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Hydraulic Behaviour of He II in Stratified Counter-Current Two-Phase Flow

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Abstract

Future large devices using superconducting magnets or RF cavities (e.g. LHC or TESLA) need He II two-phase flow for cooling. 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 and theoretically. Experiments were conducted on two different pipe diameters (40 and 65 mm I.D. tube) for slopes ranging between 0 and 2%, and for temperatures ranging between 1.8 and 2 K. This paper introduces the theoretical model, describes the tests, and provides a critical review of the results obtained in He II counter current two-phase flow.

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Future large devices using superconducting magnets or RF cavities (e.g. LHC or TESLA) need He II two-phase flow for cooling. 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 and theoretically. Experiments were conducted on two different pipe diameters (40 and 65 mm I.D. tube) for slopes ranging between 0 and 2%, and for temperatures ranging between 1.8 and 2 K. This paper introduces the theoretical model, describes the tests, and provides a critical review of the results obtained in He II counter current two-phase flow.

INTRODUCTION

Superconducting magnets in LHC [1] as well as superconducting RF cavities in TESLA [2] will use He II two-phase flow as the cold source. Furthermore, these two huge devices will be installed in a quasi-horizontal tunnel. The standard cooling configuration employs a co-current two-phase flow. However, if space for pumping at the outlet of the flow is not available or relatively costly to implement, counter current two-phase flow may be envisaged. This latter situation appeared more difficult to control [3] and therefore required some preliminary investigations which were performed at Grenoble thanks to the support of CERN and DESY.
A series of experiments were performed in order to investigate the limit of this cooling scheme and also to compare the dependence on slope, diameter and temperature with reference to a simple model.

CALCULATION MODEL

In most cases, experiments on counter-current flows have been performed in vertical pipes. Extensive results have been reported for water and air mixture in such a configuration. In this 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. The best explanations and predictions of this flooding phenomenon have been done using instability theory [4].

In the 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 the onset of instability. Consequently, we have developed a model based on mass and momentum balance. This model originated from discussions with the CERN team and is also based on a study carried out by Guinaudeau [5]. It represents the maximum mass flow rate allowed in such a configuration.

In this simple model, it is assumed that the flow is adiabatic, stratified, steady and established. The liquid mass flow is supposed to be equal in magnitude to the vapour mass flow, but in the opposite direction:

$$\dot{m}_l \equiv \dot{m}_v = \dot{m} \qquad (1)$$

The momentum balance applied to the liquid phase and to the vapour phase yields:

For the liquid phase:

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

For the vapour phase:

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

where x *is the abscissa,* A *the area,* ρ *the density,* g *the gravity,* S *the perimeter,* P *the pressure and* τ *the shear stress. Index* l *is for liquid,* v *for vapour and* i *for interface.*

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

When the mass flow increases, the liquid height also increases (because the prime mover term $\rho_l A_l g \sin\beta$ in equation (2) increases), leaving less and less space for the vapour flowing in the opposite direction, which results in 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 increasing the 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 mass flow for which it is still possible to solve the system of equations (2) and (3) represents the maximum liquid that can flow against the same mass flow of vapour: this is the blocking flow.

EXPERIMENTAL FACILITIES

All measurements were performed on the Superfluid Helium Test Facility at CEA Grenoble which has been described previously [6]. A schematic diagram of the experimental line is given hereafter.

