CFD STUDIES IN THE PREDICTION OF THERMAL STRIPING IN AN LMFBR

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Abstract

Thermal striping is a phenomenon, which leads to random temperature fluctuations in the interface between non-isothermal streams arising out of jet instability. Due to the high heat transfer coefficient associated with liquid metal coolant such as sodium, the temperature fluctuations are transmitted to the adjoining structures with minimal attenuation, which eventually leads to high cycle fatigue and crack initiation in the structures. Detailed computational fluid dynamics studies have been carried out to quantify the amplitude and frequency of temperature fluctuations in the structures of primary sodium system of the Indian 500 MWe pool type fast reactor (PFBR), which is under construction at Kalpakkam. Thermal hydraulic investigation consists of Computational Fluid Dynamics (CFD) simulations in two levels. In the first level, a suitable model for numerically simulating thermal stripping has been arrived at by analysing a published benchmark experiment. In the second level, analysis is carried out to predict detailed flow and temperature fluctuations in the reactor, based on the numerical scheme arrived at in the first level,. The predicted temperature fluctuations are found to be within the acceptable limits, which are arrived at based on structural mechanics investigation.

Introduction

Two flow streams at different temperatures, mixing in a fluid domain, result in an arbitrary change of temperature field of the fluid domain with respect to time. This random temperature fluctuation is termed as Thermal Striping. This temperature fluctuation phenomenon is mainly caused due to the instability of fluid jets. Because of the high heat transfer coefficient associated with liquid metal coolants such as sodium, the temperature fluctuations are transmitted to the adjoining structures with minimal attenuation, which eventually leads to high cycle fatigue and crack initiation in the structures. In a Liquid Metal cooled Fast Breeder Reactor (LMFBR), thermal striping potential exists in the upper plenum as a result of the mixing of sodium jets from fuel subassemblies (SA), breeder SA and control SA. There exists a temperature difference of about 100 ºC between the flow streams emanating from these SA.

Detailed thermal hydraulic investigations have been carried out to quantify the amplitude and frequency of temperature fluctuations in the structures of primary sodium system of the Indian 500 MWe pool type fast reactor (PFBR), which is under construction at Kalpakkam. The jet fluctuation responsible for thermal stripping is caused by jet instability as well as turbulence. Therefore, numerical simulation of the thermal stripping phenomena requires accurate simulation of turbulence. Direct Numerical Simulation (DNS) is expected to give the best simulation of this. However, the computational mesh and the time step of transient calculation employed in such simulation must be adequate to resolve the eddies responsible for temperature fluctuation. The size and life of eddies responsible for the temperature fluctuation of jets resulting in thermal stripping are not known exactly. In the absence of such information, the choice of computational mesh and time step of DNS becomes difficult. Therefore, a benchmark experimental study has been chosen for numerical simulation to arrive at a suitable computational scheme for simulating thermal stripping. Based on the necessary computational parameters arrived at from on this study a detailed simulation of thermal stripping in the reactor has been carried out. This paper gives the details and results of these studies.

Bench mark calculation

Numerous experimental works have been carried out to understand thermal striping phenomenon in fast reactors. An experimental analysis carried out by Wakamatsu et al. [1] has been considered as a bench mark problem to arrive at a computational scheme to predict thermal stripping in a fast reactor. The experimental set up is shown in Fig. 1. Hot and cold fluids are independently delivered from hot and cold water tanks to the test piece located at in the vessel. The test piece is held by a supporting pipe and is located just above the nozzles. The distance 'L', between the top of the nozzles and the bottom of the test piece is 38 mm. To avoid the influence of free surface fluctuations, the test piece and jets are arranged inside an inner vessel. The inner vessel is submerged inside the test vessel. The fluid exits the model from the outer vessel. Experiments have been carried out using water and sodium as working fluids. Schematic of the nozzle and test section is shown in Fig. 2. The geometry of the jet nozzle is rectangular (5 x 18 mm exterior). Thermocouples are installed at various monitoring locations on the test piece with two at each location with the tip of one located at the surface of the specimen and the other located at 2 mm from the surface to measure the fluid temperature fluctuations. The thermocouples used are all 0.25 mm in diameter so as to measure the temperature fluctuations with a fast response. Out of the various experimental simulations carried out a typical study in sodium with 3.36 m/s jet velocity and hot and cold jet temperatures of 448 ^{0}C and 301 ^{0}C has been considered for the numerical simulation. The distance between nozzle and plate in this case is 38 mm.

