Annals of Nuclear Energy 114 (2018) 214–226

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Numerical study on temperature fluctuation of upper plenum in FBR with a more realistic model

Qiong Cao [a,*], Shiyao Liu [a], Daogang Lu [a], Hongyuan Li [b], Mu Chang [a]

[a] Beijing Key Laboratory of Passive Safety Technology for Nuclear Energy, North China Electric Power University, Beijing 102206, PR China
[b] School of Control and Computer Engineering, North China Electric Power University, Beijing 102206, PR China

ARTICLE INFO

Article history:
Received 23 January 2017
Received in revised form 12 December 2017
Accepted 14 December 2017

Keywords:
Temperature fluctuation
Upper plenum of FBR
Head of the assembly
Central column
LES

ABSTRACT

The thermal fatigue caused by the temperature fluctuation is more serious in FBR than that in PWR due to thermal characteristic. Limited by the ability of the computer, the simplified jet models were used to study the temperature fluctuation in published literature, which can not fully reflect the real characteristic of temperature fluctuation of upper plenum in FBR. In present study, the temperature fluctuation of upper plenum with a more realistic model (i.e. three heads of assemblies and the part of central column) in FBR was simulated with LES method. By comparison, the velocity and temperature fields are more complex in a more realistic model than that of the simplified jet model. The characteristic of temperature fluctuation was obtained around the central column. In a more realistic model, the fluid produces intense mixing near interface of the adjacent different temperature regions, which lead to severe temperature fluctuation. The distributions of temperature and temperature fluctuation intensity are asymmetric. The temperature field is divided into three regions with high temperature range $\theta = 195–285°$ for the three kinds of temperature inlet conditions, while that is divided into two regions with high temperature range $\theta = 75–285°$ for two kinds of temperature inlet conditions. The changes of temperature and temperature fluctuation intensity are complicated by the influence of the head of assembly in the coordinate directions. The position of the most intense oscillation appears in the upper position of the head outlet. However, near the bottom of the central column, the thermal stratification and temperature fluctuation are still relatively obvious with the temperature difference about 30–40 K and the amplitude about 0.1–0.15 times of the maximum inlet temperature difference. Meanwhile, the obvious dominant frequency does not appear. The energy of temperature fluctuation is distributed in a wide frequency range $f < 20$ Hz.

1. Introduction

In the fast reactor, the uneven distribution of the core power leads to the uneven temperature distribution of the liquid sodium flowing out of the core in the fast breeder reactor (FBR). The temperature fluctuation will occur when the coolants are mixed in upper plenum, which may cause the thermal stress and thermal fatigue of the central column exposed in this environment. Due to the larger temperature different and high thermal conductivity of the liquid sodium, the effect is more obvious in FBR than that for PWR (Tenchine, 2010). Therefore, in order to ensure the safe operation of the nuclear power plant and reduce thermal fatigue of the central column, it is very important to carry out a research on the temperature fluctuation of upper plenum in the FBR.

The structure of the outlet in the fast reactor core is very complex. It is difficult to accurately simulate this structure. Generally, the simplified jet geometric structures were often used to study the characteristic of the temperature fluctuation, which including the parallel two jets, parallel triple jet and the coaxial jet models. Wakamatsu et al. (1995) designed the parallel two jets model to simulate the upper core structure of the fast reactor. The hot and cold flows through two rectangular nozzles were injected to a solid plate placed at a small distance above the nozzles. The attenuation of the temperature fluctuation from the fluid flow to the solid surface was obtained, i.e. 30–80% of the water attenuation ratio, 20–50% of the sodium. The triple jets model was also studied by the experiment and simulation.

Tokuhiro and Kimura (1999) carried out an experiment based on the parallel three quasi-planar vertical jets, arranging a cold nozzle in the middle and two hot nozzles on both sides with the water velocity 0.5–1 m/s, temperature 25–42 °C. The distributions of the velocity and temperature were obtained from the experi-

* Corresponding author.
E-mail address: lian24111@163.com (Q. Cao).

https://doi.org/10.1016/j.anucene.2017.12.042
0306-4549/

Nomenclature

S_{ij}	large-scale strain rate tensor [–]
L_s	mixing length for subgrid scales [mm]
C_s	Smagorinsky constant [–]
κ	von Kaman constant [–]
d	distance to the closest wall [mm]
V	volume of the computational cell [mm^3]
z	height [mm]
r	radius [mm]
r^*	normalized radius [–]
z^*	normalized height [–]
D_h	hydraulic diameter [mm]
T	temperature [K]
T_1	inlet temperature of No.1 head of assembly [K]
T_2	inlet temperature of No.2 head of assembly [K]
T_3	inlet temperature of No.3 head of assembly [K]
C_p	specific heat capacity [$J \cdot kg^{-1} \cdot K^{-1}$]
T^*	normalized temperature [–]
T_{max}	the largest inlet temperature of three heads [K]
T_{min}	the smallest inlet temperature of three heads [K]
T_i	transient temperature [K]
T^*_{avg}	normalized average temperature [–]
T^*_{RMS}	normalized root-mean-square temperature [–]
T_{avg}	average temperature [K]
N	total number of calculated temperature [–]

