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Diameter effect on supercritical heat transfer☆

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ABSTRACT

The objective of this review is to assess and analyze the literature on the effect of tube diameter on heat transfer at super-critical (SC) pressures. The review is based on SC heat transfer data obtained in tubes with a diameter range of 3.18 to 38.1 mm, cooled by carbon dioxide, water, R-22, and R-12. The majority of experimental studies show that, for the same flow conditions, the heat transfer coefficient (HTC) in the 'normal' heat transfer mode increases with a decrease in tube diameter. Furthermore, it was found that at SC pressures, heat transfer is more prone to deteriorate in large tube diameters. In the "deteriorated" heat transfer mode, the HTC also appears to decrease with an increase in tube diameter.

1. Introduction

The objective of this review is to improve our understanding of the diameter effect on supercritical heat transfer (SCHT). The diameter effect will be examined for each of the three types of heat transfer modes at SC pressures, i.e. (i) normal heat transfer, which is similar to that of subcritical region away from the critical or pseudo-critical regions, (ii) enhanced heat transfer which provides more efficient heat transfer compared to that in the normal heat transfer region, and (iii) deteriorated heat transfer, which provides less efficient heat transfer compared to that in the normal heat transfer region (Pioro and Duffey [1]). In the 'normal' heat transfer mode, the heat transfer can be predicted using conventional single-phase Dittus–Boelter type correlations.

Ackerman [2] and others postulate a boiling-like process occurring at SC pressures (similar to sub-cooled nucleate boiling at subcritical pressure) that gives rise to the sudden increase in the HTC over that of normal forced convection. Lee and Haller [3] also observed improved heat transfer, especially at temperatures very close to pseudo critical. These conditions occur at high mass flows. When the bulk fluid is close to the pseudo critical temperature, agglomerations of vapor-like fluid cells detach from the wall and break up the laminar boundary layer, thus resulting in more turbulence and consequently a higher HTC.

Heat transfer deterioration (HTD) is characterized by a sudden decrease in the heat transfer coefficient (HTC) or a sharp increase in the wall temperature. Pioro and Duffey [1] cite references discussing two plausible types of HTD occurring at supercritical pressures. The first type occurred at the entrance section of a tubular test section at low mass fluxes and high heat fluxes, whereas the second type occurred in the tube at locations where the wall temperature exceeded the pseudo-critical value. The mechanism for the first type of HTD is still not well understood. Explanations for the second type of deterioration include the following two: (i) the occurrence of "pseudo-film boiling" (similar to film boiling at subcritical pressures), where a low-density fluid layer forms near the wall and prevents the high-density bulk fluid from rewetting the heated surface (Ackerman [2]), and (ii) strong variation in thermo-physical properties near the pseudo-critical temperature (Wang et al. [4]).

Wang et al. [4] reported that heat transfer deterioration should be avoided in power plants operating at SC pressures, whether these be nuclear reactors or fossil-fuelled plants. The consequences of HTD (or overheating of the heated surface) could include accelerated corrosion and/or failure of the heated surface. Wang et al. [4] compared the heat transfer characteristics of SC pressure water to that of subcritical pressure water in vertically-upward flow in tubes. They also noted that the HTD of SC water is similar in mechanism to post-CHF heat transfer at subcritical pressures: both are caused by the blanketing of the heated surface by a low-density fluid. This blanket will have a lower thermal conductivity then the bulk of the fluid and will cause the wall temperature to rise.

In the case of subcritical pressures, the CHF and film boiling heat transfer are primarily affected by the mass flux, pressure, fluid enthalpy (or inlet subcooling and heated length), and tube diameter. According to Collier and Thome [5], at constant local thermodynamic quality, the CHF decreases with increasing tube diameter. In case of SC pressures, Lee and Haller [3] found that heat flux and tube diameter were the important parameters that affect the lower mass-flux limits below which pseudo-film boiling will occur. Song et al. [6] noted that the flow in the larger diameter tube was prone to deterioration in the heat transfer due to buoyancy as discussed in Section 5.

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Nomenclature

C_p	specific heat
d	diameter
g	acceleration due to gravity
G	mass flux
h	heat transfer coefficient
H	enthalpy
k	thermal conductivity
L	length
N_q	heat loading factor
P	pressure
q	heat flux
T	temperature

Greek

ρ	density
μ	viscosity

Dimensionless numbers

Bu	Buoyancy
Ec	Eckert number
Gr	Grashof number
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number

Subscripts

b	at bulk fluid temperature
eq	equivalent
exp	experimental
F	at film temperature
pc	at pseudo-critical temperature
varp	at variable physical properties
w	at wall temperature

Abbreviations

DNB	departure from nucleate boiling
HT	heat transfer
HTC	heat transfer coefficient
HTD	heat transfer deterioration
ID	inside diameter
OD	outer diameter
ODHT	onset of deteriorated heat transfer
SC	super critical

The post-CHF heat transfer at sub-critical pressures and the deteriorated heat transfer at SC pressures are critical parameters in the safety analysis of a nuclear reactor. It is therefore important to determine the effect of diameter on SCHT.

