Counter-Current Flow Study in a 65 mm I.D. Tube Scaled for the TESLA Design

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I INTRODUCTION

The Service des Basses Températures of the CEA/Grenoble is conducting research at its Cryogenics testing station into the two-phase flow of superfluid helium in pipes with various slopes and diameters (refs: 1, 2 and 3). This research was initiated with the support and co-operation of CERN and led, through investigations of flow behaviours, to the qualification of the approach adopted for cooling the 2000 superconducting magnets at the LHC.

Two-phase superfluid flow experiments were carried out in both co-current and counter-current mode, with parallel development of two computer codes.

In the co-current experiments, the vapour sucked in by the pumps at the end of the line adds a frictional force for moving the liquid that is additional to gravity. The main characteristics to be investigated are the stability conditions of this flow, and the pressure loss it generates.

In the case of the counter-current experiments, the vapour and the liquid flow in opposite directions and the friction exerted by the vapour hinders the movement of the liquid. Under certain conditions the force of gravity is no longer sufficient to move the liquid, which is then halted by the friction of the vapour.

The future TESLA linear accelerator is likely to incorporate certain sections cooled by co-current two-phase superfluid flow, and others cooled by counter-current flow. The latter situation appears more difficult to control (indeed CERN has decided not to use counter-current flow following the qualification tests) and therefore necessitates some preliminary investigation. Since SBT Grenoble is at present the only laboratory with experience in this field (having both a test station and a theoretical model), co-operation with DESY was begun in 1997.

The planned tests were carried out within the allotted time. The general behaviour of counter-current two-phase superfluid flow was observed in slightly sloping pipes, and interpreted using the calculational model. A video recording was made with the DESY participants to demonstrate the flow behaviour.

This report introduces the theoretical model, describes the tests, and provides a critical review of the results obtained.

II CALCULATION MODEL

In most cases, experiments on counter-current flows have been performed in vertical pipes. Thus, extensive works have been reported for water and air mixture in such configuration. In that case, the liquid flows down and the gas flows up. As the gas mass flow increases, the flow changes from annular film flow to wavy annular flow until the flooding occurs. At this point, the counter current flow ceases and the liquid phase starts to be carried upwards. Best tentative of explanations and predictions of this flooding phenomenon have been done using instability theory. In present case, the pipe is slightly inclined, and the annular flow is replaced by stratified flow. Furthermore, the moving force (i.e. gravity) is very low compared to the vertical configuration and we infer that limitation deduced from momentum balance occurs before than instability onset. Consequently, we have developed a model based on mass, momentum and energy balance. It should represent the maximum mass flow rate allowed in such configuration.

As part of a counter-current superfluid two-phase flow investigation conducted with the co-operation of CERN, we developed an elementary computer code which can simulate counter-current two-phase flow in particular conditions (the assumptions made in the calculation are given in the next section). This model originated from discussions with the CERN team and is also based on a study carried out by H. GUINAUDEAU (ref. 4).

II.1 EQUATIONS USED AND ASSUMPTIONS MADE

a) Assumptions made and justifications:

* **The phases flow separately** (this was verified experimentally, and is due to the great ratio between the liquid and vapour densities, the low slope considered, and the relatively modest velocities of the liquid and vapour phases).

* **In a straight section, the liquid-vapour interface is horizontal** (in fact, the presence of waves that can develop at the interface is taken into account in an overall manner using the interfacial coefficient of friction).

* **The liquid phase has a constant velocity** (since the Reynolds numbers are generally above 10^5, this assumption of a flat velocity profile is consistent with a turbulent regime).

* **The vapour phase has a constant velocity** (same remark as above, with each type of flow assumed to be monodimensional).

* **Flow is adiabatic** (experiments will be carried out in these conditions, alternatively the model will be modified).

* **Flow is steady**

* **Flow is established** (meaning that neither entry effects, nor the length of the pipe which here is assumed to be infinite, are taken into account).

b) Equations of conservation used:

To begin with, we give a schematic diagram for defining the different characteristics used in the conservation calculations:

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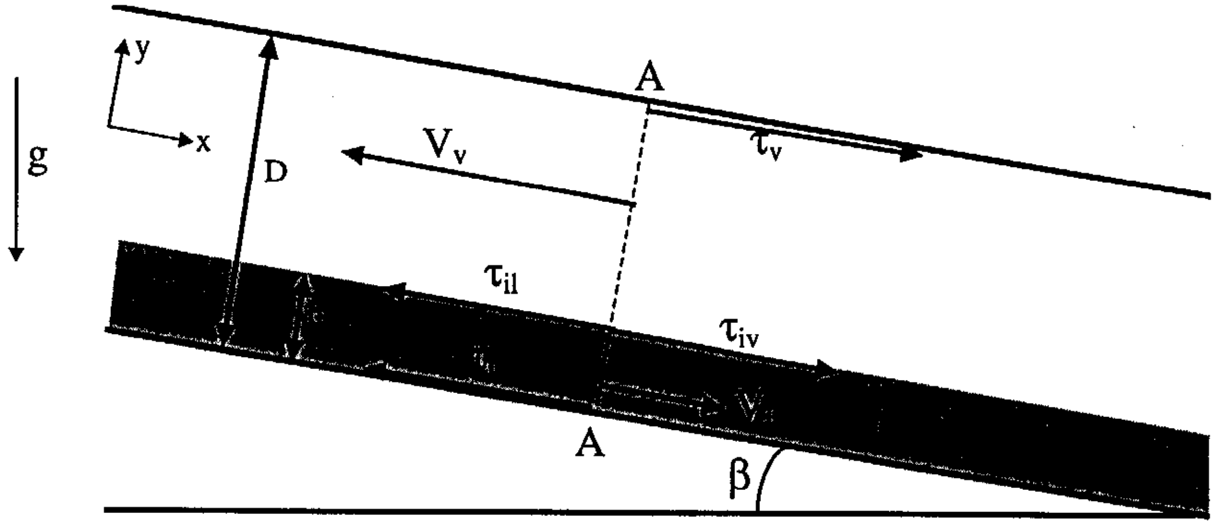
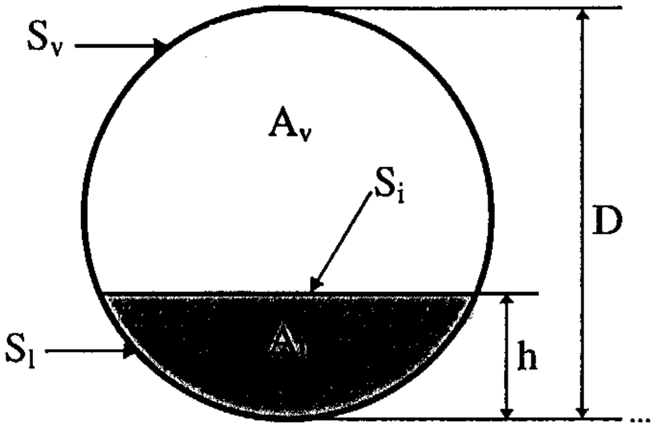


Characteristics of counter-current two-phase flow



View of the straight section (section AA)

The equation for the conservation of mass expresses the fact that the liquid mass flow equals the vapour mass flow in a straight section. In addition, this liquid (or vapour) mass flow is constant over the entire length of the line (assumption of adiabatic flow):

$$\dot{m}_l = \dot{m}_v \tag{1}$$

The equation for the conservation of momentum is applied to the liquid phase and to the vapour phase (the term on the left of the equations is zero because the flow is adiabatic).

liquid side:

$$0 = -\tau_l S_l - \tau_i S_i + \rho_l A_l g \sin\beta - A_l\left(\frac{dP}{dx}\right) \tag{2}$$

vapour side:

$$0 = -\tau_v S_v - \tau_i S_i - \rho_v A_v g \sin\beta - A_v\left(-\frac{dP}{dx}\right) \tag{3}$$

where

$\tau_l = f_l \dfrac{\rho_l V_l^2}{2}$ (4) $\tau_v = f_v \dfrac{\rho_v V_v^2}{2}$ (5) $\tau_i = f_i \dfrac{\rho_v (V_v - V_l)^2}{2}$ (6) *where*

