Effect of Circular and Elliptical Nozzle Ends in the Analysis of Thermal Striping Phenomenon Occurring in Liquid Metal Cooled Fast Breeder Thermal Reactors

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Abstract - *Thermal striping is a complex thermal hydraulics phenomenon, which generates random fast temperature fluctuations, originating from the incomplete mixing of hot and cold jets of fluid in the vicinity of adjoining structural wall surface. 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. Thermal hydraulic investigation consists of Computational Fluid Dynamics (CFD) simulations in two levels. In the first level, a suitable model for numerically simulating thermal striping has been arrived at by analyzing a published benchmark experiment. In the second level, analysis is carried out to predict detailed flow and temperature fluctuations in the model, based on the numerical scheme arrived at in the first level and Power Spectral Density analysis is carried out for frequency of fluctuations, and also to examine the effect of different nozzle ends (Circular and Elliptical) on the frequency and temperature fluctuations with the change in the flow rates of hot and cold jet, length between test plate and top of nozzle, gap between the nozzle and outlet height. Finally an experimental setup has made and results are compared.*

Key Words: Thermal striping, Jet, Mixing, CFD, Nozzle

1. INTRODUCTION

1.1 Overview

Thermal striping is a phenomenon, which leads to random temperature fluctuations in the interface between non-isothermal streams. This fluid thermal fluctuation is transferred to the structural components in vicinity without much boundary layer attenuation. 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, propagation and finally failure of the component. In Liquid Metal cooled Fast Breeder Reactors (LMFBR), it occurs in the upper plenum as a result of the mixing of sodium coolant jets from fuel sub-assemblies (SA), control rod SA, and blanket SA, have different temperatures. The mixing of fluids with such different temperatures results in temperature fluctuations (of a frequency of several Hz) in this zone. The average temperature rise through the fuel sub-assemblies is normally set at about 150ºC. That through the breeder sub-assemblies or the control rod sub-assemblies varies throughout their life, typically from 50ºC for a new subassembly to 150ºC for a fully burn-up subassembly. Thus, there exist two streams mixing with temperature differences of up to 100ºC. When such a non-isothermal fluid mixed at the vicinity of any structure causes thermal cyclic stresses. The characteristics of thermal striping are essentially important to be examined because of the occurrence of thermal fatigue cracks due to high-cycle temperature fluctuation on the structure surface. Material fatigue may occur when the amplitude and number of strain cycles are sufficiently high. Thermal striping occurs at a few locations in LMFBR in the reactor assembly at the interfacial region in the hot pool between the fuel SA and blanket SA where hot sodium from fuel SA and relatively cold sodium from blanket SA mix, predominantly on the core cover plate of control plug, region in the cold pool where the primary exit sodium from intermediate heat exchangers (IHX) mixes with the cold pool sodium, region of cold pool where main vessel cooling flow exits the cooling circuit, elbows, valves and at mixing 'Tee' junctions in the secondary sodium pipelines.

1.1.1 Thermal striping failures and its limit

There are a few reported failures, in the form of extensive cracking due to thermal striping in the operating reactors at secondary sodium pump vessel in Phenix (Gelineau and Sperandio, 1994) two sodium leaks were detected during the inspection campaign in the secondary sodium circuit. The first failure was on the weld line in the expansion tank in the vicinity sodium discharge area. The second one was found at the C- seam weld on main pipeline near mixing tee, Tee junction of an auxiliary pipe of the secondary circuit in SPX (Gelineau and Sperandio, 1994), control rod guide tube in prototype fast reactor (PFR) (Bettes et al., 1994), and primary cold trap in BN 600 (Sobolev and Kuzavkov, 1994) after operation for about 10 years. Thermal striping was

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identified as a possible reason. In view of these reported failures, the structural mechanics specialists have been investigating thermal striping phenomenon both experimentally and theoretically. Investigations focus both on thermal hydraulics and structural mechanics aspects.

