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Adaptive mesh method applied to the thermal hydraulic program of system code with a judging criterion based on the matrix error

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ABSTRACT

In this paper, an adaptive mesh method is described and applied to the one-dimension thermal hydraulic program in a system code for simulating the two-phase flow problems. The adaptive mesh method has been widely used to solve various engineering problems, but it is still rarely applied in existing thermal hydraulic system codes which are of great significance for reactor design and analysis. Compared with the uniform mesh, the mesh size could be adjusted automatically. It is helpful to locate the discontinuity points or deal with the large gradient solutions with this method, especially for some local phenomena that occur in phase transfer or two phase flow problems. Based on it, the computational accuracy and efficiency are improved, when solving the partial difference equations. The applicability of the adaptive mesh method in a system code is a major issue, and the first step is studying the feasibility of the adaptive mesh method in thermal hydraulic programs. In this paper, the finite volume method and the Newton-Raphson algorithm are applied in the code as the numerical method of two-fluid model. Furthermore, the code also includes heat transfer models, friction models and a flow regime map, which are important in simulating hydraulic phenomena. Depending on the algorithm, a judging criterion for determining the location where mesh refinement is needed is proposed. Three typical numerical examples are given to verify the feasibility and effectiveness of the adaptive mesh algorithm in solving the one-dimension two-phase flow problems of local phenomena and show great agreement with theoretical or experiment results.

1. Introduction

Thermal hydraulic system code for reactor is of great significance for reactor design and analysis. The flow and heat transfer features in reactor, operational parameters in power plant and different physical phenomena in different accidents and transient conditions could be analyzed through the system codes. There are still some errors in these system codes which are wildly used today, though most of them are verified by a large number of experiments and quite mature. These errors mainly come from model defects, numerical solutions, the impact of mesh, and so on (Liu et al., 2009). In typical thermal hydraulic system code, as Relap5, users usually change the time step and mesh size for more accurate result and higher computational efficiency. If the problem has a smooth result, which contains none discontinuity point or changes slightly, the result is satisfactory with uniform mesh. If the problem is not smooth enough, the calculation result may has large errors or may wastes a lot of computing resources (Wang et al., 2012).

It is generally acknowledged that thermal hydraulic system codes are very complicated. They involve a lot of specific models such as flow regime map, heat transfer models and equations for frictions. The codes also consist of control variables, logic trips, point kinetics scheme for core power and material conduction. In addition, they include several special process correlations for local phenomena that are not reproduced by fluid system equations and that need to be included for the correct simulation of the overall behavior of the plant such as chocked flow, CCFL and so on. All these things are coupled to the mesh distribution which would impact the calculation results in some cases such as problems in steam generator and condenser. Two phase flow would appear in these components, of which the simulation results are sensitive to the mesh distribution. The original intention is to figure out a proper way to reduce the effect from the mesh distribution and apply it into some specific components.

At present, the majority of the system code are based on the hydrodynamic equations, and solving these equations with proper numerical algorithms is the core of these code. Numerical solution

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process consists of two parts: discretization and solving procedure. The first step is to get the discrete equations through choosing proper discretization method and space-time discretization. Then solve the discrete equations with appropriate numerical method. The error which comes from the space discretization is an important factor which affecting the computation accuracy (Chen, 2000). Space discretization is directly connected with the mesh distribution. It is a problem that how to reduce the error which comes from the mesh distribution. The adaptive mesh method is proposed to improve the calculation accuracy and efficiency.

Adaptive mesh method is a kind of way that rearranges the mesh or changes the size of grid according to the characteristics of physical problems, the differential equations, the shape of calculation zone or calculation algorithm features. Since the adaptive mesh method was advanced, the adaptive mesh method has been developed to various derivations. Ever since Berger and Oliger proposed the adaptive mesh refinement (AMR) (Berger Marsha and Oliger, 1984); R. Li proposed the moving mesh method (Li et al., 2001), G. W. Yuan proposed the adaptive coordinate transformation methods (Yuan et al., 2005) and so on (Maire et al., 2008); (Loubère et al., 2010) . What's more, it has been widely applied to various fields, such as some microstructures and extreme situations (Nikolas (Provatas et al., 1998), marine ice sheets program (Cornforda Stephen and Martinb Daniel, 2013), neutron transport (Nahavandi et al., 2015) and astrophysics field (Fryxell et al., 2000).

Adaptive mesh refinement (AMR) which is a typical type of adaptive mesh method is adopted in this paper. This method is proposed and developed by Berger and Oliger at 1984 (Berger Marsha and Oliger, 1984). After that, this method is implemented to hydrodynamics by Berger and Colella (Berger Marsha and Colella, 1989), and extended to three dimension problems by Bell (Bell et al., 1994). AMR technology is in wild use, and has been developed a variety types. So far, it is applied to solve lots of physical problems, including neutron transport equation, Helmholtz equations (Wang et al., 2012), variable density incompressible Navier-Stokes equations (Almgren et al., 1998), viscous incompressible flow (Howell Louis and Bell John, 1997).