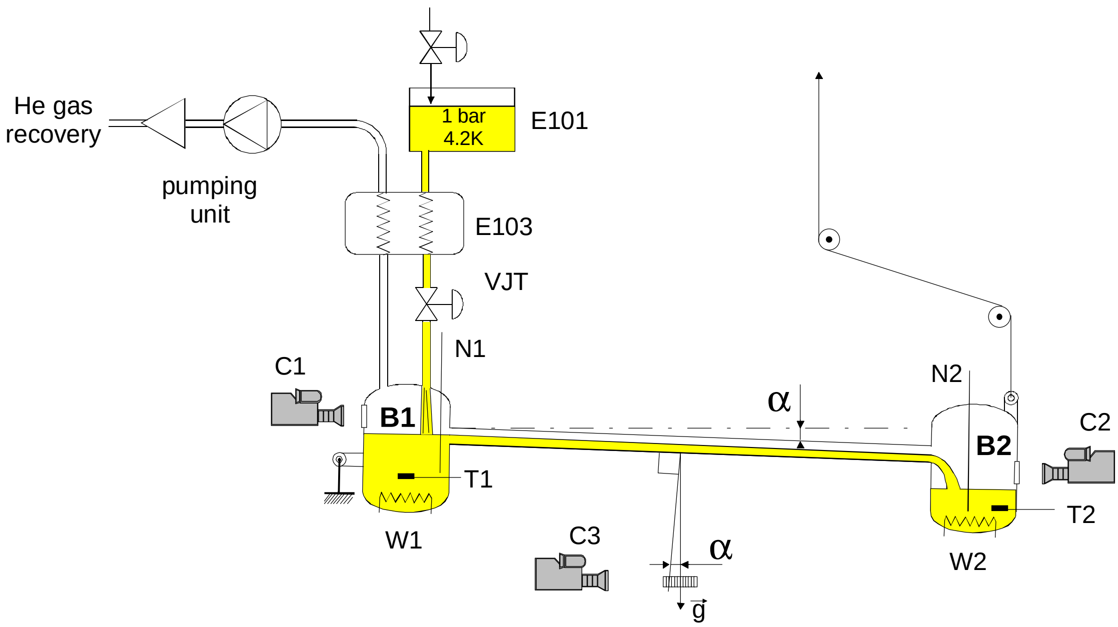

Figure 1 HeII counter current flow cooling scheme

Helium flows from the tank **E101** at a temperature of about 4.2 K, 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 test line (40 mm or 65 mm I.D. tube) joining **B1** to **B2** flows under gravity to the chamber **B2**. It faces a counter current of vapour evaporated by the heater **W2** operated by an electric current which is regulated to produce the required flow in the line. The vapour is then drawn through **E103**, after which it enters the pumping system.

Temperature of the two-phase flow is measured using two carbon thermometers placed in **B1** and **B2**.

Pipe slope is measured either by using the “plumb line” method or the “lake” method described hereafter. With all heaters and liquid supply shut off, a bath of liquid is obtained. The liquid-vapour interface is then practically horizontal. Simply comparing the height of superfluid in the two viewing zones gives the slope of the tube once the distance between the two zones is known. Pictures are taken using black-and-white CCD cameras positioned in the vacuum space in the vicinity of the line and operating at a temperature between 2 and 300 K.

Since the liquid level in **B2** is kept constant, the liquid mass flow entering **B2** is equivalent to the vapour mass flow leaving. Its value is deduced from the power **W2** necessary to regulate the level in **B2:**

$$\dot{m}_l = \mathrm{W2}\, L_{sat}$$

RESULTS AND ANALYSIS

Flow behaviour

In all the counter-current experiments, the helium level in **B2** was controlled and kept constant by regulating the power injected by the heater **W2**. The helium level in **B1** was controlled (using the heater **W1**) so as to allow a variable gravity-driven quantity of liquid helium (mass flow m_1) to enter the line. As the level in the compartment **B1** is raised, the flow in the line **B1**-**B2** increases, together with the power **W2**. However, above a certain liquid level in **B1**, the power **W2** 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. If liquid level in **B1** goes higher than the top of the tube, the vapour leaving **B2** creates a passage through the liquid. From this we conclude that blocking rather acts to limit the flow to a maximum value than to reduce the flow rate to zero.

Comparison between model and experiments

The figures 2 and 3 compare measurement and calculation. Dependence of the measured blocking mass flow on slope, diameter and temperature agrees with the predictions. The dependence on slope and diameter can be deduced from open-channel behaviour, but the trend with temperature is only two-phase flow dependent. As the temperature increases, vapour velocity decreases (due to density growth) which reduces the interfacial shear stress and blocking appears at higher flow rates.