It is known that the important parameters affecting the structural damage due to thermal striping are the frequency and amplitude of temperature fluctuations. Higher frequency of fluid temperature fluctuation cannot penetrate the wall, whereas in the case of the low frequency fluctuation, the temperature distribution in the wall becomes mild in depth direction and results in smaller amplitude of the stress. Thus, the middle range frequency of the fluid temperature fluctuation has large importance. The range of frequency oscillations under which thermal striping is found to be 0.1-10 Hz.

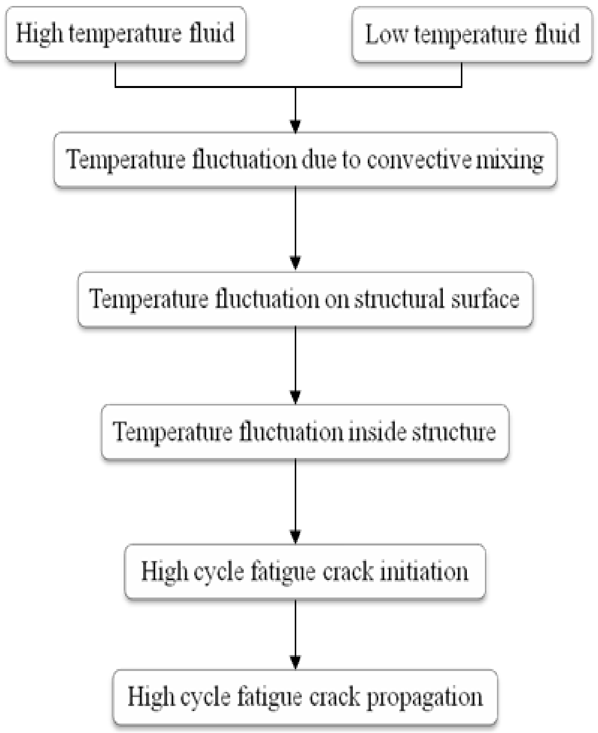

Fig. 1.1: Mechanism of thermal striping phenomena

1.1.2 Analysis of thermal striping phenomenon

The thermal striping phenomena analysis is carried out in two phases. The first phase is thermo-hydraulics analysis, in which the fluid temperature oscillation is predicted and frequency of fluctuation is found. The second phase is thermo-structural analysis, in which the structural response is predicted by taking the fluid temperature frequency of oscillations from the thermo hydraulic analysis. The Fig.1.1 shows the mechanism of the thermal striping phenomena.

1.1.3 Problem description

To predict thermal striping phenomena on core cover plate of a control plug and converting that to a basic and simplified model i.e., parallel water jet model in which rectangular plate simulates the core cover plate of the control plug and two water jet nozzle simulates the coolant coming out of sub-assemblies (SA) and also to examine the effect of length, velocity, gap between the nozzle and outlet height on thermal striping.

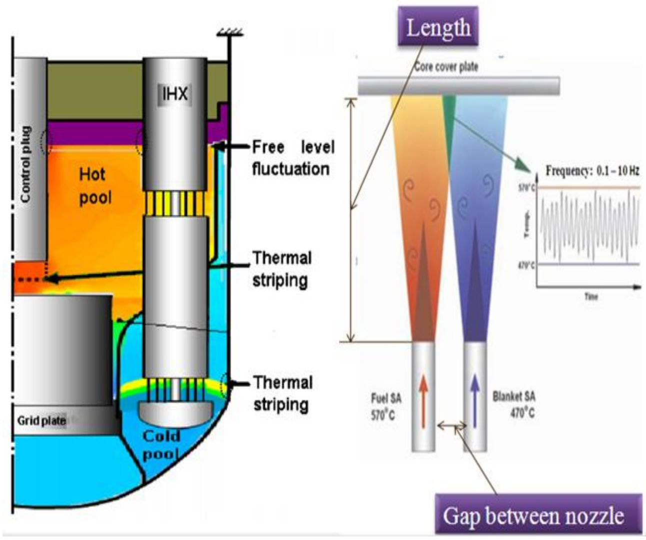

Fig. 1.2: Thermal striping phenomena in the vicinity of core cover plate

Figure 1.2 shows the pattern of temperature fluctuations at different locations of pool type reactor in thermal striping phenomenon and shows different places of thermal striping in pool type nuclear reactor, problem definition and also terminology used in further work.

