COUPLE, A Coupled Neutronics and Thermal-Hydraulics Code for Transient Analyses of Molten Salt Reactors

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INTRODUCTION

Molten Salt Reactor (MSR) is the only one using liquid fuel in the six candidate reactors of the Generation IV advanced nuclear power systems with expected remarkable advantages in safety, economics, sustainability, and proliferation resistance. Fast spectrum MSR favorable safety-related parameters make possible nuclear waste burning. New MSR concepts are: molten salt actinide recycler and transmuter (MOSART), thorium molten salt reactor (TMSR), and molten salt fast reactor (MSFR) [1]. A strong coupling between neutronics and thermal-hydraulics due to fuel movement in MSR induces many new challenges in reactor analyses from the perspective of both theoretical models and solution methods. Intensive studies on the fundamental issues of MSRs are performed at KIT and other institutes and universities. As concerns simulation of transients, the SIMMER code has been extended and used at KIT [2] for MSR simulations, in which phase transitions, e.g. salt boiling under hypothetical accident conditions can be modeled. The SIMMER simulations may take a lot of computer time due to a very general code framework. If transient simulations are performed for near nominal conditions, a simpler modeling may be used.

Based on previous theoretical studies [2-4], a neutronics and thermal-hydraulics coupled code named COUPLE is developed at KIT/IKET, initially for MSRs transient analyses near operating conditions. Furthermore, a refined channel model is developed for the core region, which makes the code also applicable to other types of reactors, i.e. those with solid fuel.

CODE DESCRIPTION

The COUPLE code has a modular structure, which mainly includes four parts shown in Fig. 1. The red arrows indicate the coupling strategy and data transfer between the neutronics module and the thermal-hydraulics module.

The single-phase thermal-hydraulics model for fluid-fuel reactors can be generally set up based on the fundamental laws of the mass, momentum and energy conservation equations. The Euler model was incorporated initially and extended later for taking into account turbulence effects by the K-ε model. Salt flow effects on the delayed neutron precursor distributions in space are considered in the neutronics model. The multi-group neutron diffusion and precursors balance equations are written as:

$$\frac{1}{v_g}\frac{\partial \phi_g}{\partial t} = S_g + \chi_{p,g}(1-\beta)\sum_{g'=1}^{G}(\nu\Sigma)_{f,g'}(r)\phi_{g'}(r,t) + \sum_{i=1}^{I}\chi_{d,i,g}\lambda_i C_i(r,t) + \sum_{g=1}^{G}\Sigma_{g'\to g}(r)\phi_{g'}(r,t) - \Sigma_{t,g}\phi_g(r,t) + \nabla\cdot D_g(r)\nabla\phi_g(r,t)] \quad (1)$$

$$\frac{\partial C_i(r,t)}{\partial t} = \beta_i\sum_{g'=1}^{G}(\nu\Sigma)_{f,g'}(r)\phi_{g'}(r,t) - \lambda_i C_i(r,t) - \nabla\cdot[UC_i(r,t)] \quad (2)$$

The last convective item in Eq. (2) is due to the salt flow effects, the essential difference between liquid-fuel and solid-fuel reactors.

The B method (first interfaces, then nodes) for mesh setting up is adopted, and the variables are assigned for a staggered mesh. The vectors, such as the velocity ones, are assigned on the interfaces, while the scalars are at the node centers. The mesh can be divided in uniform or non-uniform ways flexibly. The finite volume method (FVM) is adopted to discretize the fluid-dynamics equations to ensure the conservation of the discretized equations. The fully implicit discretization scheme is used in time. The power law scheme (PLS) is used for scalars (combination of convective and conductive items). The stability-guaranteed second-order difference (SGSD) scheme is used for the vectors.

The set of the discretized equations is a large and sparse matrix. The alternative direction iteration (ADI) method combining with the tri-diagonal matrix algorithm (TDMA) is used as the basic computation algorithm. The calculation flow is shown in Fig. 2.

