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Development of Coupled Lattice Boltzmann and Finite Element Method for Fluid-Structure Interaction Problems in Commercial Nuclear Power Plants

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1. Introduction

A commercial nuclear power plant is a complex engineering system which demands extremely high safety and reliability. As the nuclear power plant becomes more compact with a higher density of energy production, the design of a new nuclear power plant becomes more challenge for engineers. A commercial nuclear power plant contains various complex fluid-structure interaction problems that are critical to the safety of the system. These include active and passive interaction between pressure vessels/pipes and the contained and/or surrounding various kinds of fluids including multiphase flows. Such fluid-structure interaction can cause an unexpected failure of the system resulting from instability, resonance, unnecessary contact, fretting, fatigue, etc. As a result, it is critical to assess all possible fluid-structure interaction problems detrimental to the nuclear power plants. However, physical testing of all these problems is almost impossible to conduct. Therefore, it is necessary to have a reliable and efficient analysis tool to assess those fluid-structure interaction problems occurring at the nuclear power plants.

In this regard, Korea Institute of Nuclear Safety has embarked on a research project to develop her own original software (computer program) in application to complex fluid-structure interaction phenomena, which is critical for regulatory safety evaluation of commercial nuclear power plants [1-2].

This paper presents the approach and methodology for the development of the fluid-structure interaction analysis computer program as well as the result of preliminary study conducted to develop a promising coupled technique which will be used for designing the computer program.

2. Approach to the Development of FSI Computer Code

Modeling multiphase flow using the conventional CFD is quite a challenge and difficulty to perform. On the other hand, the Lattice Boltzmann Method (LBM) is a promising numerical technique to analyze such a complex multi-phase, multi-component, and thermally coupled flow problem. As a result, the LBM will be considered to model the thermally coupled multi-phase/multi-component flows with phase changes while the Finite Element Method (FEM) will be selected for the structural modeling because their own merits to the respective applications. Finally, the coupling between LBM and FEM will be investigated for FSI applications in the nuclear power system containing complex multi-phase, multi-component, and thermally coupled flow field.

In order to achieve the goal of the present study, the following tasks will be conducted.

(1) Extensive literature survey of the lattice Boltzmann method to find out its current state of arts as well as to determine essential research topics for our fluid-structure interaction application to commercial nuclear power plants.
(2) Development of a set of benchmark problems which will be used to validate the computer codes to be developed. The problems will be selected as close as possible to the commercial nuclear power applications.
(3) Preliminary results of the effective coupling between the lattice Boltzmann method and the finite element method for fluid-structure application.
(4) Preliminary results of some of the benchmark problem set using other commercial software, if possible.
(5) Detailed planning of experimental studies for other benchmark problems.

3. Description of Lattice Boltzmann Method

The lattice Boltzmann method has evolved very rapidly during last two decades since its first appearance in the middle of 1980. Especially, the technique has been developed intensively for the last decade. Initially, the lattice Boltzmann method evolved from cellular automata, and later it was extended from the Boltzmann equation.

Cellular automata, which were invented by von Neumann in the late 1940s, provide simple local models of complex global systems using local rules. Cellular automata consist of a regular lattice of cells to which a set of Boolean variables are attached. Then, a set of local rules specify the time evolution of the states from a cell to neighboring cells. The cellular automata have some limitations because it uses Boolean quantities. In order to overcome this, the lattice Boltzmann method was developed using real-valued quantities [3].

The LBM uses the particle distribution function, f(x,v,t), where f represents the number of particles at the point x at time t, moving with velocity v. Then, the collision and propagation of the particles is expressed as

$$f_i(x+\mathrm{e}_i dt, t+dt) - f_i(x,t) = \Omega_i(f_i(x,t)) \tag{1.1}$$

where Ω_i is the collision operator and $\boldsymbol{e}_\mathrm{i}$ is the local particle velocity along the *i*-th direction. The local particle velocity $\boldsymbol{e}_\mathrm{i}$ is discrete in the given lattice. For example, for a 2-D lattice, the velocities for the nine possible directions are

$$\mathbf{e}_\mathrm{i} = \begin{cases} (0,0) & i=0 \\ \left(\cos\{(i-1)\pi/2\}, \sin\{(i-1)\pi/2\}\right)c & i=1,2,3,4 \\ \left(\sqrt{2}\cos\{(i-1)\pi/2+\pi/4\}, \sqrt{2}\sin\{(i-1)\pi/2+\pi/4\}\right)c & i=5,6,7,8 \end{cases} \tag{1.2}$$

where *c=dx/dt* and *dx* and *dt* are the lattice constant and the time step size, respectively. On the other hand, a 3-D lattice called D3Q15 has one center, 6 faces, and 8 corner grid points.

For the BGK model, the collision operator is expressed as

$$\Omega_i = -\frac{1}{\tau}(f_i - f_i^{eq}) \tag{1.3}$$

where τ is the relaxation time and f_i^{eq} denotes the local equilibrium distribution. This local equilibrium is derived from the Maxwell-Boltzmann equilibrium distribution. Using its quadratic expansion, the local equilibrium distribution for fluid flow of the D2Q9 model is given as

$$f_i^{eq} = \rho w_i \left[1 + \frac{\mathbf{v}\cdot\mathbf{e}_\mathrm{i}}{c^2} + \frac{(\mathbf{v}\cdot\mathbf{e}_\mathrm{i})^2 - c^2\mathbf{v}\cdot\mathbf{v}}{2c^4} \right] \tag{1.4}$$

in which ρ is the fluid density, **v** is the fluid velocity, *c* is the lattice speed. In addition, w_i is the weighting parameter for each velocity direction, and it is given below for the 2-D lattice:

$$w_i = \begin{pmatrix} 4/9 & i=0 \\ 1/9 & i=1,2,3,4 \\ 1/36 & i=5,6,7,8 \end{pmatrix} \tag{1.5}$$