1.2 Objectives

The main objectives of the present study are
1. To predict the amplitude of temperature fluctuation and frequency in mixing zone region.
2. To study the effect of different nozzle ends (Circular and Elliptical).
3. Design and fabrication of parallel water jet model.
4. Modeling /Simulation for the system.
5. Conducting of experiment (i.e., parallel water jet model).
6. To obtain a suitable computational scheme to quantify the frequency and amplitude of the temperature fluctuations that occurs near a mixing zone.
7. Comparison of results.
8. Based upon the comparison of experimental and computational analysis the computational parameters such as mesh size and time step are optimized.

2. EXPERIMENTATION

2.1 Details of Experimental Setup and Fabrication Details

Fig. 2.1: Photograph of nozzle ends.

Fig. 2.2: Photograph of the experimental setup.

Figure 2.1 shows the nozzles used in experimental setup and Fig.2.2 shows the photograph of complete experimental setup. The following are the main parts of the experimental setup.

- Parallel water jet box
- Pumps
- Control valves
- Hot water tank
- Electric heaters
- Cold water tank
- Cooling system
- Thermocouple
- Data logger
- Computer

Thermal striping phenomenon is carried out inside the parallel water jet box with dimensions 300x200x300mm on the test plate by mixing two non-isothermal jets coming out of parallel nozzle. M-seal sealant and Araldite epoxy resin are used to avoid the leakages within the box. The centrifugal pump having capacity of 0.5HP each is used to pump hot and cold water from their respective tank. The hot water tank is having the capacity of 200 liters and is well stirred to gain uniform temperature. The temperature drop is found to be 15 min / °C. The maximum experiment duration is 2 minutes, so that the tank is well enough to maintain the require temperature during the experiment. The cold water tank with capacity of 100 liters is used and water is filled till the cooling system copper tube coils is immersed completely in water to avoid temperature drop ice flakes are used to maintain it to the required temperature. The length of the test plate is varied by using screw mechanism. The thermocouple is placed in the test plate by making a hole. Test plate is adjusted to bring the thermocouple exactly at the middle of the two nozzles. Thermocouple is fixed to data logger and then by using data logger software configuration is set and the input is detected and time of recording is set in the scan button and quick graphs are obtained and finally it is exported in the excel spread sheet format.

2.2 Experimental Procedure

The thermal striping experiments are conducted in the following sequence.

- Initially the required nozzles velocity is fixed by measuring the flow rate. The control valve is fixed in this position for a particular velocity.
- Water is heated in hot water tank up to 95^0C. The water is stirred periodically to achieve the uniform heating. The temperature of water in continuously monitored using a thermocouple as temperature of the steam coming is very high to measure with thermometer.
- Water is cooled in cold water tank up to 5^0C and ice flakes are to maintain it to the required temperature. The water is stirred periodically to achieve the uniform cooling. The temperature of water in continuously monitored using a thermometer.
- After attaining the required temperature i.e., hot water 95ºC and cold water 5 ºC, the heating and cooling is stopped and pumps are switch on.
- Water jets coming out of the nozzles are allowed to hit on the test plate and wait till the test plate is completely immersed in the water.
- After 1 minutes temperature data of thermocouple is recorded using data logger and stored in computer excel sheet.
- The above procedure is repeated for different nozzle (Circular and Elliptical)
- Changing one parameter at a time and keeping other parameters constant, above procedure is repeated.

3. COMPUTATIONAL ANALYSIS

This chapter describes the details of the computational simulation. This includes, the domain considered for the computational simulation and the different parameters of computation, such as, grid size, time step and turbulent models selected. This also includes the mathematical modeling of the selected turbulence model.

3.1 MODELING IN SALOME 7.5.1

Figure 3.1 shows the domain considered for the computational analysis with boundary types. Three-dimensional domain is created in the preprocessing package SALOME7.5.1. Hybrid tetrahedral meshing was done and the number of cells is above one lakh. The grid size of 10 mm and 5 mm was considered initially and because of monitored temperature fluctuations vanished in SALOME7.5.1 after some flow time, later 1mm mesh size has considered. The boundary condition types are specified in the SALOME 7.5.1. The velocity inlet boundary type is considered for both nozzle, the out flow boundary type is considered for the outlet of experimental setup and wall boundary type for test plate. Continuum solid boundary type is considered for whole test plate and continuum fluid boundary type is considered for nozzles and the outlet. Finally save the file in (*.med) format before reading in the SALOME 7.5.1.

