Assessing the accuracy of energy turbulent diffusion dispersion correlation in a porous two-fluid model dedicated to PWR core simulations

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Context

CATHARE is a 2-fluid thermal-hydraulic code developed at sub-channel scale in order to simulating 3D thermal and mechanical phenomena occurring in the primary and secondary circuits of Pressurized Water Reactor (PWR) under a wide variety of accidental situations. One of the medium-term objectives of system code CATHARE-3 is modeling a PWR core at assembly scale to simulate various accidental situations such as the loss of coolant accident (LOCA) and steam line break accident. This requires that the one-phase and two-phase models are adapted to the assembly scale, which needs take into account not only the phenomena inside channels but also the exchange between channels. However, there exists 3D models for the whole core and sub-channel scale models, which have a certain degree of validation. For more macroscopic three-dimensional models, we only have global validations without local measurements, which is necessary for the validations of each closure law's separate effects. The objective of the project is improving the sub-channel scale models and developing the assembly scale models in CATHARE-3 system code with the help of sub-channel scale simulations and experiments results.

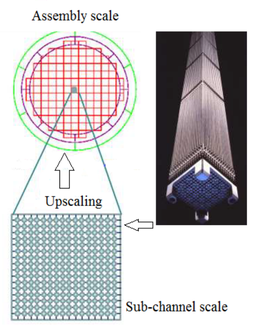

Fig 1. From sub-channel scale to assembly scale

Governing Equations In CATHARE

The double-averaged mass, momentum and energy balance equations in CATHARE read [1]:

$$\frac{\partial}{\partial t}\left(\phi\alpha_k\rho_k\right)+\nabla\cdot\left(\phi\alpha_k\rho_k V_k\right)=\underbrace{(-1)^k\,\phi\Gamma_k}_{\text{Interfacial mass exchange}} \tag{1}$$

$$\alpha_k\rho_k\left(\frac{\partial \mathbf{V}_k}{\partial t}+\mathbf{V}_k\nabla\mathbf{V}_k\right)=-\alpha_k\nabla P+\left(p_i+\underbrace{p_i^T\nabla\alpha_k}_{\text{Void dispersion}}\right) \tag{2}$$
$$\underbrace{-(-1)^k\tau_i+\mathbf{t}_{pk}}_{\text{Interfacial and wall friction force}}+\alpha_k\rho_k\mathbf{g}+\frac{1}{\phi}\nabla\cdot\left(\alpha_k\rho_k\underline{\tau_k^T}\right)$$

$$\frac{\partial}{\partial t}\left(\phi\alpha_k\rho_k e_k\right)+\nabla\cdot\left(\phi\alpha_k\rho_k\mathbf{V}_k e_k\right)=\underbrace{\phi q_{ke}+S_c q_{pk}}_{\text{Interfacial and wall heat transfer}} \tag{3}$$
$$+(-1)^k\,\phi\Gamma H_k-P\left(\frac{\partial\phi\alpha_k}{\partial t}+\nabla\cdot\left(\phi\alpha_k\mathbf{V}_k\right)\right)+\nabla\cdot\left(\phi\alpha_k\mathbf{q}_k^T\right)$$

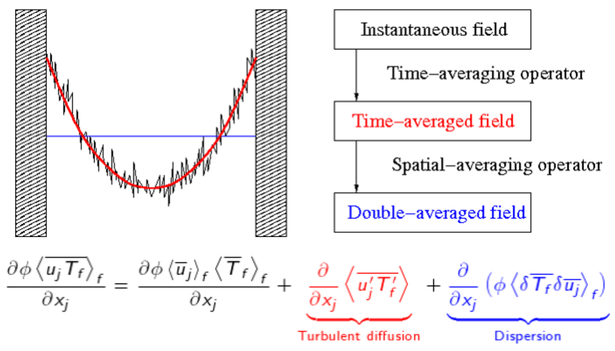

Fig 2. Origin of turbulent diffusion and dispersion

For simplicity, the intrinsic phase and time averaged quantity ϵ is presented by ϵ_k. ϕ is the porosity. The momentum and energy turbulent diffusion and dispersion terms $\underline{\tau_k^T}$ and $\mathbf{q}_k^T$ came out during the double averaging process of the local convection terms (see Fig 2.). In 2011, M. Valette [3] proposed a semi-empirical relation for the energy turbulent diffusion and dispersion coefficient, established for rod bundle PWR-type geometries:

$$\mathbf{q}_k^T=\left(\alpha_{tk}^{\phi}\underline{I}+\underline{D_{dk}^{\phi}}\right)\phi\nabla e_k,\ D_d^{\phi t}=\frac{A\sqrt{\langle k\rangle_f}D_h}{Pr_t^{\phi}}$$

where the $\langle k\rangle_f$ is the spatial averaged turbulent kinetic energy, A is a geometry parameter and adjusted to 0.5 for the PSBT Benchmark, $D_d^{\phi t}$ is the transverse component of the thermal dispersive tensor.
In the present work, this model, especially the relation between coefficient A and Re, is assessed and improved with PSBT single-phase tests and PNNL steady state tests.