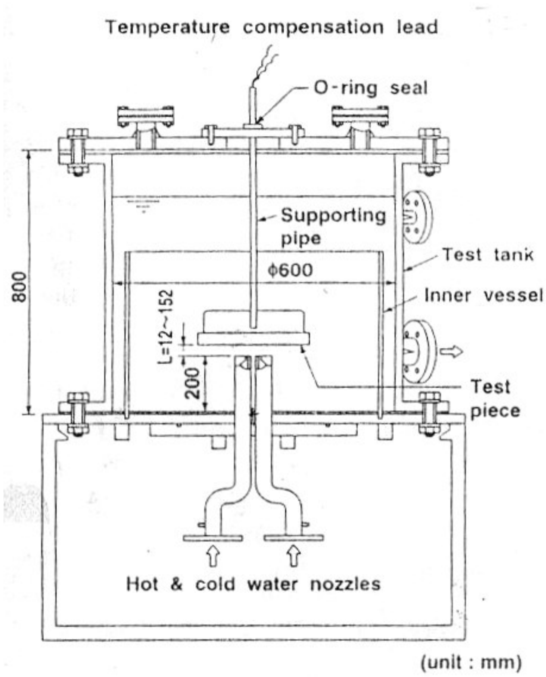

Fig. 1: Experimental Setup [1]

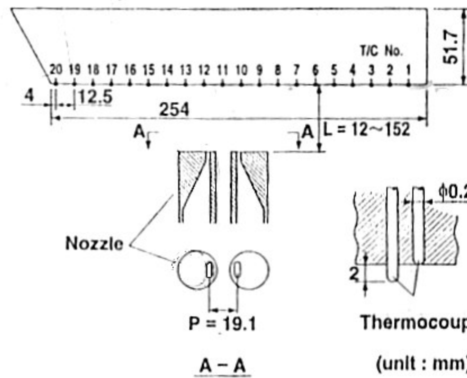

Fig. 2: Schematic of the nozzle and test section

The geometry of the nozzle being nearly rectangular with a size of 5 mm x 18 mm, the flow profile developed in the fluid domain would be nearly symmetric along the length direction of the nozzle. Hence, a two dimensional computational domain is considered with a nozzle width of 5 mm. The geometric details of the 2D model considered for the analysis is shown in Fig. 3.

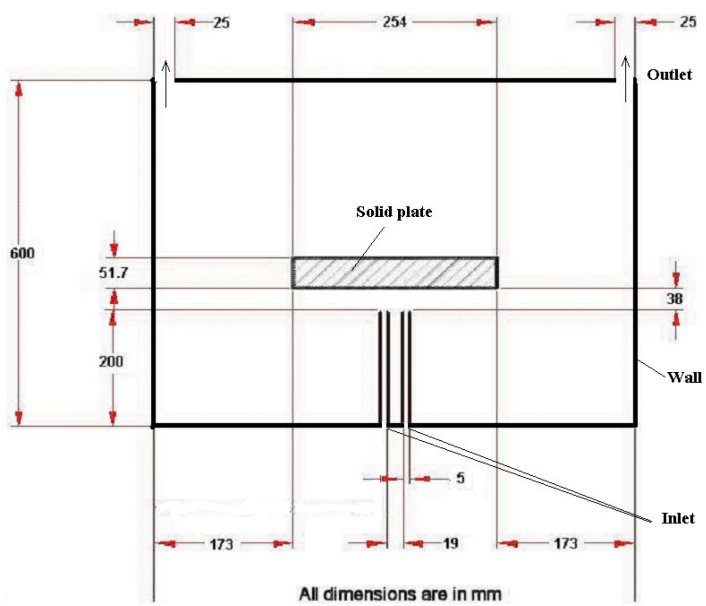

Fig. 3: Schematic of the computational model with boundary conditions

Nozzles inlets are specified at the bottom of the domain. The nozzle flow is modeled up to its exit as flow between parallel plates. Outlets from the domain are specified at the top of the domain. The size of the outlet is selected such that re-entrant flow from outside the domain is prevented and there is only outflow from the whole area of the outlet boundary. This is required to be ensured, to avoid the re-entrant flow influencing the temperature profile of fluid in the domain. Test piece is modelled as stainless steel block with conjugate heat transfer between fluid and solid. All the boundary walls are modelled as adiabatic. The computational grid considered in the analysis is varied as a parameter to determine the required mesh size to simulate the temperature fluctuation observed in the experiment. Fine mesh is considered only in the region of interest, i.e. between the jet top and the plate. Comparatively coarse mesh is considered in other regions. A typical computational mesh used for the calculation is shown in Fig. 4. Computations are carried out using the general purpose CFD code PHOENICS.