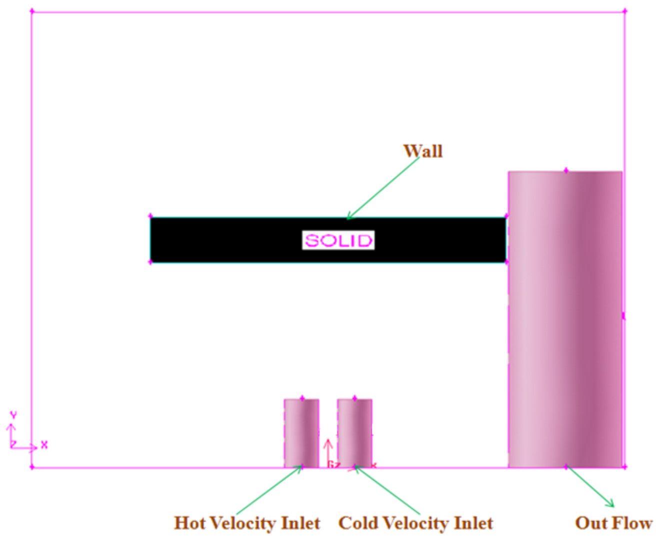

Fig 3.1: Domain with boundary types considered for the analysis

3.2 ANALYSIS METHOD USED IN SALOME 7.5.1

After creating the model in SALOME 7.5.1, the mesh file is read in the SALOME 7.5.1. Check the mesh file in SALOME 7.5.1 using check option and compute the file for nodes and volumes using compute option. The analysis is carried out in two phases. In the first phase a steady state run is performed till a converged solution is reached and then in the second phase unsteady run is performed by considering the steady state results as initial values to achieve the quick convergence. Steady state run is performed by using a basic turbulence k-ε model. As the flow is incompressible, Pressure based Navier-stokes implicit formulation is selected. The water with piecewise linear temperature variable properties are entered in the materials properties panel and for stainless-steel constant user defined values are given. Include gravity effect and viscosity effect from operating condition menu. Enter the boundary condition values in the code saturne and then select the section from where to initialize the iteration. Steady state run is performed till the convergence is reached. In the second face change the iteration type to unsteady state and then select the LES scheme. As a standard practice in case of Large Eddy Simulations scheme was used for the discretization of pressure equation, and the Energy equation was discretized using 2nd Order Upwind scheme. The typical boundary conditions given are shown in the Table 3.1.

Table 3.1: Typical boundary conditions

Sl.No.	Boundary condition	Value
1	Cold water inlet velocity*	15 m/s
2	Hot water inlet velocity*	15 m/s
3	Cold water inlet temperature	278 K
4	Hot water inlet temperature	368 K
5	Turbulence Intensity	4%