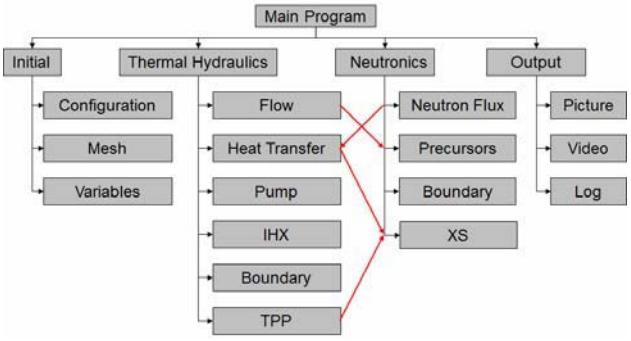


Fig. 1. COUPLE code structure

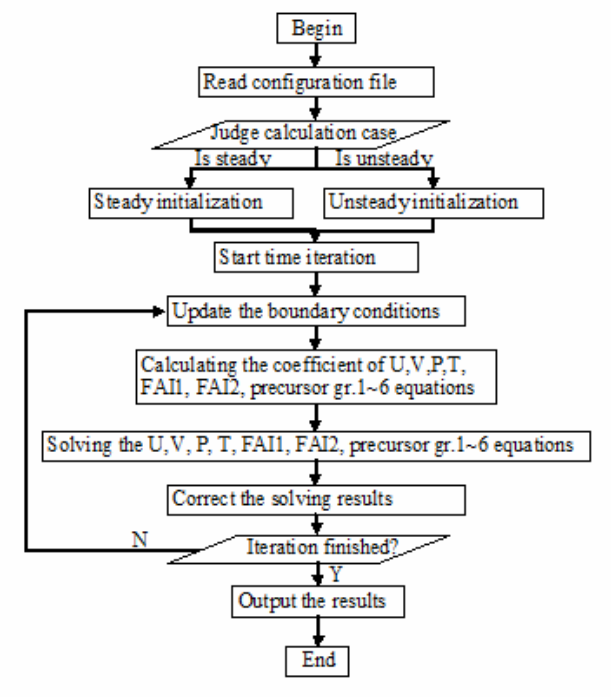


Fig. 2. COUPLE code calculation flow

CODE VERIFICATION AND IMPROVEMENTS

The COUPLE code was verified by diverse methods. The functional modules such as the heat transfer module, the flow module and so on were verified separately, while the integrated code was verified by a FLUENT-based program for the MSFR [1] calculation. Fig. 3 compares the temperature profile at the core middle plane, while Fig. 4 displays the power density distributions in 2-D for comparison. They show good agreement. The COUPLE code verification by SIMMER-III was performed preliminary and will be processed deeply in the future.

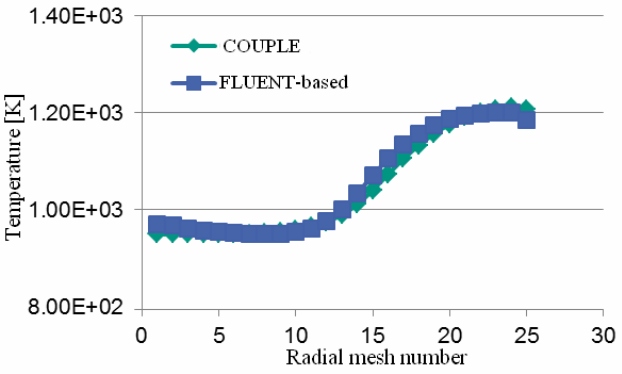
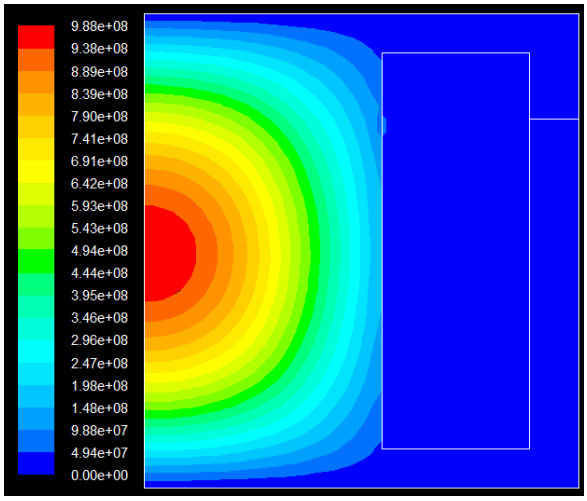
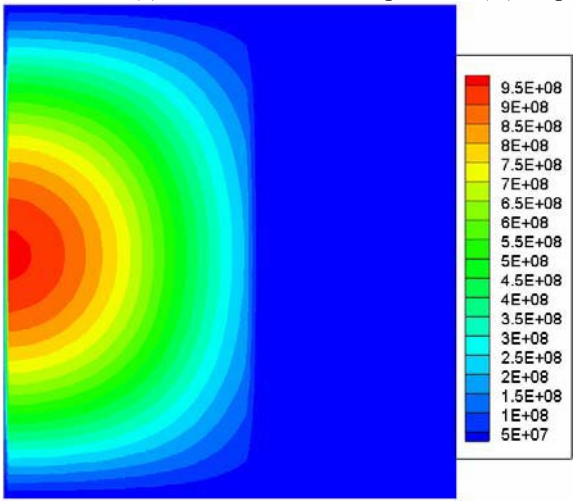


Fig. 3. Temperature comparison between FLUENT-based program and COUPLE

To extend the COUPLE code to solid-fuel reactors application, the refined channel model was developed to simulate the solid active core region with the fuel pin-subassembly configuration, while the other part of the pool uses same models as before. This new extension has been tested in a natural convection LBE reactor.



(a) FLUENT-based temperature (K) map



(b) COUPLE temperature (K) map

Fig. 4. Power density comparison between FLUENT-based program and COUPLE.

REFERENCES

1. M. Brovchenko, E. Merle-Lucotte, et al., Molten Salt Fast Reactor transient analyses with the COUPLE code, submitted ANS 2013 summer Mtg., Atlanta, US.
2. S. Wang, A. Rineiski, D. Zhang, Molten Salt Fast Reactor analyses with SIMMER-III Code, submitted ANS 2013 summer Mtg., Atlanta, US.
3. D. Zhang, A. Rineiski, and S. Qiu, "Comparison of Modeling Options for Delayed Neutron Precursor Movement in a Molten Salt Reactor," *Trans. Am. Nucl. Soc.*, **100**, 639 (2009).
4. D. Zhang, A. Rineiski, and S. Qiu, "Kinetics Models for Safety Studies of Fluid-Fuel Reactors", *Trans. Am. Nucl. Soc.**104***, (2011).