A 3-D Hydraulic Resistance Model of the Porous Media Approaches for the CANDU-6 Moderator Analysis

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1. Introduction

The CFD analyses of complex geometries usually require some approximations and simplifications. Consider the fluid circulation flowing around the 380 circular tubes like the moderator circulation through the Calandria tube (CT) matrix of the CANDU NPPs. For this case, it is more common to assume the tube matrix as a porous medium. A flow across a single circular cylinder is one of the classical flow problems, which is not yet understood in detail. One may want to use DNS or LES for more accurate results. The possibility to predict the flows of such a complexity by DNS is restricted to the low Reynolds number range (Tremblay et al. [1]). Even LES requires quite a large number of cells more than hundreds of thousand per tube and consequently a huge computing time. Therefore, by discarding the detailed phenomena of the interaction between the tube surfaces and the fluid flows such as a laminar separation and vortex shedding, the tube matrix in the core region is conventionally approximated as a porous medium.

2. Governing Equations

The assumptions of the porous media approaches are that the control volumes and control surfaces are large relative to the interstitial spacing of the porous medium, and that the given control cells and control surfaces are assumed to contain both the fluid and the distributed solids (Todreas & Kazimi [2]). A direct application of the conservation principles gives the following governing equations in a porous medium.

$$\frac{\partial(\rho\gamma)}{\partial t}+\frac{\partial(\rho\gamma_A u_j)}{\partial x_j}=0 \qquad (1)$$

$$\frac{\partial(\rho\gamma u_i)}{\partial t}+\frac{\partial(\rho\gamma_A u_j u_i)}{\partial x_j}=-\gamma_A\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu_e\gamma_A\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right]+B-R \qquad (2)$$

$$\frac{\partial(\rho\gamma H)}{\partial t}+\frac{\partial(\rho\gamma_A u_j H)}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\Gamma_e\gamma_A\frac{\partial H}{\partial x_j}\right)+\gamma Q \qquad (3)$$

A fluid flow passing through a porous medium experiences an acceleration due to a passage contraction and a deceleration due to obstruction or a passage extraction. Because a flow acceleration is concerned with the area of a flow passage, it is modeled only by its porosities. For a flow deceleration, flow resistance due to obstruction consists of a form drag and a frictional pressure loss, which are strongly dependent on the shape and the distributing pattern of the obstacles as well as the flow characteristics. Thus, the resistance source term R should be implemented carefully with empirical correlations case by case, to account for the deceleration.

3. Hydraulic Resistance Source Terms

The Calandria tubes are arranged in a square lattice form, and the pitch-to-diameter ratio is 2.183 (CT diameter = 0.131 m). Define attack angle, ϕ, to be the angle between the CT axis and the flow vectors and θ to be the angle between the flow direction in the lateral plane and the tube array. A 3-dimensional pressure drop per unit traveling length can be expressed in the form of

$$\frac{\Delta p}{\Delta L}=\left.\frac{\Delta p}{\Delta L}\right)_{\substack{cross\\flow}}\square\left(S_V\big/S_{90}\right) \qquad (4)$$

Here, the multiplier of the RHS is a ratio of the pressure loss through the inclined tube banks to the cross flow pressure loss, which depends on an attack angle.

For the transverse (lateral) flow across the tube bank, Hadaller et al. [3] investigated the pressure drop of the fluid flows crossing staggered and in-line tube banks, in which the tube Reynolds number range is 2,000 to 9,000 and the pitch-to-diameter ratio is 2.16. Regardless of the tube array configuration, the empirical correlation for the pressure loss coefficient (PLC) is

$$\mathrm{PLC}\equiv\frac{\Delta\mathrm{P}}{\mathrm{N_r}\cdot\rho\cdot\frac{\mathrm{V_{fs}}^2}{2}}=4.54\cdot\mathrm{Re}^{-0.172}\ . \qquad (5)$$

