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HEAT TRANSFER NEAR CRITICAL CONDITION IN TWO-PHASE HE I THERMOSIPHON FLOW AT LOW VAPOR QUALITY

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ABSTRACT

Heat transfer near critical conditions in two-phase thermosiphon flow configuration with boiling helium has been investigated. The experiment was made at the steady-state conditions in a 14 mm diameter vertical copper tube, uniformly heated over a length of 1.2 m. Transition from the nucleate boiling to the film boiling regime and critical heat flux are measured at five locations along the heated tube. Critical heat flux are predicted within 30% by the Katto's and Sha's correlation for two-phase forced flow and within 20% by the Lehongre's correlation specific to natural boiling helium excepted for low value of *L/D*.

INTRODUCTION

The study of critical heat and mass transfer in a two-phase He I thermosiphon has been motivated by the construction of the 4 tesla superconducting solenoid magnet for the Compact Muon Solenoid; one of the interaction detectors for the Large Hadron Collider. This magnet is cooled down with a normal helium two-phase natural circulation loop around atmospheric pressure. This experimental study aims to determine the critical heat flux (CHF) as a function of the heated length of the tube and also presents boiling curves where a hysteresis effect on the temperature excursion is detailed. Most existing studies on vertical two-phase flow boiling helium are in forced flow configurations [1-8]. Among them, some authors presented critical heat flux (CHF) data [3-8] and analyzed with more or less sophisticated correlations based on a physical model. To the best of our knowledge, only a few experimental works are available in the literature concerning natural boiling flows in helium [9-14]. Lehongre *et al*. [9] and Johannes and Mollard [10] are the only ones to present CHF results as a function of the distance from the inlet of the flow, *L*, and the diameter of the tube, *D*. Lehongre *et al*. investigated CHF on tubes of 1 to 5 mm diameter and 25 to 400 mm in length while Johannes and Mollard presented results for square cross-section tubes having hydraulic diameters around 8 mm with the aspect ratio comprised between 110 and 10 and the tube length of 100 and 200 mm. Both authors found that the CHF is proportional to $(L/D)^{-0.88}$ proposed originally by Lehongre *et al*.

EXPERIMENTAL APPARATUS AND CHF DETERMINATION PROCEDURE

As it is shown in FIGURE 1, the experimental apparatus is composed mainly of a liquid-vapor phase separator, a test section and its associated downward tube. A complete description of the apparatus is found elsewhere [13]. The test section consists of a 1.2 m long copper tube of 14 mm inner diameter, wrapped with super-insulation. The instrumentation consists of heaters, Ge thermometers and pressure sensors. The Five Ge thermometers are inserted in small copper blocks brazed to the tube and placed along its length at different locations from the entry of the flow (0.07m, 0.3 m, 0.6m, 0.9 m and 1.2 m). These sensors have been calibrated within 5 mK. All wiring is wound and glued with GE varnish to a copper thermal anchor held at 4.2 K. In the range of ΔT investigation, several Kelvin, heat loss through the temperature sensors wiring is negligible, therefore we consider that the temperature measured represents that of the inner wall. There are two mass flow-meters used in this experiment, a "gas flow-meter" at room temperature and "a Venturi flow-meter" measuring the liquid mass flow rate (i.e. total mass flow rate) inside the downward tube. The gas flow-meter is capable of measuring up to 4.2 g/s of He gas at room temperature with a precision of $\pm$ 0.01 g/s. The precision on our total mass flow rate measurement varies from 10% at low mass flow rates down to 2% at high mass flow rates. Pressure differences are obtained with a room temperature sensor. Pressure taps are connected to the sensor with 2 mm diameter stainless steel tubes. Each tube is U-shaped and heated (0.1 W) to evaporate any residual liquid in order to reduce errors in pressure determination. The vapor quality, x, is obtained by dividing the vapor mass flow by the total mass flow. The range of our study are a total mass flow rate 0-22 g/s, vapor quality at the exit 0-25%, a heat flux 0-2.2 kW/m^2 and the length to diameter of the tube ratio $5 \leqslant L/D \leqslant 85$. The critical heat flux, CHF, is determined for each sensor by the following procedure: the heat load on the test tube is increased by steps of 50 W/m^2 that constitutes less than 5% of the preceding heat load around the critical heat flux values. With this procedure, we considered that CHF is determined with an uncertainty less than or equal to 50 W/m^2, less than 5 % for the CHF value found in this study.

