Effects of a Tube Diameter on the Heat Transfer in Upward Flows of Supercritical CO_2

Hyungrae Kim, Yoon Yeong Bae, Jin Ho Song
Korea Atomic Energy Research Institute, 150 Deokjin, Yuseong, Daejeon 305-353, Korea
khr@kaeri.re.kr, yybae@kaeri.re.kr, dosa@kaeri.re.kr

1. Introduction

Heat transfer characteristics of supercritical carbon dioxide are being investigated experimentally at KAERI [1]. The primary goal of the experiments 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 for water. To provide benchmark data for a CFD analysis is another goal of the research. The experiments have been performed for flows in vertical tubes, and tests in an annular channel are planned. A circular tube does not reflect all the aspects of the flow phenomena in a reactor core. However, a test in a circular tube can benefit from existing water experiment results and its simple geometry is well suited to benchmark turbulent models in CFD analysis [2] for supercritical pressure flows.

The experiments were executed in tubes of an inside diameter of 4.4 mm and 9.0 mm, respectively. The two stages of experiments showed effects of a tube diameter on the heat transfer and provided data for a later similarity analysis. The experiment in the larger tube is not yet completed. Thus, a preliminary comparison of the results from two tubes is presented.

2. Experiment Conditions

The two test sections have the same geometry except for their inside diameters. The total lengths of the test sections are 3 m. Direct current through the tube wall generates a uniform wall heat flux along a flow direction. The working fluid is CO_2. Table 1 shows the selected test cases for the smaller tube.

A proper comparison of the results for the two tubes requires some considerations for flow similarities. Similarities for the fluid pressure and temperature are satisfied by keeping the same reduced pressure (P/P_{cr}) and the bulk temperature normalized to a pseudo-critical temperature. Mass fluxes in the two test sections are proportioned to the tube diameters so that the Reynolds numbers are identical. Thus, the mass flux in the larger tube is about a half of that in the smaller tube. Three schemes are explored to investigate a proper scaling method for the wall heat flux.

The first method keeps the same mass flux and heat flux in both tubes. This maintains a constant ratio of the heat flux to the mass flux but breaks the Reynolds number similarity (labeled B's in Table 2).

The next one satisfies the Reynolds number similarity by scaling the mass flux according to the ratio of the diameters. However, the heat flux is identical in both tubes. Thus, the bulk enthalpy increase per heating length is the same for both tubes (labeled C's in Table 2).

The last scheme is to scale the heat flux so that the non-dimensional boundary condition (Eq.(1)) is the same for the compared cases. This fulfills the Reynolds number similarity and creates the same ratio of the heat flux to the mass flux for the two tubes (labeled D's in Table 2).

$$\left.\frac{q''D}{k_b T_b}\right|_{4.4\,mm} = \left.\frac{q''D}{k_b T_b}\right|_{9.0\,mm} \quad (1)$$

Jackson et al. [2] stated that the tests in two systems of the same fluid, Reynolds number, and normalized wall heat flux (Eq.(1)) result in the same wall temperature profile on a bulk temperature or enthalpy scale.

Table 1 Selected cases for the tube of a 4.4 mm ID

Heat Flux [kW/m^2]	Mass Flux [kg/m^{2}sec] 400	1200
30	● A1	-
50	■ A2	● A3

Table 2 Compared cases for the tube of a 9.0 mm ID (A-B : same mass flux (G) and heat flux (q''), A-C : same Re and enthalpy rise per length, A-D : same Re and normalized heat flux. ● : normal heat transfer cases, ■ : deteriorated cases. Filled marks designate the completed cases and hollow ones show the planned cases.)

Heat Flux [kW/m^2]	Mass Flux [kg/m^{2}sec] 200	400	600	1200
15	○ D1			
25	□ D2		○ D3	
30	■ C1	■ B1		
50	■ C2	■ B2	●C3	●B3

3. Results

Generally, the larger tube shows a less efficient heat transfer. Heat transfer begins to deteriorate at a lower heat flux in the larger tube than in the smaller tube for the same mass flux. The effect of a system pressure diminishes in the larger tube. Only the comparison of case A3 and related ones is provided in detail due to a limited space.

Fig. 1 shows the measured Nusselt numbers for cases A3, B3, C3 in Table 1 and 2. The horizontal axes are bulk enthalpy normalized to a bulk enthalpy at a pseudo-critical temperature. All the cases show a normal heat transfer mode. The figures show that B3, which is tested at the same mass flux and heat flux as A3, is very similar to A3 more so than C3. C3 shows a much lower peak Nusselt number than A3 near the normalized bulk enthalpy of 1.0. The peak heat transfer coefficient in C3 is about a quarter of that in A3 since the ratio of the diameters (D_{large}/D_{small}) is about 2 and the heat transfer coefficient is inversely proportional to a diameter ($h_{large}/h_{large} = \left(Nu_{large}/Nu_{small}\right)\left(D_{small}/D_{large}\right)$). Meanwhile, B3 shows very similar trend for the Nusselt numbers and heat transfer coefficient to A3.

