Effect of spray cooling on heat transfer in a two-phase helium flow

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Abstract

We describe an experimental study of the phenomenon of spray cooling in the case of liquid helium, either normal or superfluid, and its relationship to the heat transfer between an atomized two-phase flow contained in a long pipe, and the pipe walls. This situation is discussed in the context of the cooling of the superconducting magnets of the Large Hadron Collider (LHC). Experiments were conducted in a test loop reproducing the LHC cooling system, in which the vapor velocity and temperature could be varied in a large range. Shear induced atomization results in the generation of a droplet mist which was characterized by optical means. The thickness of the thin liquid film deposited on the walls by the mist was measured using interdigitated capacitors. The cooling power of the mist was measured using thermal probes, and correlated to the local mist density. Analysis of the results shows that superfluidity has only a limited influence on both the film thickness and the mist cooling power. Using a simple model, we show that the phenomenon of spray cooling accounts for the measured non-linearity of the global heat transfer. Finally, we discuss the relevance of our results for cooling the final focus magnets in an upgraded version of the LHC.

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1. Introduction

Many large scale cryogenic facilities use vaporization of circulating liquid helium to cool cryogenic devices. This is the case of the Large Hadron Collider (LHC) at CERN, the superconducting magnets of which are cooled by a pipe containing a two-phase (vapor-superfluid) stratified flow of 4He pumped down to 1.8 K [1,2]. This paper reports on experiments carried out in a similar pipe geometry at larger vapor velocities, such that the liquid flow is partly atomized into a spray of small droplets. Our aim is to investigate how the deposition of these droplets on the pipe walls improves the heat transfer between these walls and the 4He flow, due to the spray cooling phenomenon. To the best of our knowledge, this paper provides the first study of this phenomenon for liquid helium.

Spray cooling has been extensively studied for usual fluids, due to its numerous practical applications, from the cooling of hot metal in steel industries, to that of power circuits in electronics [3]. For cryogenic fluids, it has been applied to the cooling of hydrogen reservoirs in weightlessness conditions [4]. However, helium has physical properties which make it difficult to extrapolate the results obtained with other fluids. Because its surface tension is much smaller than that of water, and the influence of this parameter on atomization is still debated [5,6], one cannot predict the droplets impinging flux from experiments on water–air two-phase flows [7]. Furthermore, in the superfluid phase, an impinging liquid droplet could spread much faster than in the normal phase [8], which may give a specific bouncing probability, hence cooling efficiency. Therefore, the influence of atomization on heat transfer in a two-phase superfluid helium flow has to be investigated experimentally.

In earlier studies conducted in a test pipe installed at CEA-Grenoble, global thermal measurements [9] revealed an improvement, at large enough vapor velocity, of the global heat transfer between the pipe and a surrounding subcooled helium bath. Simultaneous optical observations [10] show that this improvement was correlated with the appearance of a mist of liquid droplets atomized from the bulk liquid by the fast vapor stream, suggesting that it was due to the cooling effect of the liquid spray. The experiment described in this paper differs from these previous studies in two respects. First, we use local probes to directly measure the effects of the spray deposition (film formation on cold surfaces and spray cooling of heated surfaces), enabling to correlate them to the local spray density, as measured by optical means. Second, we use a new cryogenic facility delivering a liquid flowrate nearly three times larger than previously possible. This allows us to extend the available range of physical parameters controlling atomization, such as the vapor velocity and the temperature, and to compare, for similar atomization conditions, heat...
transfer in the superfluid and normal phases. Besides being possibly relevant for future developments of the LHC, our results show that spray cooling by superfluid helium does not fundamentally differ from spray cooling by normal liquid helium. This conclusion is of interest for evaluating the efficiency of spray cooling for other purposes, such as cooling cryogenic helium reservoirs in weightlessness conditions.

The outline of this paper is as follows. Section 2 describes the cryogenic system and the experimental probes, namely the optical set-up for the characterization of the droplets mist, the surface capacitances for detecting the film formation, and the global and local thermal probes for measuring the heat transfer. Section 3 presents selected results qualitatively demonstrating the relationship between atomization, film deposition, and spray cooling. Our results on spray cooling are quantitatively analyzed in Section 4, focusing on three points: its sensitivity to superfluidity, its efficiency, and its relationship to the global heat transfer. Section 5 finally discusses the relevance of our results for cooling the final focus magnets in an upgraded version of the LHC.

2. Experimental set-up

2.1. Flow generation

Our experiments were performed in the Cryoloop test line installed at the Service des Basses Températures at CEA-Grenoble. The two-phase helium flows in a pipe of diameter $D = 40$ mm, contained in a 10 m long horizontal cryostat with a slight downwards slope ($-0.6\%$) (Fig. 1).

A specially developed refrigerator [11] with large cooling power (400 W at 1.8 K) delivers a controllable flow of liquid of up to approximately 20 g/s to one end of the pipe. There, this liquid is partly evaporated by a heater in order to obtain downstream an essentially stratified two-phase flow. At the other end of the pipe, the remaining liquid is evaporated, and the exiting vapor is pumped through cold compressors followed by a room tempera-

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3 This ensures a gravitationally driven flow at low vapor velocity.

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4 More precisely, the temperature slightly decreases along the pipe, reflecting the pressure drop due to friction. This gradient increases with increasing vapor velocity and decreasing temperature, and is less than 6 mK/m for all our conditions. The resulting temperature difference between the different probes is negligible.

5 The distributed heat leak from the thermal shields -about 1 W per meter- also contributes to the vaporization. At the end of 10 m line, where we measure the properties of the atomized mist, the integrated heat leak is 10 W. This value is added to the heating power applied at the inlet to obtain $W_{\text{line}}$. 