*only for a particular run

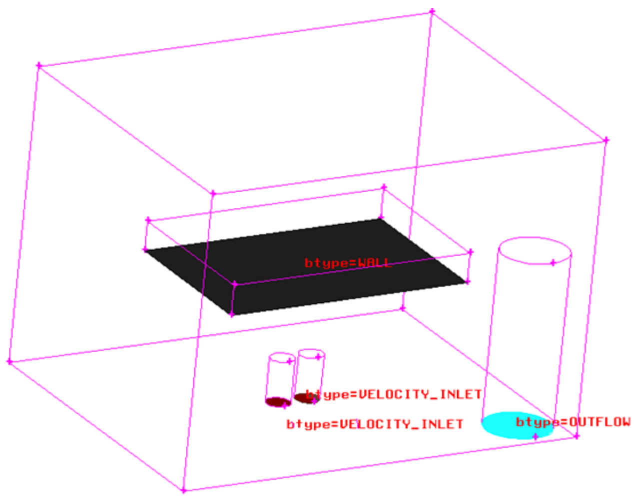

Fig. 3.2: Circular nozzle domain with boundary conditions

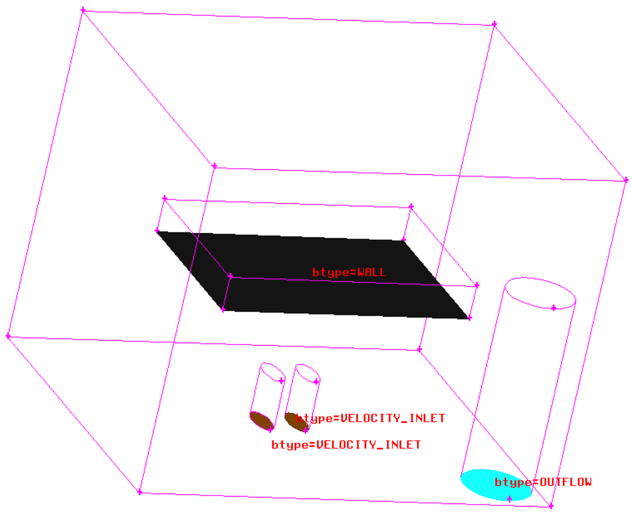

Fig. 3.3: Elliptical nozzle domain with boundary conditions

Once the iterations are converged, the unsteady state run is performed by taking the steady state values as initial guess. The Large Eddy Simulation scheme is selected for unsteady run. The unsteady state run is performed for 1 second with the time step of 0.0001s. The maximum number of iterations per time step is given as 100. The points corresponding to the thermocouple locations in experimental setup are selected in the domain and the temperature fluctuations are monitored at the selected points.

4. RESULTS AND DISCUSSION

4.1 Computational Simulation Results

The computational simulations are done for different nozzle ends and also by changing different parameters like length, velocity, outlet height and gap between nozzles. Changing one parameter at a time and putting other parameters constant. Below are the results obtained from SALOME 7.5.1 for parallel impinging Water jet model with different nozzle ends for steady state k- ε turbulence scheme was selected and iterated till converge solution obtained and then under unsteady state time step of 0.0001s, Large Eddy Simulation turbulence scheme was selected with mesh size of 1 mm.

