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Thermal-hydraulic comparisons of 19-pin rod bundles with four circular and trapezoid shaped wire wraps

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HIGHLIGHTS

- Model for 19-pin assembly with four wire wraps in each pin is established.
- Both circular shaped and trapezoid shaped wire wraps are tested.
- Details of flow structure and heat transfer inside assembly are obtained.
- Comparisons on global heat transfer and frictional pressure loss are evaluated.

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ABSTRACT

Coolant in wire-wrapped fuel assembly flows not only in axial direction but also in a transverse direction. This special flow is critical for momentum exchange and heat transfer in fuel rod bundle. To obtain a better performance wire-wrapped fuel assembly for advanced reactor cores, in this paper, the characteristics of turbulent flow and heat transfer inside 19-pin heated rod bundles where each pin is wrapped with four circular shaped and four trapezoid shaped wires are numerically studied, respectively. Considering the geometric complexity, the advanced hybrid-grid technique that combines the structured hexahedron grids and unstructured pentahedral grids is adopted to divide the modeling assembly. The validity of both RSM and SST k-ω model is assessed by comparing calculated pressure loss with the available experimental data to determine a proper turbulence closure. Special attention has been paid to understand the effect of secondary flows created by the wire wraps on the reduction of coolant temperature variation. Additionally, in order to assess the effectiveness of the different shaped wires, comparisons on both global heat transfer and associated penalty in pressure loss are evaluated. Results indicate that the frictional pressure loss of the rod bundle with circular shaped wires is smaller than that with trapezoid shaped wires, while the global heat transfer is equivalent. However, the trapezoid shaped wires give a lower maximum temperature as well as a uniform temperature distribution within the subassembly in comparison with circular shaped geometry.

1. Introduction

Heat generation in nuclear reactor cores generally takes place in fuel assemblies with axial coolant flow. The most important task for thermal-hydraulic design of reactor cores is the reliable prediction of the flow field and temperature distributions in the fuel rod bundles (Natesan et al., 2010). To promote coolant mixing between adjacent sub-channels and enhance the rate of heat transfer, the fuel rods are mostly arranged in bundles of triangular configuration and each pin is wrapped with wire spacers following a helical pattern around the pin axis. These wire wraps create secondary flows in the bundles which lead to a more efficient local mixing and thereby fewer hot spots. Besides, they also play a fixed role to reduce mechanical vibration and maintain proper spacing between adjacent fuel rods. However, the application of wire wraps also gives additional pressure loss penalty. To ascertain the complicated effects of wire wraps on the operation of the fuel assembly and provide a check on the design of reactor cores, detailed thermal-hydraulic investigations on wire-wrapped rod bundles are essential.

Since one advantage of the wire spacer is an enhanced lateral mixing of coolant, extensive experimental works have been carried out to study flow mixing and the nature of secondary flows induced by the wire wraps. Collingham et al. (1970) investigated a 7-pin rod bundle and observed that the wire wrap causes a forced

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Nomenclature

α	upper base length of trapezoid (mm)
b	bottom base length of trapezoid (mm)
c	trapezoid height (mm)
c_p	specific heat capacity (J·kg^{-1}·K^{-1})
D	rod diameter (mm)
D_s	wire diameter (mm)
D_h	hydraulic diameter (mm)
F	frictional factor
$F_{h,j}$	diffusional energy flux in direction x_j
H	helical wire pitch (mm)
K	thermal conductivity (W·m^{-1}·K^{-1})
L	width across flats of the hexcan (mm)
p	pressure (Pa)
p_{static}	static pressure (Pa)
p_{total}	total pressure (Pa)
p_{out}	static pressure at outlet (Pa)
P	rod pitch (mm)
pe	Peclet number, Pe = RePr
pr	Prandtl number, $Pr = \mu c_p/K$
ΔP_f	frictional pressure loss (Pa)
q_w	heat flux density (W/m^{-2})
Re	Reynolds number, Re = $\rho u_{in} D_h/\mu$
T	temperature (K)
T'	fluctuations about the ensemble average temperature (K)
T_w	wall temperature (K)
T_f	bulk temperature of the coolant (K)
u_i	velocity component in direction x_i
u_j	velocity component in direction x_j
u_{in}	inlet velocity (m·s^{-1})
u'	fluctuations about the ensemble average velocity (m·s^{-1})
x_j	Cartesian coordinate (i = 1, 2, 3)
x_j	Cartesian coordinate (j = 1, 2, 3)
δ_{ij}	Kronecker delta
ρ	density (kg·m^{-3})
μ	dynamic viscosity (Pa·s)
τ_{ij}	viscous stress tensor components