$f_v = f_l = f$ and $\dfrac{1}{\sqrt{4f}} = -2\log\left[\dfrac{k}{3.7D} + \dfrac{2.51}{\mathrm{Re}\sqrt{4f}}\right]$ (7), where the roughness k is estimated at 50 µm

and

f_i is defined using the correlation of Andritsos and Hanratti (1987):

$$\text{For } V_{gs} \le V_{gsc} \quad f_i = f_o = \frac{1}{4} 0.3164\,\mathrm{Re}^{-0.25} \tag{8a}$$

For $V_{gs} \geq V_{gsc}$ $$f_i = f_o\left(1+15\sqrt{\frac{h_l}{D}}\left(\frac{V_{gs}}{V_{gsc}}-1\right)\right) \qquad (8b)$$

where $V_{gsc} = 5\sqrt{\frac{\rho_0}{\rho}}$ and $\rho_0 = \rho(300K, 1\,Bar) = 0.1625\ kg/m^3$

It is also possible to devise geometrical relationships linking the wetted perimeter, the liquid cross-section, etc. to the quantities D and $\frac{h}{D}$ only. These relationships are as follows:

$$S_v \hat{=} D\,\mathrm{Arccos}\left(2\frac{h}{D}-1\right)$$

$$S_l \hat{=} D\left(\pi - \mathrm{Arccos}\left(2\frac{h}{D}-1\right)\right)$$

$$S_i \hat{=} D\sqrt{1-\left(2\frac{h}{D}-1\right)^2}$$

$$A_v \hat{=} \frac{D^2}{4}\left[\mathrm{Arccos}\left(2\frac{h}{D}-1\right)-\left(2\frac{h}{D}-1\right)\sqrt{1-\left(2\frac{h}{D}-1\right)^2}\right]$$

$$A_l \hat{=} \frac{D^2}{4}\left[\pi - \mathrm{Arccos}\left(2\frac{h}{D}-1\right)+\left(2\frac{h}{D}-1\right)\sqrt{1-\left(2\frac{h}{D}-1\right)^2}\right]$$

Resolving the problem involves determining the flow characteristics (liquid height, pressure drop, velocity of the liquid and that of the vapour) for a given liquid mass flow (which here equals the vapour mass flow), wherever possible.

In fact when the liquid mass flow is increased, the liquid height also increases (because the prime mover term. $\rho_l A_l g \sin\beta$. in equation (2) is increased), leaving less and less space for the vapour flowing in the opposite direction, which has the result of increasing the frictional forces due to the vapour (the term $\tau_i S_i$ in equation (2)). The calculation is done in such a way as progressively to increase the liquid mass flow. Once this exceeds a certain value, it is no longer possible for equations (2) and (3) to be satisfied simultaneously. The final value of liquid mass flow for which it is still possible to solve the system of equations (2) and (3) represents the maximum liquid flow that can flow against the same mass flow of vapour: this is the blocking flow.

II.2 CASE OF OPEN CHANNEL FLOW

When the vapour mass flow is sufficiently low, it has only little interaction with the liquid, and in fact the pressure drop $\frac{dP}{dx}$ is practically zero. All the terms in equation (3): $0 = -\tau_v S_v - \tau_i S_i - \rho_v A_v g \sin\beta - A_v(-\frac{dP}{dx})$ are negligible.

The problem then comes down to investigating a open channel liquid flow and all that remains is equation (2) modified thus:

$$0 = -\tau_l S_l + \rho_l A_l g \sin\beta \qquad (2')$$

either using equation (4)

$$v_l = \sqrt{\frac{2A_l}{fS_l} g \sin\beta}$$

or

$$\dot{m}_l = \rho_l A_l \sqrt{\frac{2A_l}{fS_l} g \sin\beta} = \rho_l A_l \sqrt{\frac{Dh_l}{2fS_l} g \sin\beta}$$ where

$Dh_l = \frac{4A_l}{S_l}$, the hydraulic diameter

The liquid flow increases with the slope β and with the liquid cross-section ($A_l \sqrt{Dh_l}$ generally increases more quickly than S_l), and remains practically independent of the temperature because only the density of the liquid is involved, and this is practically constant between 1.8 and 2 K. This behaviour has been observed during measurements made using low liquid levels.

II.3 THE MAXIMUM MASS FLOW APPROACH

We have previously considered the behaviour of counter-current two-phase flow in the case of low flows. It is interesting to compare the results of the complete calculation with those of a open channel flow calculation and to determine when these begin to diverge.

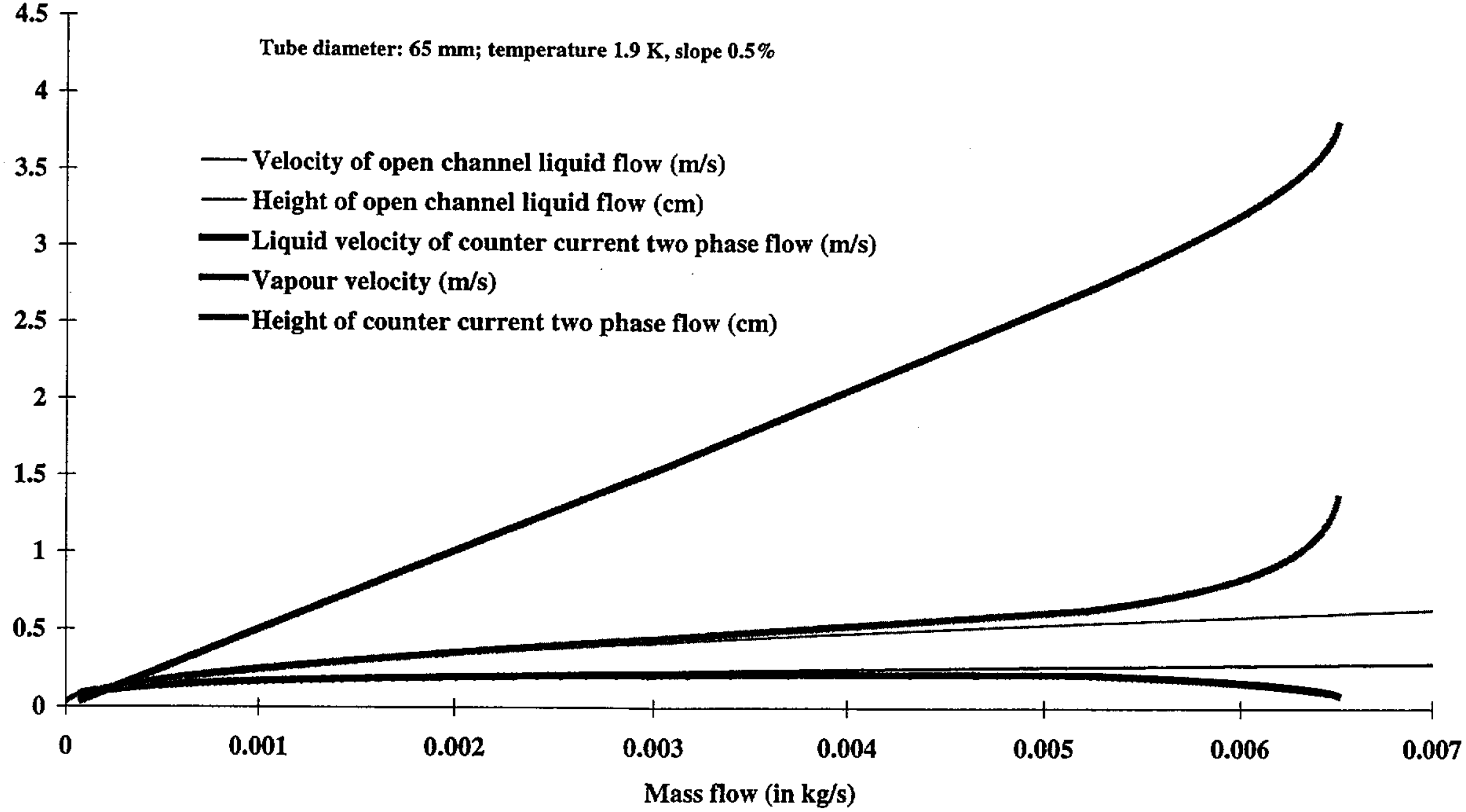
The following figures illustrate the detail of the characteristics calculated for a diameter of 65 mm, a slope of 0.5% and a temperature of 1.9 K.

