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# The effect of various pressure drop and flow mixing correlations on subchannel calculation of sodium temperature distribution in a 19 pins wire wrapped bundle

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A B S T R A C T

Fuel assemblies of sodium cooled fast reactors are usually designed in wire wrapped configuration and subchannel analysis is an efficient approach for thermal hydraulic analysis of wire wrapped assemblies especially when two phase or transient analysis is required. As the subchannel method is a lumped parameter approach, for calculation of pressure drop and flow mixing, suitable correlations should be provided. So for subchannel analysis of wire wrapped assemblies various pressure drop and flow mixing correlations have been developed and reported in literatures. In this work, normalized temperatures of single phase sodium at the outlet of different channels of ORNL 19 pins wire wrapped bundle are calculated by subchannel approach. In these subchannel calculations, different pressure drop and flow mixing correlations are used. Then the calculated normalized temperatures are compared with experimental results of ORNL 19 pins bundle to find out which pressure drop and flow mixing correlations of wire wrapped assemblies, give the most accurate result.

## 1. Introduction

Calculation of sodium temperature distribution in fuel assembly is one of the important issues in thermal hydraulic analysis of Sodium cooled Fast Reactors (SFR). The fuel pins of sodium cooled assemblies are designed in hexagonal arrangement and are usually wire wrapped. The mechanisms which are important to the distribution of temperature in these assemblies are: thermal conduction, turbulent mixing and cross flow induced by radial pressure gradients. One computational method which provides detailed information about temperature distribution within the fuel assembly is CFD method. CFD analysis of wire wrapped assemblies due to the existence of helical wires and close gap between wires and fuel rods and extremely challenging geometry of wire wrapped assemblies, requires high computational power and only recently CFD has been able to accurately model wire wrapped sodium bundles (Fricano and Baglietto, 2014). Another method in thermal hydraulic analysis of wire wrapped assemblies is subchannel method. Subchannel approach is a lumped parameter approach which uses much less number of control volumes and as a result much less computational power in comparison to CFD method. So in analyses which very detailed information is not required, subchannel method is the best choice especially when transient or two phase or parameter study is required. Many interesting researches have been performed by subchannel method in different areas of thermal hydraulic analysis of fuel assembly. For example Wang et al. (2013a) have developed the subchannel analysis code of supercritical reactor (SACOS) code, which is also applicable for pressurized water reactor to perform the uncertainty study of subchannel calculations and their investigation show that the uncertainty analysis methods can provide larger reactor design criteria margin to improve the economy of reactor (Wang et al., 2013a). Ma et al. (2012) have studied the heat transfer rates of both triangular and square lattices based on annuli theory with modifications to consider the effect of hydraulic diameter, temperature difference, interactions and shape differences. Ma et al. have concluded in their work that the interaction correlation factor is generally equal to the thermal mixing length scale used in the subchannel analysis (Ma et al., 2012) and they provide a new correlation of thermal mixing length scale. Wang et al., (2013b) have developed a subchannel analysis code of steady state (SACOS-PB) for analysis of advanced lead bismuth fast reactors (ALBFR) and in their work they perform investigations on the optimum pitch to

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fuel diameter. Usual subchannel codes are designed for the land-based reactor cores (Cai et al., 2016). Cai et al. (2016) have developed a subchannel analysis code to evaluate the thermal hydraulic parameters of the reactor core under motion conditions. Pramuditya et al. (2013) have performed subchannel calculations for wire wrapped assemblies by considering the thermal expansion of pins and wires.

Two general approaches can be considered in subchannel analysis of wire wrapped assemblies. One is the conventional approach which is based on averaged flow area and averaged wetted perimeter. In this approach the wires are assumed to be smeared uniformly in all subchannels. Another approach is geometry change method in which the effect of wires on coolant area change is considered. Kim et al. (2002) and Pramuditya et al. (2013) have performed subchannel analysis based on geometry change approach. In conventional approach in which the average position of wires is considered, different pressure drop correlations like CTD (Cheng Todreas Detailed), Rehme, Novendstern, Engel, …and different flow mixing coefficients like Cheng-Todreas, Rogers and Rahir, …there exist. Chun and Seo (2001), Bubelis and Schikorr (2008), Chunu et al. (2011), Chen et al. (2014) and Chang et al (2016) have performed investigations on some pressure drop correlations in wire wrapped assemblies. Chun and Seo (2001) have compared the five pressure drop correlations namely, Cheng-Todreas (both simplified and original), Novendstern, Engel and Rehme with pressure drop of a wire wrapped 19 pins experimental fuel assembly and concluded that both original and simplified Cheng and Todread correlations show good agreement with experimental pressure drops for all flow regions. Bubelis and Schikorr (2008), investigated experimental pressure drop of three fluids like water, air and sodium in wire wrapped assemblies and concluded that in general the friction factor correlations providing a good fit to most of the experimental data are in order: Rehme, Sobolev, Novendstern, modified Engel, modified Baxi and Dalle-Done. Chunu et al. (2011) performed measurements of single and two phase pressure drop for sodium flow in 12 pins wire wrapped bundle and concluded that for single phase sodium flow, Sobolev and Baxi and Dalle-Done correlations give good pressure drop. Chen et al. (2014) provide a useful review about the different pressure drop correlations for wire wrapped assemblies. Chang et al. (2016) performed experiments on sodium flow in 37 pins wire wrapped bundle and concluded that predictions by Cheng-Todreas are the best fit for the experimental data. Also Tian et al. (2014) have made modifications for COBRA-EN subchannel code to perform subchannel analysis of Pb-Bi cooled reactors and in their work they calculate the temperature distribution within a 19 pins wired wrapped bundle with different flow mixing coefficients.