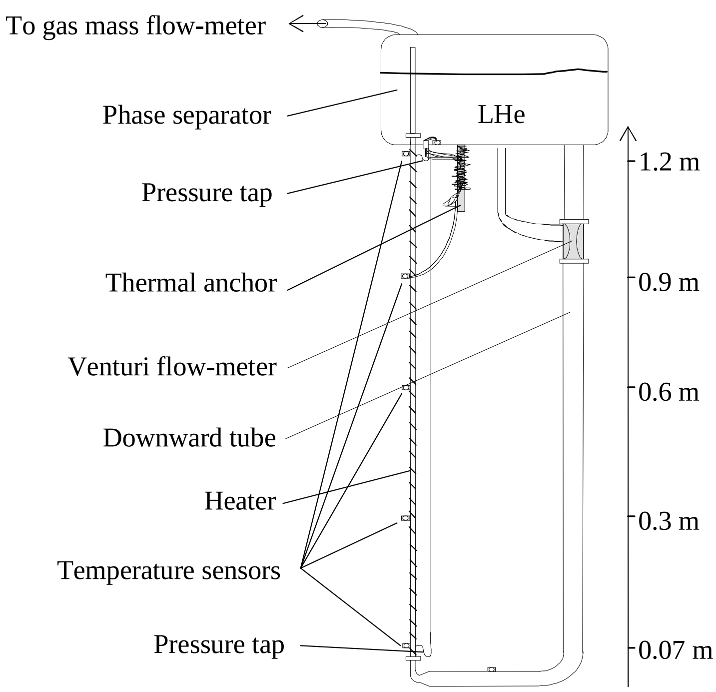

FIGURE 1. Schematic of the test section.

EXPERIMENTAL RESULTS

Boiling Curves

FIGURE 2 and 3 present the evolution of the temperature difference between the wall and the fluid, ΔT, for different sensors, as a function of increasing and decreasing heat flux density q_{up} *and* q_{down}, respectively. Fluid temperature is measured without applied heat on the test tube before each experimental run. FIGURE 3-(a), (b), (c) and (d) correspond respectively to different *L/D* ratios, *L* being the distance from the entry of the flow and *D* the diameter of the tube, that are 21.4, 42.8, 64.3 and 85.7. For clarity, we present here only two experimental runs in these figures. The features of these boiling curves are found to be similar for a dozen tests. These two runs are representative of the experimental reproducibility. The evolution of ΔT for the sensor located at 7 cm from the entrance, corresponding to an *L/D* ratio of 5, is presented in FIGURE 2 where the different regimes below partial dry-out can be distinguished. One can see that the evolution of ΔT is linear below q=700 W/m^2, representative of single-phase convection flow (spc) [15]. Sub-cooled boiling might occur in this regime but our experimental apparatus is not capable of detecting it. After the convection regime, the rise in the slope indicates the onset of partial nucleate boiling (pnb). For higher heat flux, *dq/dT* becomes more or less constant corresponding to the fully developed nucleate boiling (fdnb) [15]. FIGURE 2 also exhibits the hysteresis effect below critical heat flux is reached. When the heat flux is reduced after attaining a value of heat flux, the heat transfer regime presents a higher heat transfer coefficient. This typical trend is due to the fact that the nucleation sites remain active for lower heat flux. It has been observed and studied below CHF by Solodovnikok et al. for two-phase helium in forced flow conditions [16]. They showed that the hysteresis does not take place in the (spc) regime but in both boiling regimes, the (pnb) and (fdnb) regimes at any intermediate heat flux below the critical heat flux. This effect not only causes thermal hysteresis but also a dynamic hysteresis effect which is depicted in FIGURE 2 (b) where the difference of pressure, Δp, between the bottom and the top of the tube is presented. This effect is clearly seen on the Δp where smaller value is obtained for decreasing heat flux. Because boiling sites are still active and produce vapor, equivalent amount of vapor is produced for smaller heat flux. So for the same heat flux, in the decreasing heat flux curve, more vapor is present, creating a larger resistance to the flow, but a substantially smaller hydrostatic head, resulting in a lower Δp than for the increasing heat flux curve.

