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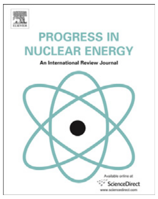

Flow and temperature developments in a wire-wrapped fuel pin bundle of sodium cooled fast reactor during low flow conditions

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ABSTRACT

Laminar flow of sodium in the entrance region of a seven pin nuclear fuel bundle with helically wound spacer wires is numerically investigated. Pin diameter, pin pitch, helical wire pitch and Reynolds number are varied as parameters. Evolutions of cross-stream velocity, friction factor and Nusselt number are critically studied. Nusselt number and friction factor exhibit periodic spatial oscillations in the entrance region, contrary to monotonic reduction observed in straight ducts. For identical Reynolds number, the friction factor exhibits a strong dependence on helical pitch of wire wrap where it increases as the pitch shortens. On the contrary, the Nusselt number does not exhibit such a strong dependence on helical pitch. A strong non-zero cross-stream velocity prevails in the fully developed region, contrary to that observed in straight channels. The mean value of non-dimensional cross-stream velocity is found to scale as $\pi d/H$, where, d is the pin diameter and H is the helical pitch. The friction factor and cross-stream velocity are relatively high in tight pin bundles. Based on parametric studies, a correlation is proposed for fully developed friction factor in pin bundle.

1. Introduction

Flow and temperature developments in the entrance region of channels and tubes have attracted the attention of heat transfer researchers due to the large heat transfer coefficient and friction factor in the entrance region. A detailed survey of literature in this area can be found in Shah and London (1978). Flow in the entrance region of elliptical ducts and eccentric annular ducts were studied by Feldman et al. (1982) and Velusamy and Garg (1993). Entrance flows in semi circular ducts were studied by Manglik and Bergles (1988, 1996). All these studies dealing with straight channels indicate that both the friction factor and heat transfer coefficient decrease monotonically along the flow direction in the developing region to stabilize to a constant value in the fully developed region. But in coiled tubes, the heat transfer coefficient and friction factor exhibit a non-monotonic variation in the developing region. Lin et al. (1997) found that both the friction factor and Nusselt number are oscillatory in the entrance region of helical pipes. They also concluded that laminar flow of water with high Reynolds number generates a mild oscillation in friction factor and a relatively strong oscillation in Nusselt number in the entrance region. Acharya et al. (1993) have studied the flow through coiled tubes and found that the Nusselt number in the entrance region falls well below the fully developed value. The complex interaction between growth of boundary layer along the duct wall and the development of secondary flows due to coiled geometry of tubes, leads to this non-monotonic variation. The heat transfer coefficient and friction factor in the entrance zone, even reduces below the fully developed value. But, in the developed region, the heat transfer coefficient and friction factor are constant.

In the case of nuclear fuel pin bundles, helically wound spacer wires are used to protect the fuel bundle against flow induced vibration. Provision of spacer wires generates secondary flows in the entrance region of pin bundle, which promotes mixing of coolant. Growth of boundary layers around a large number of fuel pins and their interaction with developing secondary flows need to be understood. To the best knowledge of these authors, developing flow in the entrance region of fuel pins with helically wound spacer wire has not been reported in open literature. This forms the motivation for the present work.

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Recently, Govindha Rasu et al. (2013) studied turbulent flow development in the entrance region of bare fuel pin bundles. They also observed similar spatial oscillations in Nusselt number and friction factor. Also it was found that more the number of pins larger is the thermal development length. Natesan et al. (2010) carried out a numerical analysis of turbulent flow and temperature in a 19-pin bundle for a length of one helical pitch. Nusselt number and friction factor at the end of one helical pitch were compared with fully developed data. It was found that while the friction factor matches with the experimental data the Nusselt number does not. Water flow through a seven-pin bundle with helical wires was studied by Sreenivasulu and Prasad (2011). They also considered an axial length of only one helical pitch in their study. Tenchine et al. (2012) analysed the thermal hydraulics of a 61-pin bundle for a length of nine helical wire pitches. But their study does not report entrance region heat transfer characteristics.

Based on the above literature survey, it is clear that flow through helical tubes behaves differently in the entrance region compared to that in straight tubes. Also, most of the earlier studies reported for pin bundles are either for fully developed flows or for only one helical wire pitch length. The entrance region behaviour in pin bundle with helical wires is not reported in open literature for laminar flows. The present paper attempts to study this aspect, wherein pin bundle with multiple helical pitch length is considered and flow in the entrance region is examined critically. Further, detailed parametric studies are carried out for various values of helical pitch, pitch to diameter ratio and Reynolds number.

