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Heat transfer of water flowing upward in vertical annuli with spacers at high pressure conditions

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ABSTRACT

Experimental studies on heat transfer to water flowing upward in a concentric annular channel are carried out at the SWAMUP test facility at both subcritical and supercritical pressure conditions. The vertical annuli contain a heated inner tube of 8 mm outer diameter and an unheated outer tube of 15.3 mm inner diameter with spacers without mixing-vane. More than 500 test data were obtained with the following test conditions: pressure from 15.5 to 26.0 MPa, mass flux from 500 to 1600 kg/m^{2}s, heat flux from 0.45 to 1.4 MW/m^2 and bulk temperature from 310 to 390 °C. Test data are also compared with those obtained in tubes of similar hydraulic diameter. The results show that heat transfer coefficient in annuli without spacer effect is slightly lower than that in circular tubes, whereas a significant enhancement of heat transfer is obtained in annuli with spacer effect. The phenomenon of heat transfer enhancement and its decay behavior downstream of spacers were investigated and analyzed. A new correlation was developed to predict the local heat transfer enhancement due to spacers at supercritical pressure condition.

1. Introduction

As one of the six Generation IV reactors proposed by U.S. DOE and GIF (2002), supercritical water cooled reactor (SCWR) has such advantages like higher thermal efficiency and system simplification (Cheng et al., 2008). However, in the frame of SCWR design, there are still many technical problems, especially in the field of thermal hydraulics. The thermo-physical properties of supercritical water show strong variation in the vicinity of the pseudo-critical point, may lead to large buoyancy effect and flow pattern change in the near wall region and finally result in abnormal heat transfer behavior compared to conventional conditions.

In order to design supercritical fossil power plants, supercritical water heat transfer in tubes has been performed since 1950s. These studies have been well reviewed by Cheng and Schulenberg (2001) and Pioro and Duffey (2005). In the existing SCWR concepts (Oka and Koshizuka, 2000; Schulenberg et al., 2008; Cheng et al., 2008), various geometries of fuel assembly and different kinds of spacer grids were proposed. It showed that studies on heat transfer characteristics of supercritical water flowing in fuel bundles or channels relevant to nuclear reactors is very important.

McAdams et al. (1950) conducted heat transfer experiments with an upward flow of water in a vertical annulus of internal heating with pressure ranging from 0.8 to 24 MPa and bulk temperature ranging from 221 to 538 °C. Four thermocouples installed inside the heated rod are used to determine local HTCs along the heated rod. The total heated length was 0.312 m, and no spacers were used in their experiment. The experiments showed that with certain Reynolds number and Prandtl number, local Nusselt number decreases always as x/D_h increases, even if the temperatures along the heated rod were slightly increased. It is believed that at supercritical conditions, the entrance effect is reduced, as flow redevelops.

Glushchenko et al. (1972) conducted experiments with an upward flow of supercritical water in annuli. One side was heated. Heat transfer with both internal heating and external heating was investigated. The heated length was 600 mm. It was found that HTCs were similar to those in tube of the same hydraulic diameter D_h, in case the entrance effect is negligibly small.

In most of the SCWR design concepts, spacer grids (Cheng et al., 2003, 2008; Squarer et al., 2001; Dobashi et al., 1998) or wires (Schulenberg et al., 2008; McDonald et al., 2005; Bae et al., 2004) are proposed to positioning the fuel pins. In addition, spacers are also used to improve heat transfer. In spite of the significant effect of spacers on heat transfer, investigation on spacer effect is still very limited, especially at supercritical pressure conditions.

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Nomenclature

D_h	hydraulic diameter (m)
G	mass flux (kg/m^2·s)
ID	tube inside diameter (m)
Nu	Nusselt number
OD	tube outside diameter (m)
P	pressure (Pa)
q	heat flux (W/m^2)
Re	Reynolds number
T	temperature (°C)

Greek

ε	spacer grid blockage ratio

Subscripts

∞	position without spacer effect
x	local position downstream spacer

Bae et al. (2011) carried out heat transfer experiment of supercritical CO_2 flowing through annuli with helical wires. They found out that with wire spacer heat transfer was enhanced several times compared with that without wire spacer. Furthermore, effects of various parameters such as heat flux, mass flux and pressure on heat transfer were studied.

