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Transient sub-channel code development for lead-cooled fast reactor using the second-order upwind scheme

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ABSTRACT

For its unique safety and economic advantages, the lead cooled fast reactor has become one of the most interesting candidate reactors for the Generation IV nuclear system. To study the thermal-hydraulics of the core under transient conditions, KMC-SUBtra–a sub-channel code for transient thermal-hydraulic analysis of lead cooled fast reactor has been developed. The code uses a modified pressure gradient method to solve the simultaneous equations of the fluid mass, momentum and energy containing cross flow and turbulent mixing, in which the axial pressure gradients are solved as pending variables of the simultaneous equations. A staggered mesh scheme is used for scalar and vector quantities and the second-order upwind scheme is adopted in the discretization of the convection term. The code was validated and verified by the experimental data and CFD simulation results on the steady and transient conditions so its capability for lead cooled reactors was confirmed. The transient flow and heat transfer in the fuel assembly with time-varying boundary conditions were studied, which revealed different transient thermal characteristics of the coolant and fuel rods. In addition, the results calculated using different order upwind schemes were compared and showed the second-order derivative of the axial flow is small.

1. Introduction

Aiming at better safety, sustainability and economic practicability of nuclear reactors, the Generation IV International Forum (GIF) presents six most promising Gen-IV advanced reactors, in which the lead cooled fast reactor (LFR) has shown its unique potentiality due to its high boiling point, chemical inertness, low vapor pressure and good natural circulation ability (Kelly, 2014; IAEA, 2012). On the aspect of the disadvantages of LFR, such as the serious corrosion to solid materials (Gromov et al., 1997) and the production of polonium-210 under the neutron-irradiation (Buongiorno et al., 2004), some significant work has been carried out by Russia, USA and EU and great progress in the areas of materials, system design and operating parameters is supposed to be made during the next four years (Zohuri and McDaniel, 2015). Many LFRs have been designed around the world to perform system research and optimization analysis.

The design of lead cooled reactor cores requires accurate predictions of the peak temperature of the fuel rods and coolant to ensure that certain safety and economic considerations are met, that is, the highest value of each quantity must stay below the safety limit (Kim et al., 2002). To ensure these design limits are met, sub-channel codes for thermal-hydraulic analysis of reactor cores were developed to calculate the detailed temperature distribution of all sub-channels and fuel rods in the assemblies. Most of the those were developed in early times for water cooled reactors and sodium cooled reactors, like the COBRA series (Stewart et al., 1977; George et al., 1980) in the USA, SABRE4 in the UK, MATRA-LMR (Kim et al., 2002) in Korea for steady and transient analysis using cross flow and mixing models, and SUPERENERGY-2 (Basehore and Todreas, 1980) in the USA for steady-state analysis using a flow split model. In these codes the properties of lead and lead alloys were not contained and the procedures and correlations may not suit for lead cooled reactors, therefore their applicability for heavy liquid metal cooled reactors is limited. For the thermal-hydraulic study of lead alloy cooled reactors, several sub-channel codes for LFR have been developed in recent years. Modified transient analysis codes based on the COBRAs were carried out, like COBRA-PB (Tian et al., 2014), COBRA-LM (Liu and Scarpelli, 2015), and some steady-state analysis codes were specifically performed for heavy metals like ANTEO+ (Lodi et al., 2016) (Lodi and Grasso, 2017) in Italy, SACOS-PB (Wang et al., 2013) and KMC-sub (Li et al., 2017) in China. As a steady state sub-channel analysis code developed by University of Science and Technology of China for the lead cooled reactor, KMC-sub showed good accuracy in the validation work and gave valuable information in the design of SNCLFR-100 (Li et al., 2017). However, in the transient

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accident conditions where the boundary conditions change speedily, the steady-state codes cannot give accurate results for the disregard of the thermal-hydraulic inertia; moreover, the existing transient codes for LFR are based on classical sub-channel codes and they haven't been fully validated especially in transient cases. Thus a transient sub-channel code for LFR is required and its verification and validation (V&V) should be rounded in quantities and cases.

Compared with the steady state, the governing equations in transient code are different and new algorithms with code architecture are required. In particular, the heat flux becomes more complex than equaling to the power density of fuel rods and the fuel energy equation can no longer be solved by the integral thermal conductivity method because of the existence of non-steady term. Besides, due to some new Lead−Bismuth Eutectic (LBE) experimental data published in recent years, heat transfer and pressure drop correlations suitable for the sub-channel analysis of lead-bismuth eutectic coolant can be verified and re-selected. Although the first order upwind scheme was usually used for the discretization of the convection term in sub-channel codes, its rationality still needs study and the second order scheme remains worthy to be tried.

In this study, a new transient sub-channel code for the best estimation of lead cooled reactor cores, called KMC-SUBtra, was developed based on the experimental and theoretical results that have been accumulated so far. The code was written in the standard C++ programming language and the use of variable-sized arrays makes the code's memory size changes easily according to the size of the calculation case. The program adopted the staggered grid and the second-order upwind convection scheme to get computational results. Efficient solution algorithms for sparse linear equations were written in KMC-SUBtra so the calculation can be done in a short time. The models and solution method used in the KMC-SUBtra are described in detail in Section 2.

After the development of the code, the experimental data and CFD software were used to do the validation and verification of the code. Section 3 introduces the V&V work of the steady-state and Section 4 presents transient verification and discussion. Meanwhile, the difference of results calculated using different order upwind schemes was studied, providing some references to the development of sub-channel codes.