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<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$\Delta V$</td>
<td>variance of the axial velocity distribution</td>
<td></td>
</tr>
<tr>
<td>$\eta$</td>
<td>liquid viscosity</td>
<td></td>
</tr>
<tr>
<td>$\eta_l$</td>
<td>liquid kinematic viscosity</td>
<td></td>
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<tr>
<td>$\Phi$</td>
<td>useful liquid volume flux for spray cooling</td>
<td></td>
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<tr>
<td>$\Phi_{\text{inc}}$</td>
<td>incident liquid volume flux per unit area</td>
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<tr>
<td>$\rho_v$</td>
<td>vapor density</td>
<td></td>
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<tr>
<td>$\rho_l$</td>
<td>liquid density</td>
<td></td>
</tr>
<tr>
<td>$\Sigma$</td>
<td>droplets surface density per unit volume</td>
<td></td>
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<tr>
<td>$\tau_p$</td>
<td>particle relaxation time</td>
<td></td>
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<tr>
<td>$D$</td>
<td>pipe diameter</td>
<td></td>
</tr>
<tr>
<td>$d$</td>
<td>droplets diameter</td>
<td></td>
</tr>
<tr>
<td>$d_0$</td>
<td>droplets mean diameter</td>
<td></td>
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<tr>
<td>$e$</td>
<td>thickness of the liquid film deposited by the droplets (averaged over the probe area)</td>
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<tr>
<td>$f$</td>
<td>spray cooling efficiency</td>
<td></td>
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<tr>
<td>$g$</td>
<td>gravity acceleration</td>
<td></td>
</tr>
<tr>
<td>$L$</td>
<td>latent heat per unit mass</td>
<td></td>
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<tr>
<td>$m$</td>
<td>total mass flow</td>
<td></td>
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<tr>
<td>$m_v$</td>
<td>vapor mass flow</td>
<td></td>
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<tr>
<td>$m_l$</td>
<td>liquid mass flow</td>
<td></td>
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<tr>
<td>$P(d)$</td>
<td>droplets diameter probability distribution</td>
<td></td>
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<tr>
<td>$R_K$</td>
<td>specific Kapitza resistance [Km$^2$W]</td>
<td></td>
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<tr>
<td>$S$</td>
<td>pipe section area</td>
<td></td>
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<tr>
<td>$S_t$</td>
<td>total lateral surface of the thermal probes</td>
<td></td>
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<tr>
<td>$S_a$</td>
<td>active surface of the thermal probes</td>
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<tr>
<td>$T$</td>
<td>temperature</td>
<td></td>
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<td>$T_D$</td>
<td>integral time scale of the turbulence</td>
<td></td>
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<tr>
<td>$V$</td>
<td>vapor velocity averaged over the pipe section</td>
<td></td>
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<tr>
<td>$v$</td>
<td>r.m.s. vapor transverse velocity</td>
<td></td>
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<tr>
<td>$V_{\text{imp}}$</td>
<td>droplets impact velocity</td>
<td></td>
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<tr>
<td>$v_l$</td>
<td>liquid velocity inside the deposited film</td>
<td></td>
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<tr>
<td>$W_{\text{line}}$</td>
<td>heating power applied to the line (W)</td>
<td></td>
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<tr>
<td>$W_K$</td>
<td>heating power applied to the Kapitza box</td>
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<tr>
<td>$W_p$</td>
<td>heating power applied to the thermal probes</td>
<td></td>
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<tr>
<td>$W_\text{film}$</td>
<td>film contribution to $W_e$</td>
<td></td>
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<tr>
<td>$W_{\text{cor}}$</td>
<td>critical heating power measured by the thermal probes, corrected for $W_{\text{film}}$</td>
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![Fig. 1. Schematics of the Cryoloop pipe. The two-phase helium flow is produced by partial vaporization of the injected liquid. The properties of the atomized mist are measured 10 m downstream. The global heat transfer is measured by the Kapitza box (1). The liquid level is measured by a capacitive level gauge in section (2). The liquid film deposited from the mist is measured in sections (2), (3), and (6) by interdigitated capacitive gauges. The local contribution of the mist to the heat transfer is measured by suspended thermal probes in section (6). The mist is optically characterized in sections (4) and (5).](image-url)
is the pipe cross-section area. Finally, for given vapor velocity and temperature, the liquid level is varied by changing the injected liquid mass flow \( m \) and measured by an interdigitated capacitor glued to the bottom part of the pipe, acting as a level gauge [12,13]. At constant vapor velocity and temperature, increasing the liquid mass flow increases the liquid level, hence the bulk liquid free surface and the spray density.

At a given temperature, the vapor velocity is proportional to \( W_{\text{line}} \), up to the complete vaporization of the injected liquid (\( W_{\text{line}} = \dot{m} \cdot L \approx 400 \text{ W} \) for \( \dot{m} = 18 \text{ g/s} \)). At 1.8 K (\( \rho_{v} = 0.45 \text{ g/cm}^3 \)), this allows to obtain vapor velocities from \( \approx 1 \) to 30 m/s. The later value is more than 15 times the vapor velocity at LHC. In our experimental conditions (\( T \) between 1.8 and 2.8 K, vapor velocity of several meters per second for atomization), the vapor Reynolds number lies in the range \( 10^5 \) to \( 10^6 \), so that the vapor flow is fully turbulent.

Because the vapor density increases from 0.45 to 3.4 g/cm\(^3\) between 1.8 and 2.8 K, the velocity obtained at full vaporization decreases with increasing temperature. Moreover, atomization requires to keep some liquid mass flow. This reduces the liquid flow available for evaporation, hence the operational range of velocities. Typically, for a liquid height of 3.8 mm (corresponding to a wetted fraction of the pipe of 20%), and \( \dot{m} = 18 \text{ g/s} \), the maximal velocity decreases from about 20 m/s at 1.8 K to 4 m/s at 2.8 K. In terms of atomization, this decrease in velocity is only partly compensated by the increase of the vapor density. Indeed, atomization is driven by the vapor kinetic energy density, which scales as \( W_{\text{line}}/\rho_{v} \), hence, for fixed \( W_{\text{line}} \), decreases with increasing temperature. This explains why atomization of normal liquid could not be obtained in our previous experiments [14] where the injected liquid mass flow rate was below 7 g/s. This was one of the motivations [15] for increasing this mass flow up to 20 g/s in the present experiments, allowing to compare the heat transfer for superfluid and normal helium in similar conditions of atomization [16].

The different probes described in the following sections are located within the last two meters of the ten meters long pipe (Fig. 1). Earlier measurements in a 22 m long pipe [17] have shown that, below \( V = 7 \text{ m/s} \), the global thermal transfer is identical 10 m and 20 m away from the inlet, suggesting that, for these velocities, the spray develops over a distance shorter than 10 m. Although this might not be the case for the larger velocities studied in the present experiments, the spray is most likely uniform over the pipe last two meters, making it meaningful to compare the signals from the different probes.

### 2.2. Optical characterization of the helium mist

We characterize the helium mist by light scattering measurements performed in a glass portion of the pipe (section (4) in Fig. 1). We summarize here the key points of the measurements, referring the reader to Refs. [18,19] for details.

The angular dependence of the scattered light (measured in section (5) in Fig. 1) shows that the droplets generated by the atomization process are spherical and larger than several micrometers in diameter [10,19]. In such conditions, the droplets scattering cross section is half their interfacial area, and the scattered light intensity measures \( \Sigma \), the local density of interfacial area (i.e. the total surface of droplets per unit volume). The distribution of \( \Sigma \) across the pipe cross-section is then obtained by illuminating the pipe with a laser sheet propagating horizontally perpendicular to the pipe and imaging the mist with a CCD under a 15° angle with respect to the direction of propagation of the laser sheet (Fig. 2). We also measure the profile of \( \Sigma \) along the vertical diameter by shining a laser beam propagating vertically from the top to the bottom of the pipe and imaging the light (now scattered at 90°) using the same CCD. In the central region of the pipe where the suspended probes are located, the two methods give consistent results [18].

Individual snapshots taken at a rate of one frame per second reveal significant fluctuations of the droplets interfacial density. The fluctuation level does not depend on the exposure time between 3 ms and 30 ms and is typically 15–25% of the average density, depending on physical conditions and on the position within the pipe cross-section. We average several tens of such snapshots in order to reduce the noise. The intensity of the averaged pictures is then reproducible within several %. This is comparable to the day-to-day reproducibility for given physical conditions.