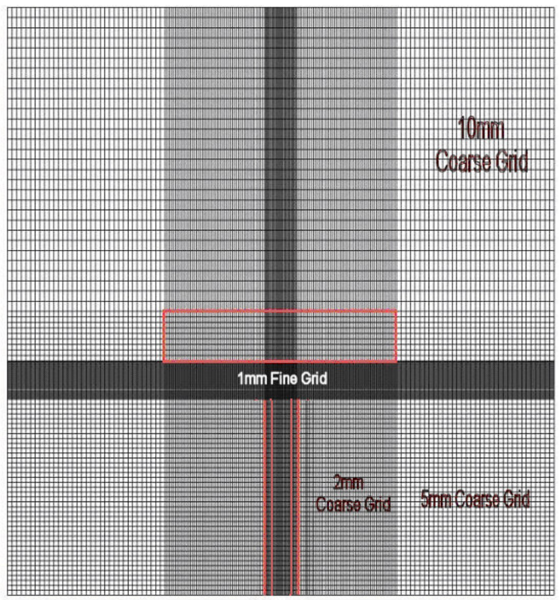

Fig. 4: Typical computational mesh used for the calculation

The analysis has been carried out for the following cases.

1. 2 mm fine mesh with 0.01 s time step
2. 2 mm fine mesh with 0.001 s time step
3. 1 mm fine mesh with 0.01 s time step
4. 1 mm fine mesh with 0.001 s time step
5. 1 mm fine mesh with 0.00025 s time step

To start with a steady state run is performed to obtain a nearly converged solution of velocity, pressure and temperature distributions. Then, with this steady state solution as the initial guess, the DNS transient is run for sufficient duration with the selected time step. Hybrid scheme [2] has been employed for spatial discretisation of advection terms in the momentum and energy balance equations. Velocity and temperature profiles in the domain obtained at various instants for case 5 is shown in Fig.

. The formation of eddies and their oscillation can be clearly observed in this figure. It can be seen that the eddy formed above the cold jet moves towards the hot jet and vice versa. Because of this movement, the size of the eddy formed above the cold jet increases and that formed above the hot jet contracts. The interface between the two eddies move from near the cold jet to hot jet. Thus, the interface between the hot and cold streams moves along the surface of the test piece. This cycle gets repeated. The oscillating movement of eddies result in fluctuating temperature pattern in the fluid as evident in the temperature field. This temperature fluctuation of fluid is communicated to solid also. This can also be observed in this figure.

