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Experimental study on convective heat transfer of water flow in a heated tube under natural circulation

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Abstract

This paper reports on an experimental study on transitional heat transfer of water flow in a heated vertical tube under natural circulation conditions. In the experiments the local and average heat transfer coefficients were obtained. The experimental data were compared with the predictions by a forced flow correlation available in the literature. The comparisons show that the Nusselt number value in the fully developed region is about 30% lower than the predictions by the forced flow correlation due to flow laminarization in the layer induced by co-current bulk natural circulation and free convection. By using the Rayleigh number *Ra* to represent the influence of free convection on heat transfer, the empirical correlations for the calculation of local and average heat transfer behavior in the tube at natural circulation have been developed. The empirical correlations are in good agreement with the experimental data. Based on the experimental results, the effect of the thermal entry-length behavior on heat transfer design in the tube under natural circulation was evaluated.

1. Introduction

Natural circulation has been widely used in thermal equipment of many industries. It is of great use for the safety of light water reactors. Natural circulation can be used to release the residual heat within the reactor during reactor accidents and events. It can also be considered as a major method of circulation cooling during the normal operation of a pressurized water reactor (PWR). For a PWR operating under natural circulation condition, the flow rate in the primary circuit is relatively low and it is mainly related to the heat power of the reactor and the flow resistance in the primary loop. In principle, to increase the heat power of the reactor can increase the flow rate in the primary circuit. However, the safety of the reactor is not only related to the flow rate in the core, but also affected by the heat transfer behavior of single-phase water flow in the core of the reactor. If the heat transfer capacity of the fluid in the core decreases during natural circulation, in order to ensure the power output of the reactor, the temperature difference between the wall of the fuel rods and the coolant must be increased, which will affect the safe operation of the reactor. Therefore, it is very important to determine correctly the heat transfer performance of the coolant in the reactor core during design and safety analysis of the PWR with natural circulation.

So far a tremendous amount of research has been done on the subject of convective heat transfer of single-phase liquid flow in tubes. This research has been reviewed, among others, by Cengel (2003), Incropera and DeWitt (2002), Ebadian and Dong (1998) and Kays and Perkins (1985). Many good correlations have been proposed for the calculation of convective heat transfer in tubes. Among these, the correlations developed by Dittus and Boelter (1930), Petukhov and Kirillov (1958) and Gnielinski (1976) can be used to estimate the heat transfer coefficients in fully developed turbulent flow regions and even in transition flow regions of tubes. Techniques dealing with convective heat transfer in the entrance region of tubes have also been proposed, e.g. by Sleicher and Tribus (1957), Kays and Perkins (1985) and Gnielinski (1976). When the wall and fluid temperature difference is large, methods to take into account the effect of temperature-varying properties on convective heat transfer have been suggested, for example, by Sieder and Tate (1936), Allen and Eckert (1964) and Petukhov (1970). A high temperature gradient in forced fluid flow in a gravity field can also increase the natural convection, and thus forced convection

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Nomenclature

C_p	specific heat (J/kg K)
d	tube diameter (m)
F	thermal entrance effect factor
f	friction factor
G	mass flux (kg/m^2 s)
g	gravitational acceleration (m/s^2)
Gr	Grashof number
k	thermal conductivity (W/m K)
L	length (m)
Nu	Nusselt number
Pr	Prandtl number
Q	heat input power (kW)
q	heat flux (W/m^2)
Ra	Rayleigh number
Re	Reynolds number
T	temperature (°C)

Greek symbols

α	heat transfer coefficient (W/m^2 K)
β	thermal expansion coefficient (1/K)
μ	dynamic viscosity (kg/ms)
ρ	density (kg/m^3)

