THE PRESENT STATE-OF-THE-ART THERMAL STRIPING STUDIES FOR SODIUM-COOLED FAST REACTORS

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ABSTRACT

The core outlet region of a fast reactor where the subassembly jets mix below the upper internal structure is concerned with safety and design issues. Due to the temperature difference between the control rod and fuel assemblies, high cycle thermal fatigue can occur in the mixing area and can produce cracks on the upper internal structure. This is called thermal striping. Several numerical and experimental works have been conducted to study the thermal striping phenomenon. In this paper we review previous works in the literatures devoted to thermal striping. For experimental works, previous studies on coaxial, double and triple jets performed at the CEA, CRIEPI, JAEA and KAERI are summarized. Several works using different working fluids, such as air, water and sodium, are mentioned. The numerical works using different turbulence models such as the two equation turbulence models, an elliptic relaxation turbulence model and a low Reynolds number differential stress and flux model have been also mentioned. The relative performances among the different turbulence models have been mentioned and their limits explained. The works utilizing a large eddy simulation method, which is currently recognized as the most suitable calculation method for thermal striping study, are included. The previous numerical studies applied to different geometries such as the planar triple and coaxial jets as well as the recent work applied to the upper plenum of the real fast reactor are mentioned. The superiority of the large eddy simulation method for a thermal striping study is explained. Finally, the thermal striping study performed at KAERI is explained in detail.

KEYWORDS
Thermal striping, fast reactor, turbulence model, large eddy simulation

1. INTRODUCTION

In a fast nuclear reactor, the fluid that flows out of the reactor core subassemblies such as the fuel subassemblies, control rod subassemblies, and blanket subassemblies have different temperatures, and the mixing of fluids with different temperatures results in a temperature fluctuation. Owing to the high thermal conductivity of the sodium, the temperature fluctuation is transported well to the solid wall. The temperature fluctuation transferred to the solid wall causes high cycle thermal fatigue at a solid wall. This phenomenon is called thermal striping. The important parameters that affect the thermal striping phenomenon are the frequency and amplitude of the temperature fluctuation. The temperature difference between assemblies could be several tens of Kelvin, and the frequency range of temperature fluctuations could be between 1Hz and 50Hz. This level of amplitude and range of frequency (especially below 10Hz) are considered potentially dangerous from a high cycle thermal fatigue point of view. Thus, an

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understanding of thermal striping is very important for the thermal hydraulic design of the reactor core to secure the structural integrity of the components in the upper plenum of a fast reactor.

2. PREVIOUS WORKS

2.1. Experimental Works

Several experimental works have been conducted in the past to understand the thermal striping phenomenon. A summary of previous experimental studies is given in Table 1. These experiments are on either a coaxial-jet or a planar triple that approximates the outlet of the fast reactor core subassemblies. The main objective of these experimental works was to find a similarity rule among the experimental data with different working fluids such as air, water and sodium since the cost of a sodium experiment is very expensive and sodium experiments require additional infrastructure and risk mitigation equipment that is not warranted if an alternative fluid can provide sufficient data. They also provided valuable experimental data for an evaluation of the thermal hydraulic computer codes and turbulence models.

Table 1. Summary of previous experimental studies

Author	Year	Jet type	Working fluid	Measured data
Ushijima et al.[1]	1990	coaxial jet	water	U , T , $\overline{u_i u_j}$, T_{rms} , $\overline{u_i T}$
Moriya and Ohshima [2]	1990	coaxial jet	sodium, water, air	T , T_{rms}
Tenchine and Moro [3]	1997	coaxial jet	sodium, air	T , T_{rms}
Hattori et al. [4]	1998	coaxial jet	air	U , T , U_{rms} , T_{rms}
Tokuhiro and Kimura [5]	1999	triple jet	water	U , T , U_{rms} , T_{rms}
Nishimura et al. [6]	2000	triple jet	water	U , T , $\overline{u_i u_j}$, T_{rms} , $\overline{u_i h}$
Kimura et al. [7]	2002	triple jet	water	T , T_{rms}
Nam and Kim [8]	2003	triple jet	air	U , T , $\overline{u_i u_j}$, T_{rms}
Kimura et al. [9]	2007	triple jet	sodium	T , T_{rms}
Lu et al. [10]	2012	coaxial jet	water	U , T , T_{rms}

2.2. Numerical Works

Several numerical works have been done in the past mainly to find the best turbulence model for an analysis of thermal striping phenomenon. Table 2 shows a summary of the previous numerical works in the literature. The authors employed the conventional $k-\varepsilon$ model as well as the low Reynolds-number stress and flux model (LRSFM). However, it is generally observed that the studies employing the Reynolds-averaged Navier-Stokes (RANS) equation method have not been very successful in capturing the oscillating behavior of the thermal striping phenomenon. Thus, the studies using a large eddy simulation (LES) method have appeared in recent publications. A brief introduction of these numerical studies is given below.

