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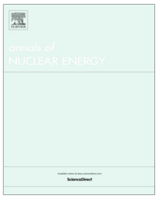

Characterization of velocity and temperature fields in a 217 pin wire wrapped fuel bundle of sodium cooled fast reactor

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A B S T R A C T

RANS based computational fluid dynamic (CFD) simulation of flow and temperature fields in a fast reactor fuel subassembly has been carried out. The sodium cooled prototype subassembly consists of 217 pins with helical wire spacers. An axial length of seven helical wire pitches has been considered for the study adopting a structured mesh having 36 million points and 84 processors in parallel. The computational model has been validated against in-house and published experimental data for friction factor and Nusselt number. Also, the transverse flow in the central subchannel and swirl flow in the peripheral subchannel are compared against reported experimental data and those computed by subchannel models.

The focus of the study is investigation of transverse and axial flows in different types of subchannels. Based on the 3-dimensional CFD study, correlations have been proposed for calculation of transverse flow, which forms an important input for development of subchannel analysis codes. Periodic variations have been observed in the subchannel axial flow rates. For the subchannels located in the central region, the peak to peak variation in the axial flow rate is ~21% and it is found to be contributed by the changes in the flow area and hydraulic resistance due to frequent passage of helical wires through the subchannel. For the subchannels located in the periphery, this variation is as high as 50%. The transverse flow in the central subchannels follows a cosine profile, for all the faces. However, there is a phase lag of 120° among the three faces that bound the subchannel. In the peripheral subchannels, a strong unidirectional transverse flow prevails in the faces perpendicular to the hexcan wall. On the other hand, the transverse flow in the face parallel to the hexcan follows a square wave pattern. The CFD results indicate that the swirl velocity in the peripheral subchannel is non-uniform, contrary to that considered in the traditional subchannel models. The mean clad temperature is seen to exhibit a non-monotonic increase along the flow direction. This phenomenon is more dominant in the peripheral pins due to large gradient in subchannel temperature and the square wave profile of the transverse flow.

1. Introduction

Helical wire-wrapped fuel pins of sodium cooled fast reactors (SFRs) are subjected to high heat flux of ~2 MW/m^2 and hence the fuel clad faces sustained high temperature leading to large creep damage. The gap between the hexcan wall and peripheral pins offers a low resistance flow passage compared to the central region, causing significant flow bypass towards the peripheral subchannels (SCs). Apart from supporting the fuel pins against flow induced vibrations, the spacer wires induce prominent transverse flow. As consequences of these, there are periodic flow oscillations in the subchannels along the stream-wise direction. Also, the clad is subjected to significant temperature variations around the circumference leading to thermal stress in the clad. The creep life of the fuel subassembly depends on the peak clad temperature, which in turn depends on hot-channel factors and hotspot factors (Waltar and Reynolds, 1981). Many of these factors depend on flow physics inside the subassembly. Due to small-scale features of the subchannels (hydraulic diameter is only ~3 mm), measurements of local cross flow and axial flow features and local clad temperature variations along the circumference are extremely difficult. This is compounded by opaque nature of sodium and difficulties in performing experiments at elevated temperatures (~500 °C). Such experiments can be attempted only for bundles with minimum number of pins. For a prototype subassembly with 217 pins (Chetal et al., 2006), generating a large power of 8 MW, the core design has to depend on computational fluid dynamics simulations. Thus, understanding the local flow and heat transfer features of a

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Nomenclature

English alphabets

C	turbulent model constants
C_p	specific heat
D	diameter of fuel pin
D_e	equivalent diameter of the bundle (=4 × flow area/heated perimeter)
D_h	hydraulic diameter of the bundle (=4 × flow area/wetted perimeter)
D_w	diameter of helical spacer wire
h_z	heat transfer coefficient at any axial section.
H	helical pitch of spacer wire
k	turbulent kinetic energy
K	thermal conductivity of coolant
Nu	Nusselt number
P	pressure (or) fuel pin pitch
Pe	Peclet number
q''	heat flux at any axial section.
Re	Reynolds number ($\rho \times V_a \times D_h / \mu$)
$S_{i,j}$	rate of deformation tensor
T	temperature
T_{bz}	bulk mean coolant temperature at any axial section
T_{cz}	mean clad temperature at any axial section
$u_{i,j,k}$	velocity components
V_a	axial velocity of coolant at inlet
V_t	transverse velocity
V^*_{Lt}	non dimensional transverse velocity, normalized with local axial velocity
V^*_t	non dimensional transverse velocity, normalized with bulk axial velocity