2. Sub-channel code models and method

The KMC-SUBtra code is developed to calculate the transient flow and temperature distribution in fuel assemblies of liquid metal cooled reactors, especially lead and lead alloys cooled reactors. Considering the high boiling point of lead or lead-alloy, the KMC-SUBtra uses a single phase model without consideration for the two-phase flow and heat transfer caused by boiling phenomena. The shear stress between adjacent sub-channels is neglected and the turbulent mixing between adjacent sub-channels is simulated under the assumption of equal mass exchange. The effect of axial heat conduction in both coolant and fuel rods is not considered too. These assumptions are used in the sub-channel analysis codes to gain the quick computation effectiveness and reasonable results. The following describes the mathematical-physical models.

2.1. Nodding and control volumes

The KMC-SUBtra code uses a staggered mesh scheme where scalar quantities such as ρ, P, h, T and vector quantities such as w, m are separated on staggered nodes (Fig. 1) in order to get the scheme close to reality and make it easier to discretize the equations. In the lateral direction, the system is discretized by the sub-channel geometry as usual. The generalized forms of the finite difference equations are listed in the next sections, in which all but in the cross flow and turbulent mixing terms the index i was omitted.

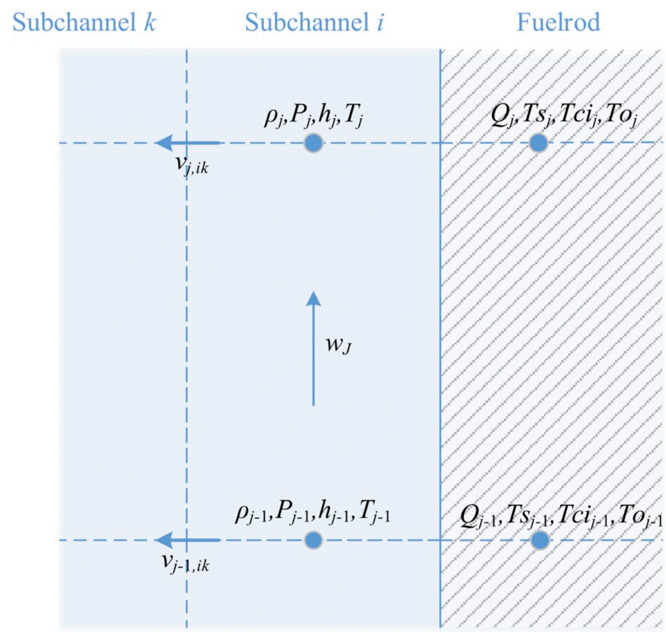

Fig. 1. The mesh scheme of the KMC-SUBtra code.

2.2. Conservation models of fluid

2.2.1. Continuity equation

$$A_j\frac{\rho_j-\rho_j^0}{\Delta t}+\frac{w_{J+1}\rho_{j+\frac{1}{2}}A_{J+1}-w_J\rho_{j-\frac{1}{2}}A_J}{\Delta z}=-\sum_{k=1}^{n_i}v_{j,ik}s_{ik}\rho_{j,ik} \tag{1}$$

where A_j is the flow area on the jth axial note, ρ_j is the coolant density on the jth axial note, Δt is the time step, w_J is the coolant axial speed in the sub-channel on the Jth axial note, Δz is the axial grid step, $v_{j,ik}$ is transverse coolant velocity from sub-channel i to adjacent sub-channel k on axial node j, s_{ik} is contact width between adjacent sub-channel i and k, n_i is the number of adjacent sub-channels of sub-channel i, and the coolant densities between adjacent sub-channels and different axial nodes are calculated as the arithmetic average of these values on nodes: $\rho_{j+\frac{1}{2},i}=(\rho_{j,i}+\rho_{j+1,i})/2$ and $\rho_{j,ik}=(\rho_{j,i}+\rho_{j,k})/2$. The upper index 0 means the value of previous time step and the variables without it are at the present time so the equation is in the implicit scheme.

2.2.2. Fluid energy equation

$$A_j\frac{(\rho h)_j-(\rho h)_j^0}{\Delta t}+\frac{w_{J+1}\rho_j h_j A_j-w_J\rho_{j-1}h_{j-1}A_{j-1}}{\Delta z}$$
$$=-\sum_{k=1}^{n_i}\Bigg[v_{j-1,ik}s_{ik}(\rho h)_{j-1,ik}+\beta(\rho w)_{j-1,ik}s_{ik}(h_{i,j-1}-h_{k,j-1})$$
$$+\lambda_{j-1,ik}\frac{s_{ik}}{l_{ik}}(T_{i,j-1}-T_{k,j-1})\Bigg]+\sum_{r=1}^{f_i}\varphi_{ir}P_rH_{r,j-1}(T_{csr}-\overline{T_r})_{j-1} \tag{2}$$

where h_j is the coolant enthalpy in the sub-channel on the jth axial note, β is the turbulent mixing coefficient, $\lambda_{j,ik}$ is the coolant thermal conductivity between adjacent sub-channel i and k on the jth axial node, l_{ik} is the turbulent length between adjacent sub-channel i and k, $T_{i,j}$ is the coolant temperature of sub-channel i on axial node j, f_i is the number of adjacent fuel rods of sub-channel i, ϕ_{ir} is the heating ratio of contact length from rod r to sub-channel i, P_r is the circular perimeter of rod r, $H_{r,j}$ is the heat transfer coefficient from the fuel rod to the coolant around rod r on the jth axial node, T_{csr} is the temperature of outer cladding surface of rod r, $\overline{T_r}$ is the average temperature of the coolant around fuel rod r: $\bar{T}_r=\sum_{i=1}^{c_r}\varphi_{ir}T_i$. And the convection term is discretized in the first-order upwind scheme. The circumferential thermal gradient of the cladding is neglected, and it is assumed that the heat flux is

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