One key point of this method is to locate the position where need mesh refinement. A common way to locate is error estimate which use a certain way to estimate the global or local error. There are lots of different error estimate ways have been used in the different adaptive mesh methods. These ways including h (Thompson Joe, 1985); (Safarzadeh, 2016) ; p (Adjerid and Flaherty, 1986), h-p (Armando Duarte and Tinsley Oden, 1996); (Nahavandi et al., 2015) error estimates, error estimates for element reference technology (Wang et al., 2012), getting the error from hessian matrix (Venditti and Darmofal, 2003), and so on (Chung and Belytschko, 1998). Another way to locate the position is depending on the physical feature. For some shock waves and boundary layers, large gradients or significant differences are employed as the indicators (Baker Timothy, 1997); (Pirzadeh Shahyar, 1999) . However, local refinement through the features does not guarantee the accuracy. Sometimes it may cause incorrect results (Warren et al., 1991). There are also other different ways to locate the position (Haussler-Combe and Korn, 1998).

Adaptive mesh method has been wildly used in various fields such as CFD software and aerodynamics (Wang et al., 2012). However, this method is rarely adopted in thermal hydraulic system codes, such as relap5. What's more Relap5 uses fine mesh rezoning scheme only for the heat structure in reflood problem while use void fraction and wall temperature as the judging criterion (Idaho National Engineering (Laboratory, 1995). The application range of this scheme is too limited. Most of these codes basically equipped with the adaptive time method, rarely with adaptive mesh method. Eliminating the effect of the mesh with this method is a huge issue.

The main content of this paper is to apply the adaptive mesh refinement to the thermal hydraulic program in system code. Since some system codes are based on the hydrodynamic equations of fluid, testing the performance of the adaptive mesh method in the thermal hydraulic part becomes the first thing. Hence the code used in the paper focus on the thermal hydraulic part which has not considered the other parts of system code including control variables, logic trips, or special process correlations. It adopts finite volume method and Newton-Raphson algorithm to solve the six-equations which is one of the cores of a system code. Newton-Raphson algorithm is a common method in solving nonlinear equations which has second order accuracy (Li et al., 2008); (Ortega James and Rheinboldt Werner, 1970) . Some system codes also choose this algorithm to solve hydrodynamic equations, as Cathare (Huang et al., 2003). Depending on the Newton-Raphson algorithm, a new error estimation is proposed to locate the position where need mesh refinement. Several numerical experiments are carried out to verify the effectiveness of the adaptive mesh refinement and error estimation. Not only accuracy is improved, but also computational efficiency is increased, compared with the results which are calculated without the method.

2. Numerical method and models in the code

Thermal hydraulic system codes are important tools for solving two-phase flow problems of reactor design and analysis. Many of these programs are based on two-fluid six-equations, and some assumptions are adopted (Liu et al., 2009). In this paper, a simplified thermal hydraulic part of a system code is developed with Newton-Raphson algorithm to test the effect of adaptive mesh method. It uses general one-dimensional node modeling for the thermal hydraulic simulating. And it includes the flow regime maps, heat transfer models and friction models. These models are referred to the ones of Relap5/Mod3.

2.1. Governing conservation equations

The ideal one dimension two-fluid six-equations can be written as follows.

Continuity equation:

$$\frac{\partial(\alpha_i\rho_i)}{\partial t}+\frac{\partial}{\partial x}(\alpha_i\rho_i\mathbf{u}_i)=\Gamma_{ij}''' \tag{2-1}$$

Momentum equation:

$$\frac{\partial(\alpha_i\rho_i\mathbf{u}_i)}{\partial t}+\frac{\partial}{\partial x}(\alpha_i\rho_i\mathbf{u}_i\mathbf{u}_i)=-\alpha_i\frac{\partial p}{\partial x}+\alpha_i\rho_i+F'''^{W}+F'''^{L}+F_{ij}'''^{I}+F_{ij}'''^{V} \tag{2-2}$$

Energy equation:

$$\frac{\partial(\alpha_i\rho_i h_i)}{\partial t}+\frac{\partial}{\partial x}(\alpha_i\rho_i h_i\mathbf{u}_i)=\alpha_i u_i\frac{\partial}{\partial x}p+\alpha_i\frac{dp}{dt}+\Phi_i'''+Q_i'''^{\Gamma}+Q_i'''^{I}+Q_i'''^{W} \tag{2-3}$$

Volume conservation equation:

$$\alpha_g+\alpha_f=1 \tag{2-4}$$

Meanwhile, some simplifies are made as follows (Idaho National Engineering (Laboratory, 1995): the pressures in the same control volume is same, $P_g=P_l=P$, the interfacial energy storage is neglected; heat transfer between interface and other phase is neglected too; Saturation parameters are used at interface.

2.2. Newton-Raphson algorithm

In this work, Newton-Raphson algorithm is used to solve two-phase flow problems. Newton-Raphson algorithm which is a common method in solving nonlinear equations has been wildly used