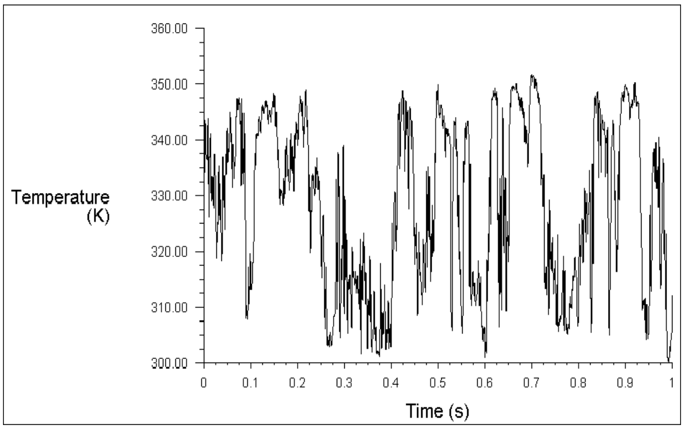

Fig 4.1: Temperature fluctuations of circular nozzle

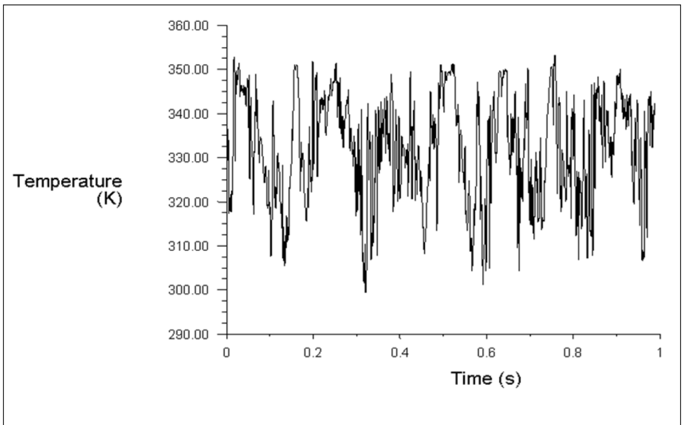

Fig 4.2: Temperature fluctuations of elliptical nozzle

Temperature of hot water is 95^{0}C and cold water is 5^{0}C.Figures 4.1-4.2 show temperature fluctuations with respect to time for different nozzle ends,when distance between jet nozzle and the test piece is 30mm (length), jet velocity 15m/s, gap between the jet nozzle 5mm and the outlet height of 60mm.This temperature time series data is used for power spectral analysis for finding frequency. From the graphs it is observed that temperature fluctuations are more in case of circular nozzle and simulations are done for the time of one second because of computational solving time limitation.

4.1.1 Power Spectral Density Analysis

Due to the random nature of the temperature fluctuations curve, it is not possible to find the frequency of the curve by counting the number of cycles per second. The method employed to identify the frequency components of the random curves is Power Spectral Density (PSD) analysis. The Power Spectral Density curves describes how the power or energy of a signal or time series is distributed with frequency. Here power can be the actual physical power, or more often, for convenience with abstract signals, can be defined as the squared value of the signal.

The most dominating power of a frequency is taken as the frequency of the curve in random signals. But in this parallel water jet model temperature fluctuations are both random and periodic. So a method called white noise frequency band technique is used to calculate the frequency of fluctuation. The unit of Power Spectral Density (PSD) is generally taken as power or energy per Hz. White noise is a random signal or process with flat power in Power Spectral Density (PSD). In other words, signal contains equal power within a fixed band width at any center frequency. In this logarithmic frequency scale is taken and it is flat with equal power per cycle.

4.2 Comparison of Experimental and Simulation Results

After fabrication work of parallel water jet model, the minimum gap between the nozzles is 22mm. With this gap experiment was conducted for length=30mm and velocity=15m/s. Temperature fluctuations have been recorded for the time of 5s in each nozzle run. And in case of simulation again the model is made in SALOME 7.5.1 for this gap with the same boundary conditions and 1mm grid size of tetrahedral for time step of 0.0001s.

Fig 4.3-4.10 show the temperature fluctuations of both experimental and simulation results. In case of experimental temperature fluctuations recorded for the time of 5s by using data logger which is interface with the computer and in case of simulation the same computational method has been used which is discussed in simulation part.

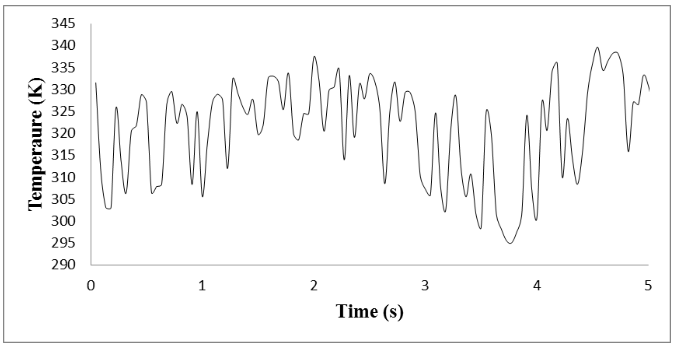

Fig 4.3: Temperature fluctuations of circular nozzle (Experiment)

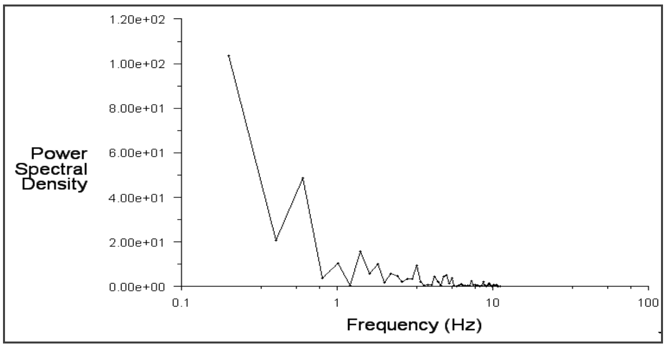

Fig 4.7: Power spectral density curve of circular nozzle (Experiment)