From the first two figures, it is possible to analyse the flow behaviour as the flow increases. At low flow, the characteristics of two-phase flow and open channel flow are similar (typically at 3 g/s, there is a difference of 7% in liquid height, which results in a difference of 10% in liquid velocity). However as the flow increases, the vapour velocity plays an increasingly important role and the curves of two-phase flow and open channel flow rapidly diverge. It will be noted that all the two-phase flow characteristics above 5.2 g/s show greater curvature. This stems from the correlation used to define the interfacial friction. At this flow rate of 5.2 g/s, we reach the critical velocity of the vapour defined by equation (8b) and the interaction between vapour and liquid is enhanced. Finally, the blocking flow is defined as in the last calculation done and here is equal to 6.51 g/s.

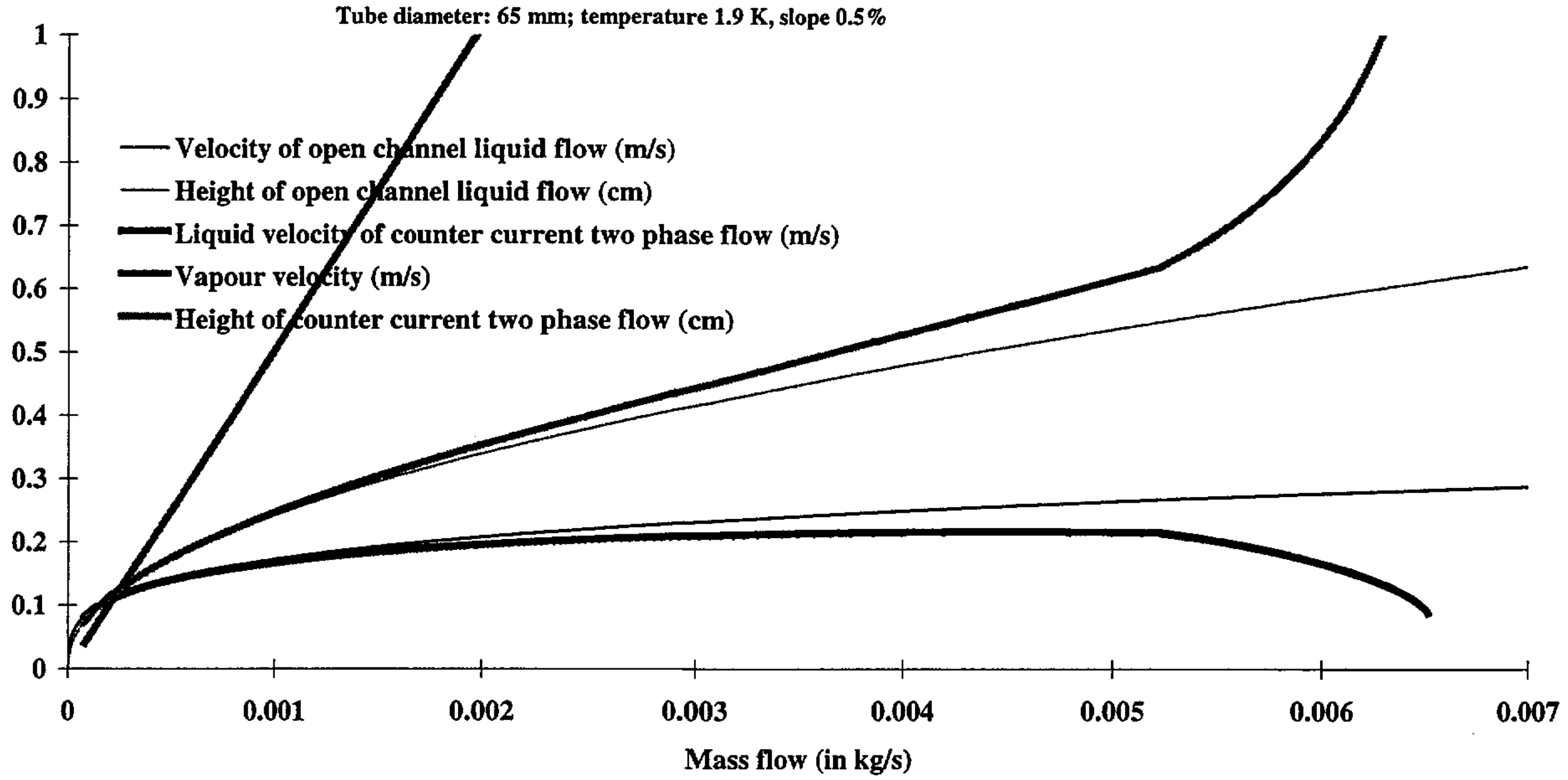
The figure showing the liquid height as a function of flow normalised to blocking flow shows that for a flow equal to 80% of the blocking flow the height in the tube is less than 0.65 cm, or 10% of the diameter. This small amount of space taken up by the liquid in the pipe gives confidence in a calculation done using equations of conservation rather than an approach based on instability methods.

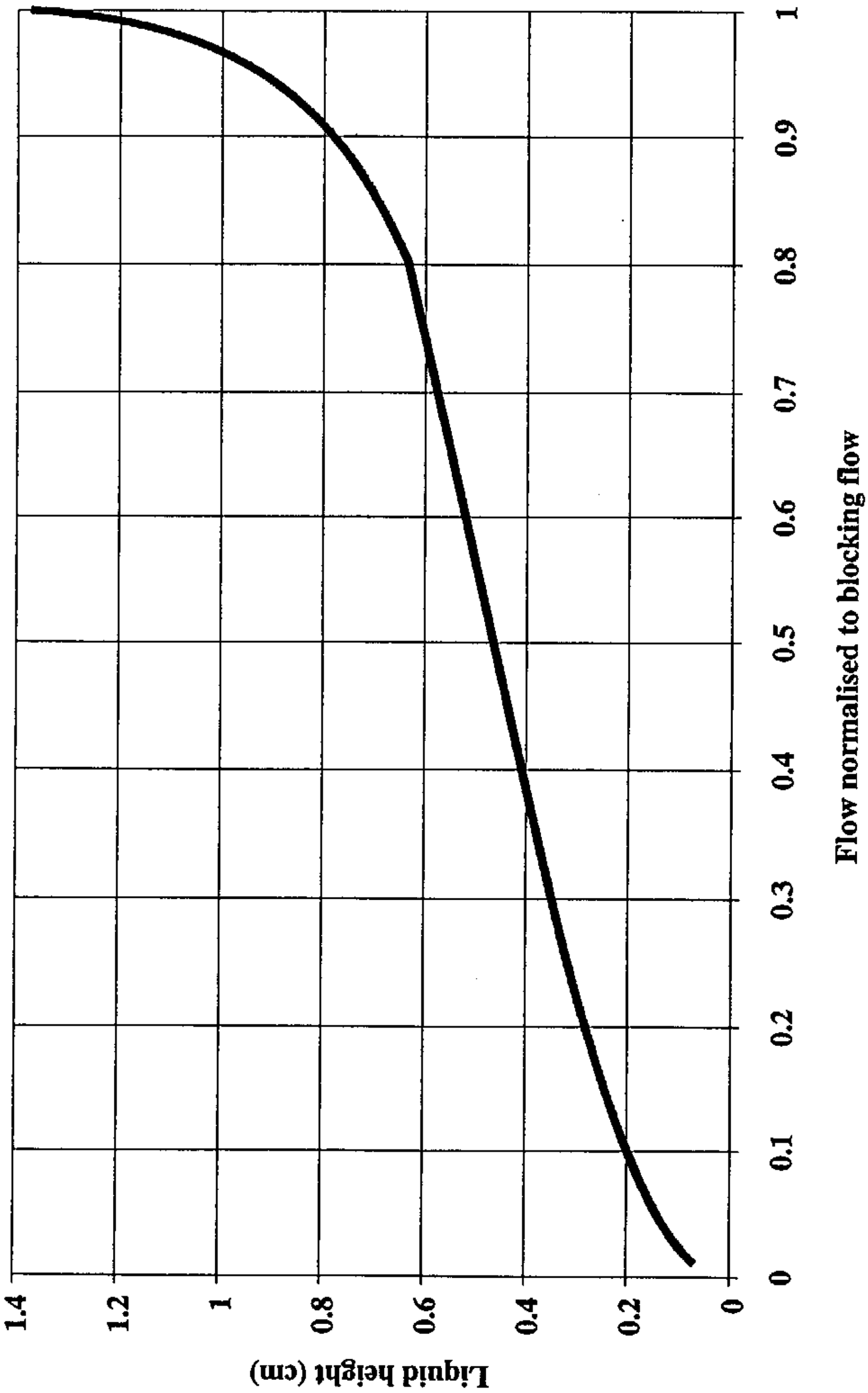
Finally, the figure giving the open channel flow characteristics (with a possibility of reaching 300 g/s when the tube is practically completely filled) clearly shows the limits due to the slowing of the liquid by the vapour flowing in the opposite direction and means that we can only utilise open channel flow model for flow rates below one third of the blocking flow.