Ushijima et al. [1] carried out numerical calculations for a coaxial-jet with different temperatures using the high Reynolds-number differential stress and flux model (HRSFM). The time-average of the velocity and temperature generally agreed with the measured data; however, some discrepancies were found in the turbulence quantities, such as the turbulent heat fluxes. Nishimura et al. [6] conducted a numerical calculation for the triple-jet experiment conducted by Tokuhiro and Kimura [5] using the LRSFM together with the $k-\varepsilon$ model. They showed that the LRSFM can simulate appropriately the experimental results most importantly with respect to the oscillatory motion and consequently the time-averaged profiles of the flow pattern, while the $k-\varepsilon$ model consistently under-predicts the extent of the mixing, such that a transverse mean temperature difference exists far downstream of the jets. Kimura et al. [7] conducted the same computations for the triple-jet flow, but added the computed results using the quasi-DNS (Direct Numerical Simulation). They showed that the coherent oscillation observed in the experiment could be properly simulated by the LRSFM and quasi-DNS, and that the $k-\varepsilon$ model and the LRSFM under-predicts the amplitude of the temperature fluctuation. They also showed that the power spectrum density profiles of the temperature fluctuations predicted by the quasi-DNS were in good agreement with the experimental data, and the prominent frequency component due to the coherent oscillation of the jet could be predicted by LRSFM. Nishimura and Kimura [11] also performed numerical simulations employing the LRSFM together with the $k-\varepsilon$ model for their triple jet experiment and also confirmed that the RANS equation based methods are not very successful. Choi and Kim [12] investigated the effect of the turbulence model in predicting the thermal striping and conductedcalculations using three different turbulence models such as the two-layer $k-\varepsilon$ model [18], SST (Shear Stress Transport) model [19] and elliptic relaxation model [20], which are currently used by many investigators. They found that only the elliptic relaxation model can predict the oscillatory behavior of the temperature fluctuation, even though the predicted amplitude of the temperature fluctuation is smaller than that of the experiment. This shows that despite the recent successes with the RANS methods, none of the turbulence models tested was able to predict the correct level of temperature fluctuations. Chacko et al. [14] conducted an LES for the triple jet experiment by Nam and Kim [8], and found that the LES can produce the oscillation of temperature fluctuation properly, while the SA (Spalart and Allmaras) model [21] and realizable $k-\varepsilon$ model [22] predicts the amplitude and frequency of the temperature fluctuation very poorly indicating that the LES method is an appropriate calculation method for the thermal striping. The works by Cao et al. [15] and Tenchine et al. [16] also confirmed this observation. Based on these observations, Choi et al. [17] recently performed the LES for the thermal striping in the upper plenum of the PGSFR (Prototype Generation-IV Sodium-cooled Fast Reactor) being designed at KAERI (Korea Atomic Energy Research Institute).

Table 2. Summary of previous numerical studies

Author	Year	Jet type	Turbulence model	Computer code
Ushijima et al.[1]	1990	coaxial jet	RSFM	in-house
Nishimura et al. [6]	2000	triple jet	k-ε, LRSFM	in-house
Kimura et al. [7]	2002	triple jet	k-ε, LRSFM, DNS	in-house
Nishimura and Kimura [11]	2007	triple jet	k-ε, LRSFM	in-house
Choi and Kim [12]	1999	triple jet	two-layer, SST, v^2-f	in-house
Durve et al. [13]	2010	triple jet	k-ε	in-house
Chacko et al. [14]	2011	triple jet	SA, realizable k-ε, LES	FLUENT
Cao et al. [15]	2012	triple jet	LES	FLUENT
Tenchine et al. [16]	2013	coaxial and triple jet	k-ε, LES	TRIO
Choi et al. [17]	2015	PGSFR	k-ε, LES	CFX

