the diameter of the constraining tube. In a downflowing liquid, a bubble will rise where the local liquid velocity at the bubble is less than the calculated rise velocity. Simpson stated that Froude numbers ranging from 0.31 to 1.0 should be avoided (to prevent pressure pulsation and vibration) in all vertical pipe flow where entrainment of air or vapour might be possible.

1.3.4 Miscellaneous Studies

It seems that the flow field in an orifice has not been solved numerically (at high Reynolds numbers) using the Navier-Stokes equations. However, using two-dimensional hydrodynamic flow theory, solutions have been obtained for both re-entrant (Borda's mouthpiece) orifices and sharp-edged orifices (for example Vallentine [10]). These solutions neglect boundary layer effects, but give an order of magnitude estimate of the local velocity (and pressure from Bernoulli's equation) throughout a downcomer entrance.

Kelly [11], studied extensively the operation of siphons. In particular, the effect of dissolved air and gases in the siphon flow of water was investigated.
Several postulates were made as to the source of high frequency vibrations (noise) often found in siphons. Bharathan [12] and Wallis [13] have conducted several experimental studies into the subject of countercurrent annular flow. Bharathan was concerned with flooding and interfacial shear stress phenomena in air-water flow, while Wallis studied additional condensation effects in steam-subcooled water flow.

1.4 Scope Of The Present Investigation

After conducting this literature search, it was decided to conduct a systematic experimental study of the flow instability that was presumed to exist when draining (without swirl) near-saturated fluids from a chamber or vessel. Accordingly, an experimental rig was designed and constructed to model this occurrence. Flow visualization, and flow mapping of any regimes by the measurement of the dimensionless flowrate, pool depth and subcooling constituted the scope of the experimental work. The measurement of subcooling entailed the measurement of the chamber pressure and temperature.

The results of the investigation hopefully can be applied by engineers in attempts to predict and/or control the occurrence of the instability.
II. EXPERIMENTAL APPARATUS

2.1 General Concept

The apparatus depicted on the flowsheet in Figure 4 was used to investigate the flow regimes. Pictures of the experimental rig and instrumentation are shown in Figure 5. Two loops are shown on the flowsheet; a circulation loop and a siphon loop. In the circulation loop, the liquid was extracted from the lower vessel by a circulation pump and passed through a co-axial heat exchanger into the overflow vessel. A constant level was maintained in this vessel by an overflow line passing back into the lower vessel. In the siphon loop, the fluid was extracted from the overflow vessel up into the vacuum chamber (Figure 6) where it drained through an attached entrance geometry (Figure 7) into the downcomer test section. The downcomer emptied into an overflow weir in the lower vessel. Both the inlet and discharge of the siphon were kept submerged. The siphon loop was primed from a vacuum accumulator tank, which was evacuated periodically by a vacuum pump.

Compared to alternative methods, advantages of using this system to achieve near-saturated conditions in the vacuum chamber were:
(a) - regulation of the liquid temperature in the siphon loop by simply controlling the cooling water flowrate through the heat exchanger. Then by controlling the pressure in the apex of the siphon (the vacuum chamber), the liquid properties could be adjusted to achieve near-saturation.

(b) - saturated vapour conditions could be maintained in the vacuum chamber despite the presence of any non-condensibles (i.e. air leaks) that may have infiltrated the system, by continuously evacuating a small amount of vapour from the vacuum chamber and generating additional saturated vapour.

(c) - pressure control in the vacuum chamber was independent of any fluctuations due to pumping, as a siphon (with a nominal driving head of 60 cm) was used to provide the flow through the test section.

2.2 Working Fluid

As water was readily available and non-toxic it was first considered for the working fluid. However, operating the siphon loop with water (at ambient temperature) would have required a difference in elevation of approximately 10 m (between the overflow vessel and vacuum chamber) for the siphon apex pressure
to reach the saturation vapour pressure of water. Running at higher water temperatures would have decreased this height, but heating elements and insulation would have added to the overall complexity. The most serious problem would have been the effects of dissolved air in the water, as revealed by Kelly [11]. Air may have come out of solution near the apex of the siphon, lowering the average fluid density and preventing saturation from occurring at a given apex height. This phenomenon would have required apex heights for water, measured on the rising leg of the siphon, to be considerably larger than 10 m.

Freon-11', a common refrigerant, was eventually chosen as the working fluid. It has the following characteristics:

(a) - a poor solvent of both air and water
(b) - low toxicity under normal conditions of handling and usage (group 5a - Underwriter's Laboratories Classification of Comparative Life Hazard of Gases and Vapours [14])
(c) - low boiling point at atmospheric pressure of 23.8 °C

'Freon-11, CCL₃F (trichlorofluoromethane) is a registered trademark of the Du Pont corporation
(d) - relatively low cost (the least expensive of the Freons)
(e) - low viscosity and surface tension
(f) - excellent thermal and chemical stability
(g) - inflammable, non-conductive and non-corrosive
(h) - well documented thermodynamic properties

There were some disadvantages to using Freon-11 as the working fluid. It was still very expensive to purchase compared to water, and its peculiar chemical properties necessitated careful choice of apparatus material. For example, the plastic polyethylene and the elastomer neoprene both react unfavourably with Freon-11. It was very important to keep the apparatus clean as Freon-11 has a great affinity for grease and oils. The presence of these substances in sufficient quantities would have significantly affected the Freon's saturation properties.

2.3 Pipe, Tubing, Hose, And Fittings

1.3 and 2.5 cm PVC pipe and fittings were used for the Freon circuit because they were readily available and easy to assemble. PVC ball valves with teflon seats were used for throttling and shutoff purposes.
The tubing initially chosen for the downcomer test section was 3.2 cm I.D. by 1.8 m long polycarbonate tubing. It was found that when the tubing was exposed to Freon-11 under a slight vacuum, severe crazing (micro-cracking) occurred. Glass tubing of 2.54 cm I.D. was chosen as a replacement. Brass collars were fastened to the tube where the vacuum chamber O-ring seal fitted over the tube. To allow visualization of vapour formation, the top portion of the rising leg of the siphon was also fabricated out of glass tube.

The heat exchanger was a simple co-axial shell and tube type made from 2.5 cm copper pipe (shell) and 1.3 cm copper pipe (tube), with brass Swagelok heat exchanger fittings sealing the ends of the shell. Cold building supply water was used as the cooling medium.

2.4 Vacuum Chamber And Vessels

The vacuum chamber used was a 17 litre Nalgene polycarbonate bell jar (Figure 6) placed over a mounting plate, with an O-ring providing the seal. Any air present in the chamber during the experiments would have risen to the top of the vacuum chamber, since Freon vapour is denser than air. Therefore the extraction inlet to the vacuum pump was located at the top of the chamber, where it would keep the liquid-vapour interface
clear of non-condensibles.

A false floor made from two perforated aluminum plates (with a fine brass screen sandwiched between) was located around the test section entrance. Three equally spaced vertical straightening vanes were attached to this false floor. The arrangement was intended to remove large scale turbulence from the pool and to prevent the buildup of swirl. The incoming jet of Freon was dissipated directly at the chamber inlet by a wire basket filled with brass wool.

Some crazing problems were encountered with the bell jars, but these were minimized by taking care when mounting the jars so as not to form any small cracks in the walls of the jar. When present, these cracks (with their inherent stress concentrations) would rapidly propagate upon further exposure to the Freon.

An aluminum container with 2.5 cm threaded nipples attached was used for the overflow vessel, while a spare bell jar was used for the lower vessel. Loose fitting lids were placed over these vessels to minimize evaporation losses.

A 51 cm diameter by 152 cm high mild steel pressure vessel was used for the vacuum accumulator tank. It was equipped with an analog pressure gauge for local vacuum indication.
2.5 Pumps

An Eastern Model MD-80 magnetic drive pump was used to circulate the Freon. This was a seal-less pump with a polypropylene casing and impellor. Maximum capacity was rated at 1.0 litres/s with a shut-off head of 10 m. The pump was driven by a 249 W at 3450 rpm motor.

A Bendix Model AAF vacuum pump was used direct-coupled to a 373 W at 1800 rpm motor.

2.6 Instrumentation

The instrumentation measured the chamber pressure, temperature, and pool depth, the average flowrate through the siphon loop, and the peak-to-peak amplitude of downcomer flowrate fluctuations (see Figure 4).

2.6.1 Temperature Measurement

Temperature was measured with an Omega Type PR-11 general purpose platinum resistance thermometer probe (RTD) coupled with an Omega Model 199p2 digital indicator. The indicator had an analog output option (± 0.1°C resolution) for interfacing with the data acquisition system.
2.6.2 Pressure Measurement

Chamber pressure was initially measured with a Bourns Model 441 bellows/potentiometer type absolute pressure transducer, with a range of 0-101 kPa. The transducer had a static error band of 1.2% full scale, including the effects of linearity, friction, hysteresis, resolution and repeatability. It was found that this instrument was not sufficiently accurate to measure the small pressure differences necessary to characterize the subcooling. A simple water manometer was then connected to the system. It was found to be accurate for steady-state measurements but clumsy to use if the chamber pressure fluctuated. The transducer was then used only for transient measurements when the operating characteristics of the system were being studied.