Trends in different parameters for counter-current flow and open channel flow

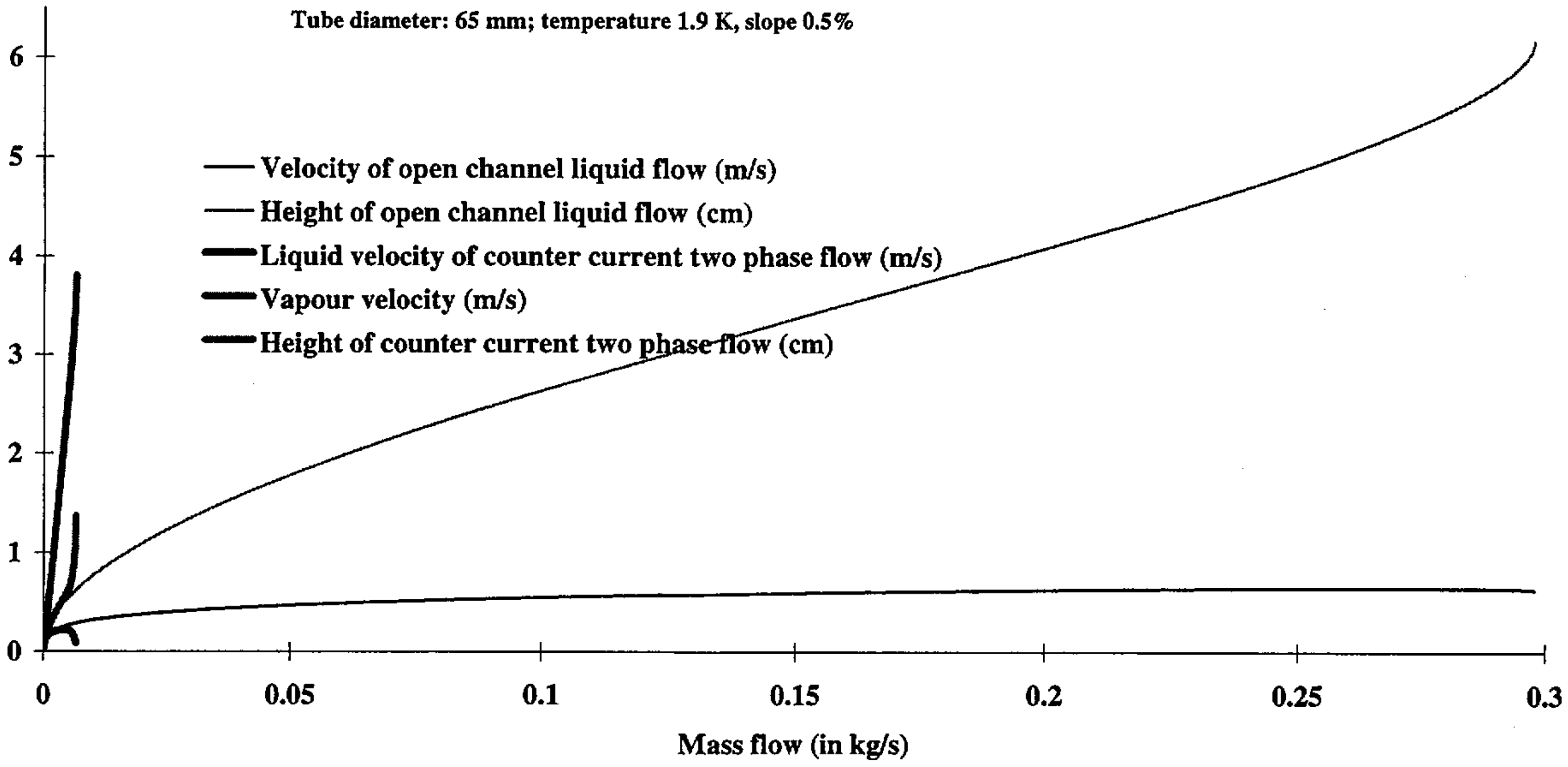


Trends in different parameters for counter-current flow and open channel flow




Tube diameter 6.5 cm Temperature 1.9 K Slope 0.5%

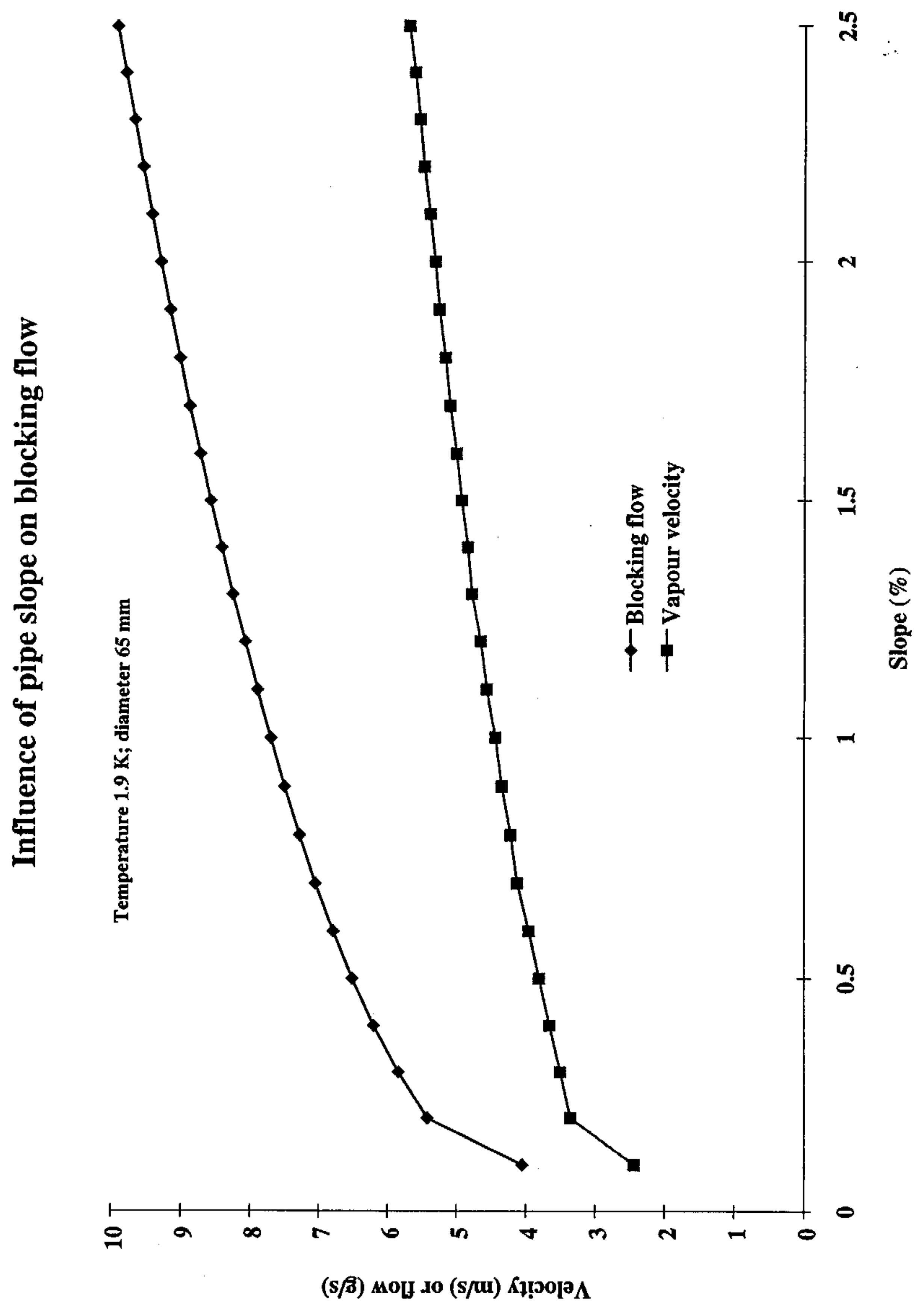
Trends in different parameters for counter-current flow and open channel flow



II.4 INFLUENCE OF TUBE SLOPE

The only "force" term for two-phase counter-current flow is the slope of the tube, so this parameter clearly has a decisive effect. If the slope exceeds a few per cent, the assumptions made in the code (for example, stratified flow) will certainly be wrong. Also, for an infinitely long pipe, any zero or negative slope means that flow is impossible.

