Nuclear Engineering and Design 332 (2018) 226–237

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

# Thermal-hydraulic effects of inserts in a fast reactor fuel bundle

G. Padmakumar[a], K. Velusamy[a,*], B.V.S.S.S. Prasad[b], P. Lijukrishnan[a], G.K. Pandey[a], P. Selvaraj[a]

[a] Indira Gandhi Centre for Atomic Research, HBNI, Kalpakkam, India
[b] Indian Institute of Technology, Madras, Chennai, India

## ARTICLE INFO

*Keywords:*
Sodium cooled fast reactor
Wire-wrap pin bundle
Sub-channel flow
Inserts
CFD
Experiments
PEC

## ABSTRACT

The efficacy of inserts in the peripheral sub channels of a model fast reactor pin bundle with helical spacer wire has been investigated by 3 dimensional computational fluid dynamics (CFD) simulations as well as water experiments. Three different types of inserts, viz., triangular, semicircular and circular inserts have been considered along with a bundle without any insert. Sub channel sodium temperature, axial and circumferential temperature distributions of clad among the pins, Nusselt number and friction factor are the parameters targeted for the investigation. The CFD model has been validated by comparing the predicted pressure drop against measured pressure drop for water flow, for the cases of bundle with circular inserts and bundle without inserts. Thermal part of the CFD model has been validated against published Nusselt number for bundles without any insert. The inserts are found to reduce flow bypass in the peripheral sub channels and promote increase in central sub channel flow. As a consequence of this, the clad temperature with inserts was found to be lower than the bundle without any inserts. However, inserts were found to increase the friction factor. The increase in Nusselt number and friction factor for circular inserts are 86% and 17% more than that of a bundle without inserts. To find the optimum insert type, a Performance Enhancement Criterion (PEC) factor has been defined. This factor is found to be the maximum for circular inserts.

## 1. Introduction

Sustained and safe operation of sodium cooled fast reactor (SFR) is characterized by the core configuration and the design limits of temperature for the various operating conditions. Understanding of the complex thermal hydraulics of the sodium coolant flow through the core is vital for arriving at these design limits. A typical fuel subassembly has a large number of small diameter fuel pins arranged in a triangular pitch and with a positive gap between the fuel pins to allow flow of coolant. The cold sodium enters the subassembly and heat transfer from the fuel pin to sodium takes place when sodium flows through these sub-channels and hot sodium leaves at the top of the subassemblies. The heat generation in fuel pins varies both in axial and radial directions because of the variation in neutron flux. The mass flow rate of coolant is not uniform in all the sub-channels surrounding the fuel pins. Hence, there are significant temperature variations around the fuel pins which give rise to local hot spots. To minimize this issue, the fuel pins are separated by spacer wires helically wound around the pins which provide support for the fuel pins and also assist in mixing of coolant among the sub-channels. The heat transfer coefficient of the coolant also increases because of this transverse flow movement of sodium in the sub-channels. The coolability of core definitely increases because of the presence of spacer wire. However, there still exists a temperature gradient across the cross section.

The central sub-channels are around the central fuel pins and the peripheral sub-channels are between the outer hexcan walls and outer row of fuel pins. The sub-channel flow areas around the central fuel pins are nearly the same. However, the edge/peripheral sub-channels have more flow areas than the central sub-channels and hence more sodium flow occurs through the peripheral sub-channels. On the other hand, the heat generation is relatively more in the central sub-channels and low in the peripheral sub-channels. This leads to large variation in the sub-channel sodium temperature, characterized by low sodium temperature in the peripheral sub-channels and high sodium temperature in the central sub-channels. Higher sodium temperatures in the central sub-channels lead to large clad temperature in the central fuel pins. To respect the peak clad temperature limits, more sodium flow into the subassembly is required.

It is important to reduce the non uniformity in the temperature distribution across the cross section of subassembly arising out of the non uniform coolant flow. The efforts towards reducing the bypass flow occurring in the peripheral sub channels would lead to a more uniform sub channel temperatures. This would also result in an optimized subassembly flow and eventually a high hot pool temperature. Approach to

---

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

https://doi.org/10.1016/j.nucengdes.2018.03.037
Received 2 December 2017; Received in revised form 21 March 2018; Accepted 23 March 2018

**Nomenclature**

| | |
|---|---|
| $D_h$ | Hydraulic diameter |
| $\Delta P$ | Pressure drop |
| f | Friction factor |
| h | Heat transfer coefficient |
| K | Thermal conductivity of sodium |
| Nu | Nusselt Number |
| $\xi$ | Hot spot factor |
| $q''$ | Heat flux |
| Re | Reynolds Number |
| T | Temperature |

reducing the peripheral sub channel flow area would be by the use of inserts which would reduce the flow areas and thereby divert more flow towards the central sub channels. In this paper, different types of inserts, viz., circular, semi circular and triangular are studied. Towards understanding the beneficial effect of these types of inserts, a 7 pin fuel bundle has been investigated. The study is mainly focused on uniformity of flow in all the sub-channels and thereby improving the heat transfer coefficient to achieve a lower clad hot spot temperature.