Parallel to these global measurements, we also measure the diameter and velocity of the individual droplets using a commercial Phase Doppler Particle Analyzer (PDPA, Aerometrics). Two horizontal, coherent, laser beams intercept inside the pipe at an angle of several degrees, forming a grid of interference fringes. Individual droplets traversing the small detection volume defined by the intercept of the laser beams and the optical detection system give rise to modulated bursts of scattered light, from which we deduce
the droplets size and velocity (along the direction parallel to the difference of the two incident wavevectors). The two beams of the PDPA are in a horizontal plane so that only the velocity parallel to the pipe is measured. Although the PDPA technique is commonly applied in fluid mechanics, the specificity of liquid helium is its small refractive index ($n \simeq 1.025$). It motivates our choice of a scattering angle of 15°, an unusually low value, in order to guarantee to be in the regime where scattered light comes from refraction through, rather than reflection on, the droplets [20].

In most cases, measurements were only performed on the pipe axis, but the vertical and radial dependence of the droplets distribution was measured for several flow conditions [21,22]. We typically find a nearly exponential distribution of diameters, $P(d) \propto \exp(-d/d_0)$, with $d_0$ ranging from 20 to 40 μm, depending on hydrodynamic conditions [22]. The velocity distribution is the same for all droplets, or droplets of a given diameter only. This shows that the droplets inertia is small enough for the droplets to follow the turbulent flow.

2.3. Capacitive film detection

In order to detect the helium film locally deposited by the droplets, we use interdigitated capacitors, evaporated on flexible Kapton foils [12,13]. A numerical simulation of the electrostatic problem shows that, for uniform thicknesses smaller than the gap between electrodes (30 or 50 μm), the capacitance changes linearly with thickness, with a slope which depends on the electrostatic characteristics of the device [13]. In this range, we can deduce from the measured capacitance the film thickness averaged over the probe area, denoted $e$. Based on this principle, different capacitors (20 mm long, 5.5 mm high) glued onto the walls of the pipe (Fig. 3) measure the height dependence of the film thickness. In addition, a planar capacitor (12 mm long, 5.5 mm high) is suspended by Kevlar wires across the pipe (at a median height of 26 mm). Unlike the capacitors on the pipe walls, which may also be sensitive to waves of the liquid level, or to the film flowing from higher elevations, it only measures the film directly deposited by the droplets.

2.4. Global heat transfer

The global capability of the two-phase flow to extract heat from the pipe walls is measured by a set-up reproducing the LHC situation (Fig. 4). This so-called Kapitza box [9] is made of two concentric tubes (40 mm and 76 mm in diameter) 40 cm long. The 1 mm thick inner copper tube contains the two-phase flow, in continuity with the stainless steel pipe. The space between the two tubes, filled with subcooled superfluid liquid at 1 bar, plays the role of the LHC magnet bath. Applying a power $W_k$ to an annular heater simulates the heat load dissipated by the magnet. The temperature of the subcooled helium is measured by two thermometers, located at both ends of the Kapitza box, and respectively close to the inner and outer walls. Global thermal exchange is characterized by the increase of this temperature as a function of $W_k$ up to typically 10 W. In this range, the heat transport in the superfluid follows the Görter-Mellink regime, and the subcooled liquid can be considered isothermal on the scale of the temperature difference between the bath and the pipe, as confirmed by comparing the two thermometers. The Kapitza resistance between the subcooled bath and the copper tube dominates the global resistance between the bath and the pipe (its contribution being ≈80%). The global heat exchange coefficient is then nearly proportional to the wetted area of the pipe inner wall. The coefficient of proportionality, i.e. the heat exchange for 100% coverage, was separately determined to be about 100 W/K at 1.8 K [14].

The heat transfer in the atomized regime is characterized by applying successive constant powers to the heater in the range 0.25–10 W, and measuring the temperature of the subcooled bath, once it has come to equilibrium (which takes 20–30 s, as determined by the heat exchange and the superfluid thermal capacity at 1 bar).

2.5. Local heat transfer

The Kapitza box measures the global heat transfer between the two-phase flow and the walls, which is the relevant quantity in the LHC case. However, it integrates various contributions (from the bulk liquid, from the film possibly deposited by waves, and from the film deposited by the stratified mist), and does not allow to separate the contribution of spray cooling to the thermal transfer. On that purpose, we use two thermal probes at two different

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**Fig. 3.** (a) View of the pipe showing the capacitive and thermal probes. Droplets deposit on these probes due to their transverse velocity. The axial distance is compressed with respect to reality. The bottom capacitive probe measures the liquid level; (b) position of the different probes projected onto the pipe cross-section. T and B are the top and bottom thermal probes; and (c) picture of the suspended thermal probes.

**Fig. 4.** The Kapitza box used for characterizing the global heat transfer between the two phase flow and the outer subcooled bath. (1) saturated liquid; (2) subcooled liquid; (3) annular heater. Two thermometers (4 and 5) are used to measure the temperature of the subcooled liquid and to check its homogeneity.
median heights (12 and 25 mm) in the last portion of the pipe (Fig. 3). The probes are suspended using Kevlar wires thin enough for the heat carried away by the saturated superfluid film to be negligible. Each probe consists in a pure (99.999%) aluminum polished plate (6 mm high, 10 mm long, and 3 mm thick) embedded in epoxy so as to leave apparent only one face. A heater and a thermometer at two different locations inside the aluminum plate allow to measure its temperature increase as a function of the applied power. The epoxy facing the vapor flow is wedged, so as to deflect the axial flow of droplets. This warrants that droplets impinge on and cool the probes mainly due to their transverse, rather than axial, motion, as is the case for the pipe walls. The aluminum thermal conductivity is large enough for the plate to be isothermal. The thermal exchange between the plate and liquid helium was separately measured by immersing the probe into a superfluid bath at 1.8 K. The cube of the plate temperature was found to be linear up to 2 W/cm², consistent with a Kapitza resistance of order 1.3 K cm²/W at 1.8 K, varying as 1/T². In the range 1.8–2.2 K, the corresponding values agree within 20% with those reported in Ref. [23].

3. Results

We have explored the spray cooling phenomenon in the superfluid phase for 25 different flows conditions in terms of liquid level, vapor velocity, and temperature. In addition, four temperatures between 2.2 and 2.8 K were studied in the normal phase, with velocities and levels chosen as to match some of the superfluid points in terms of atomization. In this section, we first describe how atomization depends on the above physical parameters. We then focus on a series of four experimental conditions, corresponding to increasing values of the vapor velocity, at constant liquid level and temperature (1.8 K) to illustrate the correlations between atomization, global heat transfer, film deposition and spray cooling. In the next section, we will use our full data set for a quantitative discussion of these correlations.

