Heat transfer during natural convective boiling in a vertical uniformly heated closed tube submerged in saturated helium

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An experimental study was carried out on heat transfer in natural boiling convection in a vertical tube closed at the bottom and connected to a liquid helium bath at the top. A 14 mm inner diameter copper tube is submerged in liquid helium near atmospheric pressure. The two phases are counter-flowing in which the vapor exits the system upward through the liquid bath while the liquid moves downward replacing the vapor. The wall temperature at different locations, the pressure drop and the vapor mass flow rate was measured, and critical heat fluxes (CHF) are determined. Evidence of flooding is witnessed in the light of the measurements and CHF values are compared with existing flooding correlations.

INTRODUCTION

Many studies related to the heat transfer in convective boiling counter-flow have been reported for critical heat flux (CHF) in a heated vertical closed tube. The closed two-phase thermosiphon, *i.e.*, the heat pipe, is the most studied boiling system (see [1, 2], for example,) and the closed bottom tube that is opened to a saturated liquid bath has been studied by few groups including, Barnard *et al.* on the refrigerant R-113 [3], Nejat on four different fluids [4] and Katto *et al.* on water [5]. In such boiling configuration, the vapor and the liquid flow in opposite directions, that is, the liquid flows downward to replace vapor. A simplistic view of such fluid flow is presented in Figure 1 (a) where the annular counter-flow type boiling configuration is assumed. The vapor flows upward at the center of the tube while a thin liquid layer on the wall flows downward. The operation limit of such a counter-flow is known as “flooding” where the liquid film expelled by the upward vapor flow disappears from the wall. This limit is achieved at a certain vapor velocity unique to a given heat flux value. This study presents experimental data on heat transfer in boiling counter-flow of liquid helium in the closed bottom tube configuration. The experimental results show the evidence of flooding in liquid helium and the critical heat transfer is compared to the open two-phase thermosiphon configuration.

EXPERIMENTAL SET-UP

The experimental apparatus, as illustrated in Figure 1 (b), consists of a liquid helium (He) reservoir and a test tube closed at the bottom with its associated instrumentations. A complete description of the apparatus is given elsewhere [6]. The test section consists of a 1.2 m long copper tube with 14 mm inner diameter. The instrumentation includes heaters, Germanium thermometers and a differential pressure sensor. Five thermometers are inserted in small copper blocks brazed to the tube at 0.07, 0.3, 0.6, 0.9 and 1.2 m, respectively, from the entry of the flow. All wiring is wound around and glued with GE varnish to the copper thermal anchor held at 4.2 K. In the range of ΔT investigated, in the order of 10 K, the heat loss through the temperature sensor wiring is negligible; therefore we consider that the measured temperatures are those of the inner wall. A gas mass flow-meter is capable of measuring flow rates up to 4.2 g/s of helium at room temperature with a precision of ± 0.01 g/s. Pressure differences are obtained with a sensor at room temperature with a precision of 1 Pa.

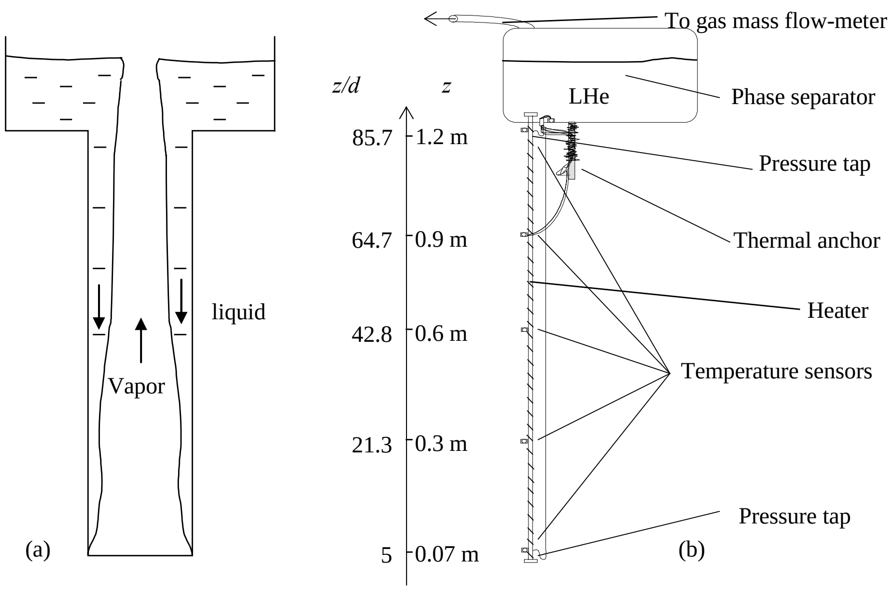

Figure 1 (a) Boiling configuration and (b) Schematic of the experimental set-up.
(*z* is the height from the entry of the tube bottom and *d* the inner diameter of the tube)