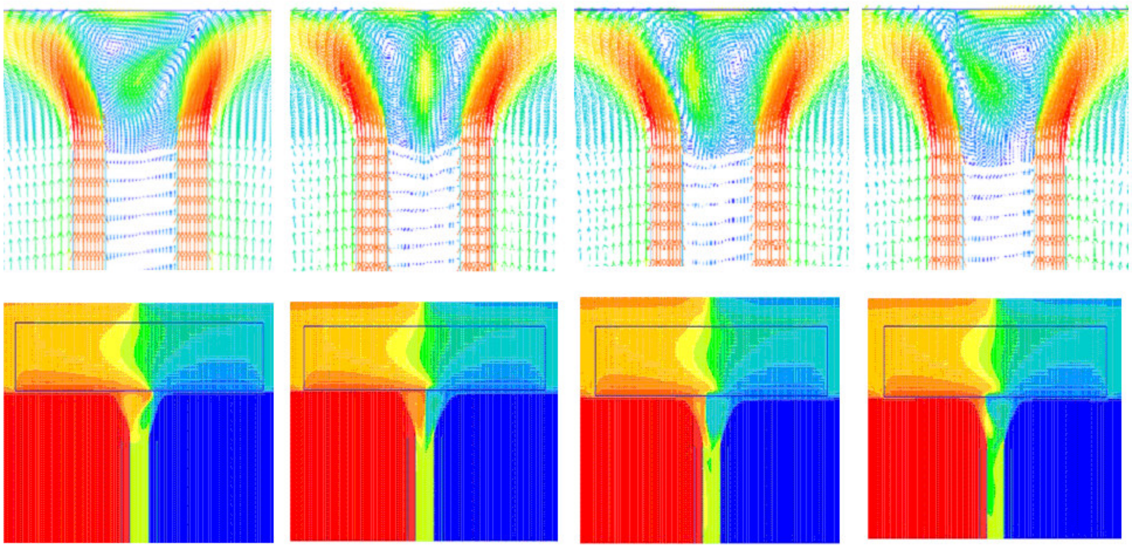

Fig. 5: Transient flow and temperature profiles near the plate

Table 1 Absolute Temperature Fluctuations and Frequency of the Fluctuations

Case No.	Grid Size mm	Time Step, s	Temperature Fluctuation		Frequency of fluctuation, Hz	
			Fluid (ºC)	Solid (ºC)	Fluid	Solid
1	2	0.01	± 0	± 0	0	0
2	2	0.001	± 7.5	± 2.5	7	7
3	1	0.01	± 45	± 35	5	5
4	1	0.001	± 45	± 30	8	8
5	1	0.00025	± 45	± 25	10	10
Experimental results			± 40	± 20	14	14

Summary of results obtained in various cases are shown in Table 1. While comparing between the results obtained for the cases with 2 mm and 1mm fine mesh sizes, it can be observed that the predicted fluid temperature fluctuation in the 2 mm mesh case are less than that observed in the experiment (± 40 ^{0}C on fluid and ± 20 ^{0}C on solid). 1 mm mesh size predicts close to the experimental results. In the case with 1 mm fine mesh size, when the time step is lowered from 0.01 s to 0.001 s or to 0.00025 s the amplitude of fluid temperature fluctuation predicted is the same at 45 ^{0}C. The predicted frequency of fluctuation in the above three cases are 5 Hz, 8 Hz and 10 Hz respectively. Because of the lower frequency of fluctuation predicted in case 3 and 4, the corresponding temperature fluctuation observed in the solid are also higher compared to that in the case 5. The frequency of fluctuation observed in the experiment is 14 Hz. Therefore, for the correct prediction of the frequency of fluctuation further lowering of time step is required. Considering the temperature fluctuation in solid, the selected mesh pattern makes a good prediction. The attenuation in the temperature fluctuation on the solid predicted in the case 5 is ~56 % where as that observed in the experiment is ~ 50 %. This is due to the lower frequency of fluctuation predicted. Further lowering of the time step improves this prediction also. Normalised fluctuating temperature observed in the numerical simulation and experiment are shown in Fig. 6.

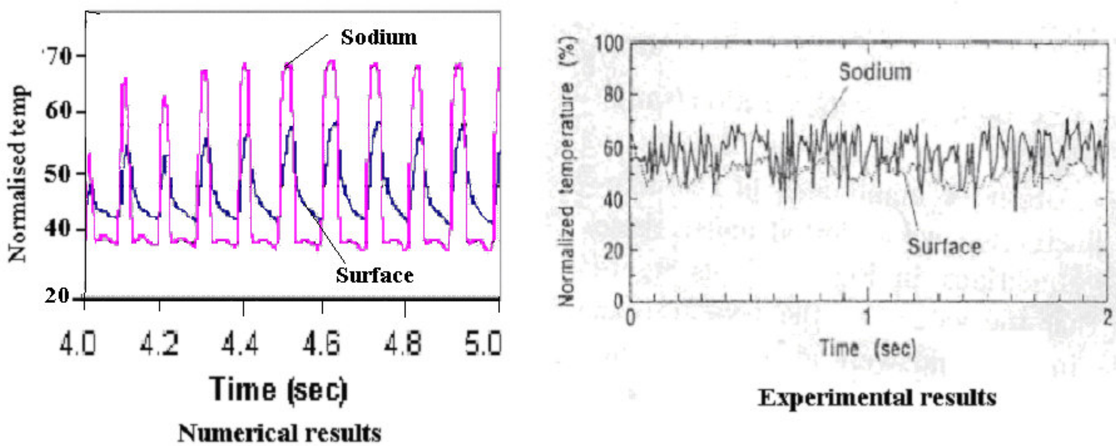

Fig. 6: Comparison between numerical and experimental results of fluctuating temperature profile

Thus, the numerical scheme with 1 mm fine mesh size and 0.25 ms time step is able to give reasonably good prediction of thermal striping phenomena. Reduction in the time step of calculation would improve the results further. However, thermal stripping in the reactor is caused by fluid jets with a diameter of the order of 100 mm compared to the 5 mm in the experimental case. Therefore, the size and period of the eddies formed in the reactor would be larger compared that in the experimental case. In view of this fact a mesh size of 1 mm and transient time step of 1 ms is recommended for the numerical simulation of thermal stripping in the reactor.