Wang et al. (2012) investigated heat transfer characteristics of supercritical water flowing in annuli with wire spacer. The test section had internal heating, a gap of 6 mm and a wire spiral interval of 100 mm. They focused on the effect of wire spacer on heat transfer characteristics of supercritical water. They found that the affected distance of wire spacer depends strongly on flow condition and spiral interval. Wire spacer eliminates the phenomenon of heat transfer deterioration, which may occur at high ratio of heat flux to mass flux. In addition, CFD simulation was applied to enable an insight into an understanding of the effect of wire wraps on heat transfer. The CFD analysis indicates that wire wraps lead to stronger turbulent kinetic energy, larger near wall velocity, lower radial temperature difference and subsequently lower wall temperature and higher heat transfer coefficient.

Recently, Yang et al. (2012) preformed heat transfer experiments of supercritical water in annuli, using 2 spacer grids and with internal heating rod and external non-heating tube. They observed heat transfer enhancement downstream the spacer grids as well as the decay behavior along with the distance. They found that the reduction in buoyancy effect caused by spaces grid is quite obvious at high heat flux conditions. However, due to short heated length, only a few thermocouples were welded in the internal rod to measure the wall temperature. Therefore, besides the heat transfer enhancement close to the spacers, it is hardly possible to investigate the decay behavior of heat transfer enhancement. Furthermore, the distance between the first spacer grid and the test section inlet is too short (only 4 times of D_h), so it is difficult to separate the spacer effect from the entrance effect.

Taking all the existing studies into consideration, further experimental investigations on heat transfer characteristics of supercritical water flowing in annuli with spacer are required, especially quantitative study on heat transfer enhancement and its decay behavior.

This paper presents experimental studies on heat transfer of supercritical water flowing upward in annuli with spacer grids. The geometric parameters, e.g. hydraulic diameter, of the test section correspond to those of SCWR-M design (Cheng et al., 2008), i.e. the diameter of the inner heated rod is 8 mm, and diameter of the outer unheated tube is 15.3 mm, resulting in a hydraulics diameter of 7.3 mm. Four spacer grids with distance ranging from 400 to 600 mm are applied. These distances are sufficiently large for the redevelopment of flow and heat transfer downstream the spacers, so that heat transfer coefficients with negligibly small effect of spacers can be obtained. Based on the present test data, a new heat transfer correlation including the effect of spacers is proposed.

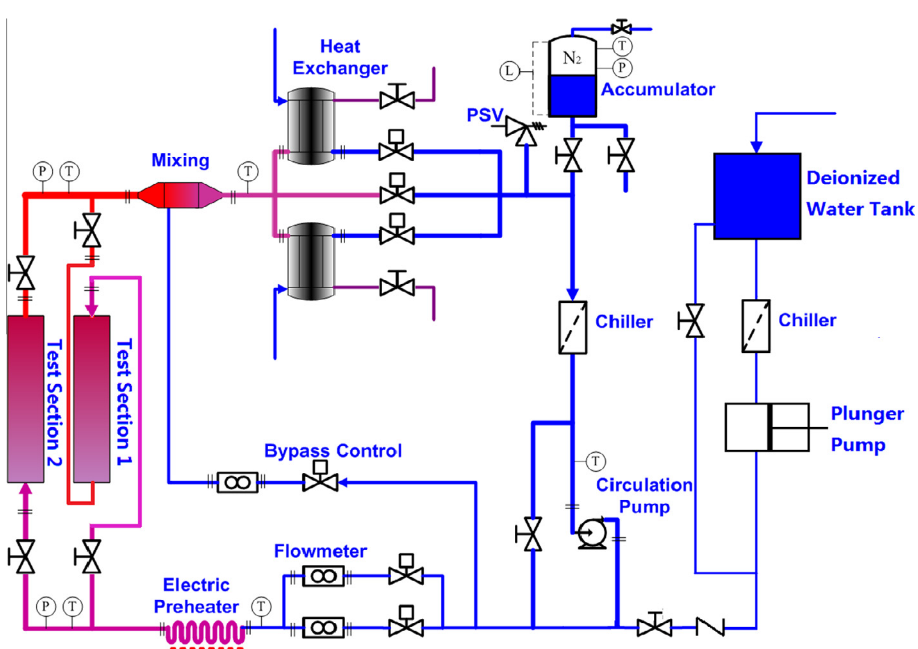

Fig. 1. Scheme of the SWAMUP test facility.