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Investigations of flow and temperature field development in bare and wire-wrapped reactor fuel pin bundles cooled by sodium

N. Govindha Rasu [a], K. Velusamy [a,*], T. Sundararajan [b], P. Chellapandi [a]

[a] Thermal Hydraulics Section, Indira Gandhi Centre for Atomic Research, Kalpakkam 603 102, India
[b] Department of Mechanical Engineering, I.I.T. Madras, Chennai 600 036, India

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ABSTRACT

Simultaneous development of liquid sodium flow and temperature fields in the heat generating pin bundles of reactor has been investigated. Development characteristics are seen to be strongly influenced by pin diameter, number of pins, helical wire-wrap, ligament gap between the last row of pins and hexcan wall and Reynolds number. Flow development is achieved within an axial length of ~125 hydraulic diameters, for all the pin bundle configurations considered. But temperature development is attained only if the pin diameter is small or the number of pins is less. In the case of large pin diameter with more pins, temperature development could not be achieved even after a length of ~1000 hydraulic diameters. The reason for this behavior is traced to be the weak communication among sub-channels in tightly packed bundles. It is seen that the pin Nusselt number decreases from center to periphery in a bundle. Also, if the ligament gap is narrow, the Nusselt number is large and more uniform. Flow development length is short if the Reynolds number is large and the converse is true for thermal development length. Helical wire-wrap shortens the thermal entry length and significantly enhances the global Nusselt number. But, its influence on hydrodynamic entry length is not significant.

1. Introduction

Fuel pins in Fast Breeder Reactors (FBRs) work in a demanding environment of high neutron flux and are subjected to various thermal loading conditions. The hostile conditions prevailing in the reactor core pose severe challenges for receiving high burn up of the fuel without compromising on safety. Towards this, a thorough understanding of the thermal hydraulic behavior of core is essential. Improving the core design and enhancing fuel performance are directly coupled to economic benefits. The average heat flux on FBR fuel pin is very large (~2 MW/m^2). However, there are significant variations in the heat generation rates of fuel pins, in both the axial and radial directions, due to variation in the neutron flux. Furthermore, the mass flow rates of coolant sodium are not uniform in the flow sub-channels surrounding the fuel pins. As a consequence, there are strong temperature variations around the fuel pins which give rise to local hot spots at locations of deficient coolant supply. Such temperature non-uniformities could influence the life of the fuel pin and also have a direct bearing on the reactor safety. Experimental determination of detailed flow and heat transfer characteristics of sodium through heat generating fuel pin bundles is very difficult due to the following reasons: (i) sub-channel dimensions are very small (typically 3 mm is the hydraulic diameter), (ii) measuring instruments are required to function at elevated temperatures (200–600 °C), (iii) flow visualization is hampered by the opaque nature of sodium and (iv) water flow cannot correctly simulate sodium heat transfer. Moreover, it is almost impossible to measure detailed temperature distribution of fuel pins in any operating reactor.

FBR fuel pins are arranged in a tightly packed triangular pitch and are housed in a hexagonal sheath known as subassembly. Due to this tight packing, the flow communication between the various sub-channels becomes very weak. As a result of this, flow development in sub-channels comprises of two regimes, viz., (i) local flow development within the sub-channels and (ii) global flow redistribution among the sub-channels. While the local flow development in sub-channels is governed by local hydraulic diameter or sub-channel hydraulic diameter, the global flow development is a strong function of the resistance for flow redistribution among the central and peripheral sub-channels. The weaker the communication, the larger is the global development length. The global development regime could be a function of pin diameter, pitch, presence of helical wire-wrap spacer, the clearance between the hexagonal sheath and the outer most pins, Reynolds number, etc. Knowledge of flow and temperature characteristics in the entrance region is very essential for the experimental determination of friction factor and Nusselt number.

* Corresponding author.
E-mail address: kvelu@igcar.gov.in (K. Velusamy).