3. THERMAL STRIPING STUDIES AT KAERI

In KAERI (Korea Atomic Energy Research Institute) Nam and Kim [6] provided detailed experimental data for the thermal striping, mainly to test the turbulence models and LES (Large Eddy Simulation). The types of test sections are a planar double-jet and a planar triple-jet, and the working fluid is air. Several experiments were performed by varying the inlet temperatures and velocities. These experimental data have been used for testing the turbulence models for the simulation of the thermal striping. Choi and Kim [12] used this experimental data to test three turbulence models; the two-layer model by Chen and Patel [18], the shear stress transport (SST) model by Menter [19], and the elliptic relaxation model by Medic and Durbin [20] which are commonly used by many authors to simulate turbulent flows. However, Choi and Kim [12] found that none of these models are able to predict the correct level of the temperature fluctuation. A validation of the LES method for a thermal striping analysis was conducted at the University of Warwick, UK in cooperation with KAERI, and this study is reported in Chacko et al. [14]. In this study, the computations were conducted for a triple jet experiment by Nam and Kim [6]. Simulations were carried out using the finite-volume CFD code, FLUENT. The three-dimensional computer model of a triple jet was constructed using the ICEM software and the 4×10^6 hexahedral computational grids were generated within the solution domain. Simulation conditions were chosen to model the triple jet experiment of Nam and Kim [6] as close as possible.

Figure 1 shows a schematic diagram of the test section in the experiment by Nam and Kim [6] for a triple-jet flow and the computational domain. Figure 2 shows the temporal variation of temperature at the measurement location using the LES and two RANS models, i.e., the SA (Spalart and Allmaras) model [21] and realizable $k-\varepsilon$ model [22], together with the experimental data. These figures clearly show that the LES method predicts the temporal variation of temperature properly, while the RANS methods result in nearly steady state solutions even though the unsteady calculation method is employed. This indicates that the LES method is an appropriate method for calculating the temporal variation of temperature in the thermal striping analysis. The predicted time-averaged temperature profiles are shown in Figure 3. These figures show that the time-averaged temperature is also rather well predicted by the RANS models. There are few differences between the results by the RANS and LES methods for the time-averaged variables. Figure 4 shows the predicted RMS (root-mean-square) of the temperature fluctuation. This figure shows that the LES method accurately predicts the RMS value of temperature fluctuation, while the two turbulence models severely under-predict it. This fact shows that the LES method is a better method than the two-equation RANS methods for the prediction of the temperature fluctuation in the thermal striping analysis.

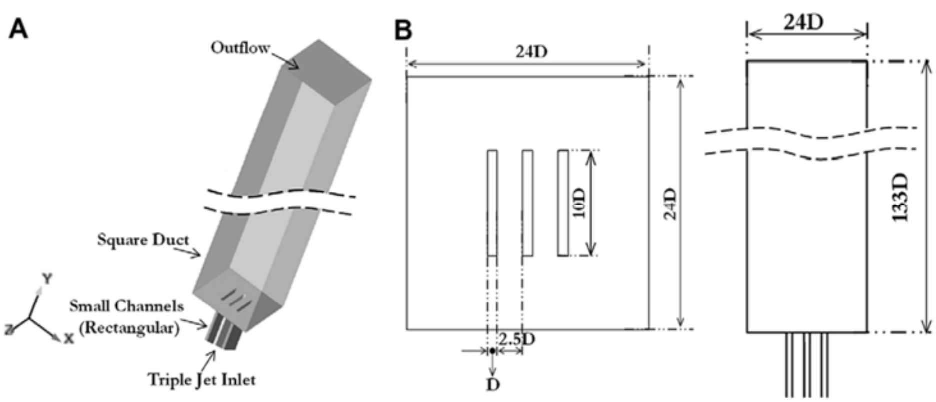
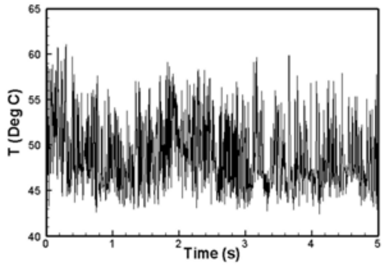
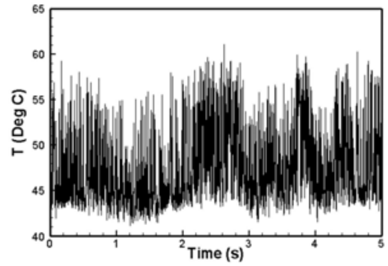