2. Mathematical model

Flow through fuel bundle is in turbulent regime during full power conditions. But during shut down condition with only decay heat generation, the flow regime is laminar. Hence, the present studies focus only on laminar forced convection. In Cartesian tensor notation, the conservation equations that govern steady laminar incompressible sodium flow and heat transfer processes in the pin bundle can be expressed as:

Continuity:

$$\frac{\partial}{\partial x_j}(\rho u_j) = 0 \tag{1}$$

Momentum balance:

$$\frac{\partial}{\partial x_j}(\rho u_j u_i - \tau_{ij}) = -\frac{\partial p}{\partial x_i} \tag{2}$$

In Eq. (2), $\tau_{ij} = 2\mu s_{ij} - \frac{2}{3}\mu\frac{\partial u_k}{\partial x_k}\delta_{ij}$ and. $s_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$

Here, μ denotes the dynamic viscosity of sodium.

Energy balance:

$$\frac{\partial}{\partial x_j}\left(\rho u_j c_p T - K\frac{\partial T}{\partial x_j}\right) = 0 \tag{3}$$

Sodium enters the tube bundle with a uniform axial velocity of $u_{z\text{-}in}$. The cross-stream velocity components u_x and u_y at the entrance are set as zero. Temperature independent sodium properties, evaluated at 420 °C have been considered in the present simulations. The values of density, specific heat, thermal conductivity and dynamic viscosity of sodium used are 852.3 kg/m^3, 1274.5 J/kg-K, 70.2 W/m-K and 2.72×10^{-4} kg/m-s respectively. The surfaces of hexcan, fuel pins and spacer wires are prescribed as no-slip walls. It may be highlighted that in the present case, the heat source is from the fuel pin and not from the wire. Secondly, the wire is in line contact with the fuel pin. Further, the heat flux on the wire-wrap is unknown. For a realistic computation, the heat conduction within the fuel pin, clad as well as spacer wire and convection in sodium have to be solved in conjugation. However, in the present studies the wire is assumed to be adiabatic, while the clad is supplied with a constant flux of 16 kW/m^2. Justification for this assumption is presented in Appendix-A. This heat flux is about 1% of the full power value in a typical sodium cooled fast reactor. The pin bundle outlet is fixed as a constant pressure boundary at zero reference value.

The three dimensional form of governing equations are numerically solved by a finite volume method. The SIMPLE algorithm (Patankar, 2005) is chosen for resolving pressure–velocity coupling in the incompressible flow formulation. For combining convective and diffusive fluxes in all the transport equations the second order upwind scheme is adopted. For achieving convergence, the tolerance on the residual values for all the governing equations is set as 10^{-6}. Fluent-6.3 code (2007) is used for the numerical solution.

The non-dimensional cross-section averaged cross-stream velocity is calculated using

$$V_{cs} = \frac{1}{A}\int_A \frac{\left(u_x^2 + u_y^2\right)^{1/2}}{u_{z-in}} dA \tag{4}$$

where, u_x and u_y are the cross stream velocity components, u_z is stream-wise velocity component and A is the cross section area normal to main flow direction.

The local friction factor (f) is calculated using

$$f = \frac{-(dp/dz)D_h}{\rho u_{z-in}^2 / 2} \tag{5}$$

where, D_h is the hydraulic diameter of the pin bundle, p is pressure and z is axial coordinate. The global Nusselt number, (Nu_G) at any axial position based on clad surface temperature ($T_{C\theta}$) of all the pins and the global bulk sodium temperature (T_{G-Na}), is calculated using

$$Nu_G = \frac{q''(D_h/K)}{\left[\frac{1}{2\pi N}\sum_{i=1}^{N}\left(\int_0^{2\pi} T_{C\theta}d\theta\right)_i - T_{G-Na}\right]} \tag{6}$$

where, q'' is the heat flux on pin surface, N is number of pins (here, it is 7) and K is the thermal conductivity of sodium.

Structured grid generation for pin bundles wrapped with helical wires is a challenging task. While generation of unstructured mesh employing tetrahedral cells is relatively easy, the number of cells required is very high. It was found that about 1.32–3.28 million mesh is required to simulate one helical pitch length of 7-pin bundle (Sreenivasulu and Prasad, 2011). This leads to a high demand on computer memory and also limits the pin bundle lengths that can be simulated. So, the usage of unstructured tetrahedral mesh is not a suitable option for the pin bundle with multiple helical pitches. To overcome this problem, a customised grid generator, GridZ (CFDExpert, 2009) is utilised for generation of structured mesh. The diameter of fuel pin, spacer wire and triangular pitch are taken as 6.6 mm, 1.65 mm and 8.28 mm respectively. The length of helical pitch is 200 mm. The Reynolds number and hydraulic diameter are 840 and 3.952 mm respectively.

Grid independency test is carried out in two ways: (i) by varying the number of grids in radial direction, and (ii) by varying the axial grid size. Two different cross-stream mesh densities, viz., 1.181 and 4.233 millions are considered for the same axial grid size by