B. TECH. PROJECT REPORT

On

Fluid Flow and Heat Transfer Attributes of an inclined pulsating impinging air jet

BY

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| 180003035 |

DISCIPLINE OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

May 2022

Fluid Flow and Heat Transfer Attributes of an inclined pulsating impinging air jet

A PROJECT REPORT

Submitted in partial fulfillment of the requirements for the award of the degrees

of
BACHELOR OF TECHNOLOGY
in

MECHANICAL ENGINEERING

Submitted by:
MUKUL BAHEDIA

Guided by:
Dr. Harekrishna Yadav (ME Department)

INDIAN INSTITUTE OF TECHNOLOGY INDORE
May 2022

CANDIDATE'S DECLARATION

I hereby declare that the project entitled **"Fluid Flow and Heat Transfer Attributes of an Inclined Pulsating Impinging Air Jet"** submitted in partial fulfillment for the award of the degree of Bachelor of Technology in 'Mechanical Engineering completed under the supervision of **Dr. Harekrishna Yadav, Assistant Professor, Discipline of Mechanical Engineering, IIT Indore,** IIT Indore is an authentic work.

Further, I/we declare that I/we have not submitted this work for the award of any other degree elsewhere.

Mukul Bahedia

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27/05/22

CERTIFICATE by BTP Guide(s)

It is certified that the above statement made by the students is correct to the best of my knowledge.

Harekrishna Yadav

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PREFACE

This report on "**Fluid Flow and Heat Transfer Attributes of an Inclined Pulsating Impinging Air Jet**" is prepared under the guidance of Dr. Harekrishna Yadav.

Through this report, I have attempted to explain how fluid flow and heat transfer attributes behave when the impingement angle of pulsating air jet is changed, and how varying frequency of pulsation at an optimal angle leads to variation in heat flow characteristics.

Through this thesis, efforts have been made to present the methodology, experimental results, and conclusions of the study in a lucid and comprehensible manner through this report. Figures, charts, Simulation models, and tables have been included to make the reading easier.

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ABSTRACT

Jet impingement technology and its underline flow and heat transfer attributes have been studied by researchers over the last few decades. Due to its high heat flux removal capacity over conventional methods, it has found its way into thermal management applications. Any system which rejects excess heat needs to be removed, otherwise, it can affect the performance of the system. For example, overheating the battery pack in an electric vehicle can deteriorate functioning and thermal runaway. Pulsating jet impingement has been proven to be one of the techniques that can improve the heat removal ability from the impingement surface.

In pulsating jets, the inlet mass flow rate varies as a function of time. Due to change in velocity, periodic entrainment of surrounding fluid occurs; resulting in a larger mass flow rate when the jet fluid reaches the surface, causing enhanced heat transfer. When a periodic impingement of vortices happens, it breaks the boundary layer, allowing more heat to be removed from the target surface.

In the current work, the effect of the jet inclination angle on the flow and heat transfer characteristics is studied. In the case of a steady jet, the inclination angle has altered the flow field drastically, and an optimal angle of ~30° has been identified for a higher heat transfer rate. As the hydrothermal performance of pulsating jet differs largely from the steady jet, the effect of inclination needs to be investigated along with the frequency of the pulsation to arrive at optimum parameters.

The transition shear stress transport with the intermittency model will be used to simulate the pulsating jet impingement. First, a validation with experimental data will be obtained to ensure the numerical model is able to capture the flow physics correctly. Thereafter, a grid independence study will be followed by parametric analysis to reach concise information on flow and heat transfer attributes of inclined pulsating jet impingement.