2.6.3 Depth Measurement

Pool depth in the vacuum chamber was measured (± 1.0 mm) against a stainless steel graduated scale mounted on the false floor.
2.6.4 Flowrate Measurement

Average flowrate in the siphon loop was measured with a Signet MK 315 paddlewheel "flosensor", with an open paddle design that minimized cavitation effects. The sensor was mounted in a 1.3 cm diameter PVC fitting with 30 pipe diameters length of straight pipe preceding the sensor. The sensor was coupled with a Signet MK 309 analog "flometer" for local indication and a MK 314-6 signal conditioner for interfacing with the data acquisition system. This method of flowrate measurement was chosen because cavitation occurs when near-saturated liquid flows through an orifice plate or a venturi. It was found that this instrument gave repeatable and accurate results (± 0.003 litres/s) providing the fluid velocity in the sensor was kept above 30 cm/s (Froude number of 0.17).

Fluctuations in downcomer flowrate were measured with a ThermoSystem Inc. Model 1010-A constant temperature anemometer coupled with a DISA Model 55D10 linearizer and a Nicolet Model 660A FFT\(^1\) spectrum analyzer. The analyzer used a Tektronix Model 4662 digital plotter for hardcopy output.

A TSI Model 1230 hot film sensor was used as the

\(^1\)Fast Fourier Transform
anemometer probe. This conical shaped sensor was constructed from a quartz rod with a quartz-coated platinum film band at the cone tip, and was chosen because of its ruggedness, spatial resolution and rigidity. The probe was placed at the discharge of the downcomer, in the fully developed region of the flow.

The TSI anemometer unit circuit consisted of a Wheatstone bridge arrangement with the probe as one variable leg and a decade resistance as the other variable leg (Figure 8). The bridge had a feedback loop which supplied sufficient power to raise or lower the probe resistance so that the bridge was kept in balance. Varying the decade resistance varied the probe operating resistance, and therefore the probe temperature. Since the heat transfer rate from the probe varied non-linearly with the liquid velocity at the probe, the linearizer was used to create a linear relationship between flowrate and output voltage.

2.6.5 Data Acquisition System

The signals from the pressure, temperature and average flowrate measurement devices were then interfaced with the department's Neff Model 620 data acquisition system and processed by a PDP-11/34 minicomputer.
Provision was made for the two types of sampling shown in Figure 9. The first type was at a constant pool depth, prompting for the pool depth and manometer reading and then sampling the temperature, and flowrate for five seconds at a sampling rate of 10 Hz. The second type was while lowering or raising the depth of the pool, sampling the pressure (from the transducer), temperature and flowrate for 50 seconds at a sampling rate of 1 Hz.

2.6.6 Photographic Studies

Film footage was shot of the regimes using a Bolex 16 mm cine camera (at 24 frames per second). This film was used for initial analysis of the regimes, with specific frames of interest developed for presentation purposes. A HaRco Mini-Max Model CTC-3000 black and white video camera was used for the preparation of a video cassette describing the regimes. Still pictures of some regimes were taken with a standard 35 mm camera using 400 ASA black and white film.
2.7 Assembly And Initial Testing

The components of the circulation loop were assembled and the loop filled with tap water. The heat exchanger response was tested with the circulation pump running. Leaks in the system were noted and subsequently repaired.

A small amount of Freon was then tested in the circulation loop to observe whether vapour-locking and cavitation would seriously impair pump performance. Some problems occurred when the Freon flowrate was reduced for a lengthy period of time, when the liquid temperature was near ambient. Occasionally the pump would seize, but it was repaired simply by dismantling the liquid end of the pump and prying loose the plastic impellor assembly from the casing. The roughened surfaces were then sanded smooth and the pump re-assembled.

Subsequently the siphon loop was assembled and tested with both water and Freon. After running water in the apparatus, it was found that it was impossible to completely drain the system. Condensation alone would leave small amounts of water in the piping. This water then could then find its way to the vapour-liquid interface in the vacuum chamber (Freon-11 and water are immiscible) where its entrainment would grossly affect
any observed flow regimes.

It was found at this stage that using an accumulator tank as a buffer provided much better vacuum control than direct-coupling the vacuum pump to the vacuum chamber.

The instrumentation was then installed and the data acquisition program written. Finally the flow conditioning elements were placed in the vacuum chamber, and the apparatus was ready for the collection of data.
III. PROCEDURE

3.1 Routine Experimental Preparation

After several test runs using water as the working fluid, a routine procedure was developed for placing the Freon into the system while minimizing the presence of water and other contaminants. The procedure, referring to Figure 4, was to:

(1) - drain the piping.
(2) - disconnect the unions coupling the piping to the vessels, and empty all vessels.
(3) - remove any residual solids from the vessels, (i.e. rust and chips of plastic) and wipe clean all surfaces of any grease and dirt with rags soaked in Freon.
(4) - disconnect the heat exchanger and blow out residual water from any low spots that did not drain completely.
(5) - reconnect the piping.
(6) - pour the Freon through a cloth filter placed in a plastic funnel, into the overflow vessel. Gravity causes the liquid to flow down through the circulation loop to the lower vessel, priming the pump.
(7) - turn on the heat exchanger by opening valve V5 (Figure 4). This allows the Freon to pick up some initial subcooling, which minimizes evaporation in the vessels and prevents cavitation and vapour-lock during pump startup.

(8) - circulate the Freon until it achieves its maximum possible subcooling.

(9) - shut the circulation pump down and skim off any visible water and contaminants present in the lower vessel, where they have now accumulated.

It was found that most of the visible solid contaminants were attracted to this thin film of water, and were easily removed. It soon became evident that complete removal of the water was not required as the pump suction tended not to entrain and circulate these impurities when the amounts present were very small.

It was necessary to externally prime the pump during water runs using the priming connection at valve V3. Air-locks prevented the gravity flow of water from the overflow vessel down to the lower vessel. However, as mentioned previously it was not required to externally prime the pump when running Freon, probably due to its lower surface tension.

The vacuum chamber and test section were aligned
and levelled and the video equipment and lighting given final preparation. The data acquisition system was "signed on" and the computer program prepared for execution.

The vacuum accumulator tank was then evacuated with the vacuum pump to approximately 50 kPa. The siphon loop was then primed to the desired pool depth by closing valve V8 and opening needle valve V7. A large amount of vapour was generated and lost (through the vacuum pump) during this initial period as the vacuum chamber and test section were cooled to the temperature of the Freon. Subsequently a small amount of gas was bled continuously from the vacuum chamber to account for the removal of any non-condensibles initially present, air leaks, and any steady-state vapour generation.

Great care had to be taken to ensure that both ends of the siphon remained submerged below the liquid Freon level. If either end became uncovered due to a low level in either the overflow or lower vessels, an air-Freon charge would shoot up into the vacuum chamber as it became pressurized.

The cooling water flowrate was adjusted by throttling valve V5 to control the amount of subcooling within the vacuum chamber. The variation of cold building supply water temperature with season allowed minimum Freon temperatures of 11°C in winter months, but
only 13°C in summer months. The maximum Freon temperature observed in the vacuum chamber was 16°C. Higher temperatures caused excessive vapour generation which caused stoppage of the siphon flow at the apex due to the absence of liquid.

3.2 Calibration

The data acquisition system used for this experiment measured chamber pressure $P_{ch}$, chamber temperature $T_{ch}$, and siphon loop flowrate $Q$, with the chamber pool depth $H$ measured manually.

Assuming device linearity, the following relationship existed between the measured voltages read by the data acquisition system and the variables measured:

\[
\begin{align*}
P_{ch} (\text{Pa}) &= K_1 \times P_V + B_1 \\
T_{ch} (\degree \text{C}) &= K_2 \times T_V + B_2 \\
Q (\text{litres/s}) &= K_3 \times Q_V + B_3 
\end{align*}
\]

where $P_V$, $T_V$, and $Q_V$ were the voltage signals read by the data acquisition system (after attenuation into the 0-1.0 volt D.C. range) and $P_{ch}$, $T_{ch}$, and $Q$ were the calculated values (in real units) output to the data file by the computer. $K_1$, $K_2$, and $K_3$ were the
calibrated proportionality constants and \( B_1 \), \( B_2 \), and \( B_3 \) were the calibrated \( y \)-intercepts. By running the data acquisition system with several known values of \( P_{ch} \), \( T_{ch} \), and \( Q \), the measured values of \( P_V \), \( T_V \), and \( Q_V \) were entered into a "best fit" linear regression program to solve for the six calibration constants.

3.3 Measurements With Fixed Pool Depth

For the purposes of flow mapping, a reading of chamber pressure, temperature, pool depth and siphon flowrate (or Froude number) was required for each measurement at constant pool depth. For these measurements the pressure transducer signal was neglected and the manometer-indicated value of chamber pressure was used. This calculated value took into account the day-to-day variation in atmospheric pressure.

The Freon level was raised to a desired pool depth where a characteristic flow regime was occurring by adjusting the chamber pressure using valve \( V_7 \) and the Froude number using valve \( V_4 \). Valve \( V_6 \) was opened to lower the pool depth if an overshoot had occurred. The cooling water flow was then adjusted until a small amount of vapour generation had occurred and the Freon reached the desired level of subcooling. The pool depth
and the manometer reading were then entered into the computer. After waiting approximately 30 seconds for any transients to die out, the data acquisition system (Figure 9) was instructed to record the chamber temperature and siphon flowrate. Time averaged values of the temperature and flowrate were then calculated by the computer. A descriptive code was then entered into the computer which described qualitatively the particular regimes observed during the measurement. The presence was noted of entrainment, cavitation, incipient drawdown, upward or downward discharge of vapour and any special characteristics of the observed regimes. Comments as to the quality of the particular measurement were also recorded. A video recording of each regime was made during this period.