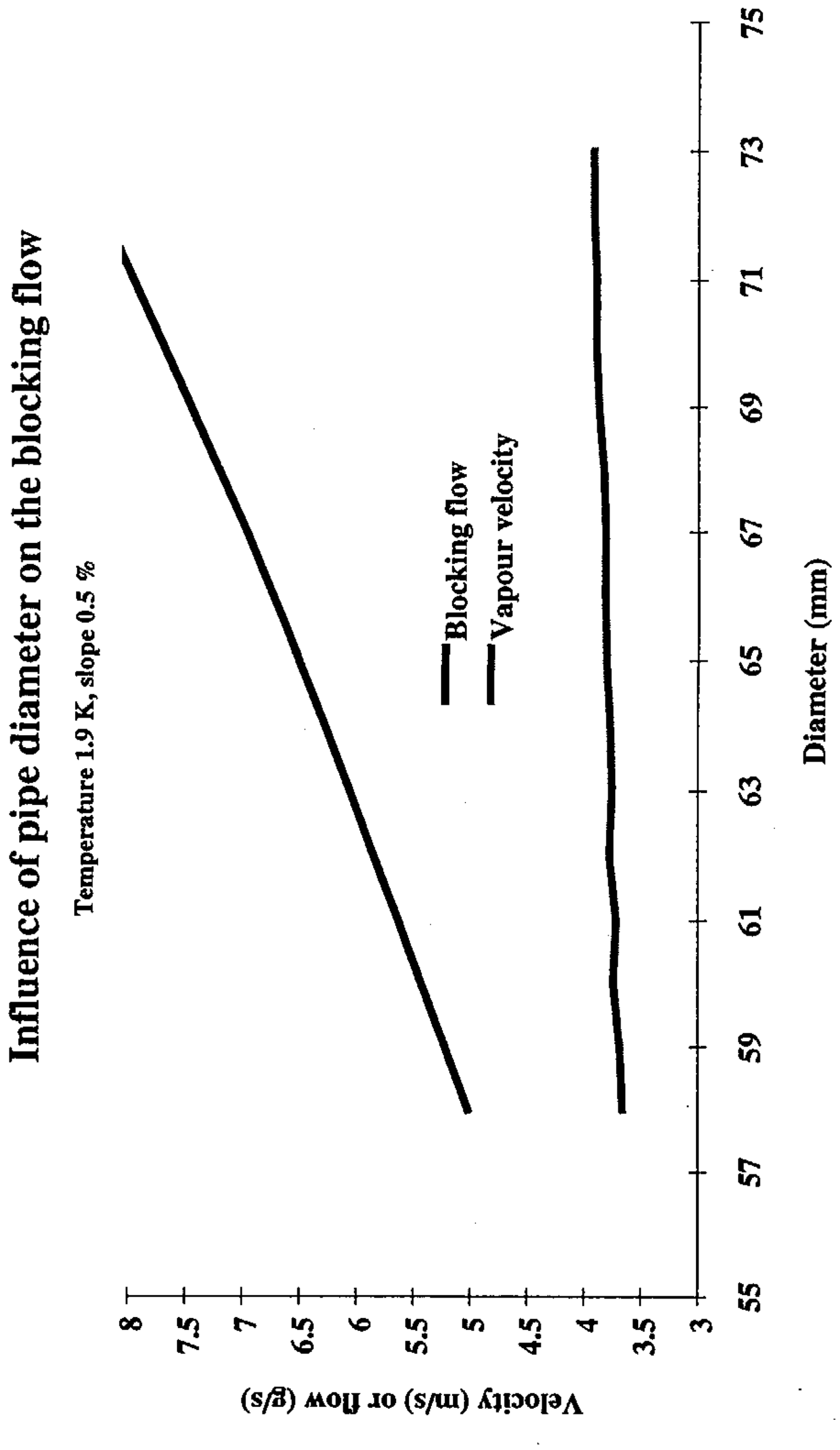
In TESLA, the nominal slope of the tube containing the counter-current flow is 0.5%, although it is possible that this varies along the 2.5 km of pipe. The next figure shows how the blocking flow changes for a slope varying from 0.1 to 2.5%, with a diameter of 65 mm and a temperature of 1.9 K.


Influence of pipe slope on blocking flow
Temperature 1.9 K; diameter 65 mm
Blocking flow
Vapour velocity
Velocity (m/s) or flow (g/s)
10
9
8
7
6
5
4
3
2
1
0
Slope (%)
0
0.5
1
1.5
2
2.5

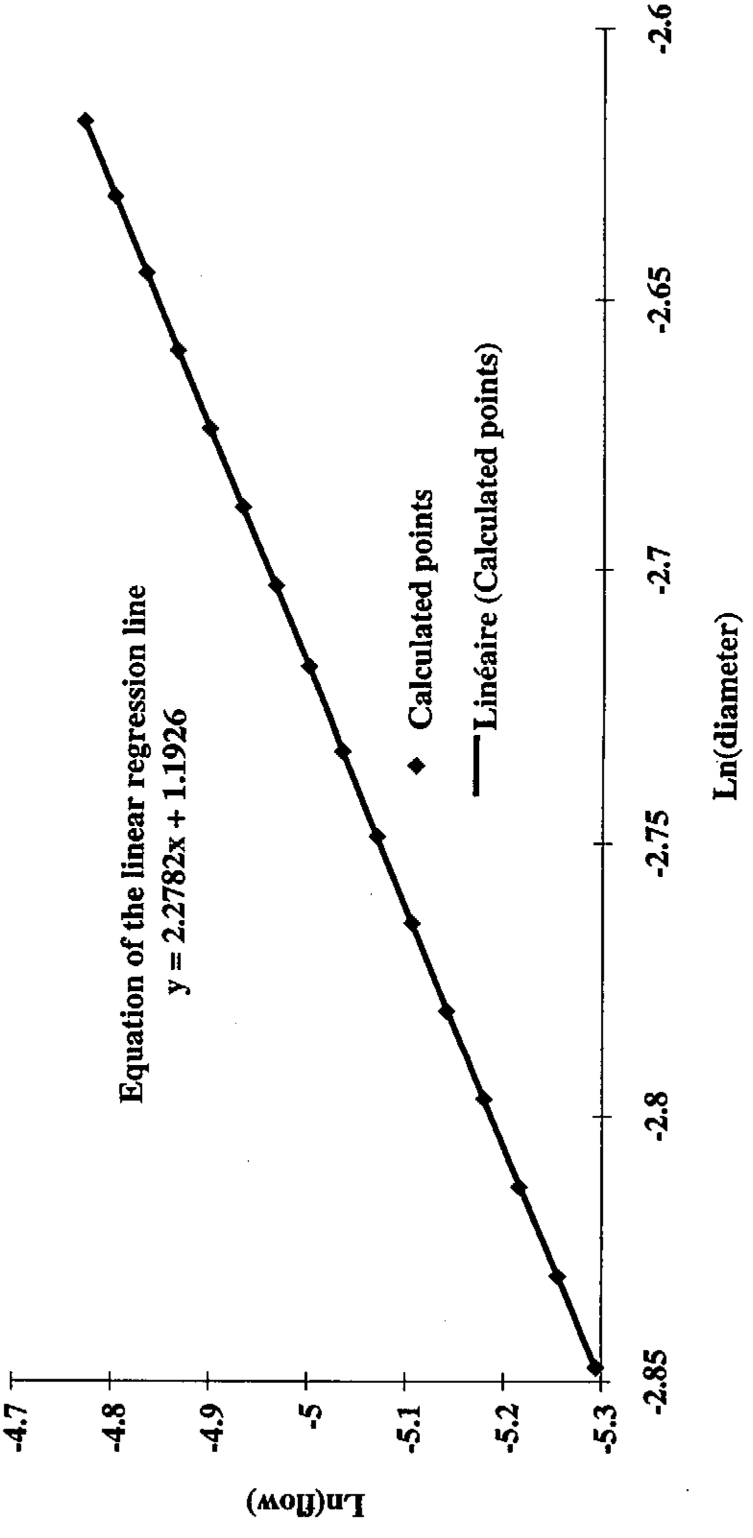
II.5 INFLUENCE OF PIPE DIAMETER AND THE CHOICE OF THE MAXIMUM DIAMETER COMPATIBLE WITH THE SBT GRENOBLE INSTALLATION