Analysis of thermal stripping in the primary circuit of LMFBR

The primary sodium system of PFBR comprises of two sodium pools viz. hot pool and cold pool. A thin walled inner vessel separates the hot pool from cold pool. The rector core, where the nuclear heat is generated comprises of several fuel, blanket, storage, reflector and shielding subassemblies (SA), which are mounted in a grid plate. Sodium from the cold pool is circulated through core to the hot pool by two centrifugal pumps operating in parallel. Sodium from the hot pool flows through four intermediate heat exchangers (IHX) to cold pool. IHX transfer energy produced by the core to secondary sodium circuit. Control plug (CP) is an important component in the reactor assembly, which is located right above the core outlet in hot pool. It is a hollow cylindrical shell structure having four compartments. It houses absorber rod drive mechanisms (ARDM), thermocouples for measuring the temperatures of sodium coming out of various fuel SA, sampling tubes and core power monitoring instrumentation. The bottom most porous plate of the CP, known as lattice plate provides structural support for the core monitoring thermowells. The solid plate above lattice plate is called core cover plate (CCP) where the thermowells are mounted. A schematic of primary circuit is shown in Fig. 1. Based on global 3D thermal hydraulic studies carried out for the primary sodium circuit earlier [3], four localized zones in the primary sodium circuit have been identified to be prone to thermal striping. They are viz. (a) fuel-breeder interface around the lattice plate, (b) fuel-breeder interface around the CCP, (c) bottom location of ARDM where fuel-control subassembly sodium flows interact and (d) main vessel near IHX outlet. These localized zones have been considered for the prediction of flow and temperature oscillations. With the velocity and temperature values prescribed for the jet streams, the oscillations in the mixing layer region (interface) have been predicted at different locations. The geometry in each case has been approximated to an equivalent two dimensional domain and the DNS calculation is performed using the general purpose CFD code FLUENT. In order to save computational time, conjugate heat transfer calculation has not been performed. Solid temperature fluctuation has been calculated based on the predicted fluid temperature fluctuation near the structures through a separate calculation. The temporal oscillations and spectral distributions for each of the configurations are presented below.

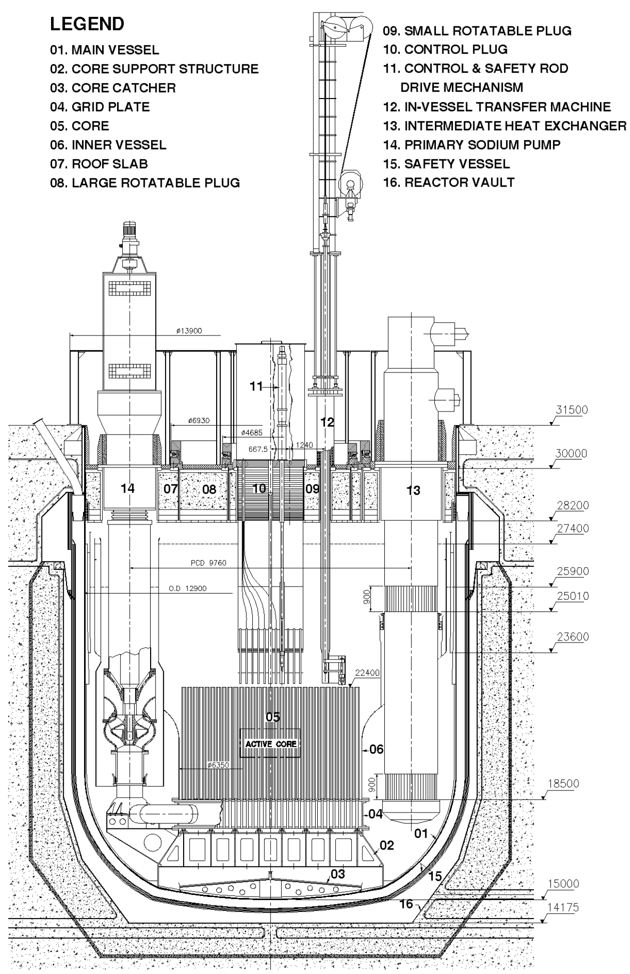

Fig. 7: Schematic of the primary sodium circuit of PFBR

Fuel-Breeder interface near core cover plate (CCP)