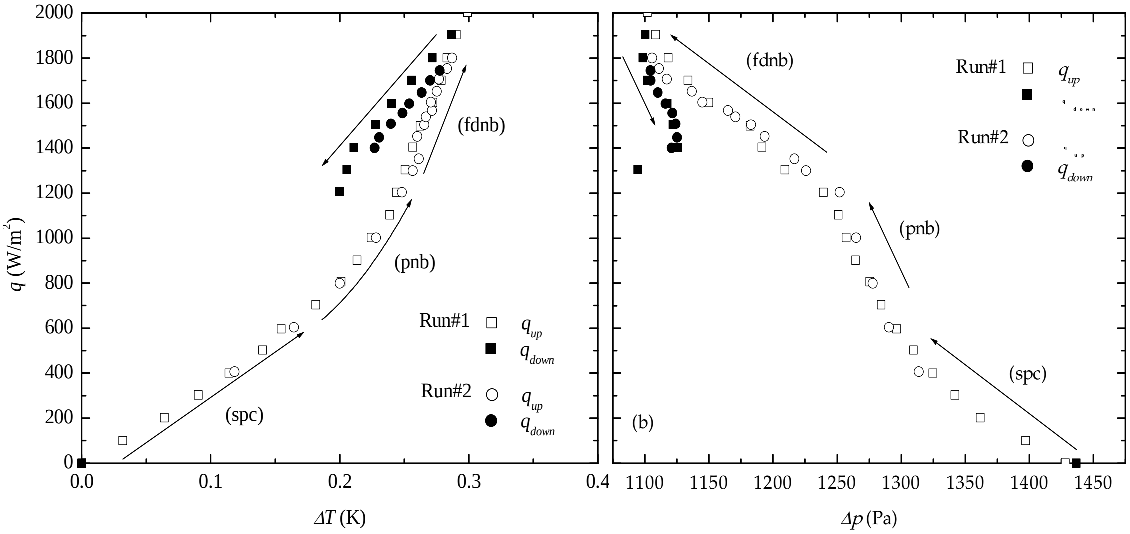

FIGURE 2. (a) Boiling curve for the temperature sensor at a height of *L*=0.07 m, *L/D*=5 - (b) Heat flux as a function of the total pressure variation of the tube, Δp.