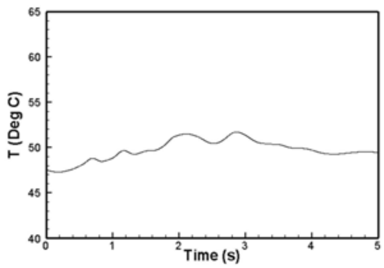
Figure 1. A schematic diagram of the experimental test section



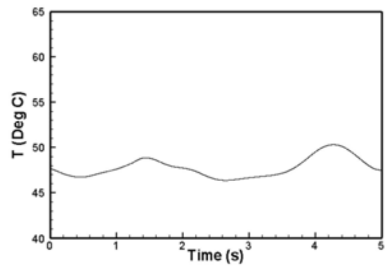
(a) experiment



(b) LES

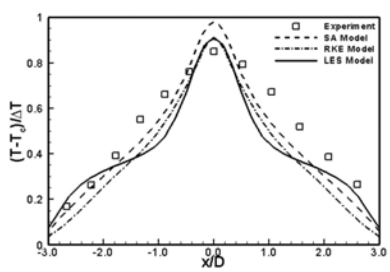


(c) SA model

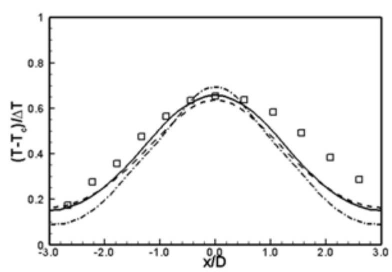


(d) realizable k-ε model

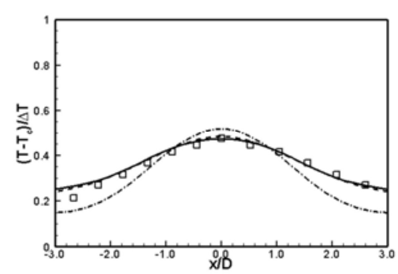
Figure 2. Time history of instantaneous temperature at the measuring point x/D = 2, y/D = 15, and z/D = 0.



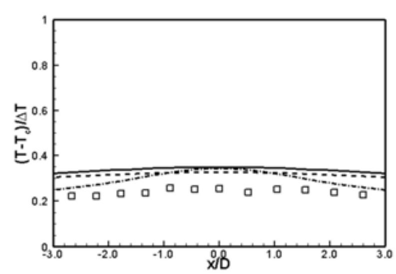
(a) y/D = 7



(b) y/D = 12

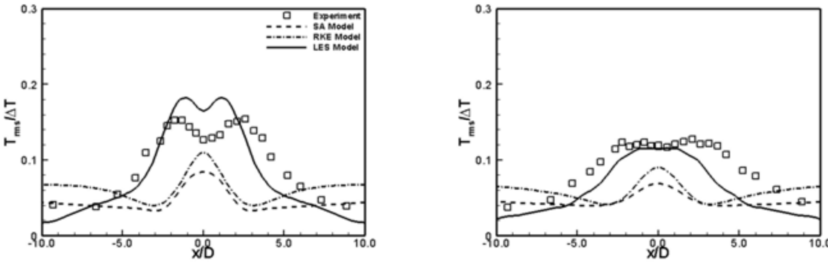


(c) y/D = 18



(d) y/D = 38

Figure 3. The time-averaged temperature profiles in the mid-span



(a) y/D = 18 **(b) y/D = 25**

Figure 4. The RMS temperature fluctuation profiles in the mid-span

Based on the above observation, Choi et al. [17] conducted an LES of the thermal striping in the upper plenum of the PGSFR (Prototype Generation-IV Sodium Cooled Fast Reactor) being designed at KAERI. Figure 5 shows the upper plenum of the PGSFR. It is different from the upper plenum of the usual pool-type fast reactor. Only the UIS (Upper Internal Structure) and four IHXs (Intermediate Heat Exchangers) are placed in the hot pool. The primary pump and the DHXs (Decay Heat Exchangers) are located outside the hot pool, which are not shown in this figure. Figure 6 shows the numerical grids used in the present calculations. More than 11.6 million unstructured elements are generated within the solution domain. More grid refinements were made in the region between the core outlet and first grid plate of the UIS as well as the inside region of the UIS. The overall views of the UIS are given in Figure 7. There are nine control rod shroud tubes and three grid plates inside the UIS. Many flow holes exist in the grid plates as well as in the inner and outer walls of the UIS. The sodium flow from the reactor core flows into the UIS, and then flows out of the UIS mostly in the ⊃-shape region (see Figure 7-(a)), and some of the sodium flows out through the outer wall of the UIS. The sodium from the UIS flows into the inlet of the four IHXs.