3.4 Measurement Of Downcomer Flowrate Fluctuations

The overflow weir in the lower vessel was removed for these measurements and a hot film probe was inserted into the discharge of the test section. The linearizer, spectrum analyzer, and anemometer unit were then turned on and warmed up for at least two hours prior to the taking of data.

The Freon was circulated through the system until it reached a temperature of approximately 13°C. The
"cold" resistance of the hot film probe was then measured and the operating resistance set at a value of 0.2 ohms higher. The probe was not temperature compensated, therefore care had to be taken to ensure the temperature of the Freon did not vary far from 13°C when measurements were taken.

The probe and linearizer were calibrated with Freon flowing through the circulation loop in a stable liquid phase regime, with the flosensor providing the known flowrate. The linearizer was calibrated by setting the "zero", the "gain", and the "exponent" so that the output voltage from the linearizer was linearly proportional to flowrate in the downcomer, with zero flowrate giving zero voltage.

The flowrate, pool depth and subcooling were then adjusted in the downcomer until the largest real time fluctuation was observed on the analyzer. Hardcopy output of the flowrate in the time domain (Froude number vs. time) and in the frequency domain (RMS power vs. frequency) was produced. The frequency domain plot was produced after ensemble averaging 16 time domain plots and performing a spectral analysis for dominant frequencies. The RMS power was formed from the square root of the ensemble average of the squared spectral magnitudes.
IV. EXPERIMENTAL RESULTS

4.1 Flow Mapping

Typical measurements of regimes obtained at constant pool depth are shown in Figures 10 to 14. The flow regimes are grouped according to the mechanism responsible for the presence of vapour in the entrance, with Figure 14 showing the locus of the most "violent" regime observed. The regimes are mapped on diagrams of dimensionless pool depth vs. Froude number. The subcooling SC present during the measurements is described statistically on the diagrams by stating the number of data points N, the range of subcooling of the points (if applicable), the average value of subcooling SCAVG and the standard deviation of the values SD. An inset is included on the diagrams to illustrate the regime being mapped. The results presented cover a range of values for near-saturated Freon-11 (SC less than 45).

Re-entrant, rounded, and sharp-edged entrances have been tested. The re-entrant entrance was investigated extensively because it was the first geometry tested, when the regimes involved were completely unknown. Also, the re-entrant shape allowed unobstructed flow visualization at the vena contracta.

Figures 10 to 17 show a reference curve from
experimental incipient drawdown data of Kalinske [9]. The points cited were from his experiment with air-water flow in a 4.4 cm diameter tube with a sharp-edged entrance. This curve is an idealization of the drawdown phenomenon as it applies to air-water flow into a liquid level below the tube entrance, but at Froude numbers below the bridging flowrate of water.

4.1.1 Incipient Drawdown

Figure 10 shows the occurrence of incipient drawdown into the re-entrant geometry, for both low and high ranges of subcooling. The drawdown cone often penetrated into a region containing vapour that had accumulated at the entrance, which caused significant variation in the results (compared to data from previous air-water experiments). The points exhibit a large amount of scatter, particularly at low values of subcooling.

Figure 11 shows similar incipient drawdown data for the rounded and sharp-edged entrances. No distinction is made between high and low values of subcooling. The diagram shows a definite trend in that drawdown occurs at lower pool depths for a given flowrate in the rounded geometry than in the sharp-edged geometry. When compared to Figure 10, it seems that re-entrant drawdown
occurs at higher pool depths than rounded and sharp-edged drawdown. The scatter for rounded and sharp-edged entrances is also significantly less than for the re-entrant case. Drawdown for the sharp-edged geometry follows very closely the sharp-edged air-water data of Kalinske [9].

Figure 18a shows a picture of the re-entrant geometry during incipient drawdown (at low values of subcooling) with bubbles present at the entrance. The drawdown cone is well defined despite the presence of bridged annular flow downstream from the entrance.

4.1.2 Onset Of Cavitation Bubbles (OCB)

In the flow of a near-saturated liquid in a region above the drawdown curve (in the initial absence of vapour), there is a limiting flowrate at a given pool depth where incipient cavitation will occur. An infinitesimally small vapour bubble will nucleate at the vena contracta of the tube entrance. At a given value of subcooling, incipient cavitation is dependent on both the Froude number and the dimensionless pool depth. A curve defining this relationship can be derived after making a few simplifying assumptions (APPENDIX A).

Once the first bubble has formed it grows in size, eventually forming a ring-shaped cavity of bubbles
(similar in shape to a "string of beads") that surrounds the periphery of the tube. The initial nucleation sequence is defined here as the "Onset of Cavitation Bubbles" (abbreviated OCB). Successive pictures of this regime in the re-entrant entrance (taken from 16 mm film) are shown in Figures 18d, 18e and 18f.

On Figure 12, experimental OCB points have been plotted for the re-entrant geometry, with low and high subcooling as the distinguishing parameter. As expected, nucleation points with high subcooling tend to occur at higher flowrates for a given pool depth than those with low subcooling. There is a large amount of scatter in the points.

Figure 13 shows OCB for the sharp-edged entrance, with the parameters of high and low subcooling. Again, points with high subcooling tend to be further to the right (at higher flowrates) on the diagram than those with low subcooling.

No evidence of pure cavitation (OCB) from a liquid-only regime was found in the rounded geometry at the flowrates possible in the present study. However, oscillating vapour bubbles were observed and often persisted at the entrance long after entrainment had occurred. Cavitation was observed at the periphery of the bubbles.
4.1.3 Requirements For A Violent Instability

At the same characteristic area on the flow map all three entrances showed a regime where the instability was subjectively judged to be "violent". Rapid bubble formation, oscillation, and collapse occurred, accompanied by the rising and spouting of large bubbles at the pool interface. This general region (but not the boundary) is shown on Figure 14 as between Froude numbers 0.25 to 0.65 at dimensionless pool depths less than 0.8.

In the rounded entrance a large bullet-shaped bubble would move every few seconds between a position at the tube entrance and a position several diameters downstream during this "violent" regime. Vapour would form at the bubble's periphery or wake. When at the upper position vapour would be ejected from the bubble in the form of smaller bubbles which would spout violently upwards against the roof of the vacuum chamber. Spouting with the re-entrant and sharp-edged geometries was much less severe and the bubbles involved were smaller.

Figure 18b shows a picture of this violent regime interacting with a drawdown cone in the re-entrant geometry, and Figure 18c shows a picture from above the re-entrant geometry during spouting.
Vapour phase existed everywhere on the diagram where flowrates were higher and pool depths lower than at a previous OCB occurrence. The regime present and the severity of any instability was found to be a function of the particular location on the flow map and the value of subcooling at that point.

4.2 Critical Pool Depth (CPD)

Despite OCB having not yet occurred (due to high subcooling), a regime with oscillating bubbles was often observed at the various entrances. Entrained bubbles passing through the vena contracta usually triggered this instability. However by raising the pool depth (keeping the flowrate constant) a depth was reached where these "semi-trapped" bubbles would rise into the chamber or exit down the tube, leaving the entrance free of vapour. The point at which this event occurred is defined here as the "Critical Pool Depth" (abbreviated CPD). CPD is shown for each entrance on Figures 15 to 17. Therefore CPD does not define a flow regime as such, but a region on the flow map that is path dependent. The CPD region is a region that must be avoided to ensure that no vapour phase will be present at the tube entrance. Sometimes at high Froude numbers and low values of subcooling (Fr greater than 0.06 and
SC less than 20) OCB would occur at higher pool depths than CPD. Physically this meant any unattached bubbles would still exit the tube at CPD, but a small and stable cavitation bubble (OCB) would reappear at the entrance.

Figures 15 and 16 show CPD for the re-entrant and rounded entrances at relatively constant values of subcooling. A "resonant" peak exists for the rounded entrance (Figure 16) at the transition between "bubble-up" and "bubble-down" flowrates (at approximately the same flowrates as for the previously mentioned violent instability). However in Figure 15, CPD for the re-entrant geometry reached a plateau at the "bubble-up" flowrate and did not decrease rapidly. Figure 17 shows this situation in the sharp-edged entrance, for low and high ranges of subcooling. Subcooling has little apparent effect on the size of the region.

4.3 Video Cassette

A video cassette was recorded showing these regimes in the three entrances. See APPENDIX C for an index to and a brief description of the regimes, and nominal values of the Froude number, pool depth and subcooling (where applicable).
4.4 Downcomer Flowrate Fluctuation

A real time plot of downcomer flowrate fluctuation (peak-to-peak) is shown in Figure 19a. This measurement was taken during the "violent" regime for the re-entrant geometry. The magnitude of fluctuation (as a percentage of the mean Froude number) is approximately 10%. Figure 19b shows a spectral analysis of the same regime. Taken over a 64 second sampling period, it shows no dominant spectral frequency other than 60 Hz noise.

Figures 20a and 21a show real time plots for the rounded and sharp-edged entrances during the violent regime. Fluctuations of approximately 27% and 15% are shown here. Figures 20b and 21b show a spectral analysis for these two respective entrances, and again no dominant frequencies other than 60 Hz noise are evident.

Figure 22a shows steady-state flowrate fluctuation of 80% for the re-entrant entrance. This measurement was of a periodic change between a bridged incipient drawdown regime and a bridged annular flow regime (see Figures 22b and 22c). The low frequency component (0.4 Hz) is the rate at which the regimes are changing. The type of bridging observed varied from that with a liquid core and vapour annulus, to that with a vapour core and a liquid annulus. The presence of the large
vapour space in the regime disqualifies it from further analysis in this project, but it does illustrate how large hydraulic fluctuations (without phase transition) can occur in downcomer flow.
V. DISCUSSION OF RESULTS

5.1 Qualifying Remarks

A clear statement of the limitations of the experimental method used must be made before a detailed quantitative or qualitative description of the observed regimes can be undertaken. This is particularly true for the material of any investigation where subjective observations of a new or pioneering nature are being made.