The maximum permissible diameter in the SBT test station has to be determined before the test line is built and it is important to estimate the influence of this parameter. The next two figures show how the blocking flow changes for a diameter between 57 and 73 mm, the slope used being 0.5%, which is equivalent to the average slope of the TESLA tunnel in the stretch where two-phase counter-current flow is envisaged. The undulations in vapour velocity are due to imprecision in the calculation (too large mesh). However, the trend remains valid: the vapour velocity can be seen to increase very slightly as the diameter increases, suggesting that the blocking flow (it is recalled that the liquid mass flow is always equal to the vapour mass flow) will be proportional to the diameter raised to the power $2+\varepsilon$. From the figure with the logarithmic scale the exponent can be calculated: a value of 2.3 is found.

In view of the calculated blocking flows and the capacity of our test station (7 g/s at 1.8 K), the maximum permissible diameter was chosen at 65 mm.


Influence of pipe diameter on the blocking flow
Temperature 1.9 K, slope 0.5 %
Blocking flow
Vapour velocity
Velocity (m/s) or flow (g/s)
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
55
57
59
61
63
65
67
69
71
73
75
Diameter (mm)

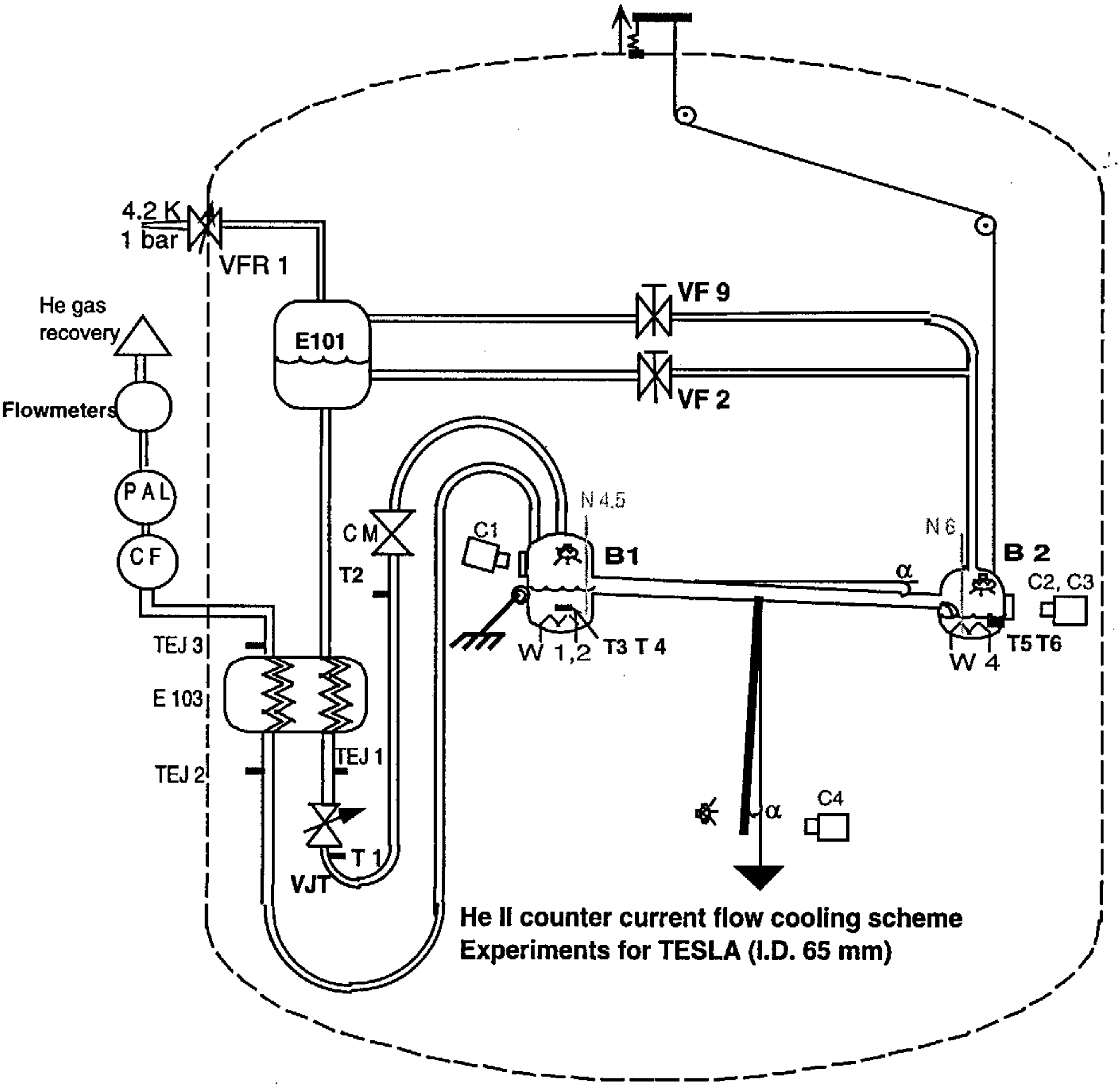
Influence of diameter for a slope of 0.5 % and a temperature of 1.9 K



III DESCRIPTION OF THE EXPERIMENT

III.1 EXPERIMENTAL FACILITY

A schematic diagram of the experimental line is given on the following page. Helium flows from the tank **E101** at a temperature around 4.2 K and a pressure of 1 bar, passes through the heat exchanger **E103** and exits at a temperature close to 2.2 K after being cooled by a counter-current of cold gas. The liquid then expands through the Joule-Thomson valve **VJT**. The resulting liquid-vapour mixture then enters the settling chamber **B1**. Any liquid above the opening into the 65 mm diameter tube joining **B1** to **B2** flows under gravity to the chamber **B2**. It faces a counter current of vapour evaporated by the heater **W4** operated by an electric current which is adjusted to produce the required flow in the line. The vapour is then drawn through the heat exchanger **E103**, after which it enters the installation's pumping system consisting of a cold centrifugal compressor **CF** (4K), a heater and a primary pump of the oil ring type (**PAL**). After passing through gas flowmeters **D3** (venturi) and **D4** (gas meter), the gas is discharged into the helium recovery zones.



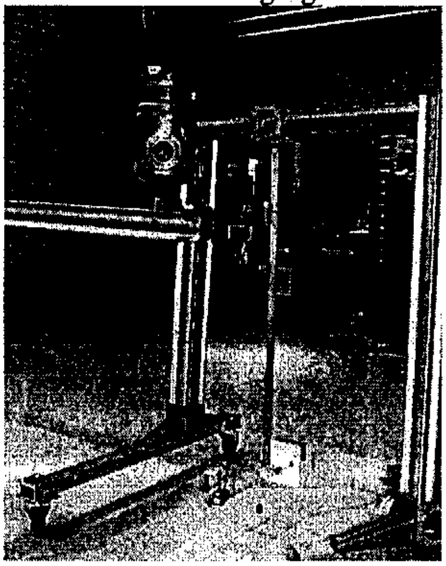
He II counter current flow cooling scheme
Experiments for TESLA (I.D. 65 mm)

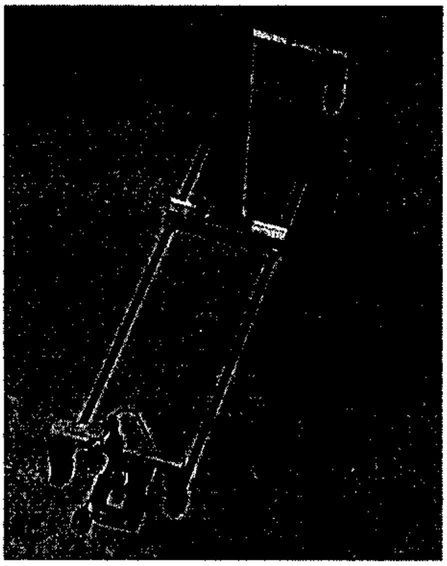
III.2 INSTRUMENTATION

The principal parameters to be determined are the slope of the pipe, and the flow rate and temperature of the two-phase superfluid helium in counter-current flow.

