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Validation of MATRA-S Low Flow Predictions Using PNL 2x6 Mixed Convection Test

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1. Introduction

The MATRA-S[1], a subchannel analysis code has been used to thermal-hydraulic design of SMART core. As the safety enhancement is getting important more and more, some features of the MATRA-S code are required to be validated in order to be applied to non-nominal operating conditions in addition to its applicability to reactor design under normal operating conditions.

The MATRA-S code has two numerical schemes, SCHEME for implicit application and XSCHEM for explicit one. The implicit scheme had been developed under assumptions that the axial flow is larger enough than the crossflow. Under certain conditions, especially low flow and low pressure operating conditions, this implicit SCHEME oscillates or becomes unstable numerically and then MATRA-S fails to obtain good solution. These demerits were known as common in implicit schemes of many COBRA families[2]. Efforts have been exerted to resolve these limitations in SCHEME of the MATRA-S such as a once through marching scheme against the multi-pass marching scheme and an adaptive multi-grid method. These remedies can reduce the numerically unstable range for SCHEME but some unstable regions still remain[3].

The explicit XSCHEM was developed to obtaining successful solutions under those unsuccessful operating conditions. The XSCHEM adopted ACE, Advanced Continuum Eulerian algorithm that is an improved ICE, Implicit Continuous Eulerian algorithm. In the ACE algorithm, specific enthalpy can be expressed with specific volume from the equation of state:

$$h^* = h_0 + \left.\frac{\partial h}{\partial \upsilon}\right|_p \left(\upsilon^* - \upsilon_0\right) \quad (1)$$

The energy equation in the control volume of a subchannel is:

$$\bar{A}_j \frac{\Delta x}{\Delta t}\left(\rho h_j - \rho h_j^n\right) + m h_j^* - m h_{j-1}^* + \Delta x\left[D_c\right]^T\left\{w h^*\right\}_j = Q_j^n \quad (2)$$

The modified energy equation is derived from substituting the enthalpies in Eq.(2) with the specific volume in Eq.(1):

$$\left(m\upsilon_j^* - m\upsilon_{j-1}^*\right) + \Delta x\left[D_c\right]^T\left\{w\upsilon^*\right\}_j - \left.\frac{\partial \upsilon}{\partial h}\right|_p Q_j^n = 0 \quad (3)$$

As the tentative axial flow, *m* and crossflow, *w* can't satisfy the Eq.(3) and an error, *E* will appear:

$$\left(\tilde{m}\upsilon_j^* - \tilde{m}\upsilon_{j-1}^*\right) + \Delta x\left[D_c\right]^T\left\{\tilde{w}\upsilon^*\right\}_j - \left.\frac{\partial \upsilon}{\partial h}\right|_p Q_j^n = E_j \quad (4)$$

The ACE algorithm minimizes residual in Eq.(4) by changing the pressure in this way:

$$\frac{dE}{dp} = \frac{\partial E}{\partial \tilde{m}_j}\frac{d\tilde{m}_j}{dp_j} + \frac{\partial E}{\partial \tilde{m}_{j-1}}\frac{d\tilde{m}_{j-1}}{dp_j} + \frac{\partial E}{\partial \tilde{w}_j}\frac{d\tilde{w}_j}{dp_j} \quad (5)$$

2. Validation

The XSCHEM is validated if it can predict thermal-hydraulics in the low flow and low pressure conditions using mixed convection test data in the PNL 2x6 rod bundle[4]. The PNL 2x6 rod bundle test measured flow velocity and temperature profiles from twenty three cases of steady states forced convection and flow transients from fifteen cases of forced to natural convection. Test section is shown as a schematic diagram in Fig.1. The cross-section has an array of 2x6 rods that have different radial power such as 1:0, 1:1, 2:1, 3:1, and 4:1. Flow redistribution within the bundle driven by the Buoyancy forces were observed under conditions of low flows and severe radial power gradients. And this test data was selected to validate the XSCHEM of MATRA-S.

The subchannel analysis model was setup as left hand side picture of Fig.1. Flow velocities and temperatures in subchannel #1~6 were compared for predictions against measurements.