3.1. Atomization

Fig. 5 illustrates how, for a given total mass flow \( \dot{m} \), atomization sets in as the vapor velocity is increased by ramping up the heating power \( W_{\text{line}} \). Initially \( (W_{\text{line}} < 50 \text{ W}) \), the only visible effect of \( W_{\text{line}} \) is to make the liquid interface wavy and to decrease its level. The latter effect is due to the combined decrease of the liquid mass flow \( (\dot{m}_l = \dot{m} - W_{\text{line}}/L) \), and the increase of the liquid velocity, due to the interfacial friction with the faster vapor flow. Atomization is visible above around 50 W, corresponding to a vapor velocity \( V = 4.5 \text{ m/s} \). The actual threshold lies between 3 and 4 m/s,
about twice the Kelvin–Helmoltz threshold for wave formation on the liquid–vapor interface, and somewhat larger than the prediction of the Ishii–Grolmes criterium [24] for atomization [18]. Above this threshold and up to 200 W, the droplets mist density and brightness increase continuously with the vapor velocity, making it increasingly difficult to locate the liquid interface. The mist at 260 W appears less bright than at 200 W. This is due to the fact that the effect of the increased vapor velocity is more than compensated by the effect of the decreasing liquid level. Indeed, the two first pictures in Fig. 6 show that, at constant temperature and velocity, the spray density does depend on the liquid level. This reflects the change in the liquid area available for the atomization process. As a consequence, in order to study the dependence of the spray density on the vapor velocity and temperature, we have tuned the total mass flow to keep a constant level, as measured by the bottom capacitance (the interface corresponding to 18–20% of the pipe perimeter). The last three pictures in the first row of Fig. 6 show that the mist density increases with the vapor temperature (hence vapor density), keeping the velocity fixed. Finally, the pictures in the second row show that the mist density also increases with the vapor velocity, keeping the vapor density fixed. Both points are consistent with the idea that the vapor kinetic energy drives the atomization process.

The pictures in Fig. 6 show that the mist is stratified, being denser in the bottom portion of the tube. This stratification can be quantified by measuring the vertical profile of the interfacial density $\Sigma$. This profile is found close to exponential, allowing to define a characteristic stratification height [18]. The stratification height does not depend on the liquid level, at constant velocity and temperature. It increases (i.e. the mist becomes less stratified) with increasing vapor velocity. This is qualitatively consistent with a model where stratification results from the competition between the fall of droplets due to gravity and their diffusion due to their interaction with the turbulent vapor [22,25]. For a monodisperse spray, such a model indeed predicts an exponential profile of the interfacial density, with a stratification height increasing with the vapor velocity (through the increased turbulent diffusivity and the reduction of the settling velocity due to an expected smaller droplet size). This model also explains the modest measured temperature dependence of the stratification height [18] (it is predicted to be proportional to the vapor viscosity, which weakly depends on temperature in the explored range).

These observations have an important practical consequence. By tuning the liquid level at a constant vapor velocity, we can study spray cooling at different temperatures for similar spray characteristics in terms of droplets spatial distribution and axial velocity. This will enable us to compare the efficiency of spray cooling between the normal and the superfluid phases.

We finally discuss the transverse structure of the mist. The pictures in Fig. 6 show that the mist is denser on the pipe median plane and the walls. In the following, this horizontal plane is assumed to be uniform and the reduction of the settling velocity due to an expected stratification.

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8 In principle, changing the temperature also affects the liquid surface tension, but the change is negligible between 1.8 and 2 K.

9 The asymmetry between left and right in Fig. 7 is due to the perspective effect (in each rectangle, the height decreases from left to right), combined with the stratification.
the different probes versus the interfacial density measured at their respective positions within the pipe section.

3.2. Global heat transfer

Fig. 8 shows measurements of the global heat transfer using the Kapitza box, for the conditions of the second row of Fig. 6. At a vapor velocity of 7 m/s, the temperature inside the Kapitza box increases linearly with the heating power, with a slope corresponding to about 25% of the pipe perimeter being wetted, close to the value determined using the capacitive level gauge (20%). As the vapor velocity, hence the spray density, increases at constant bulk liquid level, the heat transfer at small heating power \( W_p \) gradually improves. At a vapor velocity of 17 m/s, the temperature rise at \( W_p = 1 \) W corresponds to a wetted perimeter of 80%! This is consistent with the formation of a liquid film on the pipe walls, due to droplets deposition. However, in contrast to the situation at low velocity, the thermal characteristic is non-linear: the relative improvement of thermal transfer decreases as \( W_p \) increases. At 17 m/s, for \( W_p = 8 \) W, the local slope corresponds to a wetted perimeter of only 50%. This implies that the deposited film is progressively evaporated as the heat load increases.

3.3. Film deposition

Once atomization sets in, the formation of a liquid film is directly detected by the capacitive probes. As shown in Fig. 9, the average film thickness decreases from the bottom to the top of the pipe, and increases with the degree of atomization. This behavior is consistent with the mist stratification, and the increase of the mist density with the vapor velocity. The film thickness, computed assuming a smooth film, ranges from 1 to 5 \( \mu \)m. Capacitive measurements alone do not allow to discriminate a smooth film from patches of liquid. However, the two capacitive probes (2) and (3), which have a different gap between digitized electrodes (30 and 50 \( \mu \)m) and are located at the same height, give the same average thickness. This shows that, if patches exist, their maximal thickness cannot exceed 30 \( \mu \)m, consistent with the fact that the average droplet diameter, as determined by the PDPA, ranges between 20 and 40 \( \mu \)m. A striking feature of Fig. 9 is that although the vapor velocity increases dramatically the atomization, it has only a moderate effect on the film thickness. This is quantified by Fig. 10 which shows the average film thickness as a function of \( \Sigma \), the local density of interfacial area facing the capacitive probes, for our full set of atomization conditions, corresponding to different liquid levels, vapor velocities, and temperatures. Data for probe 3 are not shown, but are essentially similar to those for probe 2, located at the same height. For a given probe, the increase of film thickness with \( \Sigma \) is clearly sublinear, accounting for the weak dependence on velocity in Fig. 9. A similar behavior is observed for all probes, with a larger thickness for the bottom probes. Superfluidity has a limited influence on the film thickness, which is found only marginally larger in the normal phase.

Fig. 10 suggests that the mist interfacial density is the primary factor determining the thickness of the deposited film. This can be understood on the basis of a physical model for film deposition which will be discussed in Section 4.3, according to which the thickness varies as the cubic root of the deposited flux, itself proportional to \( \Sigma \), \( d_{\text{DP}} \), the average droplets size, and \( \eta_{\text{imp}} \), their impact velocity. The cubic root dependence explains the sublinear dependence of the film thickness on \( \Sigma \). The dispersion of data around a global trend for a given probe, as well as the thickness dependence on the probe height, probably stems from the variation of \( d_{\text{DP}} \) and \( \eta_{\text{imp}} \) between the different points of Fig. 10.

3.4. Cooling power of the mist

The non-linearity of the global heat transfer implies that, for a large enough heat flux, the droplets impinging on the pipe walls are directly evaporated without forming a liquid film. This phenomenon is directly observed using the suspended thermal probes. Fig. 11 shows the temperature of the top probe as a function of the applied power \( W_p \) for different flow velocities \( (T = 1.80 \text{~K}, \text{liquid height} = 3.8 \text{~mm}) \). The temperature is controlled by the Kapitza resistance between the probe and the deposited liquid film below a critical heat flux, and by exchange with the turbulent vapor above. The critical heat flux increases with the vapor velocity.