III.2.1 Measuring the slope

The slope of the pipe is measured using the "plumb line" method. This is illustrated on the following figures.





The "zero" corresponding to the horizontal position is determined using a high precision (better than 0.01%) spirit level. The graduated rule can be read to better than a millimetre, and the distance to the point of rotation is 1000 mm. Precision is therefore better than 0.1%. The graduations are read under vacuum with a CCD camera, illumination being provided by a low power (0.5 watt) incandescent lamp.

The slope can also be checked using the "lake" method described hereafter. With all heating and liquid supply shut off (power and the JT Valve OFF), a bath of liquid is obtained. The flow of vapour in the line is then limited to that which is generated by losses in B2 and in the line. This heat input corresponds to a vapour flow in the line of a fraction of a g/s which is insufficient to start the mass of liquid moving or to create a sufficiently sensitive pressure difference to modify the liquid level between the line entry and exit (see paragraph IV.1). The surface of the liquid is then practically horizontal. Simply reading the height of helium in the two viewing zones gives the slope of the tube once the distance between the two zones is known.

The pictures are taken using black and white CCD cameras positioned under vacuum in the vicinity of the line and operating at a temperature between 2 and 300 K. The images are recorded on tape, then digitised using a video card and a digitisation program (IMASCAN and IMAGRAPH respectively) running on a PC.

Contour extraction performed using a program developed at SBT can be used for example to determine the position of the liquid-vapour interface.

If h_{01} represents the height of liquid in the glass sector close to chamber **B1** and h_{02} the height of liquid in the other viewing sector a distance d away, the slope of the tube is

$$p\% = 100\,(h_{02} \,.\, h_{01})/d$$

Unfortunately this determination is less precise than the previous one and would be used only if the "plumb line" system failed.

III.2.2 Measurement of flow rate

Since the level of liquid in the chamber **B2** is kept at a constant value, the liquid mass flow entering this chamber is equivalent to the vapour mass flow leaving. The heating power **W4** necessary to keep the level in **B2** constant gives the value of the flow: $\dot{m}=w4\,L_{sat}$.

III.2.3 Measurement of temperature

With the total helium flow kept constant by selecting a fixed aperture in the Joule-Thomson valve, the operating temperature which was chosen to be equal to that of the liquid in chamber **B1** is adjusted by modifying the capacity of the cold pumping system. The pressure in the chamber **B1** - i.e. the temperature of the liquid boiling in this chamber - can be adjusted by modifying either the bypasses of these pumps or the speed of the compressor **CF**. The temperature is read from the thermometer T3. Since heat losses at chamber **B2** and on the line are low (see paragraph IV-1) and the pressure drop along the line is negligible, temperature changes along the line also remain negligible.

III.3 PROCEDURE

The total helium flow in the line, determined at **D3** or **D4**, is controlled by the opening of the Joule-Thomson valve **VJT**. The counter-current superfluid flow in the line between **B1** and **B2**, for its part, is produced by the evaporation of helium in the chamber **B2** due to the electric heater **W4** and to losses in the line P1.

In all the counter-current experiments, the helium level in the chamber **B2** was controlled and kept constant by adjusting the power injected by the heater **W4** in compartment **B2**. The helium level in **B1** was controlled (using the heaters **W1** and **W2**) so as to allow a variable quantity of liquid helium (mass flow m_l) to enter the line under gravity. As the level in the compartment **B1** is raised, the flow in the line **B1-B2** increases, together with the power **W4**. However, above a certain liquid level in **B1**, the power **W4** is seen to stabilise, signifying that the flow between **B1** and **B2** has reached a plateau: this is the blocking flow. The level in **B1** can then continue to increase indefinitely without modifying the value of the flow in the line.

Since there is no accumulation of helium anywhere between **B1** and **B2**, it can be concluded that at any point in the line: $m_v = m_l$

To sum up, in the line representing the abscissa x with its origin at the chamber **B2** we have:

$$m_v = m_l$$

$$m_v = \frac{W_4 + W_{losses} * x/L + W_{losses\,B2}}{L_{sat}}$$

At the chamber **B1** we also have:

$$m_v = D_4 - D_{flash} - \frac{W_1+W_2+W_{losses\,B1}}{L_{sat}}$$

III.4 LOSSES TO THE LINE

Any heat input to the line was minimised as much as possible by using superinsulation. However, heat losses by radiation from warmer components around the line, and by conduction through the supports, and finally by conduction through the gas, are still difficult to estimate. They must therefore be measured.

To do this with the system in operation, i.e., in the presence of superfluid helium flowing in the line, the following procedure is adopted: the supply valve **VJT** is closed and all the heaters switched off at the same time. The pumping system is also bypassed so as to maintain the temperature at about 2K. In this way a bath of superfluid is obtained, which can also be used for measuring the slope (see paragraph III.2). This bath slowly evaporates under the effect of thermal losses. The vapour flow is measured using the flowmeters **D4** and **D3** and therefore corresponds to the thermal losses. In this situation we have: $W_{pertes} = D4\ L_{sat}$

VI RESULTS

IV.1 LOSSES

From measurements made at various times throughout the experimental campaign, the following value for losses on the line and in the chambers **B1** and **B2** has been deduced:

$$\mathbf{Wp = 6 \pm 1W}$$

Also, monitoring the levels in the chambers **B1** and **B2**, particularly when the liquid level is such that flow between **B1** and **B2** is no longer possible, shows that most of the losses take place at **B1** (the desired situation) and that the losses at **B2** and on the line are equivalent to a vapour flow that is probably less than 0.15 g/s.

This flow rate is negligible and is disregarded in the experimental determination of the blocking flow.

Moreover, it does not interfere with the measurement of the slope, if this is done with the helium level in the tube low enough to allow the vapour to pass.

IV.2 MEASUREMENT OF SLOPES

Before the system is cooled, the pipe is positioned horizontally using a precision spirit level, and the graduated rule of the inclinometer adjusted to set the zero. The slope to produce flow is then set with the system cold, and adjusted using an inclinometer. Finally it is also checked at low temperature using the so-called "lake" method described in section III-2. It is also possible to vary the slope with the system cold, i.e. in the presence of superfluid flow.

Comparison with the two methods were done for different slopes and the next table gives the results:

Slope using Plumb line method (%)	Slope using Lake method (%)
1.35	1.19
0.1	0.14
-0.2	-0.33

The reference measurement of each slope is that given by the inclinometer (the plumb line method). However, the weight that indicates the vertical behaves like a pendulum, and since friction is practically zero the wire oscillates along the graduated rule. It is therefore necessary to define its mean position, which limits the precision of the measurement to 1 mm, or 0.1% on the value of the slope.

The different slopes used were: -0.2%, 0.1%, 0.4%, 0.6% and 0.8%.

IV.3 DESCRIPTION OF COUNTER-CURRENT FLOW

Measurements were therefore made using 5 different slopes and at temperatures between 1.8 K and 2 K. For low vapour flow values, the interface is very flat as in the co-current flow regime. As the flow increases, the interface becomes increasingly agitated (see video). "Waves" of increasing amplitude become visible. However no disturbed zone is seen in the vapour above the interface.