PNNL Tests

The PNNL 2×6 tests were conducted at the Pacific Northwest National Laboratory for investigating the buoyancy effect on flow distributions [2]. In these tests, 12 rods had different power profiles for presenting a nonuniform radial power distribution. Nine windows were located along the test section (1.778 m) and both velocity and temperature were measured traversing the sub-channels 8 to 14. In the presented test, the Reynolds number is about 1000, the power gradient between the hot rods and the cold rods is 2:1.

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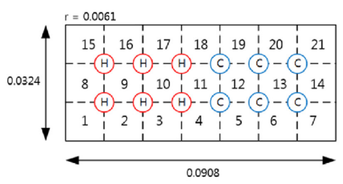

Fig 3. PNNL 2×6 rod bundle flow test (H: hot rods, C: Cold rods)

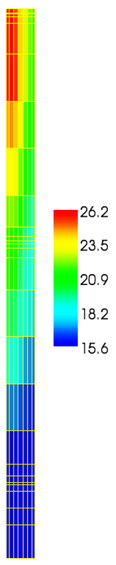

Fig 4. Temperature distribution

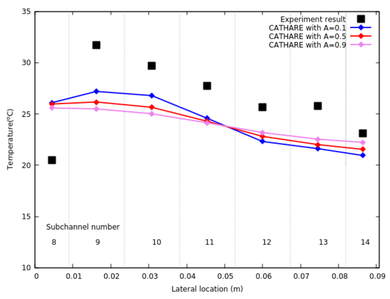

Fig 5. Radial temperature distribution with different A. Overall behavior is well predicted by the code. Discrepancies between code prediction and experimental data may be due to the uncertainty of experimental measurement (temperature measurement error was estimated of about 15%)

PSBT Tests

The single phase PSBT tests consist of 5×5 PWR type rod bundles, with spatial radial power distribution and a uniform axial profile, which could induce an asymmetrical radial temperature at the end of the heating length [3][4].

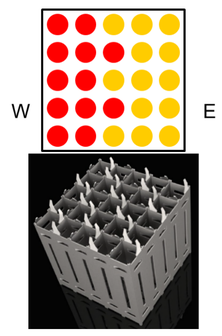

Fig 6. PSBT 5×5 rod bundle flow test and mixing vane grid

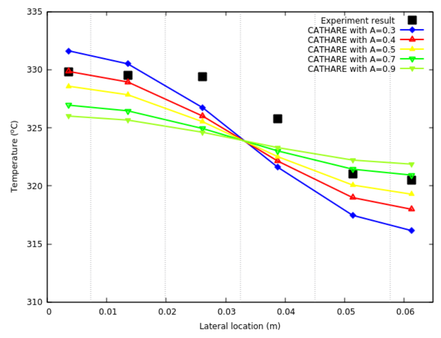

Fig 7. Temperature distribution with different A

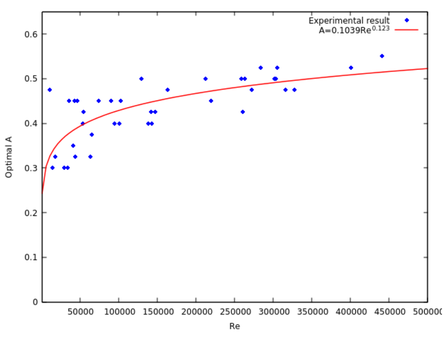

Fig 8. Optimal A for tests with different Re

In these tests, we found the coefficient A depends on not only the geometry but also the Reynolds number. A higher value of A is necessary in the PSBT tests than in PNNL tests, because PSBT test section includes some mixing vane grids (Fig 6.), which enhance the mixing between the sub-channels.

Conclusion And Perspectives

- For general comparison, the CATHARE results have good agreement with the experimental results;
- For Valette's energy diffusion dispersion model, the dependence of coefficient A over Reynolds number is found for PSBT tests and a correlation of A function of this parameter is proposed, lower values of A are found for PNNL tests due to the lower Reynolds number and absence of grids;
- Further analysis of PNNL tests are in progress in order to improve the proposed correlations;
- The future work will focus on correlations in other mixing terms;
- The final objective consists on extending these models established at the sub-channel scale for simulation at the assembly scale using up-scaling techniques.

References

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