EXPERIMENTAL RESULTS

For each experiment, the power input, q, to the tube is increased stepwise. At each step, the steady state in the wall temperature, the pressure drop and the vapor mass flow are established for a sufficiently long time. The heater power incrementing is continued until the critical heat flux is reached.

Tests have been performed with steady state final heat fluxes of 125, 130, 140, 150 and 160 W/m^2. The evolution with time of the various measured physical parameters is similar. The Figure 2(a) presents the evolution of the wall temperatures at five different locations (z). Corresponding to five different values of the z/d ratio (Figure 1 (a)), the pressure drop, Δp, across the tube length) (Figure 2c) and the vapor mass flow rate, m_v, at the exit of the tube (Figure 2d) are measured as functions of time. The time here corresponds to the elapsed time since the initial heat flux was set at 120 W/m^2. After a period of 330 s, shown by the vertical dashed line on the graphs, the heat flux was set to 130 W/m^2. During this period (where the heat flux was set constant at 120 W/m^2), it can be observed that the wall temperature has a very small increase (Figure 2 (b)), Δp decreases slowly to 910 Pa from 960 Pa (Figure 2 (c)) and m_v increased slightly to 0.2 g/s (Figure 2 (d)). The value of the vapor mass flow rate and the wall temperature rise (between 50 to 100 mK for q=120 W/m^2) are similar to the values found in the steady state measurements in an open thermosiphon configuration [6]. On the other hand, due to the counter flow configuration, that creates a larger friction between the vapor and the liquid, Δp is roughly 1.5 times smaller in our configuration than that in the boiling thermosiphon configuration for the same heat flux [7].

Once the heat flux is set to 130 W/m^2, an increase in temperatures, comparable to the one found in the boiling thermosiphon configuration, is observed for a period of 50 s. Then the wall temperatures gradually decreased (Figure 2 (b)) until finally after 172 s, a significant change of several tens of Kelvin is noted at z/d=21.3, 42.8, and 5. The wall temperature at z/d=42.8 falls towards 4.2 K after the temperature increase at z/d=5. The wall temperature increase is an order of magnitude higher here than in the boiling thermosiphon configuration [6]. Meanwhile, Δp decreases rapidly and reaches 85 Pa indicating that the tube contains very little liquid and superheated vapor. The brutal temperature increase occurs simultaneously with the Δp drop that can be attributed to flooding. The large decrease in Δp combined with the wall temperature drop towards the saturation temperature immediately preceding the large jump is also an evidence of flooding. Flooding is the phenomenon that manifests when the velocity of the vapor is fast enough to generate large waves at the interface between the falling liquid film and the rising vapor core. It has the effect of reducing the liquid film thickness, explaining that the temperature drops towards the saturation temperature, and finally expelling the liquid from the tube. Moreover, the onset of the temperature rise at z/d=5 corresponding to the temperature decrease at z/d=42.8 also suggests the occurrence of flooding: as the liquid is expelled at z/d=5, it may rewet the tube at z/d=42.8.