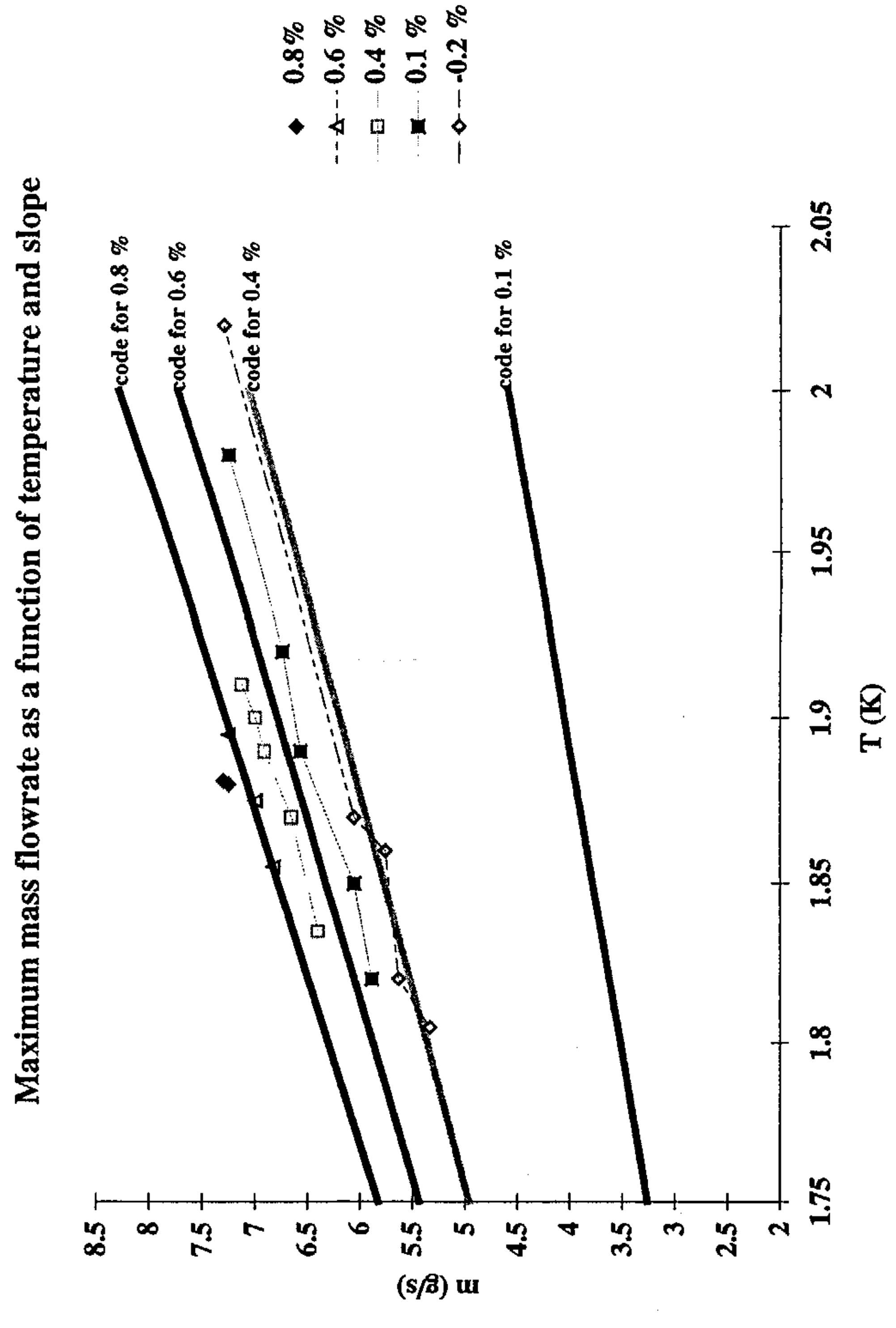
As blocking approaches, the interface is extremely agitated and the frequency of the "waves" increases. When the maximum value of **W4** prior to blocking is reached, the controlled liquid level **N5** is around the centre of the tube.

If the level **N5** is raised further, the power W4 remains constant and the flow in the tube appears to be independent of **N5**. The liquid continues to flow from **B1** to **B2**, where it is evaporated by the heater **W4**, the resulting vapour then flowing towards B1 against the flow of liquid. If the level of liquid in the chamber **B1** goes higher than the top of the tube, the vapour leaving **B2** creates a passage through the liquid.

Blocking therefore appears as a maximum limit on flow rather than a halt to liquid circulation.

IV.4 COMPARISON OF EXPERIMENTAL RESULTS AND THE CODE

The calculated and measured blocking flows are compared on the following figure.


Maximum mass flowrate as a function of temperature and slope
m (g/s)
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.75
1.8
1.85
1.9
1.95
2
2.05
T (K)
code for 0.8 %
code for 0.6 %
code for 0.4 %
code for 0.1 %
0.8 %
0.6 %
0.4 %
0.1 %
-0.2 %

The above figure shows good agreement between measurement and calculation in the trends of the data. The dependence of the measured blocking flow on temperature and slope agrees with predictions. This validates the use of the equations of conservation for calculating two-phase counter-current flow.

However a difference between calculation and measurement can also be seen.

The length of the 65 mm diameter tube used is 1200 mm, which is far from representing an infinite length. It can therefore be expected that counter-current flow remains possible up to a negative slope of -65/1200 or about -6%. The experimental points most representative of a very long pipe are certainly those made with the biggest slope. However, for a very high length/diameter ratio, the calculation would probably be too optimistic, with the calculated blocking flow higher than the actual value. The reason is as follows:

- At the pipe entry, the regime is not established and the liquid has to accelerate in order to reach a constant velocity. Since mass flow is conserved, the height of liquid in this entry section is necessarily the highest (and, similarly, higher than that calculated for steady flow). Hence it is probably this entry condition that will set the value of the blocking flow below the calculated value.

- Instabilities can occur just before the flow limit imposed by the equations of conservation is reached.

- The correlations used for wall friction and, particularly, friction at the interface, certainly need improving.

V CONCLUSION

The research carried out into counter-current superfluid two-phase flow was the continuation of work on co-current flow and benefited from all the knowledge acquired both experimentally (most of the previous experimental installations were used, with the same cameras operating in a vacuum and a low temperature, etc.) and theoretically (adaptation of the co-current two-phase calculation code). Preliminary experiments carried out for CERN made it possible to plan a well-targeted test programme, and the results are encouraging.

The overall trends (variation of blocking flow as a function of the two-phase flow temperature and of the slope of the tube) are well reproduced by the calculation code. However, owing to the low length/diameter ratio, the experiment is not representative of a very long tube and comparisons with the code should be treated with great caution. Thus, for a negative slope, counter-current flow remains possible, which is of course impossible once the diameter/length ratio is less than the absolute value of this negative slope.

Further research will certainly be necessary in order to refine our understanding, the code itself and its range of validity. The principal parameters to be varied would be the length (in order to determine the influence of the "extra slope" due to the diameter-length ratio), the slope (covering a wider range than that already explored) and the pipe diameter (which would perhaps make it possible to determine whether the calculated results more closely resemble the measured results at high diameters where instabilities are probably less). Finally, more extensive data would probably make it possible to define a more precise correlation for the interfacial coefficient of friction.

REFERENCES

1. A. Gauthier, L. Grimaud, B. Rousset. "Résultats des essais effectués sur la ligne d'hélium diphasique Φ40 de 90 m" [Results of tests carried out on the 90-metre 40 mm diameter two-phase helium line]. Note SBT-CT 97-45

2. A. Gauthier, B. Rousset, "Résultats des essais effectués sur la ligne d'hélium diphasique Φ20 de 1.3 m" [Results of tests carried out on the 1.3-metre 20 mm diameter two-phase helium line]. Note SBT-CT 97-49

3. B. Rousset, A. Gauthier, L. Grimaud, R. van Weelderen. "Latest developments on HeII co-current two-phase flow studies" to be published in Advances in Cryogenic Engineering Vol. 43

4. H. Guinaudeau "Modelling counter-current two-phase flow of saturated superfluid helium in quasi-horizontal tubes: application to the LHC cryogenic system" DRAFT of June 28, 1996 provided by the CERN LHC team.

NOMENCLATURE

A	Cross sectional area
D	Pipe diameter
f	Darcy friction factor
g	Gravitation constant
h	Liquid level
L	Latent heat
M	Mass flow rate
P	Pressure
Re	Reynolds number
S	Surface area
V	Velocity
W	Power
x	Horizontal coordinate
y	Vertical coordinate

Greek

β	Angle of incline
ρ	Density
τ	Shear Stress

Subscripts

g	Gas
gs	Superficial gas velocity $= m_v/\rho A_t$
i	Interface
l	Liquid
t	Total
v	Vapor