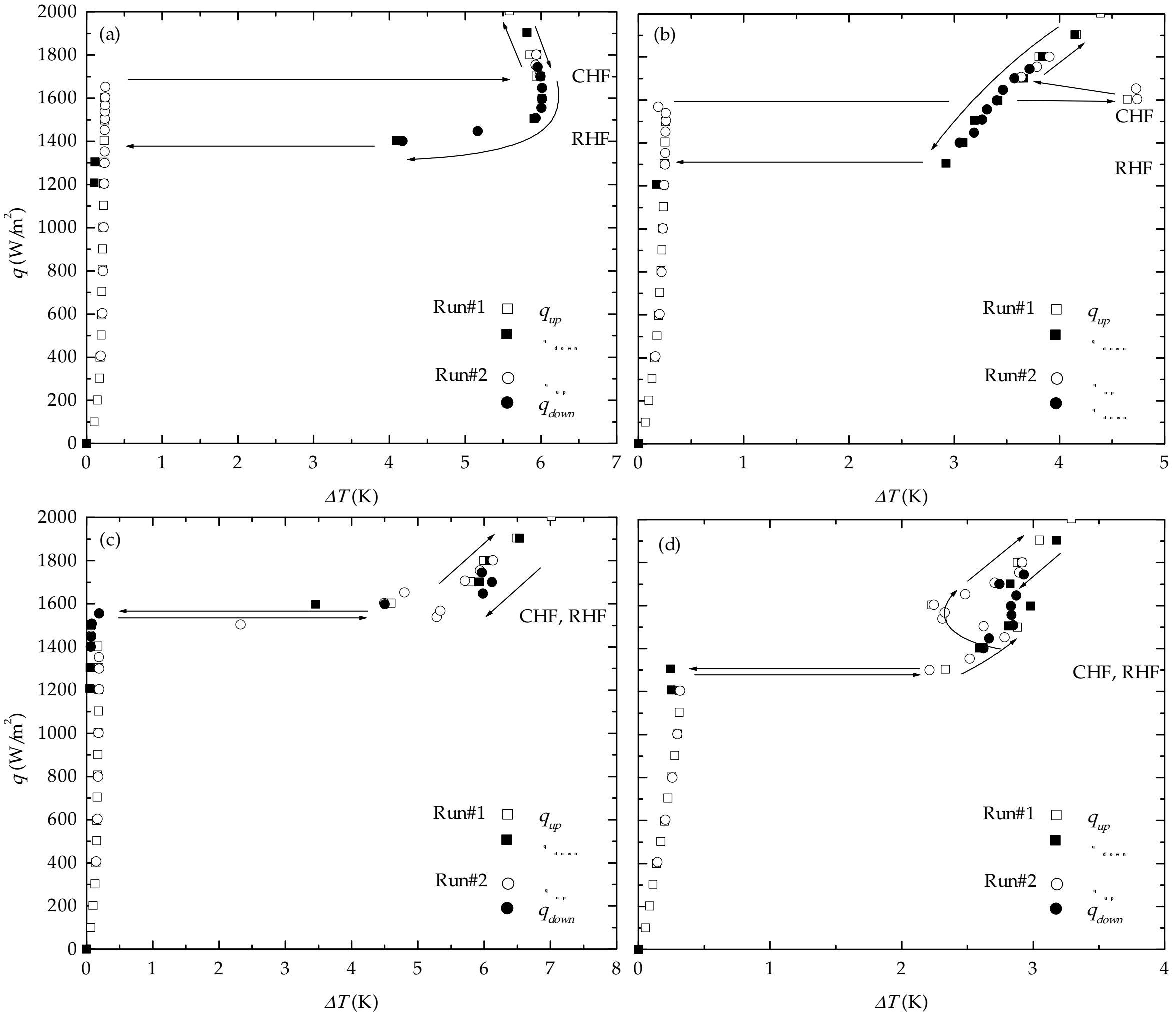

FIGURE 3. Boiling curves for the temperature sensor at different height: (a) L=0.3 m or L/D =21.4, (b) L=0.6 m or L/D =42.8, (c) L=0.9 m or L/D =64.3 and (d) L=1.2 m or L/D=85.7.

Hysteresis is also found for higher L/D ratio as depicted in FIGURE 3 where the typical drastic temperature jump, corresponding to local wall dry-out, occurs. The drastic ΔT increase associated with increasing heat flux is called the peak heat flux or maximal critical heat flux (CHF), q_{cr}. Above this particular heat flux, when the heat flux is decreased, the film boiling regime can persist for lower values of heat flux. The minimum critical heat flux, called also the recovery heat flux (RHF), q_r, is the value below which film boiling is not maintained. This also has been observed in natural boiling circulation by Panek et *al.* [12] and in forced convection by several authors. Here, hysteresis is found for L/D values below 42.8 whereas for higher values such hysteresis disappears. One has to note that hysteresis is not clearly seen by some authors [2], [4]. At low vapor quality, heat transfer is accomplished by nucleate boiling but at higher vapor quality, the flow might become annular and with increasing vapor velocity the liquid film becomes thinner. Nucleation within this liquid film may be partly or totally suppressed and this could explain the suppression of hysteresis at high L/D ratio. Several possible mechanisms can be considered for this partial dry-out. A vapor film formation under the liquid film, a sudden disruption of the liquid film, an eventual dry patch formation or a total film dry out might be the possible mechanism candidates. Although the later one would not explain that the ΔT is reduced at the critical conditions seen in FIGURE 3 (d). This phenomenon can be linked to liquid droplet heat transfer at the surface. This feature is also found for the two lower L/D values where the ΔT is reduced after attaining the critical heat flux.