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Nomenclature

C	turbulent model constants (or) coefficient in Nusselt number correlation
c_p	specific heat
D_h	hydraulic diameter (= 4 × flow area/wetted perimeter)
f	friction factor
$F_{h,j}$	effective heat flux containing laminar and turbulent contributions
k	turbulent kinetic energy
K	thermal conductivity of coolant
L	length in the flow direction
N	total number of pins in the bundle
Nu	Nusselt number
Nu_C	average pin Nusselt number based on $T_{G\text{-}Na}$
$Nu_{C\theta}$	local pin Nusselt number based on $T_{G\text{-}Na}$
$Nu_{C\text{-}SC}$	average pin Nusselt number based on $T_{G\text{-}Na}$
Nu_G	global Nusselt number
p	pressure
Pe	Peclet number ($w_{in} \times D_h/\alpha$)
q''	heat flux
Re	Reynolds number ($\rho \times w_{in} \times D_h/\mu$)
RSM	Reynolds stress model
s_{ij}	strain rate tensor
T	temperature
T_{in}	coolant inlet temperature
$T_{C\theta}$	local clad temperature
$T_{G\text{-}Na}$	global average sodium temperature
$T_{SC\text{-}Na}$	average sodium temperature of all sub-channels surrounding the pin
$\overline{T}_C$	circumferential averaged clad temperature at any Z
$u_{i,j,k}$	velocity components
w	axial velocity of coolant
w_{in}	coolant inlet velocity in Z-direction
$x_{i,j,k}$	spatial coordinates
Z	axial coordinate (stream wise coordinate)

Greek symbols

α	thermal diffusivity of coolant
δ_{ij}	Kronecker delta
ε	turbulent dissipation rate
μ_t	turbulent (or eddy) viscosity
μ	laminar viscosity
ϕ	pin diameter
ρ	density of coolant
$\rho\overline{u_i'u_j'}$	Reynolds stress
$\rho c_p\overline{u_j'T'}$	turbulent heat flux
σ_k, σ_ε	turbulent Prandtl numbers of k and ε
θ	angle around the pin
τ_{ij}	total stress

Because of non-uniform flow development in the central and peripheral sub-channels, the local heat transfer coefficients can also vary vastly among the central and peripheral pins. Also the local heat transfer coefficients can be significantly different from the global heat transfer coefficients. To the best knowledge of the present authors, no comprehensive study of flow and temperature field development in heat generating rod bundles has been reported in open literature. Further, measured heat transfer coefficients depend strongly upon (i) the tube bundle length considered in the experiments, (ii) the care exercised in measuring the circumferential temperature variation in pins, (iii) definition of bulk temperature of sodium, etc., in addition to geometric parameters. The flow redistribution among the central and peripheral sub-channels could be influenced by the gap between the hexagonal sheath and the outermost rows of pins. Hence, in the present three dimensional Computational Fluid Dynamics (CFD) studies, detailed simulations on bare pin bundles and limited simulations on wire-wrap bundles have been carried out towards addressing some of the basic phenomena concerning entrance region.

In order to maintain adequate gap between pins in the bundle to aid sodium flow and to protect pin bundles against flow induced vibration either grid spacers or helical wire-wraps are usually adopted. While the helical wire-wrap can promote flow redistribution effectively among various sub-channels with minimum pressure drop the grid spacers are not that effective (Todreas and Kazimi, 1993). The present study is directed towards developing basic understanding of the simultaneous development of velocity and temperature during liquid metal flow through pin bundles and brings to light the various factors which influence the hydrodynamic and thermal field development.

2. Literature survey

Experiments using various liquid metal coolants and different combinations of pin diameter, numbers of fuel pins, lattice structure and Reynolds number range, have been reported in the open literature. Most of these experiments do not use spacer wires around fuel pins.

Mikityuk (2009) has summarized the heat transfer correlations derived from experimental data for bare pin bundles cooled by liquid metal coolant (Fig. 1). While the Nusselt number correlation proposed by most of the authors are limited to the Peclet number (Pe) within 10,000, Friedland and Bonilla (1961) proposed a correlation for a wider range of Pe (10 < Pe < 100,000). Fig. 1 depicts a large deviation in the Nusselt number obtained through different correlations for identical Pe, especially for Pe < 5000. It may be highlighted that the number of pins considered in various experiments is reported to be different. Graber and Rieger (1972) have used the maximum number of pins (31) while Zhukov et al. (2002) used 22 pins. Other researchers have used less than 22 pins. In experiments with a fewer number of pins, the heat transfer behavior of peripheral pins assumes larger significance.

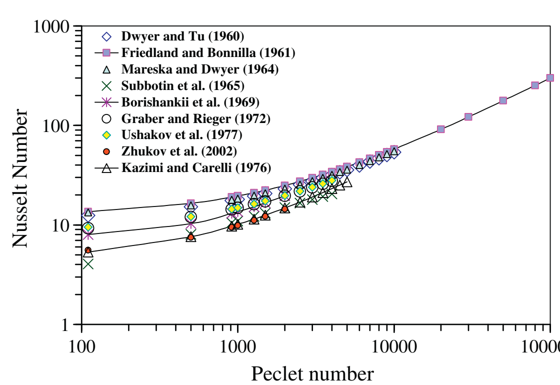

Fig. 1. Comparison of Nusselt number correlations for pin bundles (Borishanskii et al., 1969; Ushakov et al., 1977; Kazimi and Carelli, 1976).