The model configuration representing fuel-breeder interface is shown in Fig. 8. Transient calculation has been performed with a time step of 0.001 s for a duration of 80 s. The computational time taken for this study, comprising of ~ 6 lakhs meshes, is ~ 15 h in Pentium-4 processor. Evolution of velocity and temperature oscillations were monitored at various locations in the interface, with the interface being identified based on a steady simulation. In the present case, both forced and natural convective effects are taken into account. At a short distance from the mixing stream inlets, buoyancy effects are not felt strongly and periodic oscillations, which are characteristic of forced convective mixing between jets is observed. At higher vertical distances, buoyancy effects also become significant and a broader spectrum of frequencies (resulting in random velocity and temperature oscillations) are observed (Figs. 9 and 10). The dominant frequency in the mixed convection regime is seen to be 4.03 Hz. It is clear that the peak-to-peak value of temperature fluctuation in sodium is about 50 K, adjacent to the CCP.

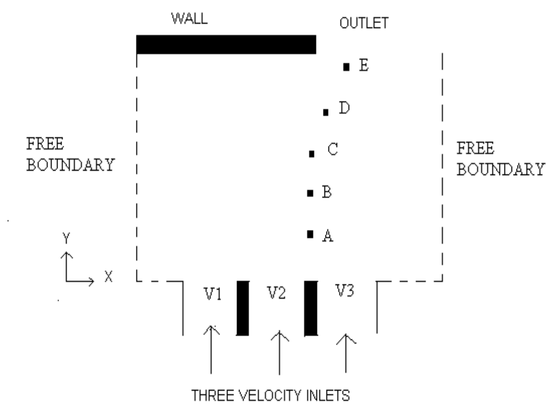

Fig. 8: Fuel-breeder interface model configuration

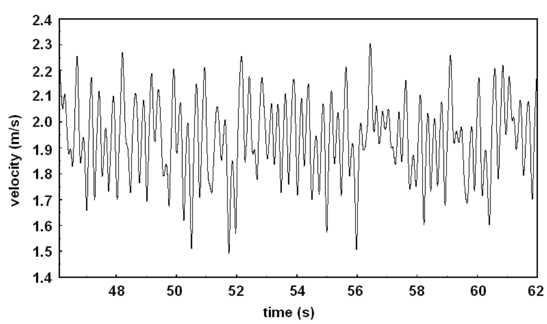

Fig. 9: Velocity oscillations near CCP

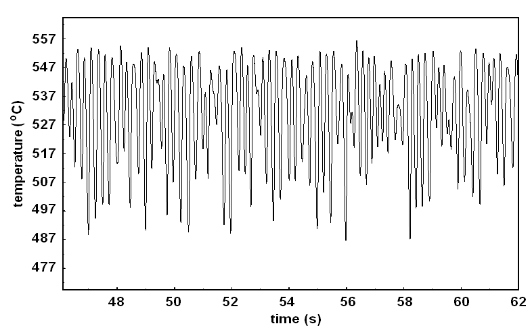

Fig. 10: Temp Oscillations near CCP

Fuel-Breeder interface near lattice plate (LP)

The configuration considered here is similar to that shown in Fig. 8. For this case also, results are qualitatively similar to the previous case. For shorter distances in the vertical direction periodic oscillations are observed, which become random with a band of frequencies at larger height from the jet inlet plane. Fig.11 depicts the evolution of sodium temperature oscillations adjacent to lattice plate, caused by velocity fluctuations. The maximum peak-to-peak temperature oscillation is seen to be 60 K, which occurs at 6.56 Hz.