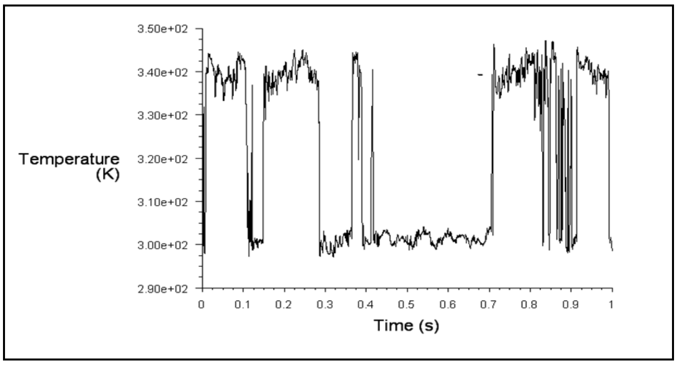

Fig 4.4: Temperature fluctuations of circular nozzle (Simulation)

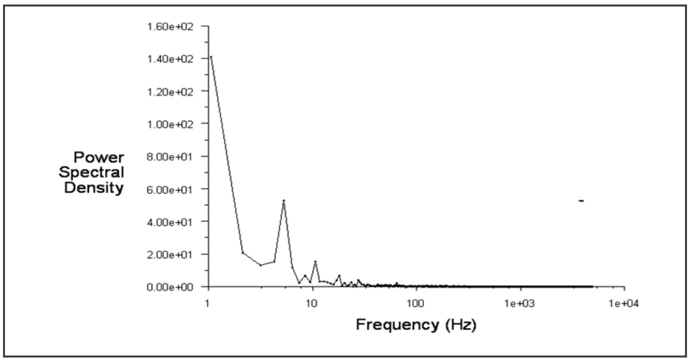

Fig 4.8: Power spectral density curve of circular nozzle (Simulation)

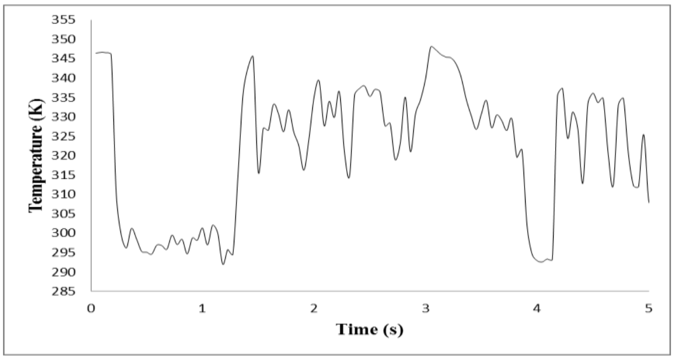

Fig 4.5: Temperature fluctuations of elliptical nozzle (Experiment)

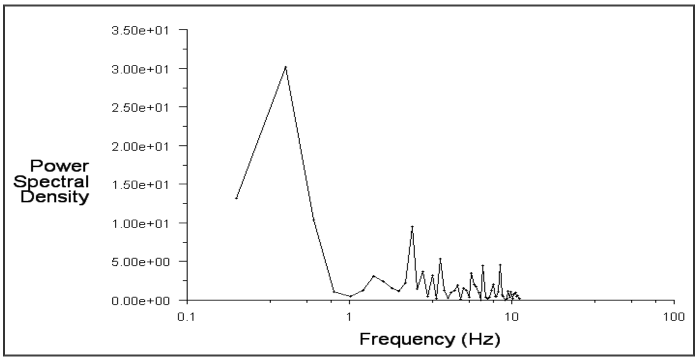

Fig 4.9: Power spectral density curve of elliptical nozzle (Experiment)