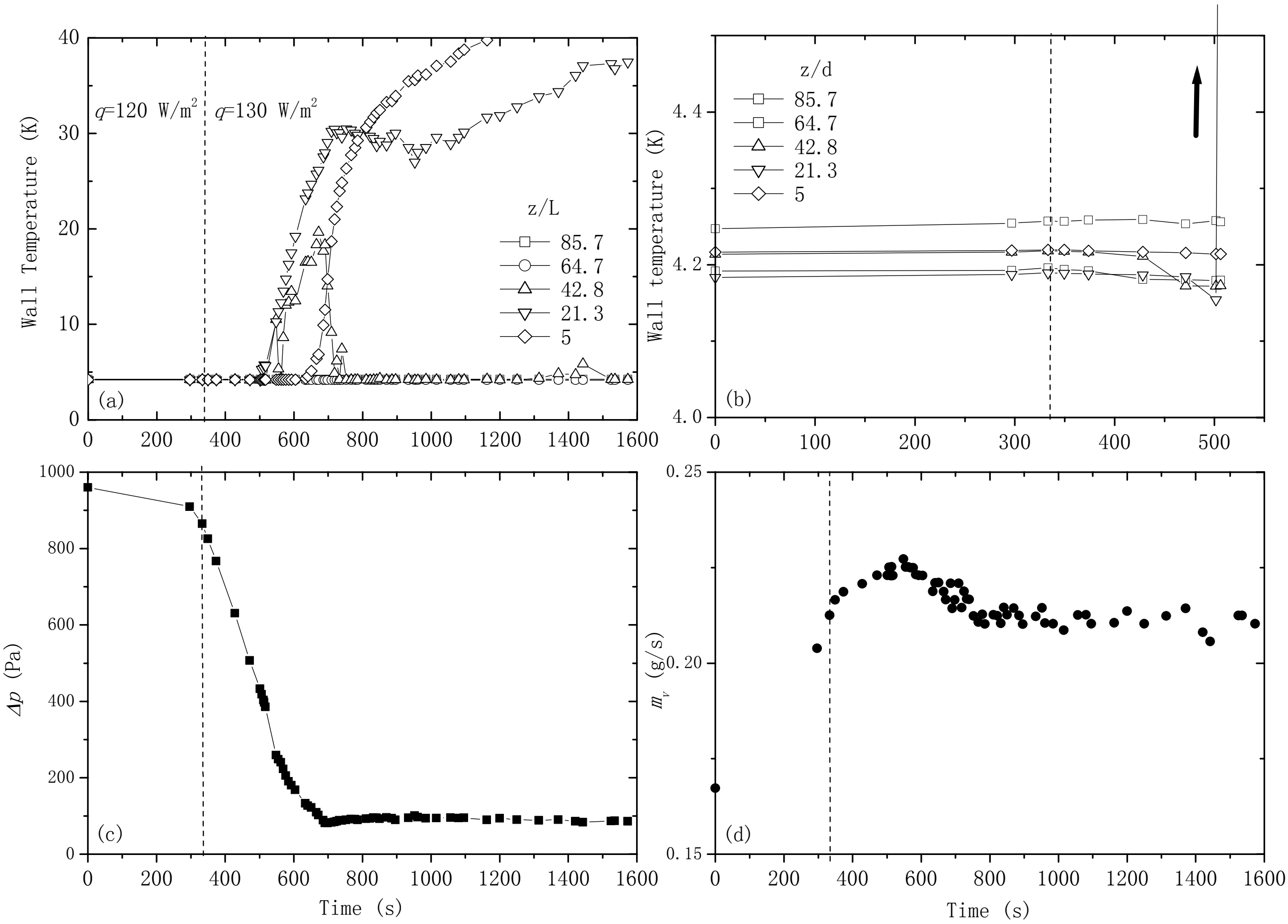

Figure 2 Wall temperature (a) and (b), pressure drop (c) and vapor mass flow rate (d)

CRITICAL HEAT FLUX DETERMINATION

The location of the onset of the CHF is defined as the location where the first temperature rise is seen such as *z/d*=42.8 in Figure 2 (a) for *q*=130 W/m^2, as it is done by other authors[2, 5]. The results of CHF onset for different heat flux values (*q*=125, 130, 140, 150 and 160 W/m^2) are presented in Figure 3 (a). The onset of temperature increase is after 1218 s at *z/d*=21.3 (*q*=125 W/m^2), after 172 s at *z/d*=21.3 (*q*=130 W/m^2), after 75 s at *z/d*=21.3 and *z/d*=42.8 (*q*=140W/m^2), after 38s and 32s at *z/d*=42.8 (*q*=150 W/m^2), and after 28 s at *z/d*=42.8 (*q*=160 W/m^2). Separate experiments have been performed at *q*=150 W/m^2 with two different liquid heights, 150 mm and 210 mm. The onset of the temperature increase, however, remained unchanged. For *q*=140 W/m^2, we find that the temperature rise appears simultaneously at the locations z/*d*=21.3 and 42.8. The general trend of the onset of CHF is similar to that in boiling water [5]. The CHF appears between the bottom and the top end of the tube. The smaller the applied heat flux is the lower the CHF onset is situated in the tube and the longer the time is required before the temperature change appears. The decrease of the temperature towards the saturation temperature before the onset is also found in two-phase water [5]. It is interesting to remark that the CHF values for helium in such a configuration are ten times smaller than for the boiling thermosiphon configuration [8].