Fig. 11. Temperature of the top thermal probe as a function of the applied power \( W_p \), for different flow velocities \( (T = 1.80 \text{~K}, \text{liquid height} = 3.8 \text{~mm}) \). The temperature is controlled by the Kapitza resistance between the probe and the deposited liquid film below a critical heat flux, and by exchange with the turbulent vapor above. The critical heat flux increases with the vapor velocity.
than for the top probe, consistent with the mist stratification. For the top probe, at 7 m/s (respectively 10 m/s), the slope above the threshold is about 90 K/W (respectively 60 K/W). We can compare these measured thermal resistances to that expected from thermal exchange with the turbulent vapor. The corresponding exchange coefficient is estimated as $h = \frac{Nu}{k/l}$, where $h$ is the thermal exchange coefficient, $k$ the vapor thermal conductivity, $l$ the length of the active probe length, and $Nu$ the Nusselt number, estimated by the Colburn formula, $Nu = 0.023Re^{0.8}Pr^{1/3}$, with $Re$ and $Pr$ the Reynolds and Prandtl numbers. The corresponding thermal resistance is about 200 K/W at 1.8 K and 10 m/s. This is comparable to the measured values, showing that the thermal behavior above the threshold is controlled by the exchange with the vapor, and confirming our interpretation of the threshold. The heating power at threshold is thus the critical heat flux (CHF) of the spray cooling literature [3]. The linear interpretation of the threshold. The heating power at threshold is thus the critical heat flux (CHF) of the spray cooling literature [3]. The linear dependence of the heat transfer above the threshold (see the curve at 10 m/s) implies that the cooling power due to the mist vaporization does not decrease as the probe temperature increases. At least in the explored range, the interaction of droplets with the wall is unaffected by the wall temperature, i.e. we operate in a regime of cold walls, with no Leidenfrost (cadelation) phenomenon where the droplets would bounce on the hot surface [26–28].

The same behavior is observed at any temperature in the superfluid phase. The decrease of initial slope with increasing temperature is in agreement with the measurements performed with the immersed probes. It reflects the decrease of the Kapitza resistance. The situation is different in the normal phase, as we now discuss.

4. Analysis

4.1. Comparison of spray cooling in the normal and superfluid phases

In order to search for a possible effect of superfluidity on spray cooling, one has to compare similar conditions of atomization in the normal and superfluid phases. To this aim, we have selected in our data set the two temperatures in the normal phase, 2.24 K and 2.33 K, for which, as shown by Fig. 12, we have a close superfluid equivalent in terms of the profile of the interfacial density along a vertical diameter, the droplets size distribution and the vapor velocity distribution on the pipe axis. The liquid flux impinging on the suspended thermal probes should then be comparable for each of these couples of points.12

Fig. 13 compares the behavior of the thermal probes for these two pairs of conditions. It shows that the behavior in the normal phase differs from that in the superfluid phase in three respects. First, the temperature signal is noisier. By averaging over a number of sweeps, we can still define a threshold below which the temperature rise varies linearly with the applied heat flux as well as a slope for the initial linear behavior. However, in contrast to the superfluid case, below the CHF, some measured data points lie above the linear behavior. Secondly, while the Kapitza resistance between the metal plate and the film should decrease with increasing temperature (which is indeed the case in the superfluid phase, as shown by comparing 1.85 K and 2 K in Fig. 13), the initial slope is larger in the normal phase than in the superfluid one. The third, and most spectacular difference, is that the critical flux is significantly smaller in the normal state, and can even vanish for a small enough level of atomization (Fig. 13b). Due to this different behavior, when plotted against the interfacial density, the critical flux seems to extrapolate to a finite value at zero interfacial density in the superfluid phase, while this is not the case in the normal phase (Fig. 14a).

At a first glance, the first and second points could be interpreted as the signature of an incomplete spreading of normal fluid droplets on the probe surface. However, we do not believe that this is the case. The behavior below the CHF may result from the large fluctuations of the incoming flux of droplets in the normal phase.13 This would also explain why some measured data points follow the linear behavior above the CHF (see in particular Fig. 13d). As for the second point, the extra thermal resistance in the normal phase ranges from 2 to 4 K/W, depending on the probe and on the temperature of the normal fluid. It can be accounted for by the poor thermal conductivity of the normal liquid, assuming a film thickness of 2–4 μm. This is a factor of two smaller than the value measured by the capacitive probes 1 and 5 for the same conditions (4–8 μm), a possible explanation for this factor of two discrepancy being a non-uniform film thickness (the thermal resistance and the capacitance do not average the film thickness in the same way). At any rate, this result suggests that, below the threshold, the surface is fully covered by the normal liquid, as in the superfluid phase.

This leaves us with the third difference, i.e. the apparent finite value at zero interfacial density in the superfluid phase. We now argue that this behavior can be explained by thermally driven superfluid mass transport from the probe cold epoxy surfaces to the heated aluminum surface, without invoking a specific behavior of superfluid droplets. For small heat fluxes, the liquid flux impinging both sides of the probe is available for cooling, and we expect the critical flux to be proportional to the total lateral area $S_t$ (about twice the lateral surface or 6 times the aluminum plate area, $S_a$, see Fig. 3c). However, the lateral superfluid flow towards the active area must be limited by the critical velocity of the superfluid film. For large applied heat fluxes, we thus expect the measured critical heating power $W_c$ to be proportional to $S_a$, plus a constant contribution $W_{film}$ proportional to the critical superfluid velocity, namely:

$$W_c = \rho_L \phi S_t \left( W_c < \frac{S_t}{S_t - S_a} W_{film} \right)$$

$$W_c = \rho_L \phi S_a + W_{film} \left( W_c >= \frac{S_t}{S_t - S_a} W_{film} \right)$$

where $\phi$ is the useful liquid volume flux for spray cooling. Accordingly, $W_{film}$ is estimated in Fig. 14a by linearly extrapolating a linear behavior to zero interfacial density. This gives 5 and 2.5 mW for the bottom and top probes, respectively. These numbers can be compared to the cooling power of a saturated film, which we have directly estimated during the calibration experiment described in Section 2.5, by partly immersing (≈10–30%) the two thermal probes into a helium bath at 1.8 K, and measuring their thermal characteristics. In this case, for applied powers larger than 10 mW, the probe temperature increases linearly with the applied heating power, but extrapolates to a finite value, of order 4–5 mW, at zero temperature difference. In our interpretation, this extra-power is carried away by the continuous vaporization of the superfluid film covering the probe above the liquid free surface. The border of the aluminum plate being ≈30 mm in length, 5 mW correspond to a critical heat flux transported by the film of order 1.5 mW/cm, i.e. roughly 5×10⁻⁴ cm²/s. Although this number is five times larger than reported for the thermally [32] or gravitationally [33,34] driven film flows on glass, the order of magnitude is similar, making our interpretation likely. The fact that $W_{film}$ for both probes is similar to the offset found in the calibration experiment supports our hypothesis

12 According to Refs. [29–31], the deposited flux may also depend on inertia effects and interaction between droplets. However, because the droplets diameters and densities are similar in both cases, the effect of these factors should be similar as well.

