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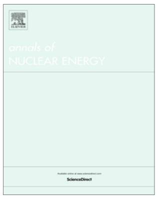

A circumferentially non-uniform heat transfer model for subchannel analysis of tight rod bundles

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ABSTRACT

The non-uniformity of circumferential heat transfer is small in conventional PWR core but becomes significant with tight-lattice core design for advanced reactors. Predicting the circumferentially non-uniform heat transfer behavior can be challenging given the considerable heterogeneity of the subchannel geometry and the drastic change of property with supercritical fluids. In this paper, a circumferentially non-uniform heat transfer model for subchannel analysis has been developed to predict the circumferential distributions of heat transfer coefficient, wall temperature and wall heat flux. In the model, the sources of the heat transfer non-uniformity are considered to be the circumferentially non-uniform flow area and the fluid property variation. To account for these two effects, new correlation with a non-uniform factor is developed. A series of tests using CFD method was performed for determining the empirical coefficients of the non-uniform factor. Furthermore, a two-dimensional fuel heat conduction model is also added to the subchannel analysis code. The new model was validated by comparing the prediction results with available experimental data of a 2 × 2 square rod bundle with supercritical water. It is demonstrated that the inclusion of circumferentially non-uniform heat transfer model leads to an improvement in the predictive capabilities for current subchannel analysis method and will improve the prediction accuracy of cladding temperatures in the design and safety analysis of reactor fuel elements.

1. Introduction

In the design of the reactor core for Super-Critical Water-cooled Reactor (SCWR), tight-lattice fuel assembly concept is adopted in order to improve the fuel utilization efficiency and reduce the radioactive waste in spent fuel (Oka and Koshizuka, 2000; Schulenberg and Starflinger, 2007; Cheng et al., 2008). In the tight-lattice fuel assembly, a notable non-uniform heat transfer profile in the circumferential direction of the fuel rod will appear and lead to an incorrect prediction of the maximum cladding surface temperature. Many researchers have performed CFD investigations of heat transfer in tight-lattice bundles and identified such non-uniform heat transfer phenomenon (Yang et al., 2006; Gu et al., 2008; Zhang et al., 2014; Podila and Rao, 2016). According to their conclusions, the circumferential temperature variation of the fuel rod should be considered in the design and safety analysis.

Although CFD method is capable of predicting the circumferentially non-uniform heat transfer in tight-lattice bundles, the great demand in CFD computational effort makes it difficult to be applied to the large-scale bundle or full-scale core simulations. As one of the conventional methods for the thermal-hydraulic analysis of fuel assembly, subchannel analysis method is indispensable and has been used for thermal-hydraulic design and analysis of the new SCWR concepts (Yoo et al., 2007; Cao et al., 2008; Ammirabile, 2010; Shan et al., 2010; Onder et al., 2012; Liu et al., 2013). In order to improve the subchannel code capability in accurately predicting the non-uniform heat transfer phenomenon, Yang et al. (2013) performed the investigations of the effect of independent parameters on the circumferential non-uniformity of heat transfer in tight-lattice bundles. They found that the solution of the radial temperature field is cosine series of angle and the circumferential temperature distribution is affected by several dimensionless numbers (angle, p/d, Pr and $\lambda_{clad}/\lambda_{coolant}$). Recently they developed the correlation of circumferentially non-uniform heat transfer coefficient and implemented the correlation in the subchannel code (Yang et al., 2017). In their model, the fluid properties were assumed to be unchanged and the effect of properties on the non-uniformity is not considered. This will affect the accuracy of the predictions near the critical point since properties change drastically in this region. It is of great interest to develop

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Nomenclature

A	area (m^2)
c_p	specific heat capacity at constant pressure ($J\ kg^{-1}\ K^{-1}$)
d, D	diameter (m)
G	mass flux ($kg\ m^{-2}\ s^{-1}$)
h	heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
Nu	Nusselt number
P	pressure (MPa), wetted perimeter (m)
Pr	Prandtl number
r	radius (m)
Re	Reynolds number
T	temperature (°C or K)
x	axial distance (m)

Greek letters

ρ	density ($kg\ m^{-3}$)
θ	angle (°)

Subscripts

ave	average
b	bulk fluid
loca	local
max	maximum
min	minimum
non	non-uniform
pc	pseudo critical
prop	property
rod	rod
SC	subchannel
w	wall

a universal model in support of better predicting of the non-uniform heat transfer.