To compare CHF data with existing flooding correlations, we only need to consider the minimum CHF value for the whole length of tube, *L*, and for this study, q_c=125 W/m^2. In an annular two-phase counter flow, Wallis gave an empirical criterion describing the velocity limit of the two-phases for flooding [9]. For the closed bottom tube configuration, the magnitude of the velocities at the top end of the tube is usually applied to this criterion. Katto presented a critical heat flux expression constructed from the continuity and energy balance equations [5],

$$q_c = \frac{{C_w}^2}{4} \rho_v L_v \left(\frac{g(\rho_l - \rho_v) d}{\rho_v} \right)^{1/2} \frac{1}{\left[1 + (\rho_v / \rho_l)^{1/4} \right]^2 (L/d)} \qquad (1)$$

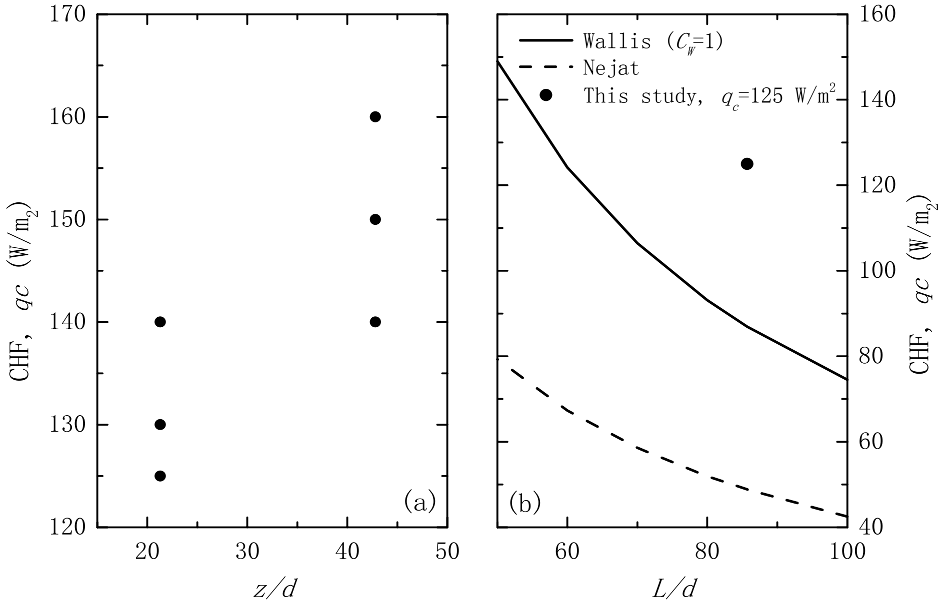

Figure 3 (a) Critical heat flux, q_c as a function of z/d and (b) comparison with (1) as a function of *L/d*

where ρ_v and ρ_l are the vapor and liquid density, g the gravitational acceleration and L_v the latent heat of vaporization and C_w a constant between 0.725 and 1. Nejat also proposed an empirical correlation based on the original Wallis configuration where he found that $C_w^2=0.36(L/d)^{0.1}$ fits his own data better [4].

The Figure 3 (b) depicts the two correlations with our minimum CHF value, which is 1.5 - 2.5 times higher than the value given by the correlations. This discrepancy can come from the error in the CHF determination. Firstly, the determination of the CHF onset brings uncertainty notably at low heat flux. Lower CHF could be found for much longer time that the ones investigated in this study. Secondly, the Wallis criteria is based on water and air in open counter-flow, which is different from our configuration where the liquid and vapor do not have uniform mass flow rate along the tube. Note that Equation (1) is developed with velocities taken at the top end of the tube. In the closed tube configuration the velocity of the vapor at the top end is higher than at lower location and therefore, it would reduce the CHF value.

CONCLUSION

In a closed bottom tube connected to a saturated helium bath, it is demonstrated that critical heat flux occurs as a consequence of flooding. Temperature increase and the variation of Δp are much higher in this configuration than for the thermosiphon configuration. The onset of CHF is not induced immediately after the application of the heat flux; rather it appears after a time duration that increases inversely with heat flux input. The CHF found in this study is much higher than what is expected from the CHF flooding correlations. To understand the mechanism behind the present findings, more investigation is needed.

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