13 The CCD images show that the interfacial density fluctuates much more in the normal phase than in the superfluid phase, at least partly reflecting the difficulty to regulate the liquid level in this phase.
that it is due to superfluid transport of the film. Under this assumption, we can compute a corrected critical heating power \( W_{\text{cor}} \), corresponding to the cooling power due to droplets directly impinging on the probe active area, by inverting Eqs. (1) and (2). Fig. 14b shows that the critical heat flux \( W_{\text{cor}}/S_a \) is approximately linear in the interfacial density \( \Sigma \).

Once corrected, the superfluid data fall close to the data in the normal phase. We conclude that the superfluidity of droplets does not significantly improve their ability to cool the heated probes.

4.2. Discussion of the critical heat flux

We are now in position to discuss the values found for the critical heat flux, i.e. the cooling power due to the spray cooling phenomenon. Theoretically, the critical power \( W_{\text{cor}} \) can be expressed as

\[
W_{\text{cor}} = \rho L \cdot \Phi \cdot S_a
\]  

(3)

\( \Phi \), the useful flux for spray cooling, is related to the incident flux \( \Phi_{\text{inc}} \) by \( \Phi = f \Phi_{\text{inc}} \), where \( f \) is an efficiency factor which measures the fraction of \( \Phi_{\text{inc}} \) which is effectively evaporated. \( f \) can be smaller than 1 if some droplets rebound on the surface, or splash emitting secondary droplets which are lost for cooling. Eq. (3) allows to measure the efficiency factor \( f \) from \( W_{\text{cor}} \) if the incident flux \( \Phi_{\text{inc}} \) is known. In our case, because PDPA measurements do not give access to the impact velocity \( v_{\text{imp}} \) of droplets on the probe surface, \( W_{\text{cor}} \) only yields the product \( f \cdot v_{\text{imp}} \), as we now discuss. PDPA measurements show that the (axial) velocity distribution of droplets does not depend on their diameter. We will assume that this holds also for their impact velocity, \( v_{\text{imp}} \). Therefore, \( v_{\text{imp}} \cdot \Phi_{\text{inc}} \) is then the product of \( v_{\text{imp}} \) by the liquid volume fraction transported by the droplets. In principle, this fraction can be computed from the PDPA size distribution. However, we have systematically measured this distribution only on the pipe axis, rather than at the thermal probes height. In order to minimize the resulting uncertainty, we use the fact that the distribution...
of droplets diameters is nearly exponential to express the liquid volume fraction as \( R/C_1 d_0/2 \). We then determine \( U_{\text{inc}} \) as

\[
U_{\text{inc}} = \frac{R/C_1 d_0/v_{\text{imp}}}{2(4)}
\]

where we take \( R \) from the laser sheet measurements at the thermal probes heights, and \( d_0 \) from the on-axis PDPA measurements. Direct measurements of \( d_0 \) at the thermal probes heights for several flow conditions show that this causes a maximal error of \( \pm20\% \) on \( U_{\text{inc}} \).

Combining Eqs. (3) and (4), we then determine the product \( f/C_1 v_{\text{imp}} \) for each value of \( W_{\text{cor}} \).

An upper bound for the spray cooling effect corresponds to \( f = 1 \), and \( v_{\text{imp}} \approx V_t \), the r.m.s. vapor transverse velocity [30,35]. Assuming an isotropic turbulence, the fluctuations of the velocity field should be comparable for all components, so that \( V_t \) should be of order \( \Delta V \), the variance of the axial velocity distribution obtained from the PDPA measurements. Fig. 15 compares \( f v_{\text{imp}} \) to this upper bound \( \Delta V \) when atomization is increased in two ways: increasing velocity at constant liquid level (which also increases \( \Delta V \)), and increasing

![Fig. 13. Influence of superfluidity on the thermal probes behavior. Thermal characteristics of the bottom (a, c) and top (b, d) thermal probes in the superfluid (SF) and normal (N) phases for similar spray conditions (see Fig. 12). (a, b): Temperatures 2 K and 2.33 K, average vapor velocities of 8 (SF) and 7 m/s (N); (c, d) Temperatures 1.85 K and 2.24 K, average vapor velocities of 10.3 (SF) and 9.5 m/s (N). The straight lines in (a) and (b) correspond to the linear extrapolation of the low heating power regime.](image)

![Fig. 14. Critical heat flux for drying the top and bottom suspended probes, as a function of the interfacial area of the mist facing the probes, measured using the laser sheet. ■: Bottom thermal probe; ●: Top bottom probe: Open and closed symbols refer to normal fluid and superfluid, respectively. (a) Linear plot of the critical heating power for small interfacial densities. The straight lines show the behavior expected from Eqs. (1) and (2), assuming the incident flux \( \Phi \) to be proportional to \( \Sigma \) and \( \frac{1}{\delta} \approx 6 \); (b) Double logarithmic plot of the critical heat flux \( W_{\text{cor}}/S_a \), resulting from the contribution of droplets impinging on the active part of the probe only.](image)

![Fig. 15. Product of the droplets impact velocity, times the spray cooling efficiency \( f \), as deduced from CHF measurements, versus the variance of the axial velocity measured by the PDPA. Closed and open symbols correspond to the top and bottom thermal probes, respectively.](image)
level at constant vapor velocity. For both thermal probes, we find that \( f_{\text{top}} \) ranges from 0.05 to 0.2 m/s. This is about one order of magnitude smaller than \( V \). For given flow conditions, \( f_{\text{top}} \) deduced from the bottom probe is comparable to or larger than the value deduced from the top probe. Finally, \( f_{\text{top}} \) tends to decrease as \( V \) increases. This is opposite to the naive expectation for \( f = 1 \), \( f_{\text{top}} \approx V \).

The \( V \) dependence for the points at constant level can be traced back to the velocity dependence of \( d_0 \). When the vapor velocity increases, the measured \( d_0 \) typically increases from 20 to 30 \( \mu \)m. Because, experimentally, the critical flux is approximately linear in the interfacial density \( \Sigma \) (Fig. 14b), Eq. (4) implies that this increase of \( d_0 \) translates to a decrease of the deduced \( f_{\text{top}} \) with increasing vapor velocity, hence increasing \( V \). The increase of \( d_0 \) with the vapor velocity is somewhat surprising as one would expect smaller droplets for larger velocities. A possible interpretation would be an artifact due to the fact that, at large velocities, the density of droplets increases, and the probability that two droplets cross at the same time the PDPA detection volume becomes significant. This can bias the diameter measurement and explain the unexpected velocity dependence of Fig. 15. Alternatively, the \( d_0 \) dependence could be genuine, and result from the increase of the stratification height, for a given droplet diameter, with the vapor velocity. In this case, the decrease of \( f_{\text{top}} \) with the vapor velocity would suggest an increase of the bouncing or splashing probability with the impact velocity. Such an effect has been reported for droplets of usual liquids [26]. If we apply to the case of helium the empirical correlation between the Ohnesorge and Reynolds numbers describing the deposition-splashing boundary in Ref. [26], we find a minimal velocity for splashing between 1.5 m/s and 2 m/s for droplets between 20 and 40 \( \mu \)m in diameter. This is only slightly larger than \( \Delta V \), which makes this interpretation plausible.