The experimental data presented in this report represents an attempt to locate the boundaries of certain observed flow regimes on a flow map. The existence of the regimes in the areas adjacent to the boundaries has been verified visually to a much greater degree of certainty than statistically indicated by the number of data points taken.

The quantitative measurement of instantaneous fluid properties during an unstable phenomenon, such as a two-phase instability in near-saturated fluid, is very difficult to do accurately. The regimes can change very quickly due to small perturbations in flowrate and pool depth, allowing non-equilibrium regimes to be observed. These regimes would not have been seen if the changes were made systematically and slowly.

A certain amount of swirl was always evident in the
chamber pool. A finite amount of vorticity was generated in the fluid at the inlet to the chamber and any swirl not removed by the flow conditioning elements would grow with time into a large and unpredictable vortex, or whirlpool. Depending on its size, the rotational core of the whirlpool could penetrate well down into the downcomer entrance where it would affect any regimes occurring there. Early in the project a straightening cross was placed over the tube entrance to eliminate this swirl. However, the boundary layers developed at the cross walls caused significant variation in regimes (see Figure 23a) as compared to those observed in flow without the straightening cross. Therefore, it was decided to use straightening vanes located radially away from the tube entrance to minimize (but not eliminate) swirl. Measurements taken of regimes where the whirlpool effect seemed large or significant were neglected.

The effect of trace contaminants in the Freon was an uncontrolled parameter that was watched closely. Losses of Freon from the operating batch were made up from a container of unused, "clean" Freon. Thus, contaminants continually accumulated in the system, and by the end of the experimental work the Freon had become "dirtier", with a slight yellow tinge not originally observed. Contaminants that act as surface-active
agents are thought to inhibit bubble coalescence, however there seemed to be no systematic variation of the degree of saturation observed (at a given chamber pressure and temperature) over the time period.

The presence of a large bridged vapour cavity trapped at the entrance required an extra parameter (the size of the cavity) to characterize fully the regimes. The flowrate became dependent on the shape and size of the vapour region, and independent of chamber pressure. This cavity usually formed at high flowrates, when the chamber pressure became high enough to force the tube liquid level (defined at zero flowrate at the same chamber pressure) below the tube entrance. This cavity nucleated as a normal ring-shaped set of cavitation bubbles (OCB), but after a short period of growth it became attached to the tube wall (Figure 23b). The cavity grew axially down the tube until the vapour detached from the wall, forming a large bubble in the center of the tube. Measurements were neglected when the vapour cavity became large enough that a decrease in chamber pressure did not cause an increase in pool depth.

When the vapour cavity occupied the core of the tube, violent up-venting of large bubbles was observed (Figure 23c) over a wide range of flowrates.

A stationary vapour cavity was not observed in the
rounded entrance but was seen frequently in the re-entrant and sharp-edged geometries.

5.2 Experimental Error

It is important in the measurement of these regimes to have a good estimate of the type and size of the experimental error involved. The three types of error involved in this work were instrumentation errors, time lapse errors, and judgement errors.

Instrumentation errors were those which described the accuracy of measurement of the particular transducers and measuring devices. Included were the assumptions of linearity made during the calibration process. These errors were relatively easy to determine using both the manufacturers' figures and errors estimated during the calibration procedure. In APPENDIX B an estimate of this type of error (using uncertainty analysis equations quoted in [15]) is; Fr ± 0.01, SC ± 1.17, and H/D ± 0.04.

Time lapse errors resulted from a delay in taking a measurement of a fluid property. This usually happened when a pool depth and manometer reading were taken manually, just before the data acquisition system recorded the chamber temperature and Froude number. Although hard to quantify, this type of error was
thought to be quite small.

Inconsistencies in judgement were inevitable when attempting to distinguish the transition from one regime to another. This third type of error was also hard to quantify and at times was probably large. The experimenter who made the observations and judgements, also turned on the lighting, activated the video recorder and adjusted the flowrate, pool depth, chamber pressure and temperature. Performance of these tasks while controlling an extremely unstable flow regime made a compromising of the quality of subjective measurement inevitable.

5.3 Incipient Drawdown

Pinpointing the location of drawdown entrainment was a very important objective since entrainment of saturated vapours was one of the mechanisms responsible for triggering the instability.

Incipient drawdown has been idealized as a regime where the liquid-vapour interface changes instantaneously from a planar surface into a pointed cone as the downcomer flowrate is increased. Actually (for a given pool depth) a drawdown cone of some type existed over a small range of flowrates. To consistently determine the exact location of the first
entrainment requires sophisticated procedures (for example those used by Harleman [8]) which did not seem warranted for this project.

The measurement of incipient drawdown in fluids with low values of subcooling was much more complicated than in the standard case of air-water flow (with high values of water subcooling). Because of the presence of vapour in the downcomer, the flow "saw" a lower effective pool depth than actually existed. This gave rise to incipient drawdown (entrainment) at much higher pool depths than otherwise expected.

The effect of subcooling on incipient drawdown for the re-entrant geometry can be interpreted from Figure 10. When incipient drawdown occurs, higher pool depths (at a given flowrate) can be expected at low values of subcooling.

The drawdown curve for the rounded entrance (Figure 11) was much lower (higher flowrates for a given pool depth) than for the other geometries. This conflicts with the data presented by Harleman, who reported no significant difference between the curve for rounded and sharp-edged geometries. However, Harleman used a much sharper parabolic entrance curvature. Since a rounded entrance will carry a larger flowrate (at a given pool depth) than a sharp-edged entrance, it seems probable the same tendency should occur for drawdown.
The drawdown cone was much "wider" in the rounded entrance than in the other geometries since the drawdown cone tended to follow the entrance curvature. This again conflicts with the findings of Harleman who stated the cones were geometrically similar in all entrances.

Kalinske [9] has reported that the re-entrant entrance has a lower drawdown curve than the sharp-edged entrance. This does not seem to be confirmed by the data presented in Figures 10 and 11, although the presence of vapour phase (in near-saturated flow) makes any direct comparison of little use.

A sketch of the streamlines in the three respective entrances (liquid-only flow) is shown in Figure 24. Of particular significance are the large separation eddies present at the vena contracta for the re-entrant and sharp-edged geometries but not for the rounded geometry. The lack of eddies in the rounded entrance explains why bubbles did not become attached at the vena contracta.

There was a much greater tendency for bubbles to become trapped (at all entrances) in Freon-11 flow than in air-water flow. This was due partially to the lower viscosity and surface tension of the Freon and to cavitation effects at the vena contracta.
5.4 Onset Of Cavitation Bubbles (OCB)

Cavitation is the mechanism that distinguishes the vertical downflow of near-saturated liquid from that of liquid at higher values of subcooling. As mentioned in the introduction, the static pressure gradient in the downflowing liquid can have a minimum value at the vena contracta. This occurrence depends on the value of the local velocity head at this point. The velocity gradient at the entrance could be obtained by potential flow methods or by solving the Navier-Stokes equations numerically for each entrance geometry. The amount of approximations made necessary to solve for the flow field may make the final result of little practical significance when small amounts of vapour are present. However, by making the same simplifying assumptions as stated in APPENDIX A one can predict the general shape of an OCB curve on a diagram of dimensionless pool depth vs. Froude number (at a given value of subcooling and chamber pressure). Theoretical curves for different values of subcooling are shown for the case without entrainment in Figure 25a and the case with entrainment in Figure 25b. Note the predicted sensitivity of OCB to changes in subcooling that are small compared to the experimental error (SC ± 1.17).

There were several factors that caused deviations
from these theoretical curves. At the vena contracta the pressure was higher at the tube centerline than at the tube wall. This gradient channelled the fluid into the vertical direction and explained why OCB occurred close to the tube wall (Figure 18d).

As expected, OCB was very sensitive to the presence of nucleation sites. Small undissolved vapour or gas bubbles (previously entrained by the flow in a drawdown or whirlpool) caused OCB while travelling into the vena contracta. The sensitivity of OCB to nucleation sites explains the large amount of scatter near the drawdown curve observed for all three entrances.

It was found that OCB was very sensitive to non-equilibrium effects. It was difficult to increase the flowrate (at constant pool depth) slowly enough to pinpoint the location of OCB. This was particularly true at high values of subcooling where velocities became very large at the vena contracta.

The first bubble quickly grew in size after it was generated at the vena contracta. A rapid conglomeration of other bubbles quickly formed and converged around the inside of the tube, without any significant change in pool depth or flowrate. In a few seconds the equilibrium conditions changed from a liquid-only regime to one where a ring-shaped vapour cavity surrounded the periphery of the tube. The vapour region grew larger as
the flowrate increased. Eventually some of the bubbles detached from the ring and moved either up or down the tube.

After an OCB occurrence the bubbles did not necessarily collapse at the same flowrate where they initially formed. Hysteresis of this type, between desinent and incipient cavitation has been reported previously, for example Knapp [3].

It would seem that OCB should occur at slightly lower flowrates for the re-entrant than for the sharp-edged geometry. The more pronounced change in direction (as the liquid flows over the protruding tube) causes a more severe vena contracta. This trend lacks statistical significance considering the number of data points taken.