In this paper, we introduced a new method to predict the circumferentially non-uniform heat transfer behavior in tight-lattice bundles. This work is also a strong support to the improvement of predictive capabilities in subchannel analysis. The improvements are made in two main aspects to account for the circumferential non-uniformity, which are the local heat transfer model and the two-dimensional fuel heat conduction model. The CFD data are utilized to determine the model coefficients and bundle experiment data available in the open literatures are adopted for the validation of the model.

2. The circumferentially non-uniform heat transfer model

2.1. Non-uniform heat transfer model

In this section, we construct a model for predicting the circumferentially non-uniform heat transfer in rod bundles. New modeling approach is employed to evaluate the non-uniform heat transfer behavior. Fig. 1 shows the general modeling features of the circumferentially non-uniform heat transfer behavior. This approach adopts the two-dimensional (2D) conduction model of the fuel rod in the cross section. In the 2D fuel model, the fuel rod is divided into many cells (represented by the central nodes) in the radial and the azimuthal directions. The cells on the surface of the fuel rod are contacted with the flow subchannels. In order to derive the non-uniform heat transfer performance of the fluid flow, each realistic subchannel is also divided into corresponding cells, which are referred to as the hypothetical flow units. It is noted that the hypothetical flow unit is only contribute to evaluating the geometrical effect in the non-uniform heat transfer model, but not involved in the flow field solutions. The solution of the flow field is applied to the realistic subchannel unit as usual method as in subchannel analysis.

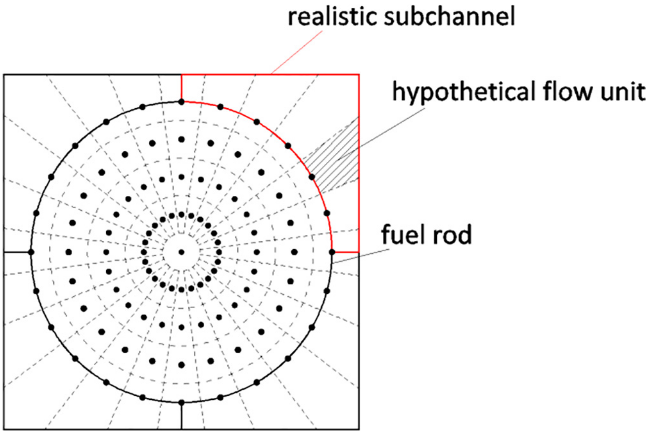

Fig. 1. General modeling approach for non-uniform heat transfer model.

In the new modeling approach, the effect of locally non-uniform flow area is considered as the primary component in the mechanism model of the non-uniform heat transfer. Another component due to the physical phenomena of fluid property variations is defined accordingly to complete the model.

2.1.1. Effect of locally non-uniform flow area

In previous numerical study of heat transfer in tight-lattice fuel rod channels, Yang et al. (2006) have found that the cause of non-uniform heat transfer behavior could be explained by the non-uniformity of the local flow areas in cross section of subchannel. Recently, Wang et al. (2017) and Chen et al. (2018) have conducted heat transfer experiments in tight-lattice bundle. Their experiment data have revealed that the circumferential heat transfer coefficient exhibited a similar distribution to that of the local flow areas. The flow resistance is higher with a lower local flow area. Thus the velocity in small flow area region is smaller than that in large flow area region. Therefore, the local heat transfer coefficient in the small flow area region becomes small as a result of small velocity, and vice versa.

The above mentioned studies have qualitatively evaluated the effect of non-uniform flow area on the circumferentially non-uniform heat transfer. In order to quantitatively evaluating the effect of non-uniform flow area, a local hydraulic diameter concept is introduced on the basis of the hypothetical flow unit concept. Considering a hypothetical flow unit i in Fig. 2, the flow area and the corresponding wetted perimeter are A and P respectively. Then the local hydraulic diameter D_{loca} is defined as:

$$D_{loca,i} = \frac{4A_i}{P_i} \tag{1}$$

In the non-uniform model, the local heat transfer coefficient is determined on the premise that the average performance of the locally non-uniform heat transfer is equally matched with the overall performance of subchannel heat transfer. A non-uniform factor F based on the local hydraulic diameter is devised to evaluate the non-uniform flow area effect. The non-uniform factor F at the wall node i is defined as: