Heat Transfer Features of Pulsating Turbulent Flow in a Pipe: Experimental Optimization

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Abstract. The heat transmission improvement methods are widely utilized to raise the level of performance of the latent heat storage systems, the heat pipe is a broadly used technique utilized to improve the transmission of heat enhancement technique. Current paper comprises use of the heat pipe to vary the heat input, pulsating frequency, and flow velocity. The Heat input is varied in 0, 25, 50, 75 and 100 watts; pulsating frequency in upstream and downstream with frequency changed from 0 to 3.33 Hz; Flow velocity varied and calculated from Reynolds number which varies from 6000 to 13000. The experimental results were carried out using the design of experiments with output parameters as coefficient of heat transfer along with Nusselt number. The behavior of coefficient of heat transfer with respect to input parameters is discussed. The Analysis of variance is accustomed to check the reliability of the outcomes. The optimized input response selected using Particle swarm optimization shows Pulsating frequency of 3.33 Hz, Heat input of 100 W and Reynolds number of 13443 giving optimum heat transfer coefficient.

Keywords: Pulsating Frequency · Nusselt Number · Particle Swarm Optimization · heat transfer Coefficient

1 Introduction

Several heat transfer improvement technologies have been established in order to upsurge the heat exchanger's overall (thermal) efficiency, ensuing in a decrease in the size of the heat exchanger as well as operating costs. In wide-ranging, heat transfer improvement methods can be categorized into two techniques, namely the active and passive method. The use of flow pulsation in the tube is one such technique that has been commonly used in industry. As pulsation is imposed on the moving fluid, the thickness of boundary layer is altered in a pulsatile flow. In the pulsatile tube wall, velocity gradient is much higher than in the steady flow, and the former provides much higher heat transfer than the latter. Pulsatile flow parameters [1] affect the efficiency of these devices in thermal engineering applications. Numerous review have been dedicated to this pulsating flow & its related heat transfer issues of the few decades. The following parts provide a

summary of these studies with a focus on the turbulence formation, pressure gradient, heat transfer as axial heat transfer enrichment and convective heat transfer & pipe flow features. A reciprocating pump or a constant flow pump can create pulsing flows in conjunction with various mechanical pulsating devices. As the thickness of the boundary layer & therefore the thermal resistance changes due to pulsation, the heat transfer to or from the flow is predicted to vary. It is known that the pulsating flow involves a constant and strictly wavering Poiseuille flow [2]. The amplitude of the vibration velocity is lesser than the time when the average velocity & the direction of flow not ever reverse. The majority of researchers [12] found a limited number of instrumental variables in their research and limited them to a relatively narrow range. The literature shows the conflicting effects of pulsation frequency on the heat transfer coefficient & encourages researchers to create both experimental and mathematical models for predicting the influence of pulsation flow on the coefficient of heat transfer. Experimental, theoretical, & computational studies on the effects of pulsation on heat transfer properties have been available by several researchers. Habib et al. [12] experimentally explored the function of laminar pulsatile flow in a tube under constant wall heat flow. Zheng et al. [8] has inspected the influence of self-oscillators on heat transfer rate which mostly depends on the resonator configuration. The higher rates of the heat transfer rates within a pipe are produced with laminar pulsating flow concluded by Faghri et al. [13] Tie-Chang et al. [14] investigation shows the no correlation between the affect the average time of the Nusselt number for varying pulsating frequency. Guo et al. [15] performed an investigation into pulsating pipe flow with variable amplitudes. In the case of small amplitudes, liable on the pulsation frequency. Hemeada et al. [16] shows the heat transfer coefficient directly proportional to amplitude and Prandtl Number and inversely proportional to frequency and increases. The effect of various input parameters on the Nusselt numbers are studied in last decade documented by some of the researchers [17–21]. This researcher showed the relationship between the Nusselt number and the amplitude and frequency of a numerical study of turbulent pulsatile flow conducted by several researchers [22–24], which is optimal for increasing heat transfer coefficient. It shows that the Wammersley number has been reported [22, 23]. Saeed et al. [24] states that for liquids with a Prandtl number less than 1 in pulsating turbulence, a sudden expansion of the pipe was observed to increase the secular deviation of the heat transfer coefficient by around 10. Various turbulent models of pulsatile flow have been investigated to know the phenomenon of the influence of pulsation on the coefficient of heat transfer & to solve these complications with conflicting results. The quasisteady flow model [25, 31] and the overflowing model are well known and often applied to these models. Park et al. [32] performed an experimental investigation to heat transfer of a pulsating turbulent flow in vertical pipe using persistent heat input over the surface with varying range of Re. Investigational outcomes are documented in relations of Womesrly numbers, therefore, it's important to understand different factors & describe a broad variety of these regulating factors to provide a full appreciative of the incorporation of pulsation into a flow along with heat transfer. The current work therefore goals to experimentally examine the influence of the pulsation frequency & the Reynolds number on the characteristics of the heat transfer of turbulent pulsating pipe flow with a broad frequency variety (6.6 to 68 Hz) and the number of Reynolds (10850 to 37100). Although the outside face of the pipe is subject

to a heat flux (consistent), the experiments are administere during a laminar pulsating channel flow, Kearney et al. [33] practically examined the time resolved arrangement of a thermal physical phenomenon. They stated that different grades of flow reverse exposed that a rise within the instantaneous thermal physical phenomenon thickness & a time of reduced instant Nusselt number was the first impact of reversed flow. They concluded that reversal of flow isn't inherently an enhancement criterion. Mostafa et al. [34] studied an investigational review of enforced convection heat transfer laminar pulsating flow within that tube [34]. Equated using steady flow, the quantity of warmth transfer decreases within the case of streamline flow. The reduction in Nusselt number is approximately 22% of the typical steady-state flow and has been reported to flow from to flow pulsation. The heat transfer function within the tube was calculated by Zohir et al. I studied. [35] to get a good variety of Reynolds numbers. For turbulent & laminar regimes, they specified the extent of improvement within the heat transfer coefficient in pulsatile flow. Many authors have conducted experimental studies on pulsating turbulent pipe flow. The results of Hesham et al. [37] showed the typical Nusselt number compared to the steady flow by Elshafei et al. Al. The warmth transfer properties of pulsating turbulence during a tube heated to a consistent heat flux are studied by others [38]. Investigated experimentally. The latest power generation systems and manufacturing processes use this situation. The outcomes demonstrates that Nu is toughly stricken by both the pulsation frequency & so the Reynolds number, when the oscillator is mounted down-stream of the pipe outlet tested. When the steady-state flow value is exceeded, its general value decreases or increases. The difference within the entrance area is additionally obvious than within the fully developed area downstream. You'll also see that the comparative mean Nu decreases or increases counting on the spectrum of frequency. Even though the deviancies are minor, at higher Reynolds number values, it seems to be obvious. The researchers use to plan experimentation of the multiple input parameters and their effect on the output response through a statistical technique called as design of experiment [39, 40]. The output response of the experiments are validated with ANOVA (analysis of variance) technique, In ANOVA, the standard deviation and statistical variation are considered. The effect of each input parameters and combination of parameters on output response also predicted [41, 42]. The Regression analysis is used to generate a mathematical model of output response as a function of input response. The mathematical model can be optimized using various optimization approaches as Genetic_algorithm, simulated_annealing, and Particle swarm optimization [42–45] etc. In this paper, experimental investigation of influence of Reynolds number, pulsating frequency, and input heat power source on turbulent flow heat transfer through pipe. The full factorial design of experiment method is employed to conduct experiments. The ANOVA is used to check reliability of the data collected through experiments. The mathematical model is generated using regression analysis which is optimized with particle swarm optimization technique.

2 Experimental Set up

As presented in Fig. 1, the investigational set-up is meant to estimate the impact of pulsation on the characteristics of convective transmission of heat in pulsating turbulent

Fig. 1. Experimental set up

pipe flow it's an exposed loop during which air is pumped as an operational fluid and, after being heated, the test portion is transferred to the atmosphere. Basically, the platform contains of three parts: the air supply assembly, the test section and the pulse generator with the required measuring and acceptance equipment. A blower, orifice meter, and flow control valves are the air supply unit and its accessories. The proposed pulsating mechanism consists of a slotted disk connected to the motor, which is further connected by a dimmer to the main supply so that the pulsation frequency can be modified. The entire system is held in front of the outlet of the pipe that constantly operates the flow through the slotted disc, thus imparts air pulsation.

Specifications of experimental setup:

- Test section: 25 mm (ID) Copper Tube, 400 mm length.
- Centrifugal blower: 1.6 HP, 500 CFM, 50 mm of Water Column
- Band type heater: 500 W, Single Phase.
- Orifice plate: 16 mm diameter
- Pulsating mechanism: Slotted rotary disc

The section for the test is as exposed in Fig. 1 the copper tube with an inside diameter of twenty five millimeter, an external diameter of twenty eight mm and a length of four hundred mm. Flexile joints clamp the test segment on both sides. The wall temperatures of the pipe are determined by the distributed thermocouples (4 k-type) from outside along the length of tube surface. Four holes lengthways the outer face of the pipe were fitted with thermocouple junctions, each having diameter 2 mm and depth 2.5 mm. Then the wires of thermocouple were inserted inside the grooves drilled parallel to its axis in the outer pipe surface by collected epoxy from the test section and linked through a multipoint switch to a several channel temperature recorder. A wire of nickel chromium having 15.5 X/m as a resistivity, has been distributed into 2 identical spans to heat up the test section of tube, the chief heater of 0.4 m entire length. By attaching them inside precise elastic Teflon pipes having thickness 0.1 mm & diameter 2 mm, the tapes of the warmers were covered by electrically insulated material and evenly wrapped around the outside tube surface. To achieve a consistent heat distribution, these tapes of heater were

Table 1. Test parameters

Parameter	Description
Heat input (W)	25 W to 100 W
Manometric difference	10 mm to 40 mm
Speed of Pulsation Motor or Frequency	30 RPM (1 Hz), 50 RPM (1.67 Hz), 75 RPM (2.5 Hz), 100 RPM (3.33 Hz).
Location of pulsation mechanism	At upstream and downstream

packed-in with aluminum films of thickness 0.2 mm. An autotransformer was utilised to provide & manage the supremacy of the two electric heater units, linked in parallel with the required voltage. Over the radiator, a layer of 35 mm thick glass wool insulation was installed, followed by a thin coating of aluminium foil. In addition, to ensure perfect isolation of the checked pipe, another layer of 45 mm thickness of glass wool was added. In order to quantify the drastic change in temperature in the entry area, the thermocouples distribution was concentrated at the beginning, along the tested tube. In this research, the heat transfer features of pulsating turbulent air flow through pipes are studied in an experimental program. The heat transfer efficiency of a flow is subjective by many factors. The number of Reynolds, the pulsation frequency & the position of the pulsation mechanism all have a considerable influence on the test segment. The pipe was heated with varied heat inputs and the pulsation mechanism was situated downstream of the test section during pulsating flow studies. The air mass flow rate was modified and kept constant when the pulsation frequency was varied upto 3.33 from 0.0 Hz. The inquiry looked into several Reynolds numbers between 6700 and 13400. It was determined to adjust the manometer water column difference from 10 mm to 40 mm in 10 mm steps in order to Experimentally Evaluate Heat Transfer via Pipe during Pulsating Flow. The heat input is a range from 25 W–100 W. Testing is carried out at without pulsation and with pulsation. Pulsation is created with the help of rotating motor, kept at outlet of flow.

- Motor speed is kept varying as 30 RPM, 50 RPM, 75 RPM, 100 RPM.
- Pulsation motor speed is kept varying as 30 RPM, 50 RPM, 75 RPM, 100 RPM.
- For selected mass flow rate of air and different heat inputs, inlet, outlet and surface temperatures of the thermocouples are noted at steady state. The same experimentation is repeated for different pulsation frequency and the corresponding voltmeter and ammeter readings are noted and power supplied to electrical heater is calculated. Air flow is measured with the help of orifice meter. Experimentation was carried on the circular pipe at various frequencies of pulsation.

Table 1 shows test parameters. The experimental set was constructed when all of the essential components were assembled. The relevant instruments have been connected in the proper configuration, and the setup is ready for testing.

Table 2. Design points for DOE.

Factors			Levels				
	Unit	Factors Notation	1	2	3	4	5
Reynolds Number	–	A	6753	9504	11618	13414	
Heat Input	W	B	25	50	75	100	
Pulsation Frequency	Hz	C (Downstream) (Upstream)	−3.33	−2.5	−1.67	1	0
			3.33	2.5	1.67	1	

3 Methodology

The experimental investigation to determine the effect of Reynolds number, Input Power and Pulsating frequency of heat pipe on the coefficient of heat transfer. The experimentations are completed as per the design of experiment full factorial methods. The validity of results are checked through Analysis of Variance. The optimization of parameters are performed using particle swarm optimization based on the regression equation and input parameters constrained.

3.1 Experimental Plan

Design of experiment (DOE) is a method by which experiments are designed in such a way that the minimum if experiments are designed to check the effect of input parameters on output response. DOE needs more than one input parameter; these are called design points. In this research, each parameter differs between three levels, making the degree of freedom of each parameter 2. For the current analysis, the complete factorial design of the experiment includes 144 experiments in order to minimize the number of orthogonal array experiments. The three input parameters, i.e. Reynolds Heat Pipe Number, Heat Input, and Pulsation Frequency, with different levels for each parameter. The input level parameters are outlined in Table 2.

3.2 Particle Swirm Optimization

In recent years, optimized findings based on the PSO approach have been observed in published literature as highly accurate. Previous studies have analyzed the heat pipe's efficiency based on the coefficient of heat transfer. Previous researchers have created and applied new optimization ways as ant colony optimization, genetic algorithms, simulated annealing, neural network-based approaches & particle swarm optimization for a variety of applications. Particle_swarm_optimization (PSO) is a method of optimization is not affected by the size or nonlinearity problem. As a consequence, the PSO technique is used to estimate the heat pipe's efficiency. The randomly produced particles termed swirm and velocity allotted for each particle created in search space are used in PSO

analysis for a number of iterations. In addition, the best location of each Pbest particle was obtained in the best fitness Gbest value.

Let,

$$X_i = \{x_i\} \text{ And } V_i = \{V_i\}$$

Additional updating velocity and the location of particles

$$V_i = W \times V_i + C_1 r_1 \{P_{best} X_i\} + C_2 r_2 \{G_{best} X_i\}$$

$$X_i = X_i + V_i$$

For P_{best} and G_{best}, acceleration constants are where r1 and r2 are (selected as 0 to 1) the random numbers as well as c1 and c2. The weight for inertia is W. For further study, the PSO code is processed.

Figures 6 and 7 represents Flow Visualisation Setup and Flow visualization with smoke injection and blue Coloured lamp.

4 Results and Discussion

The impact of the pulsation at the traits of the warmth switch is visible in phrases of the Nusselt quantity and the common coefficient of warmth switch for the pulsed glide to the corresponding numbers for the consistent glide at the identical Reynolds numbers. By various warmth input and pulsation frequency, the common warmth switch coefficient and Nusselt quantity are decided. The price of the warmth switch coefficient decided with the aid of using the experimental and theoretical technique is identical, as proven in Fig. 2. It is showed from those graphs that the experimental setup is validated. Reasonable settlement among the experimental and theoretical values of the coefficient of convective warmth switch at diverse Reynolds numbers. The distinction withinside the coefficient of experimental and theoretical warmth switch is 3–4%.

The upstream pulsating frequency is taken as positive and downstream pulsating frequency is taken as negative for the further analysis and simplicity. Figure 3 shows Deviation of heat transfer coefficient with respect to pulsating frequency for respective Reynolds number.

The coefficient of heat transfer is detected to increasing with rise in Reynolds number along with the increment in the heat power input. For 25, 50, 75, 100 W power input maximum coefficient of heat transfer is found to be the for -3.33 (downstream) Hz pulsating frequency and 13414 Reynolds number as exposed in Fig. 3 (a,b,c,d).The maximum Heat transfer rate is obtained at 100 W and 13414 and 3.33 Hz downstream frequency. The increment in heat transfer coefficient with low to high values Reynolds number is 30–37% and 20–30% with low to high values of power input.

4.1 ANOVA-Analysis of Variance

To analyse the importance and contribution of the output responses of each input parameter, the Analysis of Variance Method is implemented. The ANOVA method utilizes the
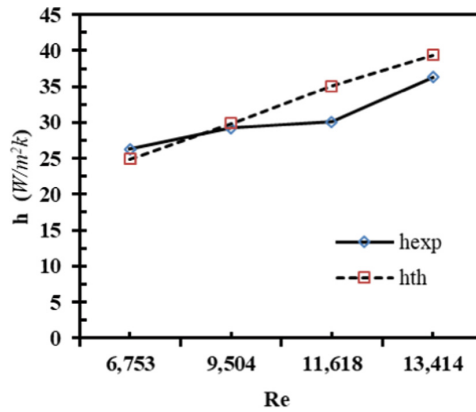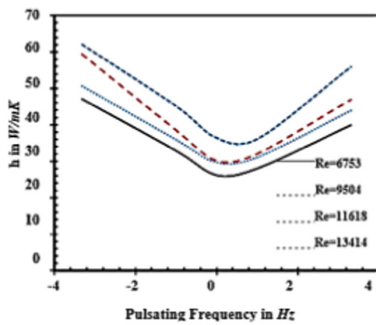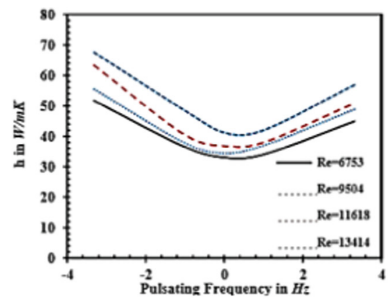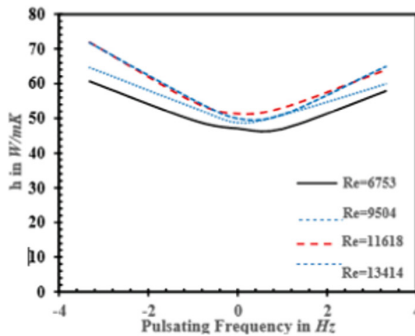
Fig. 2. Comparison theoretical & experimental heat transfer coefficient.

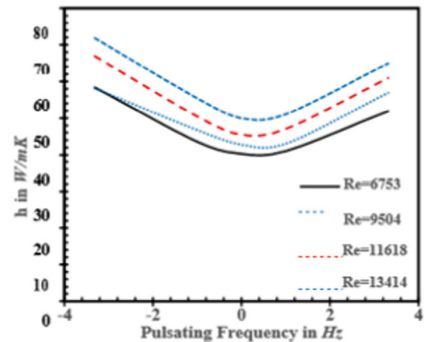**Fig. 3.** Deviation of heat transfer coefficient with respect to pulsating frequency for respective Reynolds number.

Table 3. ANOVA analysis

Source	Degree of Freedom	Adjusted Sum of Square	Adjusted Mean Square	F-Value	P-Value	% Contribution	Significance
A	4	2482.7	620.67	218.56	0.000	14.7656	Significant
B	3	3858.7	1286.25	452.95	0.000	22.9493	Significant
C	8	6125.6	765.69	269.64	0.000	36.4315	Significant
A*B	12	14	1.17	0.41	0.956	0.08326	Not Significant
A*C	24	2649.1	110.38	38.87	0.000	15.7553	Significant
Error	92	261.3	2.84				
Total	143	16814					
	R^2 98.45%	R^2 (adj) 97.58%	R^2 (pred) 96.00%				

output response variability used for calculating the number of squares and the mean of the output response square, i.e. heat transfer coefficient. F-test & the likelihood test was carried out to verify the importance and contribution of the output responses of each input parameter. To simulate experiments, the MINITAB software package is used. The results obtained by ANOVA are shown in Table 3. The Probability Test is used to define the meaning parameters of the i/p parameters in which the parameter is said to be relevant if the P-value is less than 0.05. As we can see in Table 3, all three Reynolds Number, Heat Input and Pulsation Frequency input parameters have P values smaller than 0.05, which concludes that three parameters are significant. The percentage contribution of each input parameter is also shown in Table 3. Which suggests that Pulsation Frequency contributing more to the model than other parameters for this particular model.

The R-square is 98.45 percent and the R-squared Adjusted value is 97.58 percent, which is more than 90 percent, and the R-squared Predicted value is 96.23 percent, which is more than 70 percent. The difference between the R-squared adjusted and the R-squared predicted value is less than 20 percent.

4.2 Regression Analysis

The least square method of regression is adopted to determine the regression model for individual input responses viz Reynolds number, Pulsation frequency and input heat power on heat transfer coefficient. The R2 value, P-value, and error of data is checked to see the fitness equation with actual responses.

$$h = 28.4 - 0.00159 \times A + 0.211 \times B - 0.41.C + 0.0 \times A^2 - 0.000147 \times B^2 + 1.475 \times C^2$$
$$- 0.000003 \times A \times B - 0.000125 \times A \times C + 0.00749 \times B \times C$$
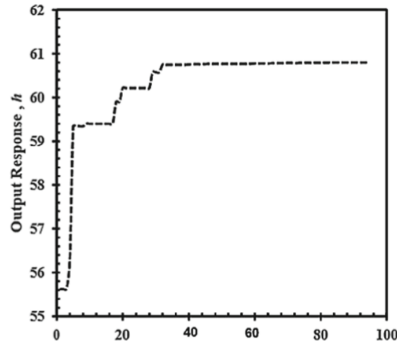
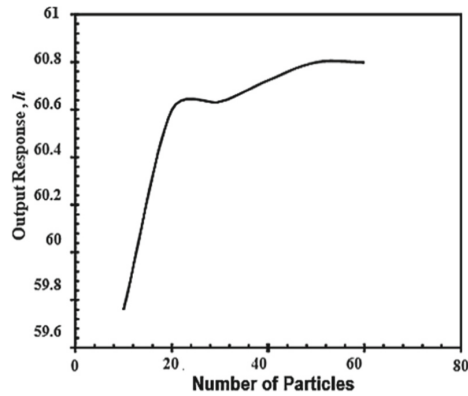**Fig. 4.** Deviation of number of iteration on heat transfer coefficient