Above the CHF, the liquid film wetting the heat transfer surface has been partly or totally removed resulting in the drastic increase of the wall temperature. Depending on the flow regime, liquid droplets may or may not wet the heat transfer surface. Under such conditions, the heat transfer coefficient is higher than that at the critical condition and therefore the ΔT is reduced. This phenomenon is clearly seen in FIGURE 3 (a) and (b) whereas for higher tube height, it seems to be reduced or even non existent. The other particularity is that this phenomenon takes place in a very small ΔT range. After this phenomenon, the q-ΔT follows the heat transfer in the film boiling regime. In practice this feature means that the physical burnout heat flux may be higher than the critical heat flux value. Another feature worth noting is the general trend for the drastic ΔT jump which decreases with L/D increasing at the critical condition. This trend is also found in other mixtures as well as in helium in forced flow conditions. With increasing L/D the vapor quality increases which has the consequences of reducing the CHF value while increasing the RHF value. It means, as already mentioned, that the heat transfer coefficient is higher in this regime due to droplet heat transfer [13], [15].

CRITICAL HEAT FLUX

Experimental Results

Results on CHF as a function of the L/D ratio are presented in FIGURE 4 (a) where it can be seen, as expected, that CHF decreases as the L/D increases. The evolution of the CHF with L/D appears linear for $L/D < 60$ whereas for $L/D \approx 85$, the CHF is lower than the linear trend. The linear relationship between the CHF and the L/D ratio is not always found in natural boiling flow in helium or other mixtures. Lehongre's results show a non linear dependency over the entire range of investigation, that is, $5 \leqslant L/D \leqslant 200$.

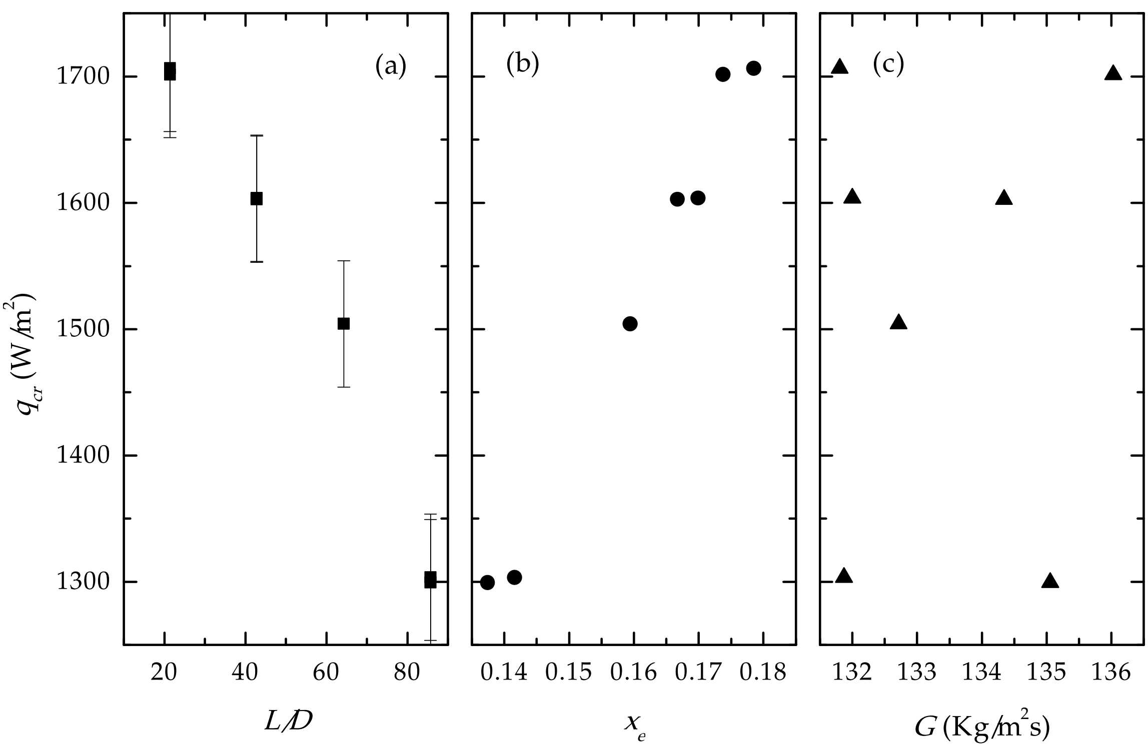

FIGURE 4. Critical heat flux q_{cr} (a), the vapor quality at the exit, x_e (b) and the total mass flux G (c) as a function of the L/D ratio

