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Comparison analysis of temperature fluctuations for double jet of liquid metal cooled fast reactor

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ABSTRACT

Thermal striping is one of great safety concerns for liquid metal cooled fast reactor, and its detailed analysis is thus very important for reactor design and operation. In this paper, large eddy simulation (LES) approach was employed for the accurate simulation of temperature fluctuations for thermal striping in double jet model by using FLUENT. The normalized amplitudes of temperature fluctuations of lead and Lead–Bismuth Eutectic (LBE) were obtained. Then in order to compare temperature fluctuations of lead-based reactor and that of sodium cooled reactor, the same calculation of sodium was also performed. Moreover, the power spectrum density (PSD) of temperature fluctuation of lead, LBE and sodium was analyzed by using MATLAB for investigating the dominant frequencies of temperature fluctuation of the three fluids. It is concluded that both amplitudes and frequencies of lead-based materials fluctuations are larger compared with that of sodium temperature fluctuations, and thermal striping should thus be paid more attention to in lead-based reactor than sodium cooled reactor.

1. Introduction

Lead-based reactor is well understood to have many favorable characteristics in terms of neutronics, thermal hydraulics and chemical features (Wu et al., 2016, 2011; Wu and FDS Team, 2006, 2008; Wu, 2007), with the prospect of becoming the first Generation IV Nuclear Energy System for realizing industrial demonstration and commercial applications according to authoritative assessment of the Generation IV International Forum (GIF) (Behar et al., 2014).

In a lead-based reactor, the coolant that flows out of the reactor core subassemblies has different temperature, and the mixing of the coolants with different temperatures results in a temperature fluctuate, which causes a high cycle thermal fatigue at the solid wall and endangers reactor safety due to the high thermal conductivity. This phenomenon is called thermal striping (Choi and Kim, 2007). Important parameters that affect the thermal striping phenomenon are the amplitude and frequency of the temperature fluctuation.

Some researches about thermal striping of sodium cooled fast reactors have been performed in the past. For examples, Muramatsu and Ninokata (1996) established two thermal hydraulics computer programs AQUA and DINUS-3 demonstrating that thermal striping conditions can be estimated efficiently by combining AQUA code and DINUS-3 code. Chacko et al. (2011) predicted the temperature fluctuations of thermal striping in a triple jet by large eddy simulation (LES) technique. The Spalart–Allmaras and realizable k-ε turbulence models were also considered along with LES and it is found that LES can well predict the correct amplitude of temperature fluctuations, while the RANS approach is poor for thermal striping.

Thermal conductivity of lead-based materials such as lead and LBE is not more than about 1/5 of sodium's thermal conductivity. However, amplitude and frequency of the temperature fluctuation induced by fluids of low thermal conductivity are believed to be much higher according to Ref. Muramatsu and Ninokata (1996). Thus temperature fluctuations at core outlet of lead-based reactors may be more obvious than that of sodium cooled fast reactors. However, so far there is lack of detailed analysis about thermal striping at core outlet of lead-based reactors or temperature fluctuation for lead-based materials.

In this paper, fundamental simulations of temperature fluctuations for thermal striping for lead-based materials and sodium were performed by LES approaches on FLUENT software. For lead, the temperature parameters were selected by referencing Advanced Lead-cooled Fast Reactor European Demonstrator (ALFRED) design report (PSI/KIT, 2012). And for LBE, the

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temperature parameters were selected by referencing China LEAd-based Research Reactor (CLEAR-I) Wu et al., 2015, which was performed by Institute of Nuclear Energy Safety Technology (INEST/FDS Team), Chinese Academy of Sciences (CAS), and FDS Team has a great influence on fusion blanket design (Wu and FDS Team, 2007a,b, 2009a; Wu, 2002; Wu et al., 2000; Qiu et al., 2000), neutronics nuclear software (Wu and FDS Team, 2009b; Wu et al., 2015) and nuclear reactor materials (Li et al., 2007; Huang et al., 2004). The temperature parameters of sodium were selected according to Ref. Muramatsu and Ninokata (1996). Then amplitude and frequency of these three fluids were compared. The main objectives of this paper are to provide references for researches about turbulent models and effect laws of thermal striping at core outlet of lead-based reactors and provide crucial parameters for future design and operation of lead-based reactors.

2. Numerical simulation

2.1. Double jet

In this paper, a double jet computational model was based on Muramatsu and Ninokata' (1996) and then it was improved. In order to take into account back flow and outlet effect, the inlet and outlet were lengthened in the computational model, as shown in Fig. 1. The length (x direction), the width (z direction) and the height (y direction) are 300 mm, 2 mm and 38 mm respectively. The width is two times than Muramatsu and Ninokata' because mesh number in z direction were also considered that more computational cells would be generated. Furthermore there is a 20 mm extended section before inlet to make fluids fully developed as much as can. The width of inlet nozzle is 5 mm and the width between the nozzles is 20 mm.