However, some differences between calculation and measurement can also be seen.

At low values of slope, the calculated blocking mass flow rate is lower than the experimental one. This is certainly due to the poor ratio of length over diameter, which allows counter-current flow even for low negative pipe slope. 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.

On the other hand, for high values of slope, the calculation seems too optimistic, with the calculated blocking mass flow higher than that measured. We explain this as follows: at the pipe entrance, 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 established flow). Hence, it is probably this entry condition that will fix the value of the blocking flow below the calculated value.

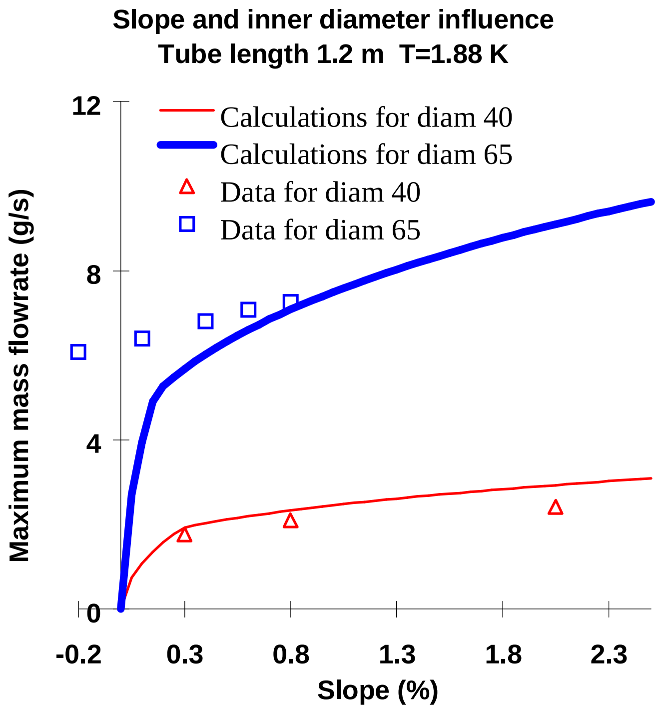

Figure 2 Comparison between calculated and experimental blocking

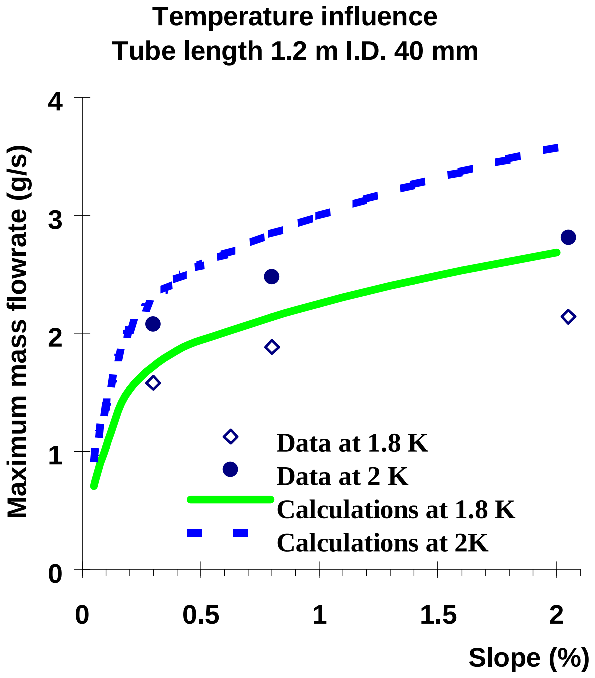

Figure 3 Comparison between calculated and experimental blocking

CONCLUSION

The overall trends (variation of blocking flow as a function of the two-phase flow temperature and of diameter and slope of the tube) are well reproduced by the calculation method. However, owing to the low length/diameter ratio, the experiment is not representative of a very long tube and comparisons with the calculations should be treated with great caution.

Further research will be necessary in order to refine our understanding, and the range of validity of the calculation method itself. Finally, more extensive data should make it possible to define a more precise correlation for the interfacial coefficient of friction.

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