Implementations of Non-Equilibrium Droplet Energy Equation and Shared Memory Parallelism into the CUPID code

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1. Introduction

A component-scale thermal-hydraulics analysis module, CUPID has been being developed for a transient three-dimensional two-phase flow analysis of nuclear reactor components [1]. CUPID is based on a two-fluid, three-field model, which is solved by using an unstructured finite volume method.

The three fields in the CUPID code represent a continuous liquid, an entrained liquid, and a vapor field. At present the two liquid fields in the CUPID code are assumed to be in a thermally equilibrium state. In this paper, non-equilibrium energy equations for droplets and continuous liquid fields were implemented and assessed. In addition, the shared memory parallelism for the CUPID code was tested using a quad-core CPU personal computer.

2. Mathematical Model and Numerical Method

The governing equations of the two-fluid, three-field model are similar to those of the time-averaged two-fluid model derived by Ishii and Hibiki[2].

$$\frac{\partial}{\partial t}(\alpha_k\rho_k)+\nabla\cdot(\alpha_k\rho_k\underline{u}_k)=\Gamma_k \tag{1}$$

$$\frac{\partial}{\partial t}(\alpha_k\rho_k\underline{u}_k)+\nabla\cdot(\alpha_k\rho_k\underline{u}_k\underline{u}_k)=-\alpha_k\nabla P+\nabla\cdot[\alpha_k\tau_k] \tag{2}$$
$$+\alpha_k\rho_k\underline{g}+P\nabla\alpha_k+M_k^{mass}+M_k^{drag}+M_k^{VM}$$

$$\frac{\partial}{\partial t}[\alpha_k\rho_k e_k]+\nabla\cdot(\alpha_k\rho_k e_k\underline{u}_k)=-\nabla\cdot(\alpha_k q_k) \tag{3}$$
$$+\nabla\alpha_k\tau_k:\nabla\underline{u}_k-P\frac{\partial}{\partial t}\alpha_k-P\nabla\cdot(\alpha_k\underline{u}_k)+I_k+Q'''_k$$

where α_k, ρ_k, $\underline{u}_k$, P_k, Γ_k, M_k, and I_k are the k-phase volume fraction, density, velocity, pressure, an interface mass transfer rate, interfacial momentum transfer, and interfacial heat transfer respectively. For a closure of the system of equations, constitutive relations and the equations of states are included.

The semi-implicit ICE scheme used in the RELAP5 code [3] was adopted as a basic numerical method, which uses a staggered grid and a donor-cell scheme. But to apply this scheme with an unstructured finite volume method, this scheme should be changed to adopt a cell-centered scheme. For this, the momentum equations were solved over a non-staggered grid and the velocities at the cell faces were interpolated by using the Rhie-Chow scheme[4].

2.1 An Implementation of Non-Equilibrium Droplet Energy Equation

The assumption of the thermally equilibrium between liquid and droplets of previous studies was not used any more, and three energy conservation equations for vapor, liquid, liquid droplets were set up. This makes the CUPID code cover the region in which the temperature of droplets is different from the temperature of liquid.

The droplet and liquid energy conservations at the thermally non-equilibrium state are given at Eq.(4) and Eq. (5), in which droplets have their own temperature and the thermal model can be adapted for droplet phase.

$$\frac{\partial}{\partial t}[\alpha_l\rho_l e_l]+\nabla\cdot(\alpha_l\rho_l e_l\underline{u}_l)=-\nabla\cdot(\alpha_l q_l)+\nabla\alpha_l\tau_l:\nabla\underline{u}_l \tag{4}$$
$$-P\frac{\partial}{\partial t}\alpha_l-P\nabla\cdot(\alpha_l\underline{u}_l)+I_l+Q'''_l-(S_E e_l-S_D e_d)$$

$$\frac{\partial}{\partial t}[\alpha_d\rho_d e_d]+\nabla\cdot(\alpha_d\rho_d e_d\underline{u}_d)=-\nabla\cdot(\alpha_d q_d)+\nabla\alpha_d\tau_d:\nabla\underline{u}_d \tag{5}$$
$$-P\frac{\partial}{\partial t}\alpha_d-P\nabla\cdot(\alpha_d\underline{u}_d)+I_d+Q'''_d+(S_E e_l-S_D e_d)$$

The interfacial heat transfer formulations were given as Eq. (6) and Eq. (7), which means the three energy equations are coupled

$$I_l=R_{gs}(T^s-T_v)+R_{ls}(T^s-T_l) \tag{6}$$

$$I_d=R'_{gs}(T^s-T_v)+R_{ds}(T^s-T_d) \tag{7}$$

where R_{gs}, R_{ls}, R'_{gs}, *and* R_{ds} are interfacial heat transfer coefficient multiplied by interfacial area concentration.

