Deterioration Criterion for Heat Transfer to a Vertically Upward Flowing Supercritical CO_2 in a Circular Tube

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1. Introduction

The Super Critical Water cooled Reactor (SCWR) concept for Generation Ⅳ has generated considerable interest recently and fair amount of research activities are being performed in several countries. A heat transfer at a supercritical pressure has been identified as one of the major research areas for the development of the SCWR. In relation to this, a heat transfer to carbon dioxide, a surrogate fluid for water, is being investigated experimentally in the test loop SPHINX at KAERI [1].

In heat transfer processes at a supercritical pressure, two regimes are distinguished for the flow of a medium. The first one is called "normal heat transfer regime," where the heat transfer coefficient varies continuously. The other one is "deteriorated heat transfer regime," where the heat transfer coefficient drops well below the expected value. Since the deterioration increases the fuel cladding wall temperature and may damage the fuel integrity, the knowledge of a function for describing the boundary between these two regimes is essentially required for the safety of fuel and reactor core.

An experiment has been performed to examine the conditions for deterioration boundaries in a circular tube, and the criterion for the onset of deterioration is presented.

2. Experiment

The detailed description of the test facility can be found in [1]. The circular tube is made of Inconel 625 and the inner diameter of the tube is 6.32 mm, which is nearly the same as the hydraulic diameter of representative subchannel of the conceptual fuel assembly design. The entrance length and heated length are about 80d and 400d, respectively. Adhesive K-type thermocouples were used to measure the wall temperature and their accuracy is ±0.75% or 2.2℃. The first thermocouple was attached to the outer surface of the tube 80d upstream of the heating point and the remaining 40 thermocouples were attached with a equal space of 50 mm. Since the entrance length in a turbulent flow is from approximately 10d to 60d independent of Reynolds number, measured regions are considered as fully developed turbulent conditions.

The tests have been performed by varying the inlet temperature, mass flux, and heat flux in the tube. For a given mass flux, the heat flux was varied to find the condition of the occurrence of a deterioration. The experimental conditions are summarized in Table 1.

Table 1. Experimental conditions

Fluid	Carbon Dioxide
Flow direction	Vertical, Upward
Inside diameter *D,* mm	6.32
Pressure *P* MPa (P/P_{cr})	8.12(1.1)
Inlet Temperature, ^oC	5~37
Mass flux *G,* kg/m^2sec	400, 500, 600, 750, 854, 1000, 1200
Heat flux *q,* kW/m^2	20~170

3. Results and Discussions

Figure 1 shows the axial variations of the inner wall temperature. At a low mass flux of $400kg/m^2s$, a remarkable increase of the wall temperature begins appearing when the heat flux is 32.4 kW/m^2. Before the heat flux reaches this value, the wall temperature profile is parallel to the bulk temperature. As the heat flux increases beyond 32.4 kW/m^2, the range of the deteriorated heat transfer region widens and the peak of the wall temperature increases as well. As the heat flux increases further, the deteriorated region expands to the lower bulk fluid enthalpy side. At a high mass flux of $1200kg/m^2s$, the degree of a jump was barely noticeable. However a close look at the temperature variation reveals temperature jumps beyond the thermocouple error bound, and those were interpreted as evidences of a deterioration.

Generally, a deterioration phenomenon can be explained by the following three physical effects: (1) flow acceleration, (2) buoyancy effect and (3) thermo-physical properties variation. In a normal heat transfer region, the wall temperature increases monotonically along the test section from the bottom to the top. When a deterioration occurs in a certain region, a normal turbulent convective heat transfer is hindered by these phenomena and a fluid's heat transfer capability drops significantly in this region. Due to this process, a region appears where the wall temperature is higher than the following region. In other words, if there is a region with a higher wall temperature than the following upper region, it can be said that a deteriorated heat transfer occurs. During the experiment, when the wall temperature of more than three successive points was higher than the following point the region was considered as a deteriorated heat transfer region. Considering the accuracy of the thermocouples only the points of a temperature difference larger than the accuracy of the thermocouples were considered. Using this criterion, deteriorated heat transfer regions are marked in Figure 2.