The re-entrant geometry protruded well above the false floor and allowed unobstructed visualization of OCB. There was a significant amount of obstruction when looking horizontally at the rounded entrance. However from a viewpoint well above the false floor the complete entrance could be seen, and no evidence of OCB was observed at the flowrates tested. The absence of cavitation was not surprising considering the smooth curvature of the entrance. The sharp-edged entrance was the most difficult to work with although OCB could still be seen easily from above.
5.5 Requirements For A Violent Instability

All three entrances displayed a regime where several small bubbles (from previous entrainment or cavitation) oscillated up and down at the tube entrance. This regime occurred in the up-down transitional range of flowrates for bubbles at the entrance. Some bubbles would rise out of the entrance, to be replaced by vapour generated at the periphery of bubbles already present. Vertical segregation of bubbles would take place according to the size, shape and location of the bubbles. Small bubbles tended to be spherical and had small rise velocities while large bubbles tended to be bullet-shaped and had large rise velocities. The location of the cavitation varied and was hard to discern as there was no fixed cavity attached to the wall. The regime looked similar to nucleate boiling but without the temperature gradient in the tube.

This oscillation was observed at Froude numbers between 0.25 and 0.50 at pool depths slightly above the drawdown curve. Raising the pool depth usually resulted in a lowering of the frequency of oscillation, but also caused an increase in the size of the bubbles and the severity of the regime. Often a drawdown cone could be seen periodically interacting with the oscillating bubbles. The drawdown cone would appear as a rising
bubble hit the pool interface, and then would disappear. When at its greatest severity this regime was the primary component observed in the regimes subjectively judged to be "violent".

5.6 The Up-Down Transition

The transitional flowrate between bubbles being expelled upwards (bubble-up) or expelled downwards (bubble-down) is defined here as the "up-down" transition. This transition has been observed to move to the right (to higher flowrates) with increasing pool depth. This trend can be explained by the larger hemispherical area made available to the flow as the depth increases, which results in lower downward velocities in the pool. This in turn allows upward buoyancy forces on the bubbles to predominate at higher flowrates.

Negligible bubble penetration down the tube was observed at flowrates below the up-down transition, while at higher flowrates penetration depended upon the particular entrance regime.

The velocity of the spouting bubble at the pool interface tended to be greater for larger pool depths, as the bubble had more time to accelerate upwards to its terminal velocity.
5.7 Critical Pool Depth (CPD)

CPD was significant as it emphasizes the importance of the up-down transition on the presence of vapour in the tube. In a constant level process (with increasing flowrate) vapour phase initially forms at OCB, but to eliminate vapour completely the process must first pass outside the OCB and CPD regions.

At high values of subcooling a tendency for the vapour bubbles to collapse and/or shrink in size should exist. In the limit (at very high values of subcooling) bubbles should readily collapse. Those that do not (due to the presence of non-condensibles) should readily self-vent as in the case of air-water flow. Yet at low values of subcooling excess vapour would actually be generated. These tendencies should cause a shrinkage of the CPD region at high values of subcooling. This is not shown by the data in Figure 17, perhaps due to the relatively small range of subcooling examined, or to the large amount of non-condensibles present at high values of subcooling.

In the re-entrant entrance with its pronounced vena contracta (Figure 24a), only bubbles on streamlines directly above the entrance will be affected by the maximum liquid velocity. Therefore at a given flowrate the tendency is smaller for bubbles in the general area
above the entrance to be swept down the tube. The plateau observed on the CPD curve in Figure 15 is explained by this phenomenon. The opposite of this effect explains why the up-down transition seems to occur at lower flowrates in the rounded entrance (Figure 16).

As mentioned in the previous chapter, CPD is particularly significant for the rounded entrance near the up-down transition. As the pool depth is raised near the CPD curve, a large bullet-shaped bubble (with a diameter nearly that of the tube) formed from merging smaller bubbles. The bubble would oscillate (every few seconds) between two positions; one several diameters downstream from the entrance and one at the entrance (Figures 26a and 26b). Severe spouting took place when the bubble was at the upper position (low hydrostatic pressure). Liquid droplets were thrown up against the roof of the chamber by rising bubbles generated in and ejected from the large bubble. A smaller amount of vapour was also evolved in the lower position but most bubbles coalesced or were swept through the tube. This regime continued indefinitely as long as vapour was generated from the lower periphery or wake of the bubble. Taitel [16] observed a similar regime in upward co-current gas-liquid flow. This entry region phenomenon, described as an oscillatory motion of
"Taylor" bubbles, was classified as "churn" flow.

5.8 Bubble Rise Velocity In The Fully Developed Region

Simpson [1] has reported that for bubbles roughly the size of the tube diameter, the up-down transition in the fully developed region of the tube should occur at approximately Froude number 0.31. During the project this phenomenon was verified for the case of air-water flow, but it did not correlate well with the observed flow of Freon-11. Large bubbles were frequently trapped in the tube around Froude number 0.46. A large amount of segregation occurred at this Froude number with only the very large bubbles remaining stationary. The difference in flowrates could be explained by the fact that (in near-saturated Freon) it was impossible to isolate a large bubble in the tube. The constant merging and separation of larger bubbles with smaller bubbles, and the momentum interchange during collision, probably had a significant effect on the buoyancy forces involved. The difference in viscosity between Freon-11 and water should have been insignificant since the flow was turbulent (Reynolds numbers varied from 9500 to 57,000 as the Froude number ranged from 0.2 to 1.2).
5.9 Expected Behaviour At High Values Of Subcooling

When the instability is plotted on three dimensional axes of dimensionless pool depth vs. Froude number vs. dimensionless subcooling, a three-dimensional volume (bounded by OCB and incipient drawdown surfaces) similar to Figure 27 is expected to exist. Only at low values of subcooling is the up-down transition under the surface of the OCB curve, where the vapour phase can readily accumulate at the entrance. The OCB surface moves to higher Froude numbers as the subcooling is increased. Incipient drawdown has been idealized as independent of subcooling.

5.10 Downcomer Flowrate Fluctuation

Interpretation of the anemometer signals must account for the low frequency oscillation produced by the experimental procedures. Therefore, the real time plots were usually quite indicative of the true velocity fluctuation, but the frequency analysis (performed over 64 seconds) may have picked up some of these low frequency components.

With the exception of Figure 20 the amount of vapour that penetrated down the tube was negligible in these measurements. In Figure 20 vapour bubbles passing
by the anemometer probe caused fluctuations in the liquid velocity at the probe, especially if the bubble was large. These fluctuations generally occurred randomly at low frequencies and were neglected in the frequency analysis.

A "violent" regime was picked for this measurement for each entrance. The magnitude of fluctuation was found to be less than 27% of the mean Froude number in each case, thus suggesting that the effect of the entrance instability on the liquid phase flowrate was small. A large amount of this fluctuation may have been free stream turbulence present in any pipe flow at the same Reynolds number. However as mentioned in the previous chapter, this does not mean that hydraulic instabilities due to periodically changing regimes could not cause fluctuation of up to and greater than 80% of the mean flowrate.

Inferences cannot be drawn as to the relative magnitude of the regime instabilities in each geometry without further measurements, but the preliminary findings suggest the rounded entrance as the most prone to flowrate fluctuation.
VI. CONCLUSIONS

6.1 General

Two-phase instabilities have been observed at a downcomer entrance in an experimental rig that drains near-saturated Freon-11 from a vessel. Regimes studied have been restricted to those without noticeable swirl and without a large bridged vapour space. In this study the regimes have been characterized for the first time, using dimensionless parameters describing the pool depth, downcomer flowrate and the subcooling at the liquid interface in the pool. Downcomer entrance geometry has been varied as an independent parameter. A video recording has been made of the regimes for future reference.

The two primary mechanisms involved in the instability were entrainment and cavitation. The entrainment regimes observed in this study can be correlated with the previously documented occurrence of air-water incipient drawdown. Drawdown was observed at higher pool depths than was expected (at a given flowrate) when vapour bubbles were present at the entrance. Cavitation, the mechanism responsible for bubble formation and growth, has been found to be very susceptible to the presence of nucleation sites and to the amount of subcooling at the pool interface.
The up-down transition, at flowrates where the local velocity at a point in the entrance is equal to the rise velocity of a particular vapour bubble, has been found to be a very important physical phenomenon. When coupled with the generation of vapour through entrainment and cavitation, a flowrate near this transition makes the instability very severe. Bubbles conglomerate at the entrance, with the vapour having no mechanism for escape from the region. Some segregation occurs, with small bubbles expelled downwards and large bubbles expelled upwards.

In general, the observed regimes in the re-entrant and sharp-edged geometries were similar. The flow regimes in the rounded geometry were unique due to the effect of the streamlined curvature reducing cavitation at the entrance.

6.2 Incipient Drawdown

The experimental results for incipient drawdown show considerable scatter with the re-entrant geometry, particularly at low values of subcooling. This is explained by the interaction between the drawdown cone and vapour bubbles, commonly found at the entrance at low subcooling.
The incipient drawdown curve for the sharp-edged geometry behaves roughly as predicted in previous air-water work [9], while the rounded geometry exhibits a lower curve than was expected. Bubbles rarely attached themselves to the tube in the rounded entrance because it had a much less severe vena contracta than the re-entrant and sharp-edged geometries.

6.3 Onset Of Cavitation Bubbles (OCB)

It was difficult to delineate a complete OCB curve at a given value of subcooling. The sensitivity to subcooling, nucleation sites, and experimental error explain the large amount of scatter. For a given pool depth, cavitation occurs at higher flowrates with higher values of subcooling. The general shape of an OCB curve can be predicted from theoretical considerations.