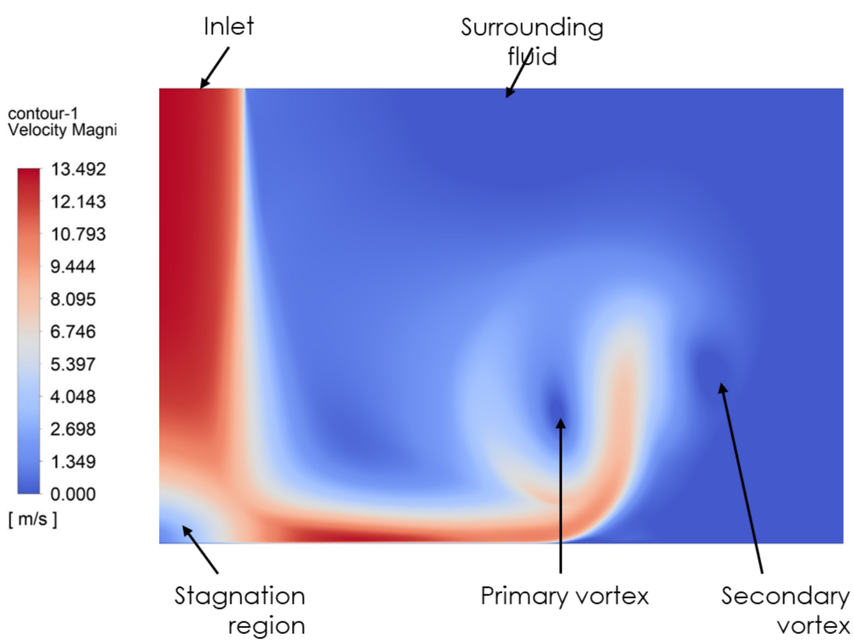
Table of Contents

List of figures

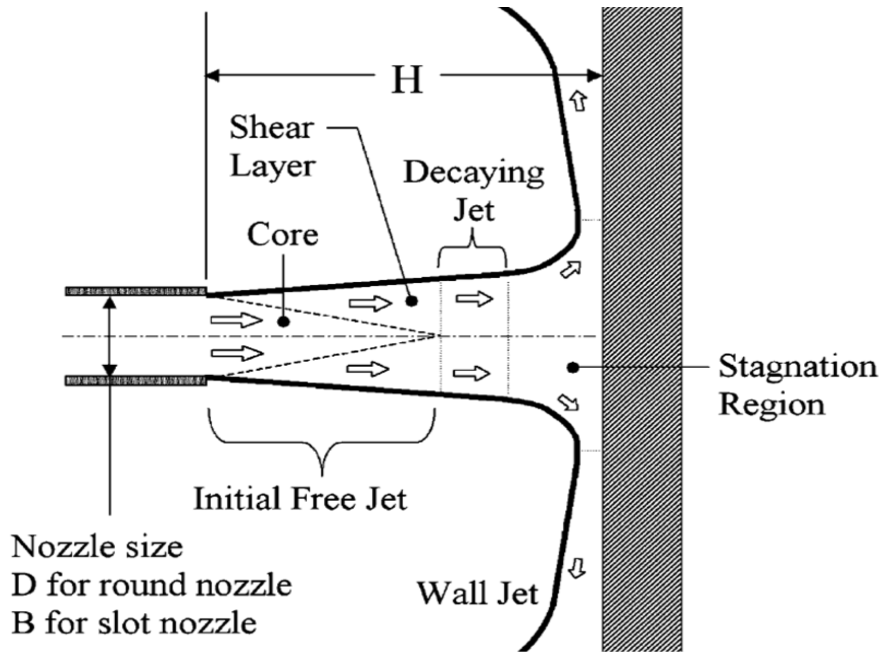
Chapter 1
Introduction

1.1 Jet Impingement

A high-velocity fluid typically generated from a nozzle-like geometry is a Jet. Heat transmission via impinging jets has been proven to be more effective where tempering of glass, drying of films and textiles, cooling of hot steel plates, and gas turbine cascade are just a few of the engineering uses of imping-jet heat transfer. Jet impingement has just been employed for cooling microelectronic components, gas turbine cooling, metal heat treatment, spray irrigation and many more applications. Air jet coming out from the nozzle exit has high kinetic energy and after the impact on the heated surface, a high heat transfer rate is achieved depending on the temperature of the surface, Reynolds number, and distance from the nozzle to plate.



Velocity distribution in 2D axisymmetric air jet impingement on a flat surface

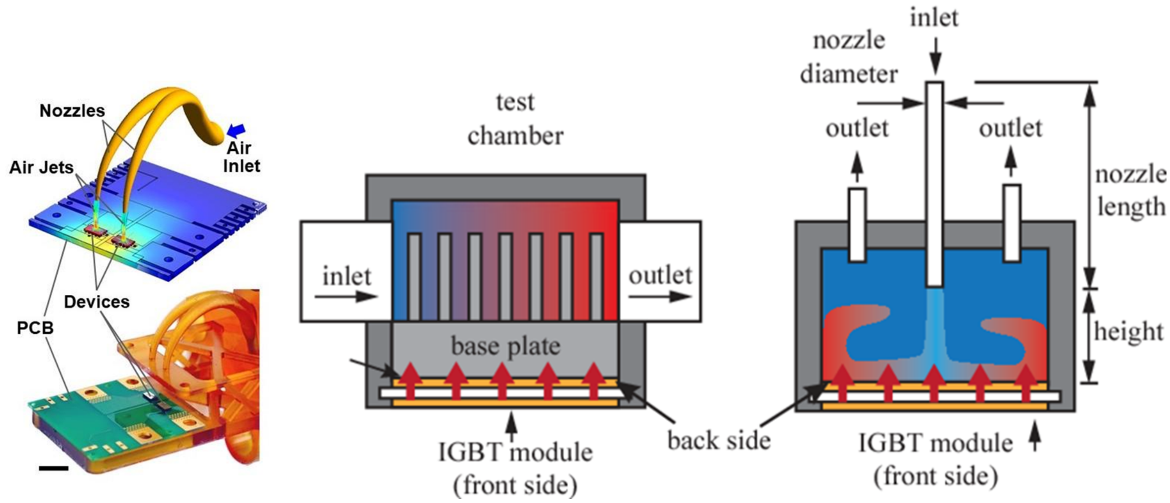


Typical regions in steady jet impingement

H: Nozzle to surface distance

D: Nozzle diameter

- **Free jet / Core region**: Area in which velocity remains constant and equal to the jet exit velocity (Velocity > 95% of Vexit).
- **Shear Layer Region**: Area before impingement excluding the free jet region. A decrease in the velocity/velocity gradient creates a shearing. Momentum transfers with the surrounding fluid, and pulls surrounding fluid inwards
- **Stagnation Region**: As flow approaches the surface, velocity gradually reduces. High static pressure buildup and de-acceleration of the flow cause high heat flux removal
- **Wall Jet Region**: The flow moves laterally outwards along the surface. Exhibits boundary layer formation over the surface.



Application of Jet impingement

1.2 Pulsating jet

When the inlet velocity profile of the air jet is pulsed and impinged onto the surface, we get a pulsating impinging jet. Because flow pulsation is widely believed to increase thermal performance due to features such as flow destabilization, higher turbulence rates, and disorderly mixing, and pulsating impinging air jets have been analyzed to investigate their potency for thermal performance. In our research, pulsating flow comprises 2 terms, the first term represents the mean velocity, and the second term takes care of fluctuations. Fluctuation terms comprise amplitude, frequency, and time.

1.3 Thesis Overview

This thesis is organized into multiple chapters, each chapter having its own objectives and conclusions.

Chapter 2 Literature Review

What work did researchers have done earlier in steady jet, pulsating jet, and inclined jet, and then how did I find the research gap?

Chapter 3 Numerical Model Validation

Numerical model was validated. Experimental data of heat characteristics from Lee's paper for different Reynolds number and r/d ratios were compared to simulation results for transition SST with an intermittency model.

Chapter 4 Simulation Setup

Computation domain, boundary conditions, mesh generation, fluid properties, turbulent modeling, and solution approach for the inclined pulsating jet is discussed, which we will use in chapter 5.

Chapter 5 Results and Discussion

This chapter summarizes the previous chapters' work and lists the obtained results.

Chapter 6 Conclusion and Future Scope

Scope of future research stemming from this report are given.

Chapter 2
Literature Review

Steady jet, Pulsating impinging jet, and inclined jet have been thoroughly studied by researchers in the past few decades. Heat transfer from long pipe nozzle has been seen in certain investigations (1–3), demonstrating that thermal and fluid attributes are vulnerable to fluctuations in inflow conditions [4,5]. O'Donovan and Murray experimented with the time aspect of both the thermal and fluid flow characteristics of an impinging air jet[6]; their findings reveal that the amplitude of the heat transfer coefficient along the wall is influenced by the formation of vortices at a height from the jet outlet. According to them, at lower values of nozzle-to-target(n-t) ratios (H<= 2D), a rapid surge in turbulence in the wall jet causes a secondary spike in the radial thermal distributions. A subsequent spike in the thermal coefficient distribution along the wall [7] for impinging jet heat transfer at lower n-t ratios (H<= 2D) correlates with a local increase in velocity normal to wall. variations due to the shift of the wall-flow velocity from laminar to turbulent phase.
In the case of pulsating impinged air-jets, despite several investigations, the results of the potential thermal convection augmentation generated by pulsing jets are highly diverse [8-15]. As a result, some studies claim a large increase in heat transmission [8-12], whereas others report no increase or even a decrease in heat transfer employing pulsing jet impingement [13-15]. The area-averaged Nusselt number indicates more consistency and bigger enhancements over the tested range of conditions using pulsing impinging jets, with a continuous increase with frequency at varied H/D values, whereas the stagnation Nu sees a decline.

A lot of research work has been done to understand fluid behavior and heat transfer attributes of steady, pulsating, oblique as well as inclined jets. But very limited research work is done for understanding inclined pulsating air jet’s behavior with physical properties like the angle of inclination and Frequency of pulsation in the impinging jet. The aim of this research is to better understand these properties with respect to quantitative values.

Chapter 3
Numerical Model Validation

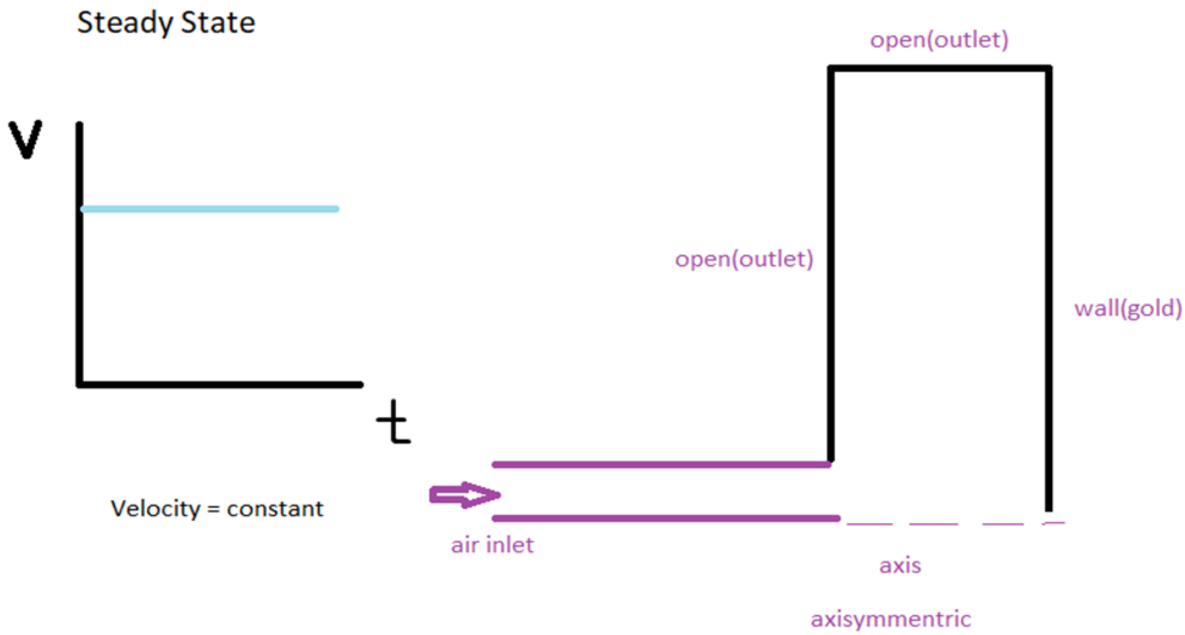
Both laminar & turbulent flow takes place at the same time in different spots. The computation of the continuity and momentum equations with a proper grid is adequate to resolve the flow phenomena in laminar flow, but a modeling approach is necessary for transitional or turbulent flows. Turbulence has a major impact on the flow's important global properties, hence reliable and accurate forecasting of turbulent flow events is necessary.

The flow mechanics and computing requirements, as well as the generated grid and accuracy, are used to determine the best model for turbulence simulations in the domain. A wall function is not an effective strategy for resolving the boundary layer due to the separation. Instead, solving the boundary layer directly can yield correct results. The generation of a fined mesh near to the wall is enough to resolve the laminar section of the boundary layer (viscous sublayer) across a relatively small height from the wall is one of the most important considerations. For their precision and efficiency, RANS models are widely employed in modeling.

The authors have discovered that combining SST model with a transition intermittency model best captures the region near to wall at an appropriate time of computation; they recommend this model to be a suitable balance between cost of computation and dependability. On one hand, The SST model without transition intermittency fails to capture the 2ndary peak, whereas this is the only model that exhibits an acceptable match with the experimental data. Because successfully capturing this behavior directly influences the accuracy of the thermal outputs, the right modeling of the 2ndary peak in the Nu number is a crucial sign of the numerical model's dependability.

Now simulation for the **steady impinging jet** was carried out and results were compared with experimental local thermal data from Jungho Lee, and Sang-Joon Lee's paper to validate the numerical transition shear stress transport with the intermittency model.

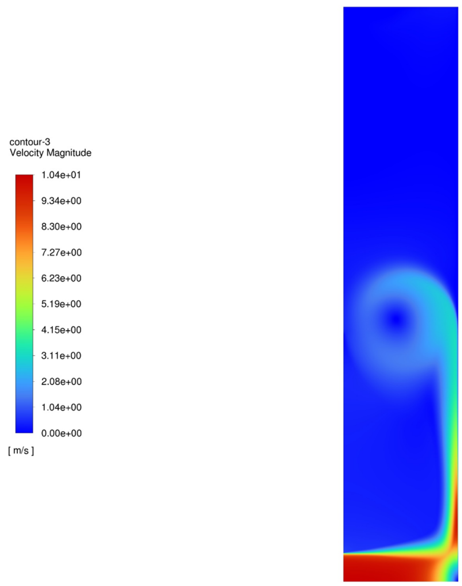
3.1 Simulation Settings



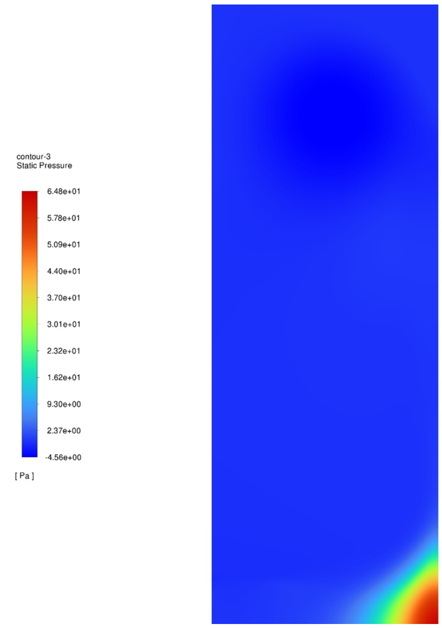
shear stress transport(SST) with the intermittency model.

SIMPLE algorithm.

discretization parameters: second-order



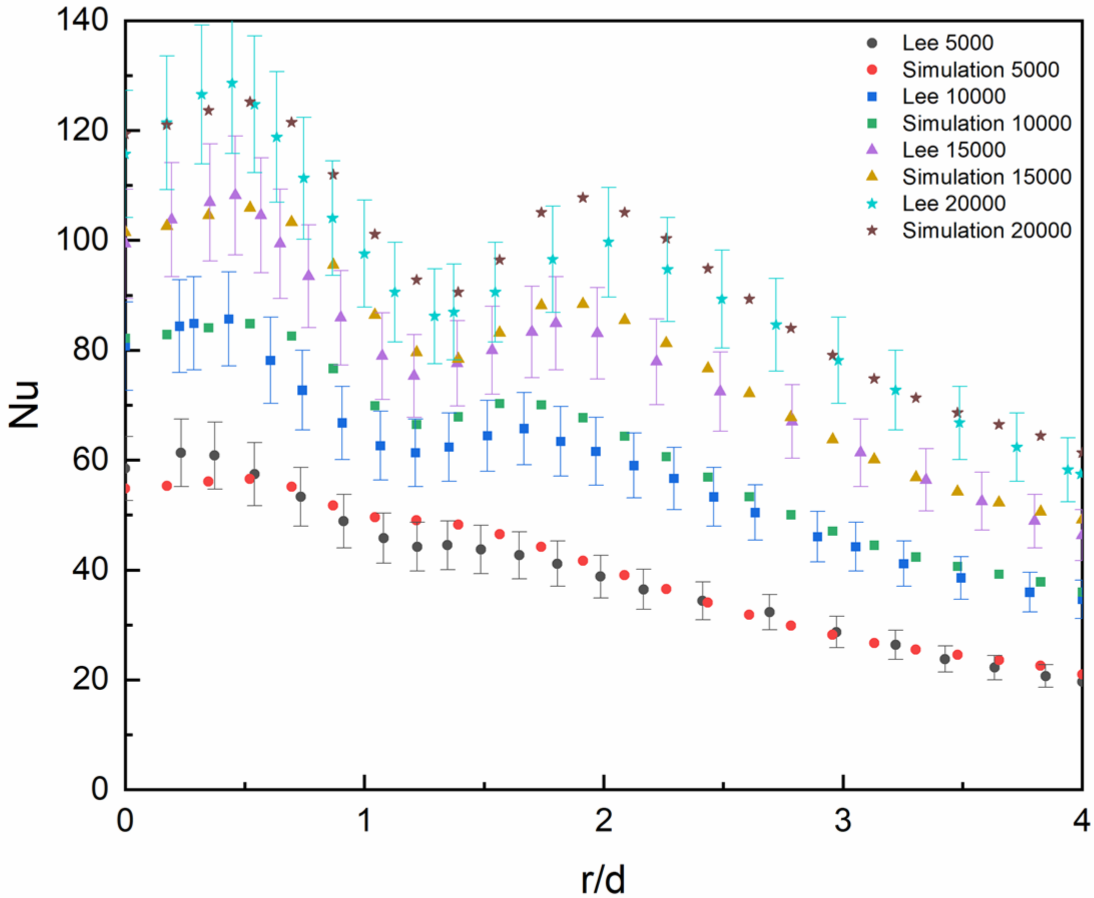
Velocity Profile of Steady Jet



Pressure Profile of Steady Jet

3.2 Validation of Numerical Model:

At r/d values = 1,2,3,4. Experimental Nusselt Number values were compared with simulation data, for different Reynolds numbers = 5000,10000,15000,20000. Less than 10% variation was observed.



As we can see in the graph, as the Reynolds number is increased from 5000 to 20000, the Nusselt number also increases. This observation is aligning with the fact that more Reynolds number means a higher velocity of the fluid. It means that convection heat transfer gets increased. Also from the graph, we can see the formation of the secondary peak near the r/d value of 2. We notice this peak because of the vortices formation and propagation, which result in a higher heat transfer rate and thus a higher Nusselt number.

Chapter 4
Simulation Setup

The commercial product ANSYS Fluent R21 is used to simulate jet impingement numerically. The near-wall region receives the most attention because it has the greatest impact on convective thermal transfer. Previous research on thermal characteristics to impinging jets could only predict flow phenomena subjectively, with only a limited extent of quantity certainty for the formulation of the energy equation, that is mainly associated with convective heat transfer. The purpose of the work is to validate the results of heat transfer simulations obtained from simulation for a steady impinging jet with the experiment's data on local heat transfer coefficients from Jungho Lee and Sang-Joon Lee's paper, in order to increase the accuracy and then use the same numerical model for an inclined pulsating jet because the flow physics are similar in both cases. We'll gain flow and heat transfer qualities this way.

4.1 Computational Domain: Geometry and Boundary Conditions

The simulation of a circular inclined pulsing jet getting impinged on a flat hot plate was done using a 2-D realm of computation and boundary conditions as depicted in the figure. The dimensions are the same as the experimental configuration that was used to validate the our model. The computational domain spreads quite far out from the region of interest (in both directions, up to an 8D radial distance from the jet midline) to preclude outlet boundary effects from affecting the results. The inlet diameter of the nozzle is taken half of the plate to nozzle distance.

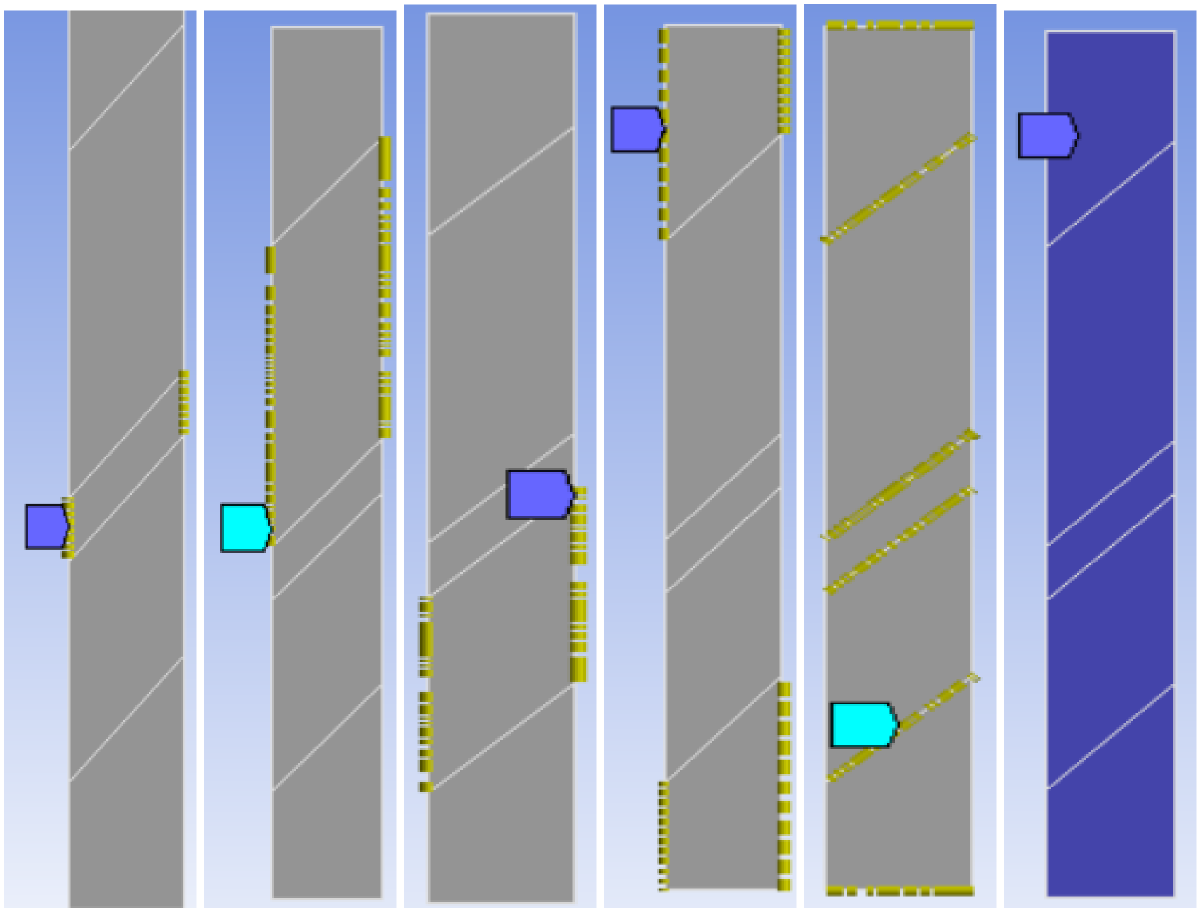
The domain's border conditions are depicted in the figure. The velocity at the entry of the nozzle is taken to be periodically sinusoidal in nature, V(time) = V_{mean} + V_{mean} * Amp*sin(omega*time). The Reynolds number utilized in the tests is used to set the time average mean velocity V_{mean}. The turbulence in the inlet is calculated using the same mapping approach that was used to estimate the turbulent energy from a different simu..

At the domain's radial outlet and unconfined top boundaries, an initial boundary condition with a fixed temperature of 25°C and 0 relative pressure is used to allow flow to exit and enter back the domain, allowing potential flow re-circulation. In accordance with the experiments, the bottom of the wall geometry is set at a constant heat flow of 8.33 watt/m^2.

4.2 Mesh Generation

Using appropriate approaches such as refining grid inside of boundary layer of wall, the resulting mesh is meant to resolve the significant flow features as a function of the primary parameters (e.g., Inclination angle, Frequency). To retain orthogonality in the domain, the network model is produced using a hexahedral mesh; Then, in regions with significant temperature, pressure, velocity, and turbulence gradients, it is repeatedly updated and changed to form a sustainable solution. A coarse mesh approach is used to generate zone with low gradient, resulting in greater control of the distance from the wall of the grid first (y+). Keeping the y+ for near-wall cells below unity provides a sufficient value of cell thickness near the wall. A minimum of 10 nodes are also inserted within the viscous laminar sublayer, close to the wall (on the order of 10^6d for the current situation). The final grid is created with a higher density of nodes at the impingement wall and the jet mixing zone.

The graph depicts the effects of various mesh sizes used in the grid independence study on heat transmission outcomes.



4.3 Fluid Properties

Because the Mach number in the area is less than 0.05, fluid can be considered incompressible. However, as temperature changes can be as high as 35°C, we should expect deviations in air properties. To account for the effect of compressibility and changing fluid properties, a property table is used to determine properties like density, viscosity, and heat conductivity in the range of 30°C to 65°C. As a result, the discrepancy in the thermal properties findings retrieved by incompressible & compressible models is evaluated to be less than 1% for the valid range of Re number in this research (5000).

4.4 Turbulence Modeling and Governing Equations

In chapter 3, When experimental data were compared to transition shear stress transmission using the intermittency model, we found that the inaccuracy is less than 10% for steady jet impingement. We'll analyze our model using the same numerical model because the flow physics are identical.

While selecting the model, the following assumptions were made:

1. constant fluid properties and incompressibility in the fluid.
2. Viscous fluids are not releasing heat.
3. The impinged plate is subjected to a constant temperature condition .

Using the above assumptions, the following equations can be used in our model:

Continuity:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial r} + \frac{v}{r} = 0$$

Momentum in the axial direction:

$$\frac{\partial u}{\partial \theta} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial r} = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left[2(v+v_t)\frac{\partial u}{\partial x}\right] + \frac{1}{r}\frac{\partial}{\partial r}\left[(v+v_t)r\left(\frac{\partial u}{\partial r} + \frac{\partial v}{\partial x}\right)\right]$$

Momentum in the radial direction:

$$\frac{\partial v}{\partial \theta} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial r} = -\frac{\partial p}{\partial r} + \frac{\partial}{\partial \theta}\left[(v+v_t)\left(\frac{\partial u}{\partial r} + \frac{\partial v}{\partial x}\right)\right] + \frac{1}{r}\frac{\partial}{\partial \theta}\left[2(v+v_t)r\frac{\partial v}{\partial r}\right] - (v+v_t)\frac{v}{r^2}$$

Energy:

$$\frac{\partial T}{\partial \theta} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial r} = \frac{\partial}{\partial x}\left[(a+a_t)\frac{\partial T}{\partial x}\right] + \frac{1}{r}\frac{\partial}{\partial r}\left[(a+a_t)r\frac{\partial T}{\partial r}\right]$$

Transport Equations for the Transition SST Model:

$$\frac{\partial(\rho\gamma)}{\partial t} + \frac{\partial(\rho U_j \gamma)}{\partial x_j} = P_{\gamma 1} - E_{\gamma 1} + P_{\gamma 2} - E_{\gamma 1} + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma\gamma}\right)\frac{\partial \gamma}{\partial x_j}\right]$$

4.5 Solution Approach

Heat transfer results from second-order discretization methods seem to be more reliable than first-order methods, but they are less stable in convergence, notably for the energy equation, which is critical in our work. A multistep technique is utilized to increase convergence: initially, Inlet flow circumstances initialize the entire domain, and the solution begins with a discretization method(1st order).

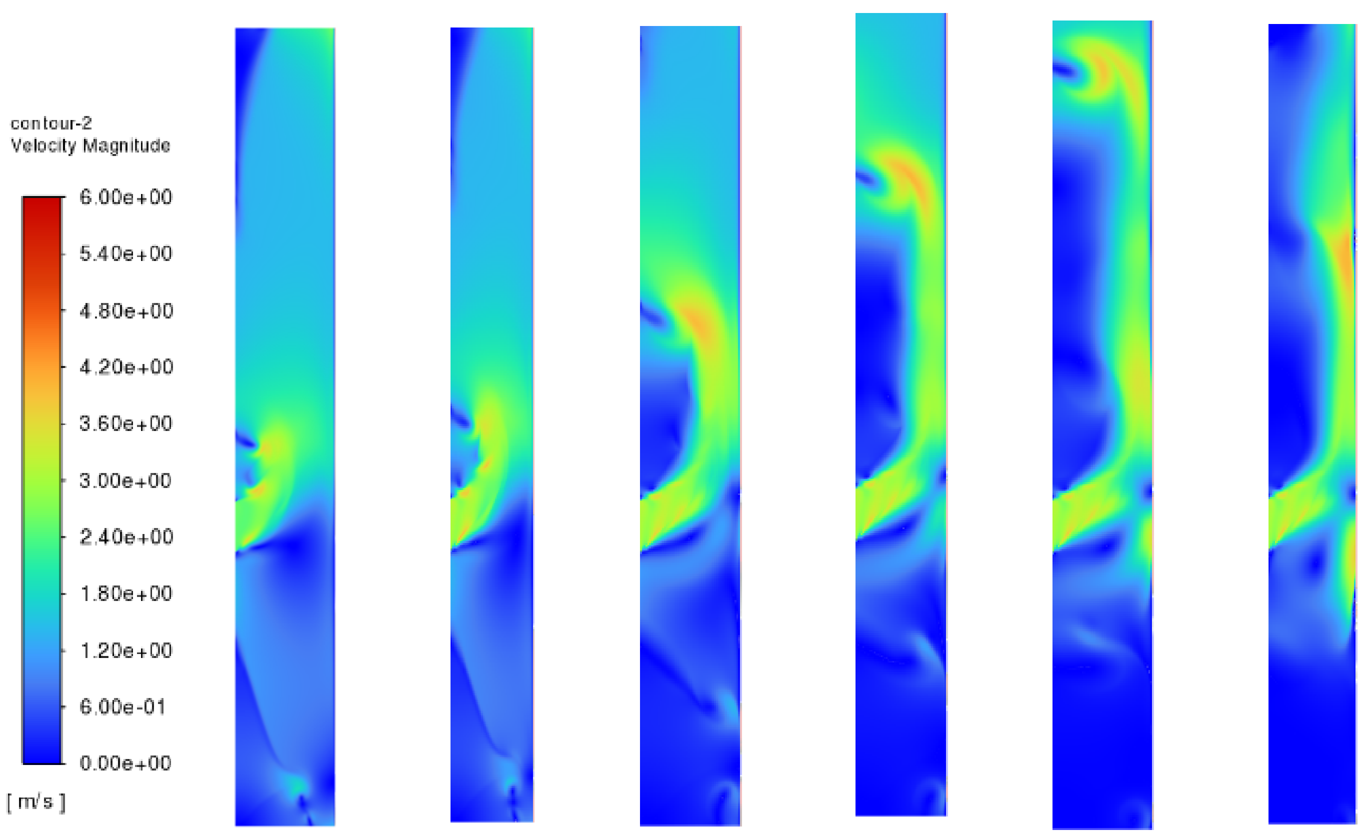
The next stage in the solution is to combine 1st and 2nd order discretization schemes using the exact convergence criteria as 10^{-6}.

Properties	**Values**
Simulation Software	Ansys Fluent
Reynold's Number	5000
Heat Flux	8.33 W / m^2
Inlet Diameter	25 mm
Nozzle to Surface distance	50 mm
Impingement Surface Length	400 mm
Impingement Angles	20, 30, 45, 60-degree
Pulsation Frequencies at 30 deg	0, 20, 30, 50 Hz