drive of the coolant between inner and outer sub-channels to reduce temperature difference. Fenech (1985) showed that the cross-flow between sub-channels increases with Reynolds number and tends to reduce the hot spot factors. Lorenz et al. (1974) found that the wire wrap improves the flow mixing and makes the average velocities in both peripheral and interior sub-channels nearly equal to the average bundle velocity. Fernandez and Carajilescov (2000) measured the static pressure and wall shear stress distributions in a 7-pin rod bundle and discovered that the dimensionless static pressure and wall shear stress profiles are nearly independent of the Reynolds number but strongly dependent of the wire wrap position. Diller et al. (2009) compared a fuel assembly designed with wire wrap spacer and traditional grid spacer. Relative to the grid spacer design, they found wire wrap design has smaller fretting wear, lower pressure loss and higher CHF. Later, an economic analysis was also presented by Shuffler et al. (2009) to investigate the potential economic benefits of fuel assembly supported by these two designs. Also, various experiments have been performed to derive suitable pressure loss and heat transfer correlations for wire-wrapped rod bundles. These include the works of Novendstern (1972), Rehme (1973, 1987), Engel et al. (1979), Cheng and Todreas (1986), Choi et al. (2003) for friction factor analysis and Arwikar and Fenech (1979), Kazimi and Carelli (1980) and Fenech (1985) for Nusselt number analysis. Chun and Seo (2001) investigated a 19-pin rod bundle to assess the performance of the existing correlations for friction factor. A similar work was reported by Choi et al. (2003) for a 271-pin fuel assembly. Recently, Chen et al. (2014) also made a detailed comparison of these correlations and evaluated their applicable ranges.

In addition to experiments, CFD simulations were also performed mainly based on Reynolds averaged Navier-Stokes (RANS) turbulence models to obtain the details of flow field and temperature distributions which are extremely difficult to measure with experimental techniques but essential for design optimization. Ahmad and Kim (2006) simulated a 7-pin rod bundle and showed that the transverse gradients induced by wire wraps exhibit directional periodicity between adjacent sub-channels. Gajapathy et al. (2007) investigated a 7-pin rod bundle with and without wire wraps. Their results revealed that the difference in bulk temperature between peripheral and central sub-channels is reduced by a factor of 4 when compared to that with bar rod. Later, the same authors Gajapathy et al. (2009) also characterized the thermal-hydraulic features in rod bundle having 7, 19 and 37 pins and their extendibility to 217-pin assembly. Raza and Kim (2008a) compared three cross-sectional shapes of the wire, viz., the circular, hexagon and rhombus and concluded that the last geometry gives the highest overall pressure loss as well as heat transfer rate. Hamman and Berry (2010) found that the peak temperature generally exists near the regions between the rod and an adjacent wire wrap, which suggested the need for design optimization to avoid localized hot spots appear. Rasu et al. (2013) investigated the flow and temperature development in the entrance region of a 37-pin rod bundle. The wire wrap was seen to shorten the thermal entry length and significantly enhance the global heat transfer whereas its influence on hydrodynamic entry length is not significant. Gajapathy et al. (2015) studied the helical pitch and wire diameter effects on the flow and temperature distribution of a 217-pin fuel assembly. They showed that the transverse flow, friction factor and Nusselt number increase with decrease in helical pitch and increase in wire diameter. Recently, Gajapathy and Velusamy (2016) also compared a fuel assembly wrapped with helical and straight wires to assess the advantages of using former case. Merzari et al. (2016) performed a series of 7-pin rod bundle simulations using RANS models (k-ε cubic model, k-ε realizable model, k-ω SST model) and showed SST k-ω model reproduces correctly the behavior in the immediate proximity of the wire while all k-ε models underestimate it. Brockmeyer et al. (2016) studied the bundle size effects on inter-subchannel mixing of inner sub-channels. They observed that the transverse velocity and mass exchange increase with larger bundle sizes and the inter-subchannel mixing is a strong function of bundle size for bundles up to 91 pins. Raj and Velusamy (2016) investigated the local flow pattern and heat transfer in a 217-pin fuel assembly with an axial length of seven helical wire pitches. The transverse flow in the central sub-channels was found to follow a cosine profile and the mean clad temperature exhibited a non-monotonic increase along the flow direction.

On the other hand, when uprating the power density of reactor cores, one of the technical issues is to improve the thermal-hydraulic performance of the fuel assembly. Relative to the single-wire wrapped fuel assembly, the design of fuel assembly with multi-wire wraps (i.e., double-wire or four-wire wraps) has