Effect of Tube Diameter on Heat Transfer to Vertically Upward Flowing Supercritical CO_2

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1. Introduction

Heat transfer characteristics of supercritical[1] carbon dioxide are being investigated experimentally in the test loop named as SPHINX(Supercritical Pressure Heat Transfer Investigation for NeXt generation) at KAERI [1]. The main purpose of the experiment is to provide a reliable heat transfer database for a SCWR (SuperCritical Water-cooled Reactor) by a prudent extension of the carbon dioxide test results to the estimation of a heat transfer for water. The produced data will be used in the thermo-hydraulic design of core and safety analysis for SCWR.

The aim of the present paper is to study the influence of a tube diameter on a heat transfer. The experiments were completed for tubes of an inside diameter of 4.4mm and 9.0mm, respectively. The heat transfer characteristics from the two tubes of different diameters were compared and discussed.

2. Experiment

The detailed description of the test facility can be found in [1]. The geometries of the two tubes are the same except for their inside diameters, respectively 4.4mm and 9.0mm. The tube is attached to the loop in a vertical direction, and it is uniformly heated by a direct current power supply. Supercritical carbon dioxide flows upward in the tube. The tests have been performed by varying the inlet pressure, inlet temperature, mass flux, and heat flux in the tubes. The experimental conditions are summarized in Table 1. A test matrix was carefully established to investigate the effect of the tube diameter on a heat transfer. Table 2 shows the test matrix for the two tubes. Two cases of normal heat transfer and one case of deteriorated heat transfer in 4.4mm tube were selected as base cases as shown in Table 2 (labeled A's in Table 2). Test cases for the 9.0mm tube were selected to be compared with the cases for the 4.4mm's with a similarity consideration (labeled B's, C's, D's in Table 2). It is found appropriate to study the effect of the tube diameter based on the following two similarity parameters, Reynolds number and non- dimensionalized heat flux.

$$\left[\frac{\rho_b u_b d}{\mu_b}\right]_{4.4mm} = \left[\frac{\rho_b u_b d}{\mu_b}\right]_{9.0mm} \quad (1)$$

[1] The terminology "supercritical" means actually "a state at a pressure over the supercritical pressure." In this paper it is used for simplicity.

$$\left[\frac{q_w'' d}{k_b T_b}\right]_{4.4mm} = \left[\frac{q_w'' d}{k_b T_b}\right]_{9.0mm} \quad (2)$$

The test matrix can be categorized into three steps. The first step was to keep the mass flux and heat flux the same for both tubes. This makes a ratio of the heat flux to the mass flux constant but breaks the Reynolds number similarity (labeled B's in Table 2).

In the second step, the mass flux was scaled to satisfy the Reynolds number similarity according to Eq. (1), but the heat flux was remained the same (labeled C's in Table 2) and accordingly the heat flux parameter similarity was not satisfied.

In the last step, the heat and mass fluxes were controlled to satisfy both parameters. Furthermore, this keeps the same ratio of the mass flux to the heat flux in both tubes (labeled D's in Table 2). In this condition, it was indicated by Jackson et al. [3] that the wall temperature profiles would be the same in the experimental measurements of tubes with different inside diameters.

Table 1. Experimental conditions

Fluid	Carbon Dioxide	
Flow direction	Vertical, Upward	
Inside diameter *D,* mm	4.4	9
Pressure *P* Mpa (P/P_{cr})	7.75(1.05) and 8.12(1.1)	
Inlet Temperature, °C	5~37	
Mass flux *G,* kg/m²sec	400~1200	200~1200
Heat flux *q,* kW/m²	10~150	15~90

Table 2. Selected cases for the tube of 4.4 and 9.0mm ID
(A's are for 4.4mm tube and the others are for 9.0mm tube. ○ : normal heat transfer case, ■ : deteriorated heat transfer case)

Heat Flux [kW/m2]	Mass Flux[kg/m²sec]			
	200	400	600	1200
15	■D1			
25	■D2		○D3	
30	■C1	○A1,■B1		
50	■C2	■A2,■B2	○C3	○A3,○B3

3. Results and Discussions

From the measured wall temperature, the heat transfer coefficient and the Nusselt numbers for the cases in Table 2 were calculated. Among those cases, one of the results for a normal heat transfer case is illustrated in Figure 1 (A3, B3, C3 and D3). The wall temperatures for cases B3 and D3 having the same ratio of the mass flux to the heat flux are very similar to case A3. Comparing A3 and B3, it can be concluded that the turbulent thermal boundary layer was thin enough and the diameter difference did not have any influence on the heat transfer behavior.