2.2. Turbulence model

LES turbulence model was introduced in this contribution. The prediction of temperature fluctuations for thermal striping by the LES approach is closer to experiment results and it can show features of thermal striping well according to the past researches. Chacko et al. (2011) performed numerical simulations of a non-isothermal triple jet flow to assess the capability and accuracy of LES in thermal striping study and demonstrated that the capability and potential of LES in the thermal striping study. Tenchine et al. (2013) carried numerical computations of triple jet flow with TRIO_U code using both k-ε model and LES approach and compared the calculation results with the previous experimental results, and indicated that the LES approach gives better results. Kim et al. (Kim et al., 2014; Choi et al., 2015) developed a numerical investigation of thermal striping in the upper plenum of the PGSFR (Prototype Generation-IV Sodium cooled Fast Reactor) employing both the RANS and LES methods by using CFX, and it can be found that the RANS solutions converged to a steady state solution even though the unsteady solution method is employed. However, the LES solution provides the temporal variation of temperature at any location of the UIS (Upper Internal Structure). It is demonstrated LES can predict better for thermal striping under transient calculation. Choi et al. (2004) studied thermal striping in an upper plenum of KALIMER. Both the RANS simulation and LES were performed using the commercial CFX codes. The simulation results of distributions of the velocity and temperature at six planes in the angular direction show that for the temporal velocity and temperature distributions within the numerical accuracy of the solution, LES approach performs better than RANS simulation.

In the LES, the Smagorinsky–Lilly model was used to model the sub-grid scale (SGS) stress tensor, considering that Chacko et al. (2011) predicted temperature fluctuations of thermal striping observed in a triple jet by using the Smagorinsky–Lilly model and the results were in good agreement with the available experimental data. The fundamental equations of LES model is given as follows (Chacko et al., 2011; Choi et al., 2015):

$$\frac{\partial}{\partial x_i}(\overline{U_i}) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\overline{U_i}) + \frac{\partial(\overline{U_i U_j})}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{P}}{\partial x_i} + \frac{\mu}{\rho}\frac{\partial^2 \overline{U_i}}{\partial x_j \partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

$$\frac{\partial \overline{\Theta}}{\partial t} + \overline{U_i}\frac{\partial \overline{\Theta}}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(k + \frac{\nu_{SGS}}{Pr^{(t)}}\right)\frac{\partial \overline{\Theta}}{\partial x_i}\right] \tag{3}$$

where $\overline{P}$ is the filtered pressure, ρ is the density, $\overline{T}$ is the filtered temperature, k is the molecular diffusivity, ν_{SGS} is the SGS eddy viscosity and $Pr^{(t)}$ is subgrid Prandtl number. $\overline{U}_i$ are filtered velocity components such as:

$$\overline{f}(x_i, t) = \iiint_{vol} G(x_i - x_i')f(x_i', t)dx_i' \tag{4}$$

$$\tau_{ij} - \frac{1}{3}\delta_{ij}\tau_{kk} = -2\nu_{SGS}\overline{S_{ij}} = \nu_{SGS}\left(\frac{\partial \overline{U_i}}{\partial x_j} + \frac{\partial \overline{U_j}}{\partial x_i}\right) \tag{5}$$

$$\nu_{SGS} = L_s^2|\overline{S}| = L_s^2\sqrt{(2\overline{S_{ij}}\overline{S_{ij}})} \tag{6}$$

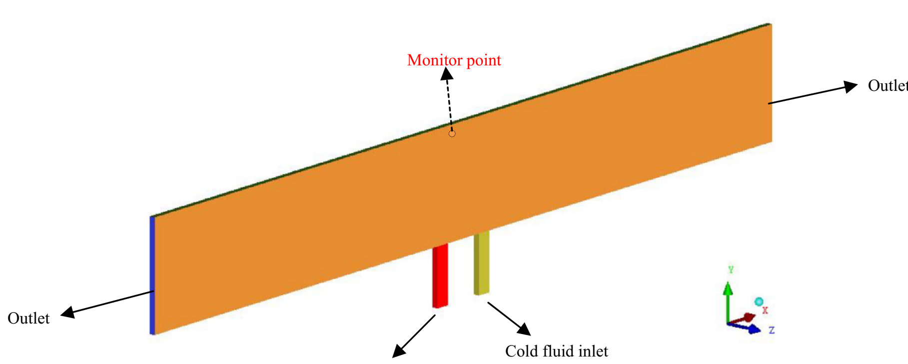

Fig. 1. Computational model of a double jet.