Even though in a natural circulation loop all flow parameters are inter linked through the balance equations, it is interesting to present the critical heat flux dependency on other key parameters of the flow such the exit vapor quality, x_e and the total mass flux, G, as presented in FIGURE 4 (b) and (c). It is to be expected that CHF varies linearly with x_e from the energy balance equation and thus with the local vapor quality [15]. The CHF dependency on the total mass flux is not obvious as it is shown on FIGURE 4 (c) since critical phenomenon appears in the regime where the total mass flux does not vary significantly with the heat flux because the frictional pressure drop is the dominant pressure gradient in this regime due to vapor creation [13, 14].

Critical heat flux correlations

The only correlation specific to natural boiling helium used in this assessment had been proposed by Lehongre *et al*. where the critical heat flux is a non linear function of the *L/D* ratio [9],

$$q_{cr}=1/(1.7+0.125\,(L/D)^{0.88}). \tag{1}$$

Most CHF correlations are based on the Kutaladze number, $Ku = q_{cr} \Big/ \sqrt{\rho_v} H_{lv} \sqrt[4]{\sigma g(\rho_l - \rho_v)}$ where ρ_v and ρ_l are the vapor and liquid density, σ the surface tension, g the gravitational acceleration and H_{lv} the latent heat of vaporization [15]. The only general CHF correlation for natural circulation boiling is the one proposed by Monde which is based on a parametric study on the ratio *L/D* established for vertical uniformly heated tube submerged in saturated liquid for several different mixtures such as water, R113 and R12. Two correlations were proposed depending on a dimensionless diameter $D^*=D/\sqrt{\sigma / g(\rho_l - \rho_v)}$ [17]. The CHF calculation is presented with as Kutaladze number,

$$Ku = 0.16/\left[1 + A(L/L_0)\right], \tag{2}$$

where L is the length of the channel where the CHF is detected and L_0 a characteristic length. $L_0=D$ and A=0.025 in the case of D*<13 and otherwise $L_0=\sqrt{\sigma / g(\rho_l - \rho_v)}$ and A=0.003. It has been verified that this correlation is accurate within 20% for $D^*<13$ when the exit of the tube is above the liquid level. Similarly our flow configuration, the two-phase mixture always leaves the heated tube above the liquid level in the phase separator, although we find D*≈48 for our configuration where Monde's correlation has not been verified.

For forced flow conditions in liquid helium, Giarratano *et al.* presented a CHF correlation based on a dimensional analysis of the equations of motion for boiling two-phase flow, where a simplified version depends only on the vapor quality, x [3],

$$Ku = 0.031 + 0.078(1-x)^{3.92}. \tag{3}$$

Keilin *et al.* also found a correlation for forced flow helium based on the Froude number for liquid flow, $Fr=v_l((\rho_l-\rho_v)/\sigma g)^{0.25}$ [5],

$$Ku = 0.0031 Fr^{0.53}. \tag{4}$$

We also compare our data to more general correlations applicable to a large range of fluids. The first is the Katto's correlation that has been tested to helium in forced flow conditions [8]. In his correlation the critical heat flux is defined for an inlet sub-cooled enthalpy, ΔH_i, and the latent heat of vaporization H_{lv} as

$$q_{cr} = q_{cr0}\left(1 + K\ \Delta Hi / H_{lv}\right), \tag{5}$$

where q_{cro} and K values are given in [8] and [15], and depends on the flow regime and physical parameters. For the comparison with data, we use q_{cro} and K values recommended for helium, which is supposed to correspond to the classical departure nucleate boiling burnout. The second set of correlations is that of Shah which has been elaborated with various mixture including two-phase helium and is summarized in [18]. The CHF correlation recommended for helium is presented as a function of the inlet vapor quality x_i and the ratio L/D as