In contrast to its dependence on \( \Delta V \), the small absolute value of \( f_{\text{top}} \) cannot be explained by an error on \( d_0 \). The comparison between \( \Sigma \) measured from the laser sheet and estimated from the PDPA measurements shows that \( d_0 \) is at most wrong by a factor of two, which cannot explain the one order of magnitude difference between \( f_{\text{top}} \) and \( \Delta V \). This implies that either, or both, the deposition efficiency or the ratio of the impact velocity to the vapor transverse velocity are significantly smaller than 1. A large inertia of droplets would explain a smaller impact velocity compared to the transverse velocity [30,36]. Following Ref. [36], the influence of inertia is described by the Stokes number \( S \), the ratio of the particle relaxation time \( \tau_p \) due to drag, to the integral time scale \( \tau_p \) describing the turbulence. \( S \) increases with the droplets size. Using values of physical parameters appropriate for helium, and the (slightly different) formulae of Refs. [30,36], we find that the reduction of the impact velocity does not exceed a factor 2 for a droplet diameter of 50 \( \mu \)m (significantly larger than the measured \( d_0 \)). This is too small to account for the large reduction of \( f_{\text{top}} \) with respect to \( \Delta V \).

This suggests that the deposition efficiency could be significantly less than unity, consistent with a splashing behavior. However, confirming this conclusion, and directly measuring the influence of velocity on the deposition efficiency would require a dedicated spray cooling experiment with a controlled incident mass flux. Until such an experiment is done, designing devices using helium spray cooling for specific applications will require prior direct measurements of the associated cooling power in the situation of interest.

### 4.3. Thickness of the deposited film

In Section 3.3, we saw that the thickness of the deposited film increases rapidly at low \( \Sigma \), and more slowly at large \( \Sigma \). In this section, we combine the measurements of the suspended probes to show that this behavior is consistent with a simple model relating the thickness to the deposited flux.

Assuming the deposition efficiency to be the same on heated and unheated walls, the deposited flux on the suspended capacitive probe can be evaluated from the critical heat flux \( W_\text{cor} \) measured by the top thermal probe, which, being located at the same height in the pipe, experiences the same spray conditions. Fig. 16 then shows the relationship between the film thickness and the deposited flux. We have also included our data for the bottom thermal probe. In this case, we use the thickness measured by the wall capacitive probe located at the same height. Considering the transverse structure of the mist, this might lead to a factor of two error in the deposited flux. Within this factor, the data sets for the two thermal probes are consistent with a 1/3 power law behavior over more than one decade in deposited flux.

Such a behavior is expected for a viscous film draining by gravity, where the thickness is determined by the balance between the deposited flux \( \Phi \) and the evacuated flux due to gravitational flow along the wall. The vertical velocity \( v(x,z) \) of the flowing film at distances \( x \) to the probe plane and \( z \) to the top of the probe, obeys the Navier–Stokes equation:

\[
\eta \left( \frac{\partial^2 v}{\partial z^2} + \frac{\partial^2 v}{\partial x^2} \right) = \rho g (\epsilon(z))^2
\]

where \( \eta \) is the viscosity of the liquid, \( \rho \) the liquid density, and \( g \) the gravitational acceleration. Except very close to \( z = 0 \), the \( x \)-derivative dominates and the velocity profile is parabolic in \( x \). Taking into account the boundary conditions for a viscous fluid (\( v = 0 \) on the wall and \( \frac{\partial v}{\partial z} = 0 \) at the film surface), the liquid local average vertical velocity is related to the film thickness \( \epsilon(z) \) through:

\[
\langle v \rangle(z) = \frac{g}{6\eta} (\epsilon(z))^2
\]

where \( \nu \) is the liquid kinematic viscosity. If re-atomization is neglected, the vertical flow at position \( z \) equals the total deposited flux between \( z = 0 \) and \( z \), that is \( 2\Phi \), which implies:

\[
\epsilon(z) = \left( \frac{6\eta}{g} \Phi \right)^{1/3}
\]

Fig. 16 shows that this power law is approximately obeyed for thicknesses larger than 1 \( \mu \)m. The modest difference between the superfluid and normal states suggests that, in the superfluid phase, the normal and superfluid components are essentially locked. The
two upper lines show the predicted values for the thickness averaged over the active height of the capacitive probe (between \( z = 2 \text{ mm} \) and \( z = 8 \text{ mm} \)), using the helium shear viscosity reported by Ref. [37]. The measured thickness is about three to four times less than predicted. A first interpretation would be that the deposition process is less efficient on the unheated surface of the capacitive probes than on heated thermal probes. This could be the case if, on a heated surface, an otherwise bouncing droplet can be evaporated during the bouncing event. However, a simple estimate shows that this cannot be the case for the applied heating powers. At the CHF, the heating power per unit area is \( W_{k}/S_{0} \) and the time necessary to evaporate a droplet of diameter \( d \) lying on the surface scales with \( d \) as \( L \rho_{l}dS_{0}/W_{k} \). This has to be compared to the duration \( t_{\text{imp}} \) of the bouncing event for a droplet impacting the surface at a speed \( v_{\text{imp}} \), which also scales as \( d \). Taking into account that \( W \) is of order several \( \text{mW/cm}^2 \), and \( v_{\text{imp}} \) is at least several \( \text{cm/s} \), the evaporation time is orders of magnitude longer than the duration of the bouncing event.

The discrepancy could then be explained by an incorrect calculated conversion factor from capacitance to thickness, leading to an underestimate of the film thickness. However, an error by a factor three seems unlikely. Moreover, in the normal phase, a larger film thickness would lead to a much larger thermal resistance between the heated plate and the film than actually measured (Section 3.4). The only remaining possibility is that, in the normal and superfluid phases, the film drains faster than predicted by Eq. (6). Due to the non-linear dependence of the velocity on thickness, this is possible if the film is not uniform in the horizontal direction. This could occur if, in both phases, the deposited droplets fall faster than they spread. Checking this point is challenging, as it requires direct imaging of the impingement process and/or the film morphology.

4.4. Contribution of the mist to the global heat transfer

The results of Sections 2.5 and 3.4 directly demonstrate the spray cooling phenomenon on a local scale. It remains to check that this phenomenon accounts for the non-linear improvement of the global heat transfer discussed in Section 3.2. On this aim, we use an approximate model to predict the global heat transfer, starting from the mist cooling power of the mist.