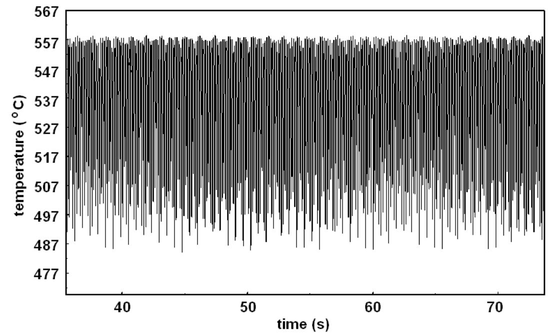

Fig.11 Temperature oscillations near LP

Fuel - Control rod SA interface at the bottom of ARDM shroud

Typical instantaneous flow field at the bottom zone of ARDM shroud tube is depicted in Fig. 12, where sodium from the fuel subassemblies and that from the control subassembly are mixing. The transient calculation was performed for a duration of ~ 300 s. The predicted results for velocity and temperature oscillations are shown in Figs. 13 - 14. Oscillations are seen to be highly random and having low frequency components. The maximum peak-to-peak temperature oscillation is seen to be 98 K with a dominant frequency component in the temperature oscillations as 12.9 Hz.

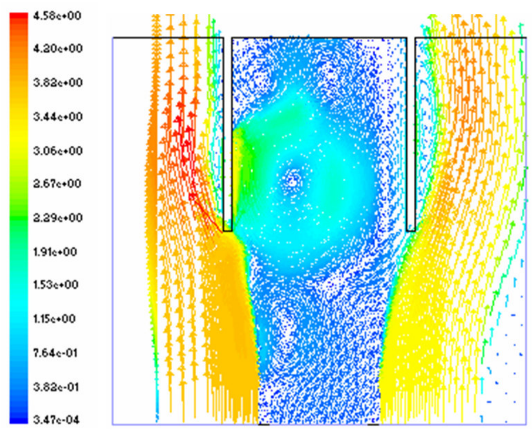

Fig.12 Instantaneous flow field at the bottom of ARDM shroud tube

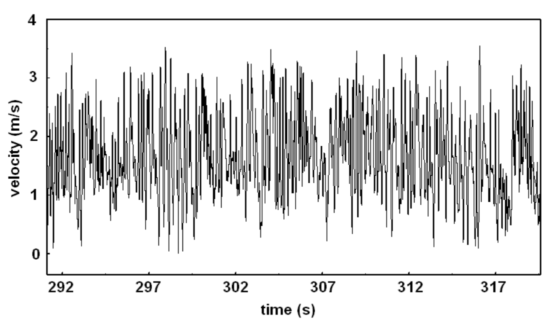

Fig.13 Velocity oscillations at the bottom of ARDM shroud tube

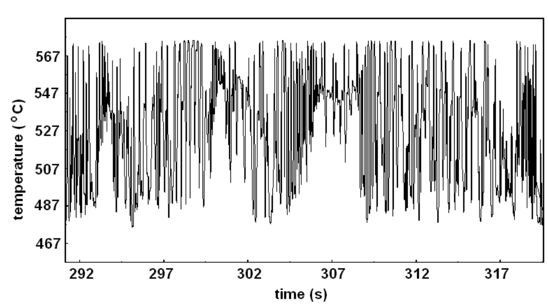

Fig.14 Temperature oscillations at the bottom of ARDM shroud tube

Solid temperature fluctuation

Based on the temperature fluctuations obtained in the fluid, the temperature fluctuations on the structure have been estimated using a 1-D transient heat conduction code developed in-house. The heat transfer coefficient of sodium has been evaluated based on the correlation proposed by Wakamatsu et al. [1] for sodium jet impingement on the structures such as CCP, LP etc. The Nusselt number for jet impingement is calculated from,

$$Nu(x) = 0.564\left(\frac{\mathrm{Re}^{0.5}}{0.3 + 0.14\left(\frac{H}{D}\right)^{0.5}}\right)\left(\frac{x}{D}\right)^{0.5}\mathrm{Pr}^{0.5}$$

where Re is the Reynolds number, H is nozzle to wall distance, D is the nozzle diameter and Pr is the Prandtl number of sodium. The resistance offered by this heat transfer coefficient is converted into equivalent conductive stagnant sodium film of thickness δ. The value of δ is given by "characteristic length / Nu". The value of conduction film thickness works out to be about 1.5 mm. Hence in the model to estimate the temperature fluctuation, a stagnant sodium film of 1.5 mm is superimposed on the metal surface exposed to striping. Transient fluid temperature fluctuations, synthesized based on the localized thermal hydraulic studies are imposed as boundary conditions over the sodium film. The resulting temperature fluctuations on the metal surface and at a point 2 mm inside of the metal surface are predicted using the transient heat conduction code.