The fluid density ρ and momentum density ρv are expressed as

$$\rho = \sum_i f_i \,, \qquad \rho\mathrm{v} = \sum_i f_i \mathrm{e}_\mathrm{i} \tag{1.6}$$

Furthermore, the fluid pressure *p* and the kinematic viscosity *ν* are expressed as

$$p = \rho c_s^2, \qquad \nu = \frac{1}{3}(\tau - \frac{1}{2})\, c\, dx \tag{1.7}$$

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where c_s is the sound of speed of the model, and dx is the lattice spacing. In equilibrium, the conservation of mass and momentum is satisfied at each lattice:

$$\sum_i \Omega_i = 0\,, \qquad \sum_i \Omega_i \mathbf{e}_i = 0 \tag{1.8}$$

4. Description of LBM & FEM Program Structure

A basic backbone structure for the coupled LBM and FEM program for FSI applications has been designed. The LBM will be used for the fluid flow while the FEM is used for the structural vibration as mentioned previously. The interface between the fluid and structural domains is coupled in a staggered manner as described below. The fluid flow solution from LBM provides the pressure loading to the structural interface boundary. Then, the vibration motion of the structure caused by the fluid pressure is obtained from the FEM. From the structural velocity, the fluid velocity at the fluid-structure interface is provided for the next fluid flow solution.

To simplify the analysis of flow-induced vibration, a pipe inside a flow is modeled as a beam rather than a shell. This will simplify the finite element model significantly and will save both modeling and computational times. Even if the pipe is modeled as a beam, its interaction with a flow occurrs on the shell surface that is represented by a beam.

5. Tasks for the FSI Code Development

The proposed tasks are described below in detail:

Task 1. Development of Efficient Coupling Techniques between Lattice Boltzmann Method and Finite Element Method

The lattice Boltzmann method and the finite element method were formulated based on totally different concepts and variables. While the direct physical variables are used in the finite element formulation, more abstract variables are used in the lattice Boltzmann method. For example, the finite element method uses displacement, velocity, pressure, etc. as the direct unknown variables. On the other hand, the lattice Boltzmann method uses particle density distribution functions in pre-assumed discrete velocity directions as the primary unknown variables. Fluid velocity can be derived from the particle density distribution functions and the given discrete velocity vectors. However, when the finite element domain meets the lattice Boltzmann domain, finite element velocity solutions cannot be directly transferred to the lattice Boltzmann equation because their mismatch of unknown variables. Hence, it is necessary to find the particle density distribution functions equivalent to the finite element velocity solutions. Unfortunately, this process does not result in unique values. Thus, this task is to determine which coupling procedure between the two methods will yield better solutions in terms of accuracy, stability, computational efficiency, etc.

Task 2. Development of a Capability in Lattice Boltzmann Method that Can Model Irregular or Complex Fluid Domain

The lattice Boltzmann technique was initially developed for a regular lattice pattern such as square or cubic grids. However, in order to apply the technique to more complex geometry problems, the technique was extended to irregular lattice cases. There have been different kinds of approaches to address the problems. The most common technique was using the finite volume formulation of the lattice Boltzmann equation. Another approach was a point-wise interpolation technique for irregular grids. Other techniques were based on the finite element method. Generally, the computational schemes for irregular meshes are much more involved than the standard lattice Boltzmann technique for regular meshes. As a result, it would be nice to model a given problem domain by combining a regular mesh zone and an irregular mesh zone. Obviously, some research is necessary to make two different formulations compatible at their interface zone boundary. We will review all those techniques and develop one for the proposed computer code.

Task 3. Development of a Turbulence Model in Lattice Boltzmann method

Most flows in power plants are beyond the laminar regime. Therefore, a turbulent model will be implemented into the lattice Boltzmann model. For turbulence modeling, a couple of different schemes will be considered. For example, two-equation k-ε turbulence model and a mixing-length algebraic model will be considered to the LBM. A sub-grid model will be also considered to represent turbulence at a larger scale. Another simple scheme such as a random walk model will be also considered. Then, one of the best models will be implemented into the program.

Task 4. Development of the Finite Element Model for Beam or Shell Structure

Most of structural components in the power plants can be represented by a beam or shell structure. As a result, a finite beam or shell element will be developed for fluid-structure interaction. The beam will be a 3-D beam element with a circular cross-section. The coupling of those structural elements with the fluid lattices will be performed.

Task 5. Conduction of Experimental Studies for Benchmark Problems

Good benchmark data obtained from experimental studies are very useful to validate any computer program. However, a careful design of experimental parameters should be selected so that the same environment can be modeled using a computer code. As a result, a preliminary computer result will be useful to design the experimental set-up and design parameters. In this aspect, a close cooperation will be given to design and execute an experiment to obtain reliable and repeatable experimental data.

6. Conclusions and Future Works

The preliminary study conducted previously showed a very promising aspect of the coupled lattice Boltzmann and finite element method for the fluid-structure interaction applications. Therefore, the coupled technique will be used for developing the proposed software. The emphasis of the present phase of research is to develop a lattice Boltzmann method to be applied to irregular and complex shapes of fluid domains so that more general fluid-structure interaction problems can be analyzed using the developed computer code. Secondly, a turbulent flow model will be included in the computer code because majority flows in power plants are beyond the laminar flow regime. The structural parts will be modeled using beam or shell finite elements. Eventually, the present phase of work will result in a basic module for fluid-structure interaction analysis. More features and complexities will be included in the next phases of the research.

References

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