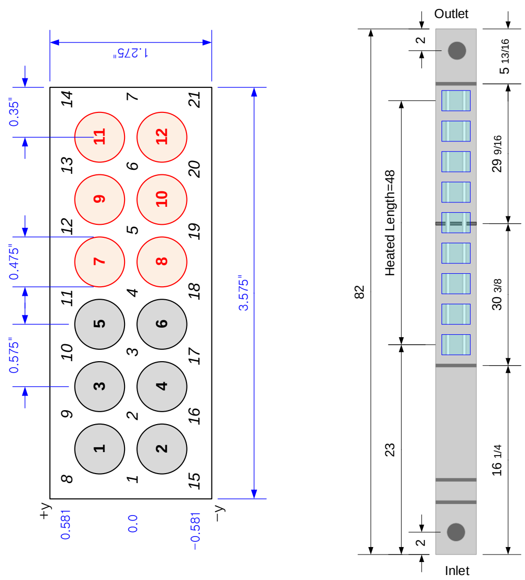

Fig.1 Schematics of PNL 2x6 Rod Bundle Test.

The first step of the validation was to investigate how much time steps are required for transient calculations reach steady state under steady state condition. Fig.2 shows the convergence history of flow velocity of channels #2, #4, and #6 at channel exit for the case 36. The flow velocity deviated largely from initial value and then saturated after 160 seconds. The results change according to the time step size and the Courant number. From these results, the 1000 seconds of null transient were calculated for steady state test data and the 1000 seconds were inserted before transient begin for the analysis of transient test data.

In the second step of the validation, results of implicit SCHEME and explicit XSCHEM were compared for the steady state. The flow velocities at subchannel #1~6 in sixteen cases and temperature rises at subchannel #1~6 in nine cases were compared as Reynolds numbers in Fig.3. The temperature rise in a subchannel was normalized as follows:

$$\theta = (T - T_{in})/(T_{out} - T_{in})_{t=0} \qquad (6)$$

Fig.3 shows that the flow velocities were agreed well with each other and the temperatures rises predicted by XSCHEM were agreed with those by SCHEME within -2~+8%.

And then a total of fifteen flow transient tests were analyzed by XSCHEM. In the flow transient, the flow velocities at the subchannel centerline were measured and they are different from the subchannel averaged flow velocities that are predicted by MATRA-S. Results of the flow transient of Case 18 were shown in Fig.4. The measured centerline flow velocity at cold channel, subchannel #2, went below the zero at 52 seconds and XSCHEM predicted average flow velocity as negative at that time. The flow recirculation within bundle driven by Buoyancy forces was predicted well when the flow velocity profile is colored and is compared to the measured arrows in Fig.5.

3. Conclusions

The XSCHEM, an explicit scheme of MATRA-S was validated using the PNL 2x6 rod bundle flow transient test. The explicit scheme agreed with implicit scheme for steady state calculations. And it showed its capability to predict low flow conditions such as negative flow and recirculation flow.

ACKNOWLEGEMENT

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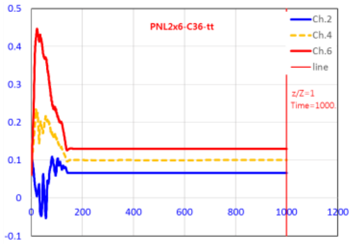

Fig.2 A Convergence History for the Transient.

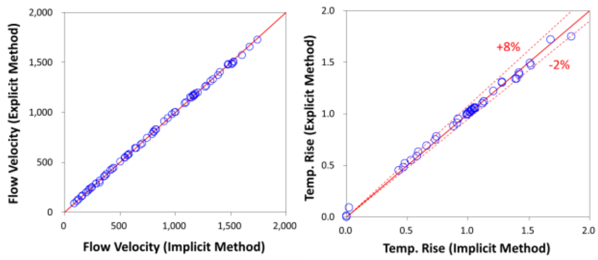

Fig.3 Implicit Method vs Explicit Method (Steady State)

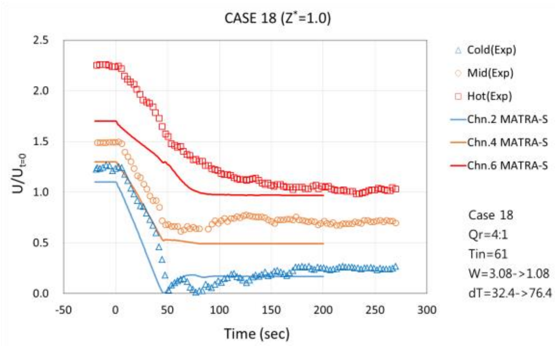

Fig.4 Transient Analysis Results for Case 18.

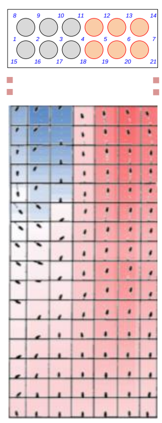

Fig.5 Recirculating Flow within Subchannels #1~6 in Case 6.