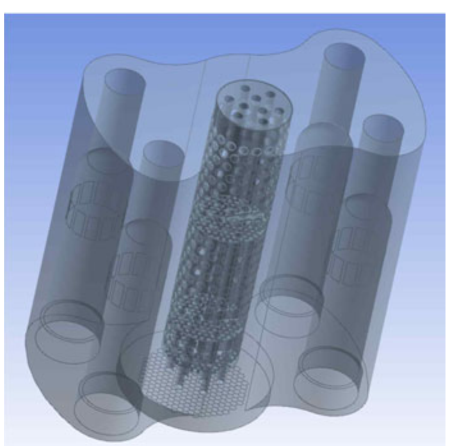
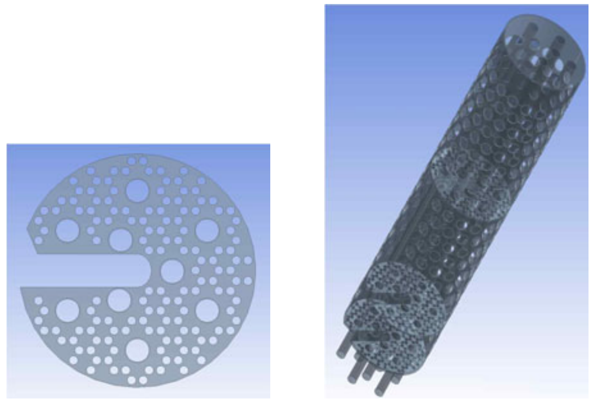


Figure 5. The upper plenum of the PGSFR.

Figure 6. Numerical Grids



(a) first grid plate **(b) UIS**

Figure 7. Shape of the first grid plate and overall view of the UIS

For a thermal striping free design, the results of the computation should provide information where the thermal striping take places severely, and should provide the amplitude and frequency of the temperature fluctuation there. We set several temperature monitoring points in the solid walls of the UIS and IHXs. Figure 8 shows the monitoring points for the temperature fluctuation in the present study. It was observed that the RANS solutions converged to a nearly steady state solution even though the unsteady solution method is employed. However, the LES solution provides a temporal variation of temperature at any locations of the UIS and IHXs. Figure 9 shows the temporal variation of temperature at certain locations of the UIS and IHX (see Figure 5 for four IHXs)) at the final period of computation (15 to 20 seconds). It was observed that the amplitude of the temperature fluctuation is the largest at the first grid plate of the UIS, and becomes smaller at the second grid plate. Among the first grid plate regions, the ⊃-shaped region is the weakest region for thermal striping. This indicates that a relatively large thermal mixing occurs at this region. The second weakest region for thermal striping is the ⊃-shaped region in the second grid plate of the UIS. It is worth mentioning that it is generally recognized that the thermal striping occurs owing to the temperature difference between the control rod subassembly and fuel rod subassembly. The monitoring points M10 to M14 are located in the first grid plate, and those are the upper points of the interface between the control rod subassemblies and fuel subassemblies. However, Figures 9-(a), (b), (d) and (e) show that the amplitude of temperature fluctuations at these locations are smaller than that in the ⊃-shaped region and is not very large, although a rather weak temperature fluctuation exists in the M13 location. However, it will depend on the magnitude of the mass flow rate of sodium from the control rod subassembly. Figure 9-(g) shows that there are no temporal variations of temperature at the IHX inlet and outer surface, indicating that the thermal striping does not occur at these regions. Figure 10 show the predicted frequencies of temperature oscillation at certain locations. It was observed that all frequencies of the temperature oscillation are lower than 15Hz. There does not exist one dominant frequency at one location when the temperature fluctuation is severe, and several oscillating frequencies co-exist in one location. However, when the temperature fluctuation is not severe, the oscillating frequency is also small and there exist one or two dominant frequencies. The thermal-hydraulic computational data produced in the present computation can be used to assess whether the first and second grid plates of the UIS can endure the thermal stress during the reactor life time. The results of these computations may help the designers establish a thermal-striping-free design.