Fig. 5. Variation of number of iteration on heat transfer coefficient

4.3 Particle Swarm Optimization

The current study aims to find the optimized accessibility for PSO based examination by considering the design of experimental results which are explained in earlier section. The objective function is determined using regression equation as a utility of Reynolds number, heat input & pulsating frequency whose maximum and minimum limits are specified. The particle size for the optimization of heat transfer coefficient is carried out by changing the particle size from 10–60, the particle size is fixed where the heat transfer results are constant. The Figs. 4 and 5 displays the deviation of particle size with respect to output.

The optimized values for heat performance is obtained at Re = 13414, Pulsating frequency 3.33 Hz downstream and Heat input 100 W. as illustrated in Table 4.

Table 4. Deviation no. of particle with optimized input response and h

No of Particle	10	20	30	40	50	60
Re	13079.836	13350.4	13361	13389.9	13414	13414
Power Input W	100	100	100	100	100	100
Pulsating Frequency Hz	−3.333	−3.333	−3.333	−3.333	−3.333	−3.333
Heat transfer coefficient W/mK	59.758	60.598	60.6312	60.723	60.800	60.800

5   Conclusions

The experimental investigation was done to define the characteristics (feature) of heat transfer for turbulent flow through the tubing. In the case of upstream and downstream position of the pulsation process, the impact of pulsation frequency, Reynold number & heat i/p on coefficient of heat transfer and Nusselt number was investigated experimentally. The heat input to the air heater band ranges from 25 W to 100 W and the flow rate of the air stream varies in such a way that the manometer of the orifice indicates a water column gap of 10 mm to 40 mm. The mechanism of pulsation is constructed using variations in the speed of the pulsation motor. The results of the experiment being studied are as follows, producing pulsation in flow boosts the forced convective heat transfer charactestics (features) through tube.

Generating pulsation of air flow, increases the average heat transfer coefficient.

- Growing of the Reynold number & pulsation frequency, increases coefficient of the typical heat transfer. The overall heat transfer coefficient enhancement is 32 percent at a pulsation frequency of 3.3 Hz. By producing pulsation in air flow, the volume of Nusselt increases. As the pulsation frequency and Reynold number increase, the Nusselt number increases. At pulsation frequency 3.3 Hz, the maximum enhancement obtained in Nusselt number is 36 percent.
- The improvement in Nusselt number & average coefficient of heat transfer were witnessed for the pulsation appliance at the up & downstream location of the pulsation mechanism with an increase in heat input.
- The analysis of variance shows the involvement of Reynolds number i.e. 14%, Heat Input i.e. (23%) and Pulsating frequency 36%. The R2 and R2 adjusted values shows the validity of the measured readings

The particle swarm optimization based on heat transfer coefficient model shows the optimized results obtained at downstream pulsating frequency of 3.33 Hz, Heat Power input 100 W and Reynolds Number 13414. The predicted model and experimental reading show the good agreement.

Appendix

Flow Visualization

Fig. 6. Flow Visualisation Setup and Flow visualization with smoke injection and blue Coloured lamp

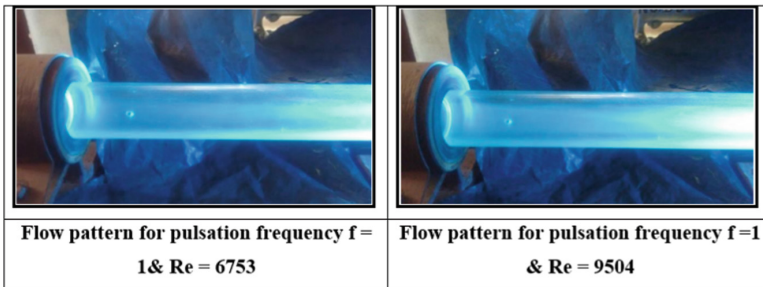| Flow pattern for pulsation frequency f = 1& Re = 6753	Flow pattern for pulsation frequency f =1 & Re = 9504

Fig. 7. Flow Patterns

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