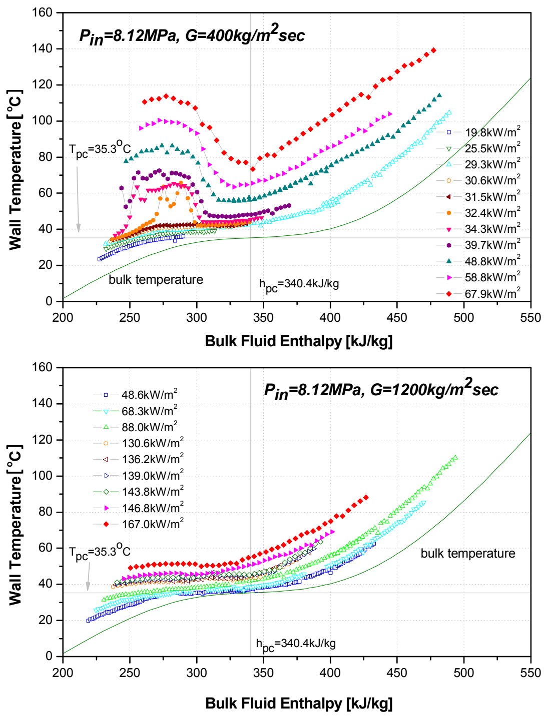

Figure 1. Wall temperature distribution for low and high mass fluxes with increasing heat flux

Methods of determining the onset of a deteriorated heat transfer have been presented by several authors. Relation (1) is the simplest one presented for water at a pressure of 24 MPa (Styrikovich et al., 1967).

$$q / \rho w \geq 0.6 \qquad (1)$$

Relation (2) was constructed on the basis of data obtained for P=22.6-29.4MPa of water(Shitsman et al., 1963).

$$q \geq 0.2(\rho w)^{1.2} \qquad (2)$$

The boundary of the onset of deteriorated heat transfer regime for carbon dioxide at a pressure of 8MPa was presented using the relation (3)(Jeon et al., 2005). The diameter of the tested circular tube was 8mm.

$$q = 0.2(\rho w)^2 \qquad (3)$$

Relation (4) was proposed for determining the boundaries of deteriorated heat transfer regime for different media(Grabezhnaya et al., 2006).

$$q = 0.6 \rho w \frac{M_{H_2O}}{M} \qquad (4)$$

Based on our experimental data, following relation is suggested for the criterion for the onset of a deteriorated heat transfer. Relation (5) is valid for the following range of the parameters: carbon dioxide, P/P_{cr}=1.1, d=6.32mm, ρw=400-1200kg/m^{2}s, q=20-170kW/m^2.

$$q = 18(\rho w)^{1.25} \text{ for } \rho w < 1000 kg/m^2 s$$
$$q = 0.1(\rho w)^2 \text{ for } \rho w \geq 1000 kg/m^2 s \qquad (5)$$

Although relation (3) was obtained from data with similar conditions to ours, it is not suitable for our data, since the criterion for determining the onset of a deterioration is based on a buoyancy parameter, while wall temperatures were used in this paper.

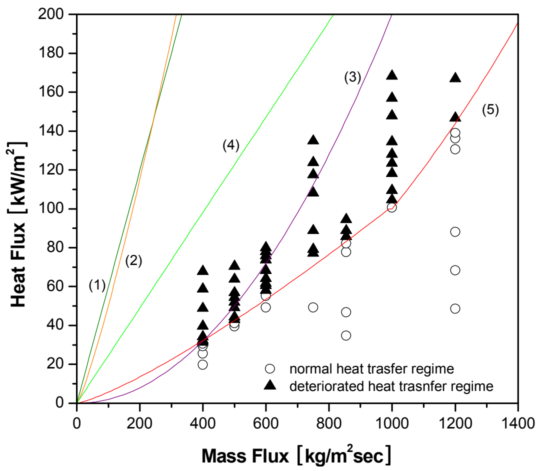

Figure 2. Comparison of deterioration criteria with the experimental results

4. Conclusion

Experiments were performed to develop a criterion for the onset of a deterioration in a circular tube. An abnormal increase of the wall temperature beyond the temperature expected by a normal convective heat transfer was used to determine the boundary of a deterioration.

The valid ranges of the parameters are limited. To obtain a more general relation, further experiments are needed to establish the influence of additional parameters such as the pressure and tube diameter, which were not considered in this paper.

REFERENCES

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