The unit traveling length ΔL divided by $\mathrm{N_r}$ is the length between the rows ΔL_{row}. One can say $\Delta L/\mathrm{N_r}=\Delta L_{row}=p\cdot\cos\theta$. From the experimental configuration, it is concluded that the free stream velocity is a multiplication of the porosity γ and the velocity magnitude in the tube bank region. Thus, by rearranging eq. (5),

$$\left.\frac{\Delta P}{\Delta L}\right)_{\substack{cross\\flow}}=\frac{\mathrm{PLC}}{p\cdot\cos\theta}\cdot\rho\frac{(\gamma V)^2}{2}\ . \qquad (6)$$

The next step is to account for the attack angle dependency. Figure 1 shows the pressure loss ratio as a function of ϕ. Khartabil et al. [4] measured the flow resistance in the test apparatus with inclined tube banks for various Re_t numbers. Figure 1 also includes data of the Engineering Sciences Data Unit [5] and the fitting curves.

4. CANDU-6 Moderator Analysis

A 35% RIH(Reactor Inlet Header) break with a loss of ECC(Emergency Core Cooling) injection was selected for the transient analysis, because this case is the bounding case out of all the DBA's which exert the largest power to the moderator following PT/CT contacts. The transient heat load to the moderator was obtained from the single channel analyses by the CATHENA and the CHAN-IIA codes. The heat loads were implemented as source terms of the energy equation into the cells at the locations of each channel and bundle. The calculation has been successfully done until 1,200 sec after a LOCA and the results are displayed in Fig. 2. Even though the minimum subcooling goes down below the subcooling margin of 28°C at an early stage of the transient, neither film boiling nor dryout would occur because no combination of a low moderator subcooling and a high PT contact temperature happens during the whole transient.

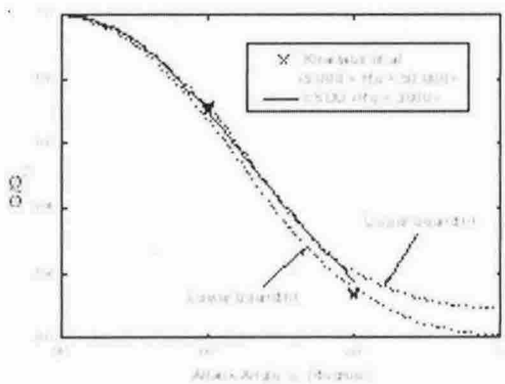

Figure 1 : Effect of the attack angle on the pressure loss ratio

5. Conclusions

In this study, a new 3-dimensional hydraulic resistance model for the porous media approaches has been developed and applied to the CANDU-6 moderator transient analysis for a bounding case of LLOCA with a LOECC. It is concluded that film boiling or dryout would not occur during the transient.

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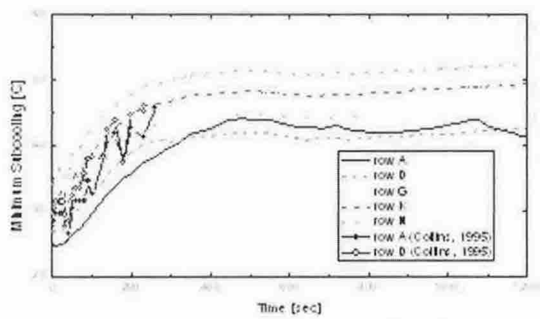

Figure 2 : Local minimum subcooling of 5 selected rows and a comparison with a previous simulation

NOMENCLATURE

- A = area [m^2]
- D = diameter [m]
- L = length [m]
- N_r = number of rows per unit length
- P = pressure [N/m^2]
- P = pitch [m]
- $Re_t = \dfrac{\rho V_{fs} D}{\mu}$ =tube Reynolds number
- u = velocity components [m/sec]
- $V = \sqrt{\sum u_i^2}$ = velocity magnitude
- Vol = volume [m^3]
- $\gamma \equiv \dfrac{Vol_f}{Vol_T}$ = volume porosity
- $\gamma_A \equiv \dfrac{A_f}{A_T}$ = area porosity
- μ = fluid viscosity [kg sec/m^2]
- ρ = fluid density [kg/m^3]

Subscripts

- f = fluid
- fs = free stream
- T = total
- t = tube