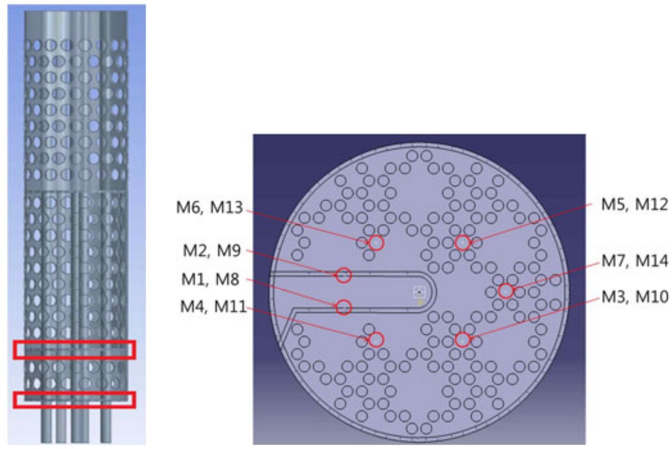
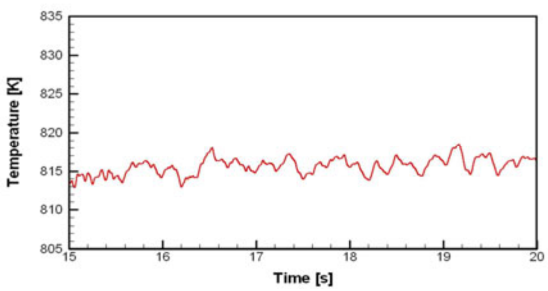
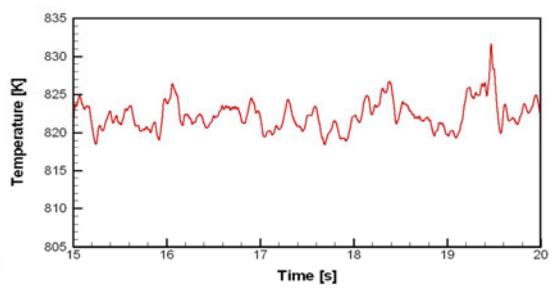


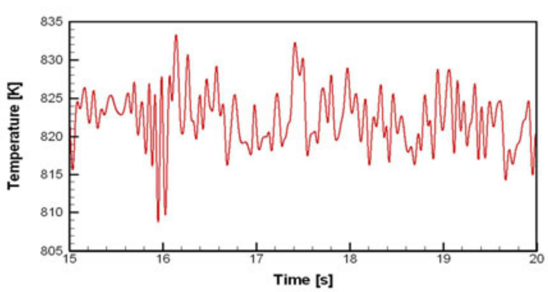
Figure 8 Temperature monitoring locations
(M1 to M7: Second Grid Plate, M8 to M14: First Grid Plate)



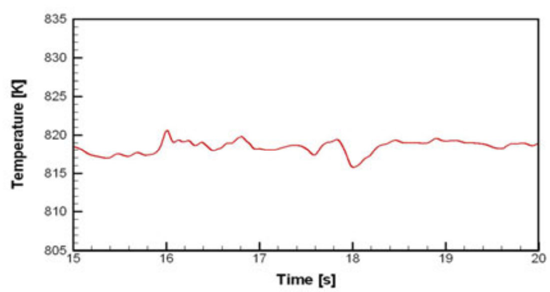
(a) at M12 location



(b) at M13 location

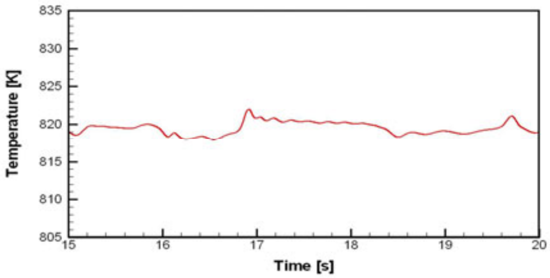


(c) at M9 location

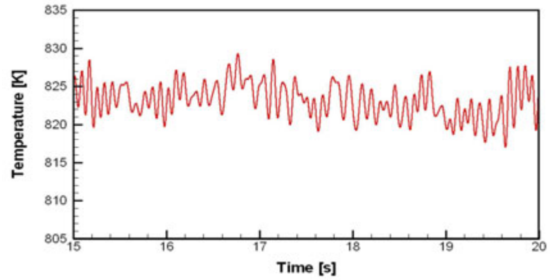


(d) at M5 location

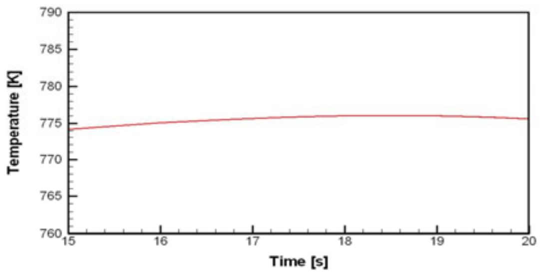
Figure 9 Temporal variation of temperature at various locations (continued)