In this review we will first review the papers on diameter effect on normal and deteriorated heat transfer at SC pressures, then discus their findings and the similarity between sub- and supercritical heat transfers, and finally provide some overall conclusions.

2. Diameter effect in normal heat transfer

Song et al. [6] investigated the SCHT of a vertical upward flow of carbon dioxide in two different diameter tubes; 4.4 and 9.0 mm ID. At the high mass flux, only normal heat transfer was encountered. They noted that the HTC in the larger ID tube is consistently lower than that in the smaller ID at bulk temperatures below and above the pseudo-critical temperature.

Kim et al. [7] used the same equipment and experimental conditions of Song et al. [6], and found the same results. In addition, they tested a concentric annular flow geometry having an 8 mm ID and 10 mm OD. For the annular test section, the equivalent diameter (based on the heated perimeter) was almost identical to the diameter of the smaller tube (4.4 mm ID). The HTC for the annulus was slightly lower than that for the 4.4 mm ID tube.

Watts and Chou [8] examined mixed convection heat transfer to water at SC pressure using two different diameter tubes, 25.4 mm ID and 32.2 mm ID respectively. They proposed correlations for mixed convection (see Table A1) that include the diameter effect. The tendency of these correlations is to decrease HTC with an increase in diameter.

Yamashita et al. [9] investigated SCHT for upflow in a uniformly heated vertical 4.4 mm ID tube using R-22 as working fluid. The results were compared with previous data obtained in larger diameter tubes (Yoshida [10], Yoshida et al. [11]). For ‘normal’ heat transfer, the HTC was larger with the smaller diameter tube, i.e. the HTC trend with the tube diameter was similar to that of the Dittus–Boelter type correlations.

Mayinger and Scheidt [12] investigated SCHT in R-12 cooled tubes (12.5 and 24.3 mm ID) with vertical upflow. For the “normal” heat transfer' regions, no effect of diameter on HTC was observed for the same flow conditions. They proposed correlations for predicting the heat transfer under conditions in the “normal” region (Table A1).

Loewenberg [13] introduced a look-up table to predict heat transfer of supercritical water. According to the look-up table, HTC decreases with an increase in diameter in the ‘normal’ heat transfer, as shown by the Dittus–Boelter correlation in Fig. 1.

3. Diameter effect on Onset of Deteriorated Heat Transfer

The Onset of Deteriorated Heat Transfer (ODHT) is strongly affected by both mass flux and heat flux, as is often illustrated graphically (e.g. Ackerman [2], Lee and Haller [3], Yamashita et al. [9], Loewenberg [13]); the ODHT can also be predicted using criteria for the buoyancy parameter (Bae et al. [14], Jackson and Haller [15]) as will be shown below.

Ackerman [2] showed the ODHT boundary on a mass velocity vs. heat flux plots similar to Fig. 2. Note that DHT (or pseudo-film boiling) occurs in the region below and to the right of the line for a given diameter, while the upper left region corresponds to normal forced-convection heat transfer. An increase in diameter will move the ODHT boundary up towards the left-hand corner, i.e. DHT will then occur earlier at a lower heat flux and/or mass flux. Ackerman [2] reported that the heat flux at ODHT increased 40% with the 9.4 mm ID tube compared to the 24.4 mm ID tube. For a given mass velocity, an increase in pressure above the critical pressure allows operation at higher heat fluxes

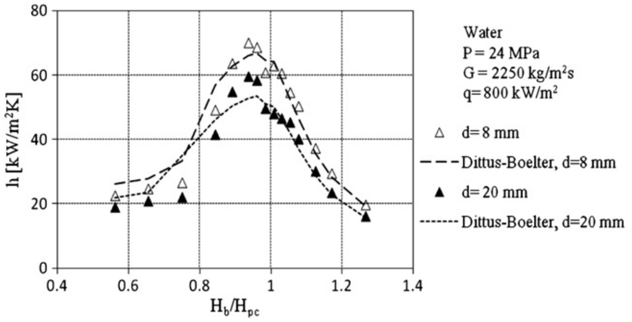

Fig. 1. Diameter effect on the HTC in ‘normal’ heat transfer region according to Loewenberg [13] look-up table for water.