Greek symbols

α	wire angle
δ_{ij}	Kronecker delta
ε	turbulent dissipation rate
μ_l	laminar viscosity
μ_t	turbulent (or eddy) viscosity
μ_{eff}	total dynamic viscosity
ρ	density of coolant
τ_{ij}	total stress
τ_w	wall shear stress
θ	angle around the pin

Acronyms

CFD	computational fluid dynamics
LES	large eddy simulation
RANS	Reynolds averaged Navier–Stokes
RNG	re-normalization group
SC	subchannel
SFR	sodium cooled fast reactor

SFR subassembly is essential for improvement in core design in the direction of augmented economy and enhanced safety. Numerous previous works investigated the thermal hydraulics of subassemblies using subchannel approach as detailed by Wantland (1974), Basehore and Todreas (1980), Kim et al., (2002), Memmott et al., (2010), Wu et al., (2013), Syeilendra and Takahashi (2013) and Liu and Scarpelli (2015). In the subchannel approach, the chief assumption is axial flow is dominant compared to transverse flow. So, the axial flow is rigorously treated by solving the governing equations, whereas the transverse flow is handled with a simplified model in the form of algebraic expressions. This approach is very handy and is well suited for parametric studies as the computational time required is relatively small compared to a CFD simulation. SUPERENERGY, MANTRA-LMR, RELAP5-3D and COBRA-LM are some of the popular subchannel codes used in SFR core design. In most of the subchannel codes for wire wrapped bundle, the effect of helical wire is axially averaged and the diversion effect of wire in peripheral region is modeled employing an analytical expression for the unidirectional swirl (Chiu et al., 1978a). Subchannel code by Wantland (1974) considered the diversion effect of wire in the inner regions using an analytical expression for transverse velocity. The transverse velocity model was derived from the assumptions that (i) only the wire passing through a face of a subchannel induces cross flow in that face, (ii) the maximum transverse flow occurs when the wire blocks the face, and (iii) the wire acts as a vane. However, the validity of these assumptions has not been explicitly established. Thanks to the advancements in CFD simulations, transverse velocity distribution can be properly predicted by 3-dimensional calculations. Further, the mass exchange between any two subchannels varies along the axial direction depending on the position of the helical wire, location of the pin in the bundle and the type of subchannel under consideration.

A large number of hydraulic experiments have been reported for SFR fuel subassembly. Many of them focused on pressure drop characterization, while a few of them were dedicated to study the intricate flow features. For example Lafay et al. (1975), conducted experiments in wire wrap 19 pin bundles, to study local pressure and peripheral flow distributions. They found that the measured value of transverse velocity is higher than that calculated by the assumption that the flow follows the helical wire. Further, they also highlighted the importance of understanding the local flow field in developing accurate mixing models for wire wrapped bundles. Roidt et al. (1980) performed experiments in scaled up 1/6th sectors of fuel and breeder subassemblies with air as the working fluid. They established the static pressure gradient and transverse velocity field within various subchannels. Fernandez and Carajilescov (2000) studied a 7-pin bundle for understanding static pressure and wall shear stress distributions using air as the working medium. They reported that since dependence of wall shear stress on Reynolds number is negligible, the wire generated cross flow greatly masks any secondary flow that is induced by the turbulence. Bogoslovskaya et al., (2000) experimentally predicted the transverse flow of liquid metal in a 19 pin bundle. They observed a sinusoidal pattern in transverse flow field.

Extensive experiments have been performed by many researchers to derive suitable pressure drop correlations for wire wrapped rod bundles. These include the works of Novendstern (1972), Rehme (1973), Engel et al. (1979), Baxi and Dalle-Donne (1981), Cheng and Todreas (1986), Choi et al. (2003), Bubelis and Schikorr (2008) etc. Recently, Chen et al. (2014) made a detailed comparison of these correlations and evaluated their applicable ranges. Correlations for fully developed Nusselt number in wire wrapped rod bundle were proposed by Kazimi and Carelli (1976).

In the recent past, the number of CFD investigations on pin bundle thermal hydraulics has been on the rise. Ahmad and Kim (2006) carried out thermal hydraulic analysis on 7 and 19 pin wire wrapped bundles by solving the RANS equations over one pitch length, using the periodic boundary condition. They reported that in wire wrapped fuel subassemblies, subchannel fluid temperatures surrounding the central pin are not identical. Further, this temperature gradient around the pin is periodically repeated for