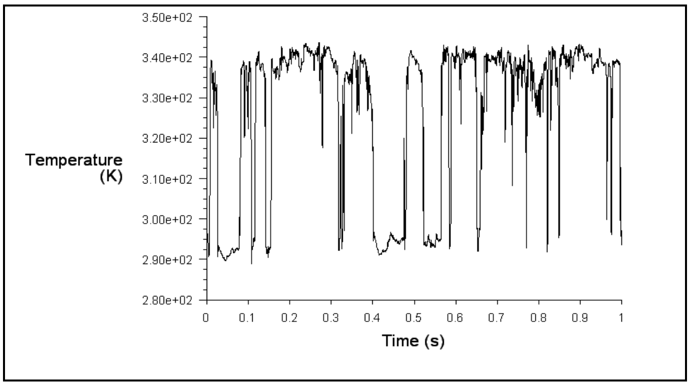

Fig 4.6: Temperature fluctuations of elliptical nozzle (Simulation)

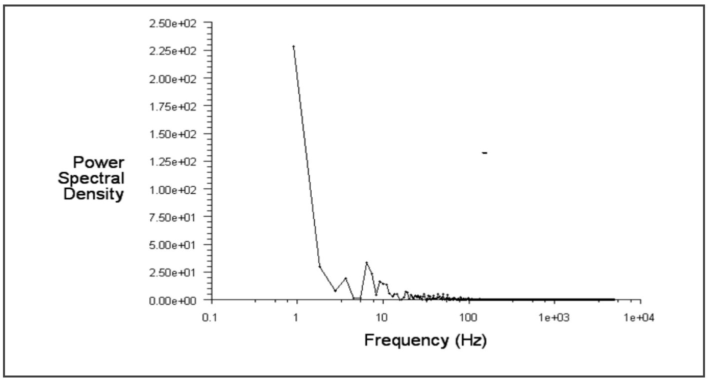

Fig 4.10: Power spectral density curve of elliptical nozzle (Simulation)

Table 4.1: Comparison of experimental and simulation results

Nozzle	Amplitude of temperature fluctuation (K)		Frequency fluctuation (Hz)	
	Simulation	Experimental	Simulation	Experimental
Circular	52	47	1.58	0.57
Elliptical	55	54	2.12	0.88

Simulation and experimental results of amplitude of temperature and frequency fluctuation are compared for the different nozzle ends at the thermocouple location. From the Table 4.1 it is observed that the fluctuations are more in the simulation compared to experimental results, which is due to the sampling frequency of the data logger and also thermocouples response time. From the graphs it is observed that the amplitude of temperature fluctuation in simulation results are slightly higher than that of the experimental results. This is due to the atmospheric conditions and heat loss within the whole system. But in case of frequency fluctuation the variation is mainly due to the different sampling frequency in experiment and simulation. Thus an average percentage error of 61.72 exists in the frequency fluctuation result. Simulation results are in reasonable agreement with that of experimental results. Therefore the size and period of eddies formed in the reactor would be larger compared that in the experimental case.

5. CONCLUSION

It has been found from the studies that a computational mesh size of the order of 1mm and transient time step of the order of 0.0001s can give a reasonably accurate prediction of frequency and temperature fluctuation. Based on the results of this study, analyses have been carried out to predict thermal stripping in Parallel impinging water jet model and also to examine the effect of the length (distance between top of the nozzle and the test plate), velocity, gap between the jet nozzle and the outlet height. The major results are summarized as follows

1. When length=30mm and gap=5mm, peak-to-peak temperature increases with the increase in velocity of flow. But in the case of frequency it first increases with the velocity and then decreases at higher values.
2. When length=30mm and velocity=15m/s, peak-to-peak temperature increases with the increase of pitch between the nozzle and reaches a maximum value and then decreases.
3. With the outlet height only a minor variation is observed in peak-to-peak temperature and in the frequency of fluctuation. Hence with the change of outlet height there will not be much effect on thermal striping.
4. Circular nozzle is found to be better for different nozzle velocities, when gap=5mm and length=30mm.
5. With the increase of length, the radial slope of jet over the region increases slightly with the discharge height and frequency of fluctuations decreases as more and more mixing occurs before the jet strikes the plate and turbulence level are higher, when velocity=15m/s and gap=5mm.
6. Circular nozzle is found to be better for shorter length(less than 30mm) and Elliptical for longer length. When gap=5mm and velocity=15m/s.
7. From the FFT analysis it has been observed that the frequency fluctuations of experimental results are lesser than that of simulation results due to limitation of data logger and thermocouple.

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