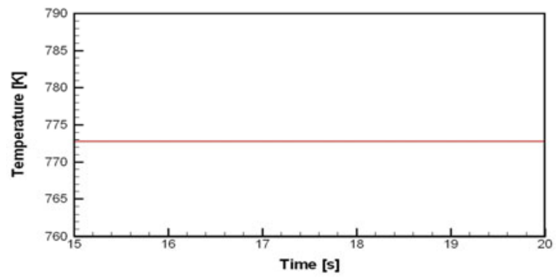
(e) at M6 location



(f) at M2 location

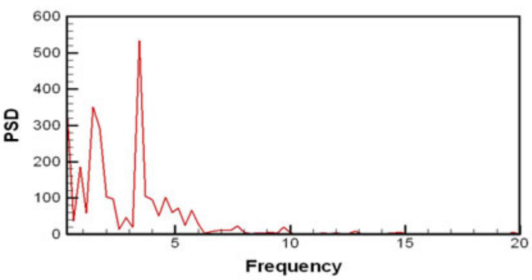


(g) at the IHX inlet

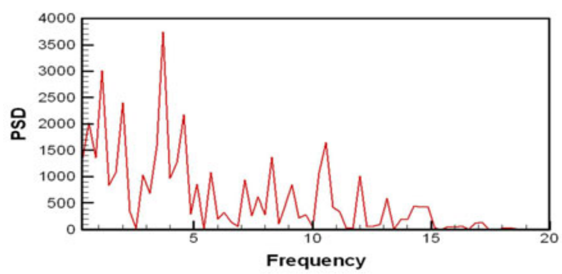


(h) at the IHX surface

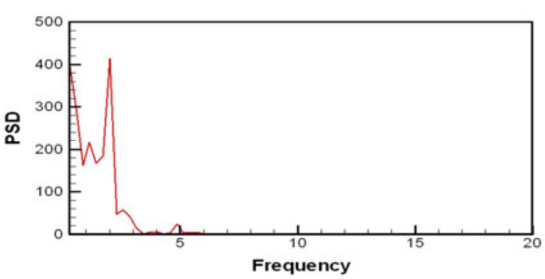
Figure 9 Temporal variation of temperature at various locations



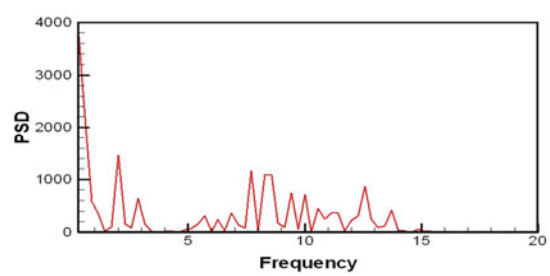
(a) at M12 location



(b) at M9 location



(c) at M5 location



(d) at M12 location

Figure 10 PSD diagram at some locations

4. CONCLUSIONS

Previous experimental and numerical works on the thermal striping are summarized in detail. Several experimental works using different working fluids, such as air, water, and sodium, are mentioned. Numerical works using different turbulence models such as the two equation turbulence models, elliptic relaxation turbulence model, and low Reynolds number differential stress and flux model are also mentioned. The shortcoming of the current RANS models for predicting the thermal striping phenomena is explained. The thermal striping studies performed at KAERI are then explained in detail. This includes the RANS and LES solution of the experiment conducted by Nam and Kim [6], and the LES solution of thermal striping in the upper plenum of the PGSFR. From the LES solution, it was possible to find the region where the thermal striping is severe as well as the amplitude and frequency of the temperature fluctuation there. The data of the temporal variation of temperature produced in this study will provide input data for an investigation of the structural integrity of the UIS. Thus, this kind of computation is important for a thermal hydraulic design of the reactor core, as well as the mechanical design of the UIS.

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