$$\frac{q_{cr}}{GL_v} = 0.124\left(\frac{L}{D}\right)^{-0.89}\left(\frac{10000}{Y}\right)^{n}(1-x_i), \tag{6}$$

where $Y = \left[\frac{GDCpl}{kl}\right]\left[\frac{G^2}{\rho_l^{\,2} gD}\right]^{0.4}\left[\frac{\mu_l}{\mu_v}\right]^{0.6}$ and $n=(L/D)^{-0.33}$ for helium with $Y > 10^4$.

These correlations have been compared to our data but the correlations given by Giarratano et *al.* and Keilin et *al.* are not presented in this paper. They give CHF value much higher than our data, two to three times higher for the Giarratano's correlation and from four to six times higher for the Keilin's. Obviously these correlations do not have a universal character, which may be due to the fact that their experiment was performed on a 2 mm ID tube. Under the same conditions, smaller tubes present smaller CHF value [15] and these correlations lead to much higher value when applied to our set up. FIGURE 5

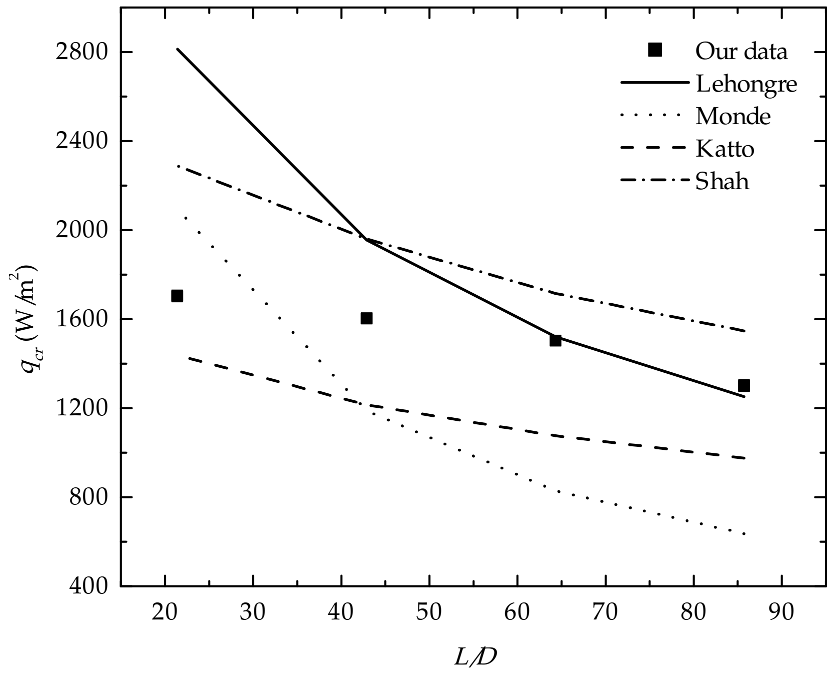

FIGURE 5. Comparison between experimental data and the different correlations as a function of L/D.

presents the comparison of our data to the CHF given by the different correlations. The correlation of Lehongre agrees within 20 % with our data except for the highest value of CHF at *L/D* = 20. Monde's correlation always under estimates our results except for the highest value of CHF at *L/D* = 20. The likely reason for such estimation is that this correlation has been established for a flow configuration where the tube is submerged which creates a counter flow of liquid and therefore reduces the CHF. The most accurate result to our data is found in average by the correlations of Katto and Sha that predict our data within 30%. The evolution with *L/D* is also similar. This is expected since our data have been taken within all physical and flow parameters included in these correlations.

CONCLUSIONS

Critical heat flux in helium two-phase boiling convection around atmospheric pressure has been studied in the low vapor quality range. Boiling curves exhibit classical features such as hysteresis below and at the critical conditions. Above the critical condition and for a very short temperature difference range, the heat transfer is enhanced due to rewetting of surface by liquid droplets. CHF results are fitted within 30 % by general correlation and by helium correlation except for low value of *L/D*.

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