In this work, the effect of some pressure drop correlations and combination of them with some flow mixing correlations on subchannel calculation of single phase sodium temperature distribution in ORNL (Oak Ridge National Lab)19 pins wire wrapped bundle is investigated. For this purpose a steady state single phase subchannel program for ORNL 19 pins bundle has been developed in FORTRAN. Then the sodium normalized temperatures at the outlet of some specified channels calculated by different pressure drop and flow mixing correlations are compared with experimental results of ORNL 19 pins test bundle. ORNL 19 pins bundle has been selected as reference for two reasons. The first is that this experiment considers variety of liquid sodium flow rates and radial power distributions, which provides comprehensive benchmark and the second is that according to Gajapathy et al. (2009), 19-rod bundle is the smallest domain which can describe the flow pattern in larger bundles.

## 2. Subchannel method governing equations and numerical solution procedure

In subchannel method the mass, energy and axial momentum equations are solved for coolant centered subchannels which have been specified by solid lines in Fig. 1. For lateral momentum equations, separate control volumes between adjacent subchannels are employed (dashed lines in Fig. 1). Hence lateral momentum equations are solved based on staggered scheme. The width of the staggered control volume, $l_k$ in Fig. 1, is commonly considered to be equal to the distance between centers of two adjacent subchannels.

The subchannel mass, momentum and energy conservation equations for single phase and steady state conditions are:

Mass conservation equation:

$$\rho_{i,j}A_iw_{i,j} - A_i\rho_{i(j-1)}w_{i(j-1)} + \sum_k \delta_k A_{kj}\rho_{kj}u_{kj} = 0 \tag{1}$$

Energy equation:

$$\begin{aligned}\rho_{ij}A_{ij}w_{ij}h^*_{ij} - \rho_{i(j-1)}A_{ij}w_{i(j-1)}h^*_{i(j-1)} \quad &+ \sum_k \delta_k A_{kj}\rho_{kj}u_{kj}h^*_{kj}\\ = \dot{q}_{rod}V_{ij} - L_i\sum_k \omega_{kj}(h_{ij}-h_{nj}) &- \sum_k K_{kj}A_{kj}(T_{ij}-T_{nj})\end{aligned} \tag{2}$$

Axial flow momentum equation:

$$\begin{aligned}&\rho_{ij}A_iw^2_{ij} - \rho_{i(j-1)}A_iw_{i(j-1)}w_{ij} + \sum_k \delta_k A_{kj}\rho_{kj}u_{kj}w^*_{kj}\\ &= -A_i\left(p_{ij}-p_{i(j-1)}\right) - gl_i\rho_{ij}A_icos\theta - F_zV_i - l_i\sum_k \omega_{kj}(w_{ij}-w_{nj})\end{aligned} \tag{3}$$

Cross flow momentum equation:

$$A_{kj}\rho_{kj}u^*_{kj}w_{kj} - A_{kj}\rho_{k(j-1)}u^*_{k(j-1)}w_{k(j-1)} = \delta_k\frac{p_{ij}-p_{kj}}{l_{ik}}V_{kj} - F_{cross}V_{kj} \tag{4}$$

In these equations $k$ is the index of cross flow and stared quantities are calculated by upwind scheme. $K$ in energy equation is thermal conductivity coefficient and $\delta_k = -\frac{i-i_k}{|i-i_k|}$ which ‘$i$’ is channel index and $i_k$ is the index of the connected channel to ‘$i$’ through surface $k$ and also:

$$w_{kj} = \frac{w_{ij}+w_{i'j}}{2} \quad \begin{aligned}&if\ \ w_{kj}>0 \quad u^*_{kj}=u_{kj}\\ &if\ \ w_{kj}<0 \quad u^*_{kj}=u_{k(j+1)}\end{aligned} \tag{5}$$

$\omega$ is turbulent mass flow rate between two adjacent subchannels

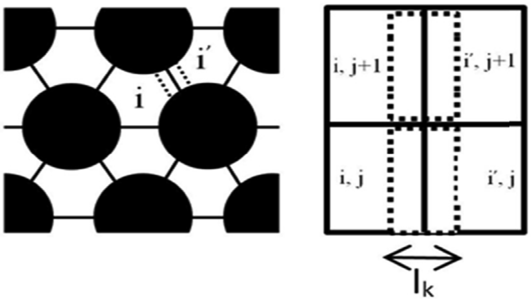

**Fig. 1.** Control volume scheme in subchannel analysis. Left: top view, right: lateral view (dashed lines are control volumes for lateral momentum and solid lines are control volumes for mass, energy and axial momentum).