Subscripts

f	fluid
w	tube wall

is accompanied by natural convection. Metais and Eckert (1964) have given the flow pattern maps to determine the flow regimes of natural, forced and mixed convection for flow through tubes. A lot of works on mixed convection heat transfer of water flow in tubes have been reported in the literature. Among these are the papers of Herbert and Sterns (1972), Rouai (1987), Joye (1996) and Celata et al. (1998). Until now, almost all the correlations for the calculation of convective heat transfer of single-phase liquid flow in tubes were obtained from experiments carried out under forced flow conditions. For most safety analyses of PWRs with natural circulation the heat transfer calculation for coolant flow in the reactor cores are performed by using the correlations taken from forced flow conditions. However, whether the heat transfer correlations obtained under forced flow conditions are applicable for natural circulation flow in these analyses remains a problem. So far only few studies on the convective heat transfer of single-phase liquid flow in natural circulation systems were published. Zvirin et al. (1981) performed an experiment in a natural circulation system to investigate the performance of the system. Based on the experimental data taken at natural circulation condition, they estimated the convective heat transfer coefficient of laminar water flow in the primary side of the heat exchanger connected in the system. It was found that the convective heat transfer coefficients obtained from the experiments were 21% below that predicted by the empirical correlation available in the literature. Zvirin et al. considered that this deviation was due to the multidimensional flow patterns in the natural circulation loop. Vijayan et al. (1991) reported an experimental study on convective heat transfer of laminar water flow in a natural circulation loop. They found that the natural circulation data of convective heat transfer were not correlated by the forced flow correlations available in literature due to the presence of secondary flows in the tubes under natural circulation.

This paper reports on an experimental study on local transitional heat transfer of single-phase water flow in a heated tube under natural circulation condition. The experimental data are compared with the predictions of a forced flow correlation found in the literature. Based on the experimental results, the empirical correlations for the calculations of the local heat transfer coefficients as well as the average heat transfer coefficients in the heated tube under natural circulation conditions have been developed.

2. Experimental loop

A schematic diagram of the test loop is shown in Fig. 1. For the experiments, demineralized and degassed water was used

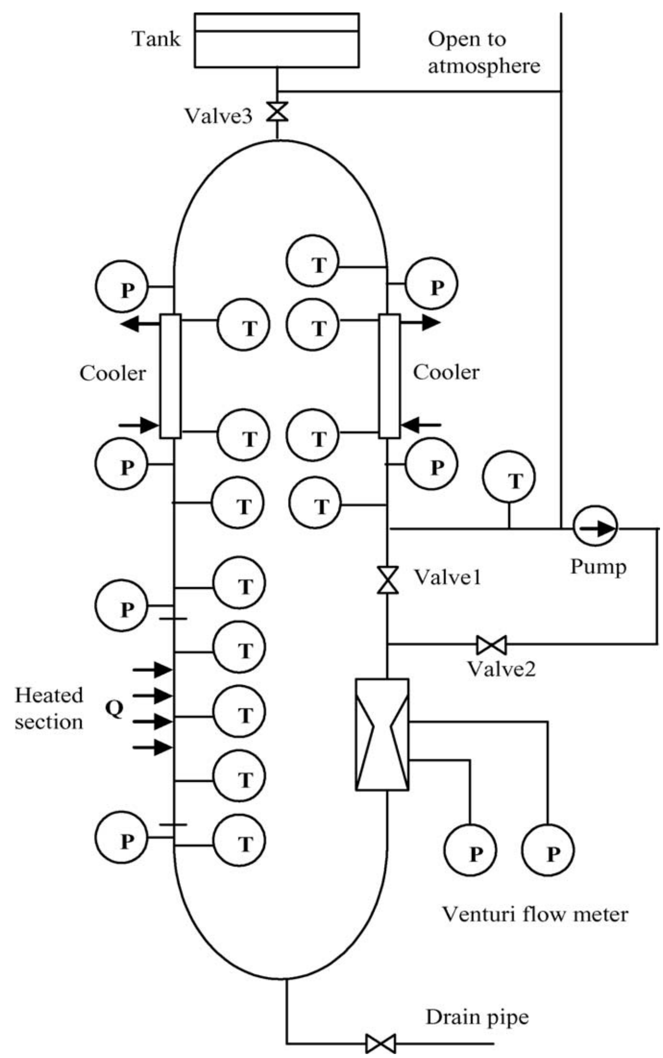

Fig. 1. Schematic of test loop.