Cavitation from an infinitesimal nucleation site (OCB) was not observed in the rounded entrance at the flowrates attempted in this study.
6.4 Requirements For A Violent Instability

The instability was most severe in the vicinity of the up-down transition for all three entrances. During this regime, a high head loss due to friction can be expected in the tube. Severe spouting up into the vacuum chamber has been observed, particularly in the rounded geometry.

6.5 Critical Pool Depth (CPD) And The Up-Down Transition

Flow mapping of the previously mentioned regimes by itself cannot predict fully the occurrence of the instability. Some regimes can be triggered by a large disturbance or entrained bubble. This may occur at subcooling higher than normally expected for OCB. To clear the tube of this disturbance the flowrate or pool depth must be changed so that it no longer falls in the region enclosed by the CPD and OCB curves. This is a particularly important requirement for the rounded entrance, where OCB does not exist.

The CPD curve is significant in that the peak occurs at the up-down transition. This peak seems to occur at lower flowrates and pool depths for the rounded geometry than for the sharp-edged and re-entrant geometries. Because of its narrow vena contracta, the
re-entrant geometry exhibits more of a "plateau" at high flowrates.

The CPD region should shrink in size at high values of subcooling. This shrinkage was not evident over the small range of subcooling tested.

Freon vapour bubbles in the fully developed region of the tube were not trapped at Froude number 0.31 as expected, but at a higher Froude number of around 0.46.

6.6 Sample Theoretical Curves

Idealized flow diagrams are shown on Figures 28, 29 and 30 for the re-entrant, rounded and sharp-edged geometries at a common value of subcooling.

At higher values of subcooling the OCB curve moves to the right (to higher flowrates) while the CPD and "violent" regions do not move but shrink in size.

6.7 Downcomer Flowrate Fluctuation

Fluctuations in downcomer flowrate of up to 27% of the mean Froude number have been observed in the "violent" regime. However, much larger low frequency hydraulic fluctuations can be expected during a periodic change of regimes such as intermittent bridging.
VII. RECOMMENDATIONS

7.1 Industrial Design

The following guidelines may prove helpful in controlling or preventing the violent instability described in this study:

(a) - operate at flowrates which avoid the up-down transition region (ie., avoid Froude numbers from 0.25 to 0.65) using flowrate control (refer to Figures 28, 29 and 30).

(b) - raise the value of subcooling in the liquid by lowering its temperature or raising its pressure, thus moving the OCB curve to a higher flowrates and shrinking the CPD and "violent" regions (not feasible in evaporator and boiler installations where saturation is a requirement).

(c) - use pool depths much greater than the downcomer diameter through level control.

(d) - if possible provide some means of visualization of the pool interface or the downcomer entrance. The performance of the downcomer can then be easily evaluated and modifications made if necessary.
7.2 Further Work

7.2.1 Modifications To The Apparatus And Instrumentation

As in any experimental study of a preliminary nature, suggestions for ways to improve the apparatus and instrumentation became obvious upon completion of the work.

A smaller circuit, perhaps using a 1.9 cm diameter test section, and smaller circulation pump and piping, would lessen the volumetric requirements of Freon used.

Use of a shorter test section, perhaps 1.0 m long, would lessen the vacuum requirements, decreasing the severity of crazing problems in the vacuum chamber. This would be accomplished without compromising significantly the length-to-diameter ratio of the test section.

A water-cooled condensor could be placed at the discharge to the vacuum pump to recover part of the Freon vapour losses. This should be attempted only if it can be achieved without a large increase in the complexity of the apparatus.

Pressure and displacement transducers should be purchased for the accurate and reliable measurement of chamber pressure and pool depth using the data acquisition system, synchronous with the measurement of chamber temperature and siphon flowrate. The float-
operated displacement transducer would be mounted inside the vacuum chamber, leaving the experimenter free to make qualitative observations and to control the regimes. Both of these instruments would probably be very expensive due to their stringent specifications (Pch ± 100 Pa in 0-101 kPa range and H ± 0.5 mm with a 0-10 cm range).

Greater vertical difference in elevation (say 1.5 m) should be allowed for between the lower vessel and the pump to lessen cavitation problems at the pump suction. Similarly a "U-shaped" loop could be placed in the siphon loop where the liquid leaves the overflow vessel, with the flosensor near the bottom of the loop. This would provide greater subcooling at the flosensor, completely ensuring no cavitation occurred on the paddlewheel.

A large, easily regulated needle valve should be used to control flow in the siphon loop. As small changes in flowrate are significant, it is important that the effects of a small change in valve position be predictable, and adjustments easily made.

A temperature compensated probe should be used for flowrate fluctuation measurement, thereby eliminating the effect of changes in liquid temperature on the indicated velocity.
7.2.2 Further Areas Of Study

The results presented here should be independently verified, preferably using a different fluid and different diameter of downcomer. Further topics that should be investigated if the instabilities are to be completely understood are:

(a) - further measurement of flowrate fluctuation (in the various regimes) for each entrance

(b) - the effect of a large uncontrolled whirlpool on the observed regimes

(c) - the effect of a horizontal entrance leading to a downcomer

(d) - minimizing the effect of the instability with specially designed entrances

(e) - the interaction and feedback between the downcomer flowrate and pressure fluctuations, and the two-phase regimes present at the entrance

(f) - the effect of the size, shape and location of the large bridged vapour space parameter on any observed regimes

(g) - using potential flow techniques [10], solve for the velocity fields for several entrance geometries. Using this information, predictions can be made for the flowrate at incipient cavitation and the
flowrates at which the up-down transition occurs.
Figure 1 - Industrial Example Of The Instability (Steam and Condensate).
Figure 2 - Incipient Drawdown With Liquid Level At Downcomer Entrance (Air-Water).
Figure 3 - Incipient Drawdown With Liquid Level Below Downcomer Entrance (Air-Water [9]).
Figure 4 - Experimental Schematic.
Figure 5 - Pictures Of Apparatus And Instrumentation.
(5a - data acquisition system and experimental rig, 5b - vacuum chamber and video camera, 5c - linearizer, anemometer and voltmeter, 5d - VCR, plotter and FFT analyzer, 5e - anemometer probe)
Figure 6 - Details Of Vacuum Chamber.
Figure 7 - Downcomer Entrance Geometries. (7a - sharp-edged, 7b - re-entrant, 7c - rounded)
Figure 8 - Constant Temperature Anemometer Schematic.
Figure 9 - Data Acquisition System Schematic.

PROMPT FOR:
DATE, Patm, CONTROL CHARACTER (CC)

SCAN:
- SAMPLE
Pch, Tch, Fr @ 1.0 Hz FOR 50 SECONDS

PROMPT FOR:
H, Pch (MANOMETER)