However, B3 violates the basic similarity requirement for the Reynolds number. Due to a lack of test result for D3, C3 is compared with a high heat flux case among the cases for the tube of a 4.4 mm ID. According to the scheme for the D's, a test at 1200 kg/m^{2}sec and 100 kW/m^2 for the smaller tube is scaled to C3. A case close to the condition is available. Fig. 1(d) shows the case similar to the C3 (Fig. 1(c)) according to the scheme for the D's. Both cases of C3 and Fig. 1(d) have the same Reynolds numbers, and the normalized heat flux in Fig. 1(d) is about 10% higher than that in C3. C3 and Fig. 1(d) show very similar Nusselt numbers and the heat transfer coefficients in C3 are about a half of those in Fig. 1(d). Recalling that the heat flux in C3 is about a half of that in Fig. 1(d), the two cases show very similar profiles of wall temperature superheat (T_w-T_b). This conclusion will become clearer when the D-cases are completed.

4. Conclusion

The heat transfer tests have been performed in two tubes of different diameters. A valid comparison requires a scaling of the mass flux and heat flux according to the ratio of the diameters. On the scaling of the heat flux, three schemes were tried on. The results show that the normalized wall heat fluxes should be matched to obtain similar wall temperature profiles among the tests in the tubes with different diameters. This confirms the suggestion by Jackson et al. [3]. The cases scaled by this rationale will be completed soon and the validity of the scaling scheme will be confirmed.

REFERENCES

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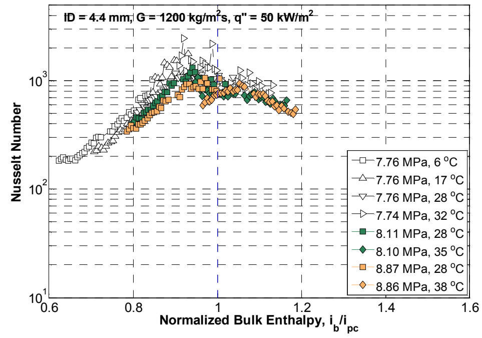
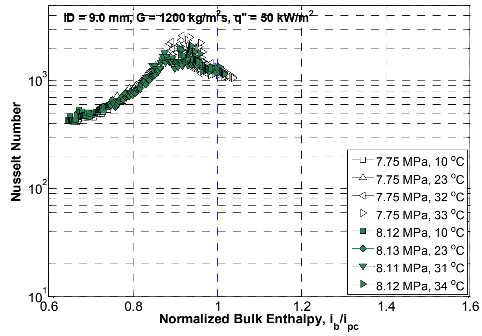
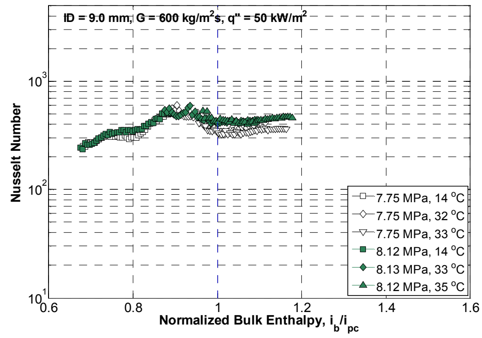


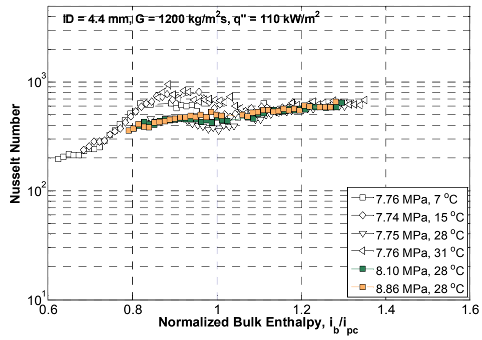
(a) Case A3



(b) Case B3 ($G_{B3} = G_{A3}$, $q''_{B3} = q''_{A3}$)



(c) Case C3 ($Re_{C3} \sim Re_{A3}$, $q''_{C3} = q''_{A3}$)



(d) A test case for the smaller tube. This case is nearly scaled to the C3. ($Re \sim Re_{A3}$, $q'' \sim q''_{A3} / 2$)

Fig. 1 Comparison of heat transfer rates in two tubes with different diameters (Legends show the test pressures and the bulk temperatures at the first wall thermocouple.).