Greek letters

τ_{ij}	subgrid-scale model stress tensor [–]
θ	azimuth [°]
ρ	density [kg/m^3]
η	kinetic viscosity [$kg \cdot m^{-1} \cdot s^{-1}$]
λ	thermal conductivity [$W \cdot m^{-1} \cdot K^{-1}$]

mental data. Further, Kimura et al. (2007) evaluated the transfer characteristics of temperature fluctuation from the fluid to the solid based on the parallel triple jet model with the sodium velocity 0.2–1.01 m/s, temperature 304.5–352.4 °C. The temperature fluctuation was severely attenuated from the sodium to the stainless (wall). In addition to, the reviews of the numerical simulation on the temperature fluctuation were also published. The temperature fluctuation is related to the small scale eddies of turbulence flow. However, the pulsation of the fluid is averaged for Reynold averge method (RANS). So, the RANS turbulence model was applied to simulate this phenomenon with a limited success, while large eddy simulation (LES) method can accurately simulate it (Howard and Serre, 2015; Chacko et al., 2011; Hu and Kazimi, 2006; Aulery et al., 2012). Chacko et al. (2011) simulated unsteady temperature fluctuation caused by the parallel jet flows with the Spalart-Allmaras, realizable k-Ɛ and LES method. The result showed that the RANS model is failed to predict the correct magnitude of the temperature fluctuation, while LES is an effective turbulence model to simulate the temperature fluctuation phenomenon. Similarly, Cao et al. (2012) simulated the temperature fluctuation caused by the parallel triple jet flows with LES method. By comparison, the numerical results were in good agreement with the experimental ones

However, Tenchine and Moro (1997) performed a coaxial jet experiment with air, water and sodium as the fluid mediums. The similarity criteria of the water or air instead of the sodium was obtained. Then, Lu et al. (2012) also carried out an experiment to study the three-dimensional temperature fluctuation caused by coaxial-jet flows. The result shown that the average temperature presented two-dimensional characteristic, while the transient temperature fluctuation was the three-dimensional.

Generally, the outlet structure of the core is composed of many heads of assemblies in the FBR, as showed in Fig. 1. However, the research objects in the above reviews are the simplified jet models. These nozzles are very different from the head of the assembly. So, the simplified jet model can't accurately reflect the actual situation of the temperature fluctuation phenomenon in the upper plenum of the FBR. Therefore, taking into account the real outlet structure of the core, three heads of the assembly with a triangular arrangement were simulated by the software FLUENT in present study. In addition to, in order to evaluate thermal stress and thermal fatigue of central column, the temperature and frequency spectrum of sodium around the central column will be analyzed.

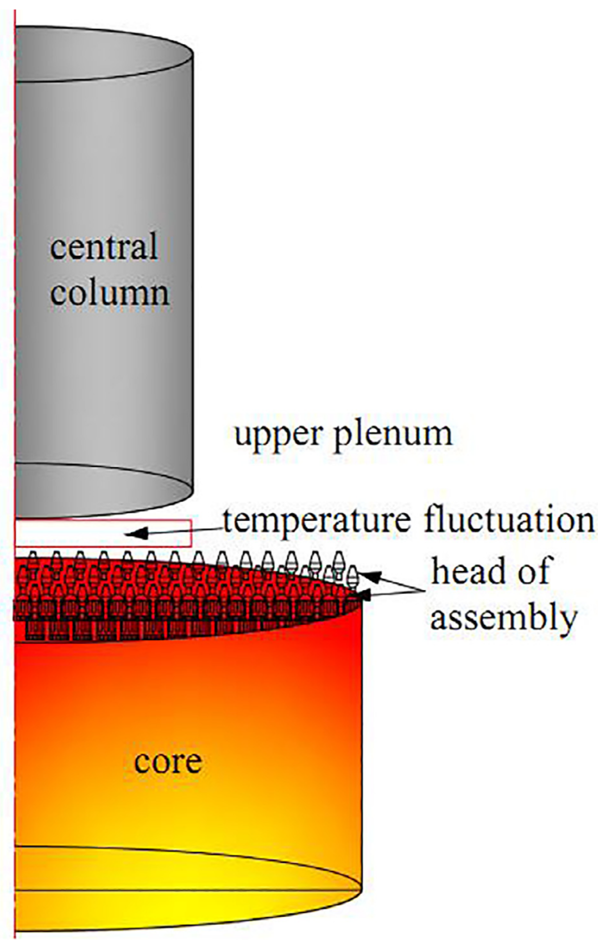

Fig. 1. Schematic diagram of the outlet in FBR core.

2. Numerical method

The temperature fluctuation is related to the small scale eddies of turbulence flow. The pulsation of velocity is averaged in Reynold averge method (RANS). So, the temperature fluctuation was simulated by RANS turbulence model with a limited success. Large eddy