2.2 An Implementation of Shared Memory Parallelism

The shared memory parallelism was implemented into the CUPID code. The OpenMP, an application programming interface(API), was used for this parallelism. The OpenMP embeded compiler which automatically detected independent sequences of instructions was used for the CUPID code. This makes the CUPID code use the resource of the personal computer which has dual CPUs commonly and often has quad CPUs nowadays.

3. Comparison of the Computation Times

The test problem was a rectangular tube of 1.0 m x 1.0 m x 2 m filled with 442.0 K water, and the subcooled water was being injected into its inlet. The outlet was assumed to be a constant pressure boundary of 0.1 MPa. The injection velocity and temperature were 0.1m/sec and 442.0 K, respectively. A volumetric heat source of Q_l = 23.0e6*min(time/10, 1) J/m^{3}sec was added to the water, and vapor was generated. Initially, the tube was filled with subcooled water. The void

fraction and the droplet fraction increased because of the evaporation and the entrainment. The steady state was obtained after 20.0 seconds. Temperatures of droplet and vapor at 30.0 seconds are shown in Figure 1. The droplet temperature was the same as the vapor temperature because of the big heat transfer coefficient between droplet and vapor.

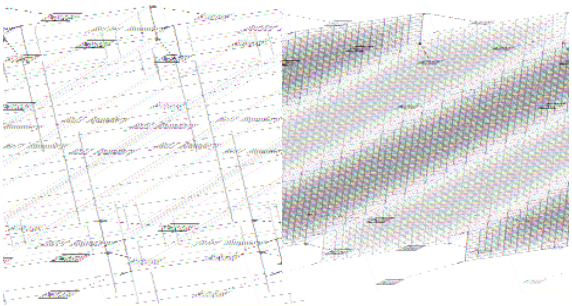

Fig. 1. Configurations of boundary conditions and meshes

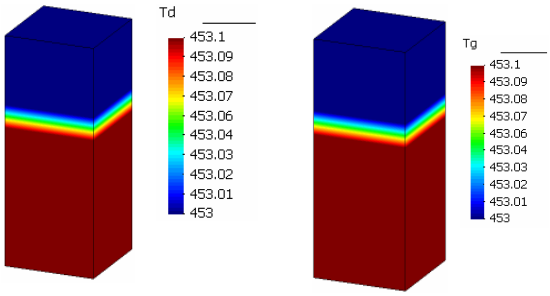

Fig. 2. Temperature of droplets and vapor at 30.0 second

The non-equilibrium model seems to be robust just like the equilibrium model, and the additional calculation time is only 8 %. As shown in Fig. 3, the additional time did not increase as the number of cell increased.

The improvement of computation speed by implementing shared memory parallelism into the CUPID code is presented in Table I. The simple adoption of the shared memory parallelism results in calculation speed up of about 111 %. Considering that most computers adopt shared memory parallelism, and that implementation of the shared memory parallelism is simple, 111 % advantage is a big advantage.

4. Conclusions

A thermal non-equilibrium model was implemented in to the 3-dimensional, 2 fluid, 3 field code. This non-equilibrium model might have the same robustness, and it only needed an additional computational time of 8 %, when compared to the thermally equilibrium model. Then, the shared memory parallelism was implemented into this computational code. This resulted in calculation speed up of 111%.

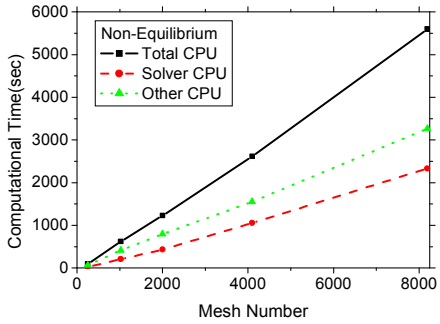

Fig. 3. The numerical characteristics of CUPID in which non-equilibrium model is implemented

Table I: The Improvement of Computation Speed by Implementing Shared Memory Parallelism(4 cpu)

Cell (#)	Problem time (sec)	Total (%)	Scalar Matrix (%)	Pressure Solver (%)
1024	30.	111	155	108
2000	30.	111	155	106
4096	30.	116	151	114
8192	30.	123	168	115

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