The case C3 shows a completely different behavior in every aspect from case A3, It is an expected result to a certain extent since it does not satisfy both the similarity parameters.

In case D3, the wall temperature profile is very similar to case A3 and so is $T_w - T_b$. The heat transfer coefficients in D3 have about a half of the value in A3 ($h_{large} / h_{small} \approx (q''_{large} / q''_{small})$), and the diameters of larger and smaller tubes are a ratio of 2:1. Therefore the Nusselt numbers in D3 have similar values to those in A3, since the thermal conductivity is the same ($Nu_{large} / Nu_{small} \approx (h_{large} / h_{small})(D_{large} / D_{small})$). The heat transfer coefficients in both cases have the maximum value at an enthalpy little lower than the pseudo-critical enthalpy. Under the condition of satisfying the Reynolds number and heat flux parameter similarities, the heat transfer coefficient is inversely proportional to a diameter ($h_{large} / h_{small} \approx D_{small} / D_{large}$). These can be confirmed by the experimental results in Figure 1. It can be concluded that the parameters given in Eqs. (1) and (2) were the proper ones for describing a similarity for a normal heat transfer at a supercritical pressure in a tube.

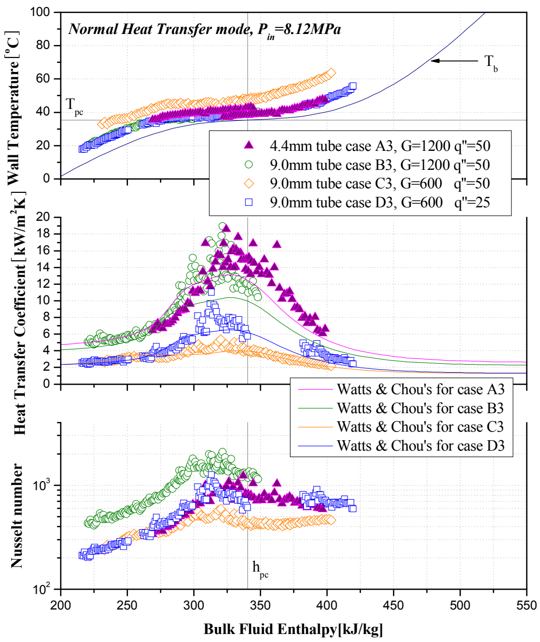

Figure 1. Similarity consideration on wall temperature, heat transfer coefficient and Nusselt number in a normal heat transfer

Figure 2 presents the experimental results for a deteriorated heat transfer mode. The case D2 of the larger tube was selected to consider the diameter effects with case A2 of a smaller tube.

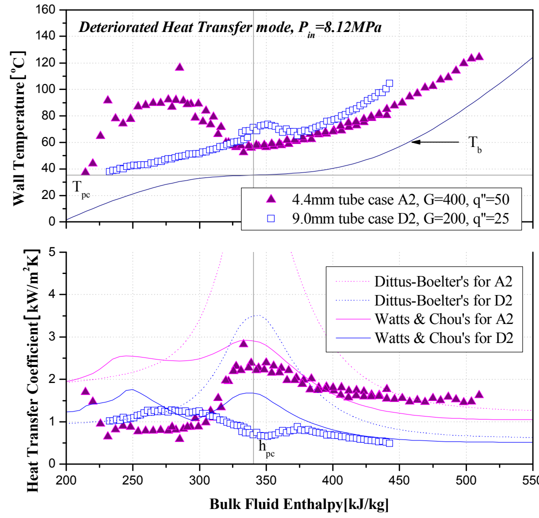

Figure 2. Effects of tube diameter on wall temperature and HTC in a deteriorated heat transfer

The effect of the diameter for a deteriorated heat transfer can not be ascertained immediately from the experimental results. Wall temperature does not coincide and the trend of heat transfer coefficient does not show any similarity at all.

4. Conclusion

A similarity consideration has been tried in two tubes with different diameters by varying the mass and heat flux.

It has been experimentally confirmed that the Reynolds number and the non-dimensional heat flux were proper parameters for describing the heat transfer behavior in tubes of an internal diameter of 4.4mm and 9.0 mm.

Under the condition of satisfying the Reynolds number and heat flux parameter similarities, the wall temperatures coincided with each other; the heat transfer coefficients were inversely proportional to the ratio of the diameters; and the Nusselt numbers coincided with each other. However the similarity for satisfying two parameters could not be confirmed for the deteriorated heat transfer cases.

REFERENCES

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