In the superfluid phase, the deposited film is isothermal and at the temperature of the bulk liquid, so that the vaporization rate is uniform along the film and the liquid free surface. The film then extends up to a height \( z_{0} \) such that the local liquid deposition rate just equals this vaporization rate. Because the mist is stratified, \( z_{0} \), hence the wetted surface, decreases with the applied heating power \( W_{k} \), increasing the thermal resistance between the pipe walls and the two-phase flow. The temperature difference \( \delta T(W_{k}) \) between the Kapitza box and the superfluid liquid in the pipe is given by:

\[
\delta T(W_{k}) = R_{k} W_{1} / S(z_{0})
\]  

where \( W_{1} \) is the heat flux through the liquid (bulk or film), \( R_{k} \) is the specific Kapitza resistance (i.e. the resistance for an unit area) between the box and the pipe, and \( S(z_{0}) \) the wetted surface up to the height \( z_{0} \). The heat flux per wetted unit area is uniform and equals \( W_{1}/S(z_{0}) \), and the vaporization rate equals this flux divided by the latent heat. \( z_{0} \) is set by the requirement that:

\[
W_{1} / S(z_{0}) = \rho_{l} L \Phi(z_{0})
\]

with \( \Phi(z_{0}) \) the deposited flux per unit wall surface. Finally, \( W_{k} \) is the sum of \( W_{1} \) and the power needed to evaporate the droplets above \( z_{0} \).

\[
W_{k} = W_{1} + \rho_{l} L \int_{z_{0}}^{D} \Phi(z) \, dz
\]

where \( dz \) is the length between \( z \) and \( z + dz \) along the wall cross-section. By scanning \( z_{0} \) from the top of the tube \( z_{0} = D \) down to the bulk liquid level, we compute \( W_{k} \) from Eqs. (9) and (10), and \( \delta T(W_{k}) \) from Eq. (8), provided \( \Phi(z) \) is known. As a simple evaluation, we take an exponential dependence for \( \Phi(z) \), with the characteristic height measured for the interfacial density \( \Sigma \). This assumes that the deposition velocity and droplets size depend less on \( z \) than \( \Sigma \), and that the deposition velocity does not depend on the orientation of the wall surface. It also neglects the transverse structure of the mist. The prefactor of \( \Phi(z) \) is set by the measured CHF of the bottom thermal probe, once corrected for the superflow effect.

Fig. 17 compares the result of this procedure to the experimental results already presented in Fig. 8. For these experiments, we have checked that the predicted \( \Phi(z) \) at the height of the top thermal probe is in agreement with that directly measured using this probe, showing that the assumption of an exponential dependence is reasonable. For the calculation, we take a liquid level of 7 mm (wetted fraction of 27%) so as to reproduce the measured exchange at small velocity (weak atomization). This height is larger than the 3.8 mm measured using the bottom capacitive level gauge. This difference could be due to the presence of a thin film deposited by surface waves above the average bulk level.

Comparison of Fig. 17a and b shows that, for large axial velocities, the model qualitatively captures the role of the droplets mist in the thermal exchange, accounting for the measured small thermal resistance at small heat fluxes and the non-linearity at larger fluxes. However, the evolution with the vapor velocity is quantitatively different. At 10 m/s, the experimental global exchange is larger than predicted based on the model. If, as above, we speculate that surface waves deposit a thin film on the walls, the measured behavior shows that this process becomes more efficient as the vapor velocity increases, which is reasonable. On the other hand, the small change of the experimental global exchange between 14 and 17 m/s contrasts with the predicted improvement resulting from the increase of the cooling power measured by the thermal probes in the same velocity range (by 30% and 100% for the bottom and top probes, respectively). Moreover, the improvement at 17 m/s is less than predicted by the model, based on the behavior of the suspended thermal probes. This discrepancy could be explained by re-atomization of the film at large vapor velocity or a reduction of the deposition rate due to interactions between droplets at large densities [38], provided that, for some unknown reason, these processes would affect the pipe walls earlier than the probes located in the pipe central region. In conclusion, our analysis suggests that the measured non-linearity of the global heat transport could involve other processes than the vaporization of the film deposited by the spray, and, at any rate, cannot be precisely predicted from local CHF measurements in the central region of the pipe only.

5. Possible application of spray cooling to an LHC upgrade

Let us finally discuss the possible relevance of our results to a LHC upgrade. Thermal exchange with the pipe is a major issue for the final focus magnets (inner triplets) which focus the beams in the interaction region. In the present version of LHC [39], the linear heat load on these magnets due to beam-induced heating is up to 10 W/m, an order of magnitude larger than for the arcs magnets, over a distance of 30 m, corresponding to an integrated heat load of

\[ \cdots \]

\[ \cdots \]
about 200 W. This head load is transported to a heat exchanger made from a corrugated copper tube inside a stainless steel pipe, where it is evacuated by vaporization of He-II flowing inside the copper tube. While 200 W is comparable to the heat load used in our experiments, the resulting vapor velocity is much smaller due to a larger pipe diameter (≈ 90 mm) so that atomization probably does not take place here. In contrast, for an upgraded version of LHC with a larger luminosity, the linear losses are expected to be in the range 20–100 W/m, depending on the upgrade level [40]. As a consequence, for the present pipe diameter, atomization could set in. While this could be avoided by using a larger tube diameter, it is interesting to consider what would be the consequences of atomization, if the present design were kept. Two questions arise. First, can the increase of the wetted surface due to atomization stand the expected linear losses? Second, how does the droplets mist increase the longitudinal pressure drop, hence the upstream temperature of the saturated liquid? Our study gives some hints. Concerning the heat exchange, an extrapolation of Fig. 8 suggests that, at 1.8 K the temperature increase due to a linear heat load of 30 W/m (\(W_K = 12 \text{ W}\)) is less than 0.25 K in the strongly atomized flow, and the pipe walls. Our results show that the critical heat flux (CHF) for a heated surface, as well as the thickness of the film deposited on an unheated vertical surface, increase with the spray interfacial density. The CHF values show that, either the impact velocity of droplets on walls is smaller than the transverse vapor velocity, or these droplets have a large probability to bounce on surface walls. For given mist conditions in terms of droplets size and velocity, the CHF, once corrected for the effect of lateral superflow, is similar in the normal and the superfluid phases. Thus, superfluid droplets are not more efficient than normal droplets for the purpose of spray cooling. The thickness of the deposited film is also similar in both phases, and can be accounted for by a simple lubrication model for a single component viscous fluid. These results suggest that the spreading or bounce dynamics of droplets may not significantly differ from those of normal droplets. This intriguing conclusion would deserve to be checked using a dedicated experiment. The interest of the present experiment, however, is that it is representative of the large-scale cooling system of LHC. From this point of view, our study shows that spray cooling does improve the thermal exchange with walls due to the formation of a liquid layer, but that this improvement is not robust, due to the mist stratification. Furthermore, because of the complex nature of the two-phase flow, this improvement cannot be precisely predicted from local measurements of the critical heat flux only. Real size measurements of global thermal exchange seem mandatory to evaluate whether spray cooling can be used to evacuate the large linear heat loads expected in the context of an upgrade of the LHC, as well as to check that, in this case, the longitudinal pressure drop induced by the mist production remains bearable.

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