SCAN:
- SAMPLE
Tch, Fr @ 10 Hz FOR 5 SECONDS

TIME AVERAGE

CONVERT TO REAL UNITS

PROMPT FOR:
DESCRIPTIVE CODE

NOTE
CC = O USED FOR ALL FINAL DATA ACQUISITION

OUTPUT DATA AT TERMINAL & IN OUTPUT FILE
Figure 10 - The Effect Of Subcooling On Incipient Drawdown For The Re-entrant Geometry. (air-water drawdown data from [9], Low SC is SC ≤ 9.0, N = 32, SCAVG = 3.9, SD = 2.6, High SC is SC ≥ 9.0, N = 8, SCAVG = 16.8, SD = 10.3)
Figure 11 - Incipient Drawdown For Rounded And Sharp-edged Geometries. (air-water drawdown data from [9], Rounded (rd) - N = 30, SCAVG = 12.5, SD = 5.6, Sharp-edged (shp) - N = 24, SCAVG = 21.9, SD = 14.5)
Figure 12 - The Effect of Subcooling on the Onset of Cavitation Bubbles (OCB) for the Re-entrant Geometry. (Air-water drawdown data from [9], Low SC is SC ≤ 9.0, N = 37, SCAVG = 4.8, SD = 2.4, High SC is SC ≥ 9.0, N = 13, SCAVG = 18.8, SD = 7.2)
Figure 13 - The Effect Of Subcooling On The Onset Of Cavitation Bubbles (OCB) For The Sharp-edged Geometry. (air-water drawdown data from [9], Low SC is SC ≤ 9.0, N = 10, SCAVG = 6.2, SD = 2.6, High SC is SC ≥ 9.0, N = 4, SCAVG = 12.4, SD = 2.2)
Figure 14 - Violent Region For The Re-entrant (re), Rounded (rd) And Sharp-edged (shp) Geometries. (air-water drawdown data from [9], re - N = 5, SCAVG = 13.0, SD = 15.8, rd - N = 3, SCAVG = 15.5, SD = 3.7, shp - N = 5, SCAVG = 9.3, SD = 1.9)
Figure 15 - Critical Pool Depth (CPD) For The Re-entrant Geometry. (air-water drawdown data from [9], N = 9, SCAVG = 21.2, SD = 6.4)
Figure 16 - Critical Pool Depth (CPD) For The Rounded Geometry. (air-water drawdown data from [9], N = 23, SCAVG = 10.1, SD = 2.1)
Figure 17 - The Effect Of Subcooling On CPD For The Sharp-edged Geometry. (air-water drawdown data from [9], Low SC is SC ≤ 9.0, N = 9, SCAVG = 6.0, SD = 1.2, High SC is SC ≥ 9.0, N = 9, SCAVG = 19.0, SD = 7.6)
Figure 18 - Pictures Of Incipient Drawdown, Spouting And OCB In The Re-entrant Geometry. (18a - drawdown cone and cavitation bubble, 18b - drawdown cone during violent regime, 18c - spouting from above, 18d, 18e, and 18f - OCB at 0, 1.8 and 2.5 secs.)
Figure 19 - Froude Number Fluctuation And Frequency Analysis For The Re-entrant Geometry. ($\Delta Fr^* = 10\%$ (approximately))
Figure 20 - Froude Number Fluctuation And Frequency Analysis For The Rounded Geometry. ($\Delta Fr^* = 27\%$ (approximately), note - small bubbles traversing by probe)
Figure 21 - Froude Number Fluctuation And Frequency Analysis For The Sharp-edged Geometry. ($\Delta Fr^* = 15\%$ (approximately))
Figure 22 - Froude Number Fluctuation In The Re-entrant Geometry During Bridging. (22a - fluctuation ($\Delta Fr^* = 80\%$ (approximately)), 22b - bridging with vapour annulus, 22c - bridging with vapour core)
Figure 23 - Miscellaneous Pictures Of The Re-entrant Geometry.
(23a - asymmetric spouting occurring with straightening cross, 23b - vapour region attached at vena contracta, 23c - spouting occurring from large bridged vapour space)
Figure 24 - Streamline Pattern In Liquid-Only Flow. 
(24a - re-entrant geometry, 24b - sharp-edged geometry, 24c - rounded geometry)
Figure 25 - Theoretical OCB Curves. Note scale change.
(25a - without entrainment, 25b - with entrainment, derived from:
\[ \frac{H}{D} = \frac{Fr^2}{2} - SC \]
with \( Pch \) of 76000 Pa (nominal), giving
\[ \frac{H}{D} = -118.9 + 7.56Tch + \frac{Fr^2}{2} \)
Figure 26 - Violent Spouting In The Re-entrant Geometry.
(26a - bubble at position near entrance with evolved vapour spouting upwards, 26b - bubble at position below entrance with evolved vapour swept downwards)
Figure 27 - Expected Behaviour At Different Values Of Subcooling. (Three-dimensional volume bounded by OCB and Incipient Drawdown surfaces)
Figure 28 - Idealized CPD For The Re-entrant Geometry At SC=9. (the OCB curve is the location of cavitation from pure liquid phase, and CPD is the depth that must be exceeded to expel any previously entrained or generated vapour)
Figure 29 - Idealized CPD For The Rounded Geometry At SC=9. (CPD is the depth that must be exceeded to expel any previously entrained or generated vapour)
Figure 30 - Idealized CPD For The Sharp-edged Geometry At SC=9. (the OCB curve is the location of cavitation from pure liquid phase, and CPD is the depth that must be exceeded to expel any previously entrained or generated vapour)
BIBLIOGRAPHY


APPENDIX A - DIMENSIONAL ANALYSIS

Two methods of dimensional analysis are used; (A1) a derivation from a simple model using Bernoulli's equation and (A2) a classical Buckingham \( \pi \) analysis.

A1 Bernoulli's Equation

Note: \( P_0 \) and \( V_0 \) are the pressure and velocity at point "o".

Assumptions:
(a) - no velocity or pressure gradient across the tube
(b) - no temperature gradient in the pool or downcomer
(c) - no vapour phase initially present
(d) - no surface tension effects
(e) - no flow separation or entrainment
(f) - no frictional dissipation in the pool
(g) - thermodynamic equilibrium exists at all times
(h) - uniform nucleation site spacing
Using Bernoulli's equation between the pool interface and point "o" and subtracting Psat

\[ Po - Psat = Pch - Psat + \rho g H - \rho Vo^2/2 \]

Dividing by \( \rho g D \)

\[ (Po - Psat)/\rho g D = (Pch - Psat)/\rho g D + H/D - Vo^2/2gD \]

But since \( Vo^2/2gD = Fr^2/2 \)

\[ (Po - Psat)/\rho g D = (Pch - Psat)/\rho g D + H/D - Fr^2/2 \]

From this equation we observe:

- \( Po - Psat = 0 \) at incipient cavitation (OCB)
- \( (Pch - Psat)/\rho g D = \) dimensionless subcooling (SC)
- \( H/D = \) dimensionless pool depth
- \( Fr = \) dimensionless flowrate

Therefore, when incipient cavitation occurs at the tube entrance

\[ SC + H/D - Fr^2/2 = 0 \]
A2 Buckingham π Analysis

The relevant independent variables are:

\( \text{Pch} - \text{Psat(Tch)}, \rho, g, D, H, V, \mu, \sigma \)

These variables are comprised of the fundamental dimensions \([M],[L],[T]\). Using \(\rho\), \(g\), and \(D\) as the recurring set of variables, the following five dimensionless groups are obtained:

\[
\begin{align*}
\pi_1 &= \frac{\text{Pch} - \text{Psat(Tch)}}{\rho g D}, \\
\pi_2 &= \frac{H}{D}, \\
\pi_3 &= V(gD)^{-\frac{1}{2}}, \\
\pi_4 &= \frac{\mu}{(\rho g V^2 D^{3/2})}, \\
\pi_5 &= \frac{\sigma}{(\rho g D^2)}
\end{align*}
\]

Making the same assumptions as in (A1) with the viscous and surface tension forces having no effect on the flow regimes (ie. the bubbles are large and their rise velocity is determined by the tube diameter) the following three dimensionless groups remain:

\[
\begin{align*}
\pi_1 &= \text{SC} = \frac{\text{Pch} - \text{Psat(Tch)}}{\rho g D}, \\
\pi_2 &= \frac{H}{D}, \\
\pi_3 &= \text{Fr} = V(gD)^{-\frac{1}{2}}
\end{align*}
\]

Note that \(\pi_3/\pi_4 = \text{Reynolds number}\) and \(\pi_3/(\pi_5 V^2) = \text{Weber number}\)
NOTE: - for each measurement a value of \(H/D, Fr\) and \(SC\) was calculated. \(H\) and \(\Delta Z\) (manometer) were recorded manually and \(T_{ch}\) and \(Q\) were recorded by the data acquisition system

Units:

\[H, D, \Delta Z \text{ (m)}\]
\[P_{sat}, P_{ch}, P_{atm} \text{ (Pa)}\]
\[V(m/s), Q(litres/s)\]

Constants:

\[\rho = \rho(\text{Freon-11}) = 1500 \text{ kg/m}^3 \text{ at } 15^\circ\text{C (from [14])}\]
\[\rho_{w} = \rho(\text{water}) = 1000 \text{ kg/m}^3\]
\[D = 0.0254 \text{ m, } g = 9.8 \text{ m/s}^2\]
Therefore:
\[ \text{Fr} = \frac{V(gD)^{\frac{1}{2}}}{4Q/(1000\pi(0.0254)^{2.5}(9.8)^{\frac{1}{2}})} = 3.96Q \]
\[ \text{H/D} = \frac{H}{0.0254} \]
\[ \text{SC} = \frac{(P_{ch} - P_{sat})}{\rho g D} \]

With
\[ P_{sat} = 2823T_{ch} + 31650 \text{ (linearized for small } \Delta T_{ch} \text{ from [14])} \]
\[ P_{ch} = P_{atm} - \rho wg\Delta z \text{ (}\Delta z\text{ from manometer)} \]

**Error Analysis**

As stated in [15], if \( Y \) is the dependent variable and \( Y = Y(x_1, x_2, \ldots, x_n) \), then the uncertainty of the result is \( Y \pm y \) with

\[ y = \left[ (e_1 \frac{\partial Y}{\partial x_1})^2 + (e_2 \frac{\partial Y}{\partial x_2})^2 + \ldots (e_n \frac{\partial Y}{\partial x_n})^2 \right]^{\frac{1}{2}} \]

where \( e_1 \) to \( e_n \) are the uncertainties or probable errors of the variables \( x_1 \) to \( x_n \) respectively.
The uncertainty estimates (e's) are:

Psat ± 300 Pa (as Tch ± 0.1°C)
Pch ± 300 Pa (as ΔZ ± 0.02 m and Patm ± 100 Pa)
Q ± 0.003 litres/s
H ± 0.001 m
D ± 0.0005 m

Placing these uncertainties into the above equation using partial derivatives from the equations defining H/D, Fr and SC, error estimates (y's) are obtained of:

ΔH/D = ± 0.04
ΔFr = ± 0.01
ΔSC = ± 1.17

Notes:
- fluctuations in chamber pressure prevented reading the manometer with greater than the above mentioned accuracy
- this analysis has neglected both time lapse and judgement errors which may be quite large
<table>
<thead>
<tr>
<th>REGIME NUMBER and PAGE NUMBER (refer to text)</th>
<th>ENTRANCE GEOMETRY, REGIME AND COMMENTS</th>
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<tbody>
<tr>
<td>#1 - p. 6,7,8</td>
<td>RE-ENTRANT</td>
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<td></td>
<td>NOTE:</td>
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<td></td>
<td>- air-water this regime only</td>
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<td>- incipient drawdown in two-component flow</td>
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<td></td>
<td>- entrainment of air bubbles with small spherical bubbles rising up into the chamber</td>
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<td>- small vortices visible periodically</td>
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<td>- trapped air bubbles rising through the false floor around the entrance</td>
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<td>- annular flow (with necking) when the liquid level is lowered below the entrance</td>
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<td>#2 - p. 36,39</td>
<td>RE-ENTRANT</td>
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<td>NOTE:</td>
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<td>- Freon-11 is shown in the following regimes</td>
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<td>- OCB from a liquid-only regime</td>
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<td>- triggering of cavitation by bubble passing through the vena contracta</td>
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<td>- violent spouting of rising bubbles</td>
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<td>#3 - p. 8</td>
<td>RE-ENTRANT</td>
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<td>NOTE:</td>
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<td>- annular flow in a liquid level well below the downcomer entrance</td>
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<td>- the lower viscosity of Freon-11 will cause a higher flowrate (and more necking) at a given pool depth than in air-water flow</td>
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<td>- nominal H/D = 0.20, Fr = 0.20 and SC = 11.1</td>
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<td>REGIME NUMBER and PAGE NUMBER (refer to text)</td>
<td>ENTRANCE GEOMETRY, REGIME AND COMMENTS</td>
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<tr>
<td><strong>#4 - p. 38,53</strong></td>
<td>RE-ENTRANT</td>
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<tr>
<td></td>
<td>NOTE:</td>
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<tr>
<td></td>
<td>- a violent instability</td>
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<td></td>
<td>- flowrate in the up-down transition,</td>
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<tr>
<td></td>
<td>therefore bubbles accumulate in, but</td>
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<td>cannot escape from the entrance</td>
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<td></td>
<td>region</td>
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<td>- cavitation occurring throughout</td>
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<td></td>
<td>the entrance region</td>
</tr>
<tr>
<td></td>
<td>- nominal $H/D = 0.28$, $Fr = 0.43$</td>
</tr>
<tr>
<td></td>
<td>and $SC = 7.7$</td>
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<tr>
<td><strong>#5 - p. 39,45</strong></td>
<td>RE-ENTRANT</td>
</tr>
<tr>
<td></td>
<td>NOTE:</td>
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<tr>
<td></td>
<td>#5a - bubbles formed in OCB cleared</td>
</tr>
<tr>
<td></td>
<td>by CPD (CPD curve above OCB)</td>
</tr>
<tr>
<td></td>
<td>- nominal $H/D = 1.42$, $Fr = 0.39$</td>
</tr>
<tr>
<td></td>
<td>and $SC = 4.5$</td>
</tr>
<tr>
<td></td>
<td>#5b - OCB at high Froude number</td>
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<tr>
<td></td>
<td>showing a vapour cavity attached to</td>
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<tr>
<td></td>
<td>the tube wall with all generated</td>
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<tr>
<td></td>
<td>bubbles (small) swept down the tube</td>
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<tr>
<td><strong>#6 - p. 38,45</strong></td>
<td>RE-ENTRANT</td>
</tr>
<tr>
<td></td>
<td>NOTE:</td>
</tr>
<tr>
<td></td>
<td>- violent regime</td>
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<td></td>
<td>- an annular cavity (similar to</td>
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<tr>
<td></td>
<td>regime #5b forms, and with</td>
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<td></td>
<td>increasing flowrate the vapour</td>
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<td></td>
<td>moves to the core of the tube,</td>
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<td></td>
<td>giving rise to spouting at high</td>
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<tr>
<td></td>
<td>Froude number</td>
</tr>
<tr>
<td></td>
<td>- nominal $H/D = 1.02$, $Fr = 0.76$</td>
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<td></td>
<td>and $SC = 9.3$</td>
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<thead>
<tr>
<th>REGIME NUMBER and PAGE NUMBER (refer to text)</th>
<th>ENTRANCE GEOMETRY, REGIME AND COMMENTS</th>
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<tbody>
<tr>
<td>#7 - p. 45,38</td>
<td>RE-ENTRANT NOTE:</td>
</tr>
<tr>
<td></td>
<td>- the annular cavity (#5b) will</td>
</tr>
<tr>
<td></td>
<td>detach as the flowrate is decreased</td>
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<td></td>
<td>into the up-down transition area</td>
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<td></td>
<td>- violent spouting then occurs</td>
</tr>
<tr>
<td></td>
<td>- the large bubbles (slugs) tend</td>
</tr>
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<td></td>
<td>to be bullet-shaped</td>
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<tr>
<td></td>
<td>- nominal H/D = 0.71, Fr = 0.39 and</td>
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<td></td>
<td>SC = 4.1</td>
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<tr>
<td>#8 - p. 53</td>
<td>RE-ENTRANT NOTE:</td>
</tr>
<tr>
<td></td>
<td>- small bubbles in high frequency</td>
</tr>
<tr>
<td></td>
<td>oscillation at verge of cavitation</td>
</tr>
<tr>
<td></td>
<td>inception</td>
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<td>- interaction and coalescence of</td>
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<tr>
<td></td>
<td>bubbles downstream</td>
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<td></td>
<td>- the instability becomes more</td>
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<tr>
<td></td>
<td>violent with increasing flowrate</td>
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<tr>
<td></td>
<td>as the bubbles become larger</td>
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<td></td>
<td>- eventually a vapour cavity</td>
</tr>
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<td></td>
<td>attaches at the entrance</td>
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<td></td>
<td>- nominal H/D = 0.32, Fr = 0.25 and</td>
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<td></td>
<td>SC = 3.7</td>
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<tr>
<td>#9 - p. 53,40</td>
<td>RE-ENTRANT NOTE:</td>
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<tr>
<td></td>
<td>#9a - OCB with small bubbles swept</td>
</tr>
<tr>
<td></td>
<td>down the tube</td>
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<td></td>
<td>- a stationary cavity forms and</td>
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<tr>
<td></td>
<td>grows in size until large bubbles</td>
</tr>
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<td></td>
<td>break loose and rise (segregation</td>
</tr>
<tr>
<td></td>
<td>of bubbles due to shape and size)</td>
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<td></td>
<td>#9b - CPD at &quot;constant&quot; flowrate</td>
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<td></td>
<td>(the pool depth must be changed</td>
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<td></td>
<td>very slowly if the flowrate at the</td>
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<td></td>
<td>flosensor is to be equal to that in</td>
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<td></td>
<td>the downcomer)</td>
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<td></td>
<td>- OCB returns after the bubbles</td>
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<td>have cleared (OCB curve above CPD)</td>
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<td>.....continued</td>
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<tr>
<td>#10 - p. 8</td>
<td>RE-ENTRANT</td>
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<tr>
<td></td>
<td>NOTE:</td>
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<tr>
<td></td>
<td>- necking chokes off the flow as bridging occurs with increasing flowrate</td>
</tr>
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<td></td>
<td>- necking is enhanced by the presence of a cavitation bubble at the entrance</td>
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<tr>
<td>#11 - p. 53</td>
<td>RE-ENTRANT</td>
</tr>
<tr>
<td></td>
<td>NOTE:</td>
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<tr>
<td></td>
<td>- high frequency oscillation of small bubbles at low pool depths and flowrates</td>
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<td></td>
<td>- interaction between oscillating bubbles and cavitation at the entrance</td>
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<tr>
<td></td>
<td>- nominal H/D = 0.59, Fr = 0.29 and SC = 5.8</td>
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<tr>
<td>#12 - p. 56,46</td>
<td>ROUNDED</td>
</tr>
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<td></td>
<td>NOTE:</td>
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<tr>
<td></td>
<td>- violent instability with spouting</td>
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<td></td>
<td>- similar to &quot;churn&quot; flow [16]</td>
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<td></td>
<td>- large bubbles remain &quot;mobile&quot; and detached from the wall</td>
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<td></td>
<td>- vapour generation at periphery of bubble</td>
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<td></td>
<td>- nominal H/D = 1.3, Fr = 0.34 and SC = 22.3</td>
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<th>ENTRANCE GEOMETRY, REGIME AND COMMENTS</th>
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<tbody>
<tr>
<td>#13 - p. 49</td>
<td>ROUNDED</td>
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<tr>
<td></td>
<td>NOTE:</td>
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<tr>
<td></td>
<td>- incipient drawdown showing large</td>
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<td></td>
<td>drawdown cone that follows the</td>
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<td>curvature of the entrance</td>
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<td>#14 - p. 38</td>
<td>ROUNDED</td>
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<td>NOTE:</td>
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<tr>
<td></td>
<td>- a large slug of vapour moves</td>
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<td>between a position at the entrance</td>
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<td>and a position downstream</td>
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<td>- all generated vapour is swept</td>
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<td>down the tube except when the</td>
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<td>bubble is at the tube entrance</td>
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<td>- violent spouting against the</td>
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<td>chamber roof</td>
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<td>- penetration of vapour down the</td>
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<td>tube</td>
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<td></td>
<td>- nominal H/D = 1.46, Fr = 0.48 and</td>
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<td></td>
<td>SC = 27.3</td>
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<td>#15 - p. 39,45</td>
<td>SHARP-EDGED</td>
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<td>NOTE:</td>
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<td></td>
<td>#15a - violent regime passing</td>
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<td>through CPD (with &quot;constant&quot;</td>
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<td></td>
<td>flowrate)</td>
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<td>- nominal H/D = 0.51, Fr = 0.33 and</td>
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<td>SC = 11.1</td>
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<td>#15b - cavitation triggered by a</td>
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<td>rising bubble</td>
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<td>- the size and shape of a &quot;large&quot;</td>
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<td>bubble becomes an extra parameter</td>
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<td>necessary to describe the flow</td>
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<td>- nominal H/D = 0.91, Fr = 0.61 and</td>
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<td>SC = 24.8</td>
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<td>#15c - incipient drawdown</td>
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<td>- nominal H/D = 0.35, Fr = 0.36 and</td>
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<td></td>
<td>SC = 25.6</td>
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