The improvement in the flow distribution among the central and peripheral sub-channels, reduction in mean clad temperature and the increase in Nusselt number as a result of inserts have been quantified. The investigation is based on 3 dimensional Computational Fluid Dynamic (CFD) simulations, where the model has been validated through experiments performed in water models. Clad temperature variation among the pins along the axial and circumferential directions, subchannel sodium temperature, Nusselt number, pressure drop and friction factor are studied in detail. The hot spot factor which is important for core design has been quantified. The pressure drop in a 7 pin bundle with and without inserts has been measured using differential Pressure Transmitter. The pressure drop values in the bundle are then compared with the CFD predicted results.

## 2. Literature survey

Various researchers have reported work on investigation of thermal hydraulics of subassemblies. 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) etc have used subchannel approach to study the thermal hydraulics within the bundle with the assumption that axial flow is dominant compared to transverse flow. In the scheme of solution, 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. Computer codes namely SUPERENERGY, MANTRA-LMR, RELAP5-3D and COBRA-LM are some popular sub-channel codes used in SFR core design. However, literatures dealing with study of modification in subassembly geometry to modify the flow behavior have been sparse. The usages of inserts as an additional feature in the subassembly to improve the hydraulics and in turn heat transfer is not reported widely. The need of such study necessitates the selection of suitable models based on existing similar works.

Many researchers have reported experiments with SFR fuel subassembly for characterization of pressure drop in the subassembly. Lafay et al. (1975), conducted experiments in wire wrap 19 pin bundles, to study local pressure and peripheral flow distributions. The pressure drop in a 217 pin subassembly was studied and friction factor was estimated by Padmakumar et al. (2017). Water experiments have been conducted covering a wide range of Reynolds number encompassing laminar, transition and turbulent regimes. The experimental results have been transposed using Euler number similarity, to determine the pressure drop for sodium flow in the reactor. The derived friction factor was also compared with the data in literature.

Other researchers who have offered suitable pressure drop correlations for wire wrapped rod bundles include the works of Novendstern (1972), Rehme (1973), Engel et al. (1979), Baxi (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. Govindha Rasu et al. (2013), investigated entrance flow characteristics in a simultaneously developing flow for bundles with a maximum of 37 pins. They found that the flow is developed within an axial length of ~125 hydraulic diameters, but temperature development is achieved only when pin diameter is small or the number of pins is low. Govindha Rasu et al. (2014), investigated development of cross stream velocity as a function of helical pitch length and number of pins. They reported the existence of periodic spatial oscillations in friction factor and Nusselt number. Gajapathy et al. (2015) conducted a CFD based computation on a 217 pin bundle and analyzed the effect of helical pitch on the flow and temperature distributions and the variation in friction factor and Nusselt number as a function of helical wire parameters.

Ginsberg and Lorenz (1973) carried out experimental mixing studies in a pin bundle water model to establish data base for validating thermal hydraulic codes. Fenech (1985) studied local heat transfer and hot spot factors for wire wrapped tube bundles. Heat transfer coefficients and hot-spot factors have been determined from measured local temperatures and calculated local mass flux in seven adjacent tubes and associated sub-channels of a 61 wire-wrap tube bundle of a gas cooled fast reactor. In an effort to increase thermal efficiency of SFR, fuel subassembly design changes were investigated by Wigeland and Hamman (2009), using CFD simulations. The goal of their study was to evaluate the effects that subassembly hexcan design changes can have on subassembly coolant flow, temperature distribution and hot channel factors. Simulations were performed for a 19-pin subassembly with wire wrap spacers. It was shown that it would be possible to raise the

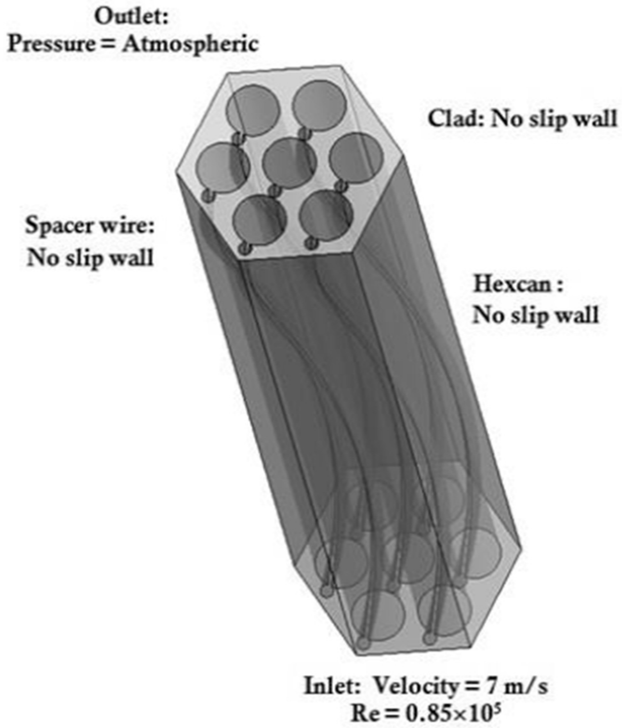

**Fig. 1.** Boundary conditions for numerical model.