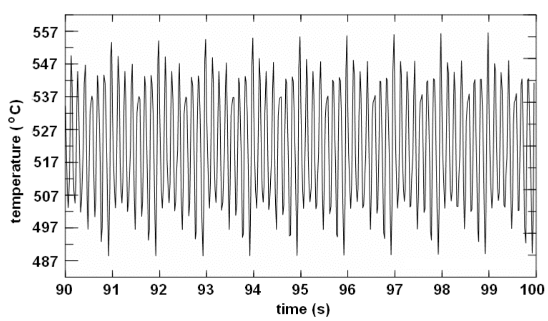

Fig. 15: Fluid temperature fluctuation near LP

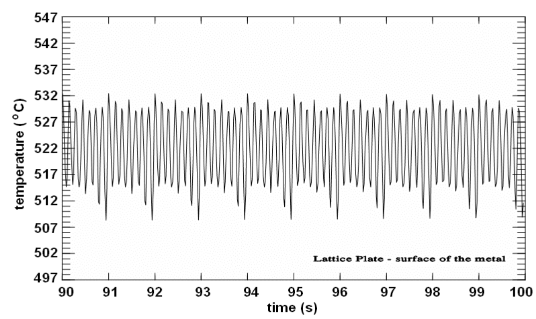

Fig. 16: Surface temperature fluctuation of LP

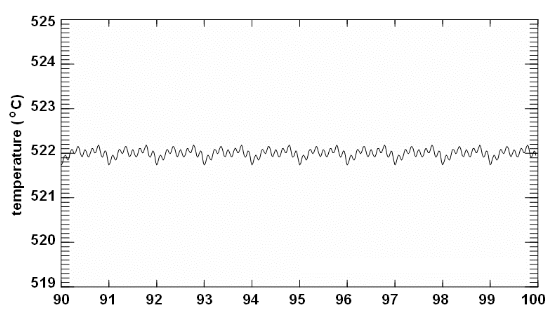

Fig. 17: Temperature fluctuation at a point 2 mm inside the surface of LP

The synthesized fluid temperature fluctuation, metal surface temperature fluctuation and fluctuation at a depth of 2 mm from the metal surface for lattice plate (LP) are presented in Figs. 15 – 17 respectively. It is clear that the peak-to-peak fluid temperature fluctuation is 60 K. The same on the metal surface reduces to 24 K. At a depth of 2 mm the fluctuation is only few K. From the fluctuating temperatures corresponding to CCP it is seen that the peak-to-peak fluid temperature fluctuation of 50 K reduces to 26 K on the surface of CCP. Similar studies corresponding to ARDM shroud tube indicated that the peak-to-peak temperature fluctuation on the surface of ARDM shroud tube is 44 K. In all the cases studied, it is seen that the metal surface temperature fluctuation is less than 50 % of the fluid temperature fluctuation.

Conclusions

A benchmark experimental study has been simulated numerically to arrive at a suitable computational scheme to predict thermal stripping phenomena. It has been found from the studies that a computational mesh size of the order of 1 mm and transient time step for the DNS calculation of the order of 0.25 ms can give a reasonably accurate prediction of temperature fluctuation in fluid and solid. Based on the results of this study, analyses have been carried out to predict thermal stripping in the primary circuit of PFBR. Three localised regions which are prone this phenomena viz. fuel-breeder interface corresponding to CCP & lattice plate and fuel subassembly - control subassembly interface corresponding to absorber rod drive mechanism shrouds have been considered. The analysis shows that oscillations with frequencies ranging from approximately 0.4 Hz to 40 Hz can occur for the flow conditions considered. The amplitude of the oscillations increases in the direction of flow within the mixing layer and it eventually decays after reaching a peak value. The oscillations tend to be close to periodic when forced convection effects are dominant, but they tend to become random when free convection also becomes significant. For the cases considered, peak-to-peak temperature oscillations of the order 50 K to 98K were noted in the fluid region. The surface temperature oscillation (peak-to-peak) on core cover plate and lattice plate, due to the interaction between fuel and breeder SA sodium jets, are 26 K and 25 K respectively. The peak-to-peak surface temperature oscillation on absorber rod drive mechanism shrouds is 45 K. These values are much less than that allowed for these structures and hence these structures are free from thermal striping problems.

References

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