Chapter 5
Results and Discussion

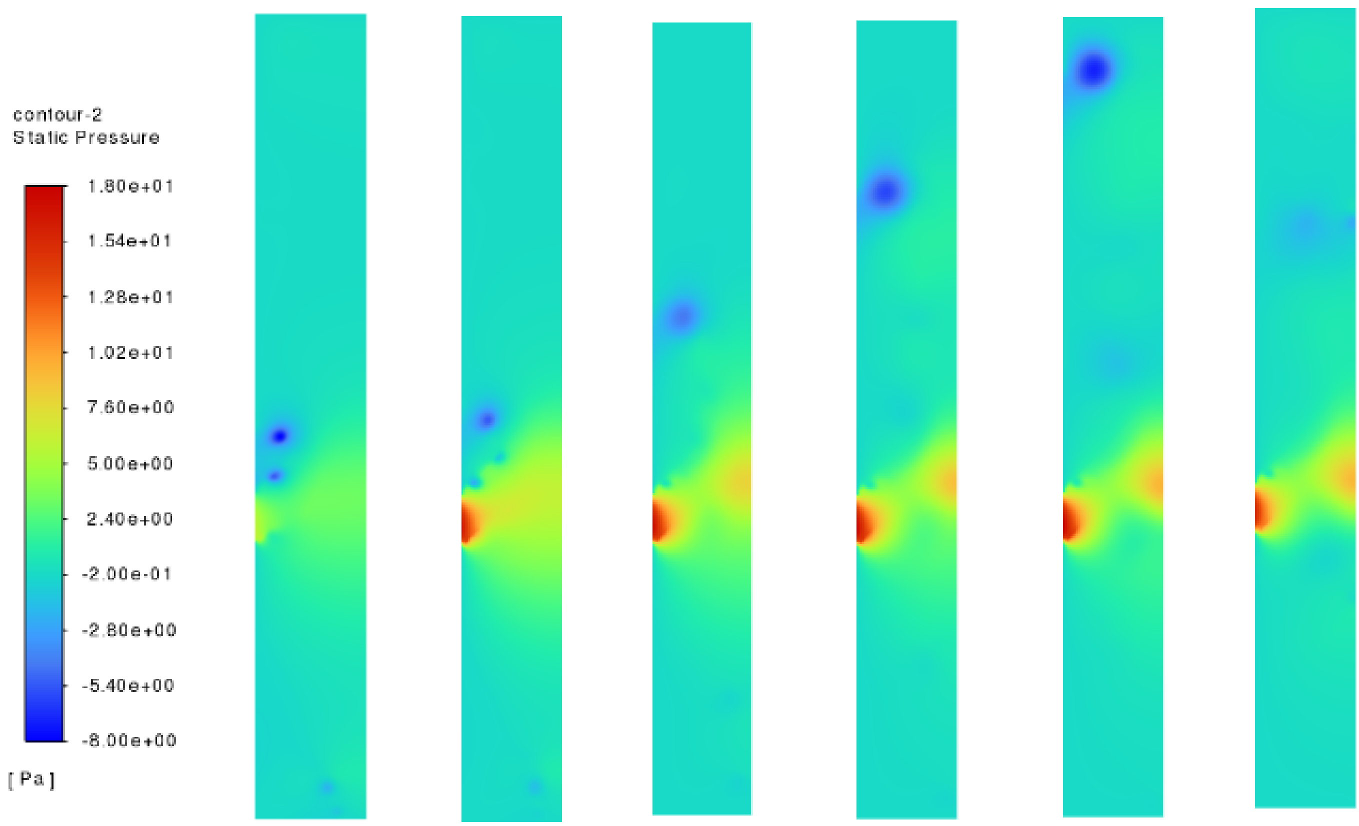
5.1 Flow Visualization

Velocity contours at 30-degree w/t time: At a 30-degree angle and 30 Hz frequency, air impinges on the heated surface. It is observed that fluid flow gets developed. Small vortices generate in each pulsation. Due to change in velocity, periodic entrainment of surrounding fluid occurs; resulting in a larger mass flow rate when the jet fluid reaches the surface, causing enhanced heat transfer. When a periodic impingement of vortices happens, it breaks the boundary layer, allowing more heat to be removed from the target surface. From the figures, we can deduce that as the fluid imping on the plate, the fluid flow gets split into two streams, i.e. downhill and uphill region.



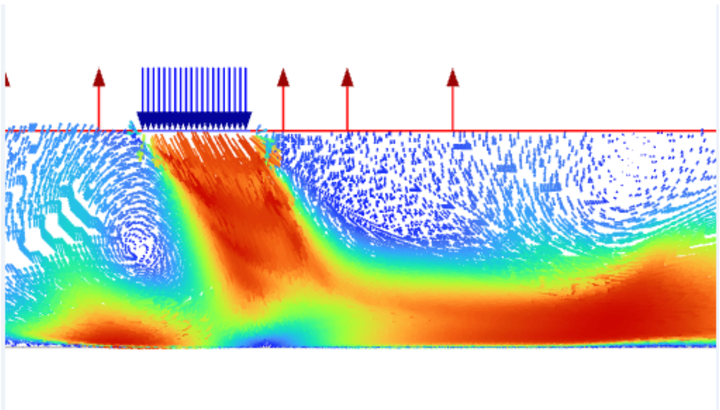
TIME(in sec) 0.0625 0.1 0.3 0.5 0.7 1

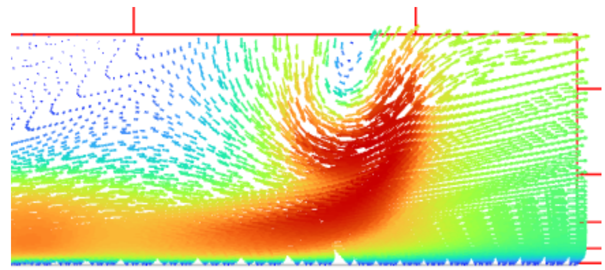
Pressure Contours at 30-degree w/t time: At a 30-degree angle and 30 Hz frequency, air impinges on the heated surface. When fluid imping on the surface, the velocity of air gets almost zero at the stagnation region, and the kinetic energy of the fluid gets converted into static pressure. A high-pressure region gets developed in the stagnation region and the pressure gradually decreases as we move away from the stagnation region. Also, vortices are regions with very low pressure. As time passes, we can see that vortices propagate with the flow.



TIME(in sec) 0.0625 0.1 0.3 0.5 0.7 1

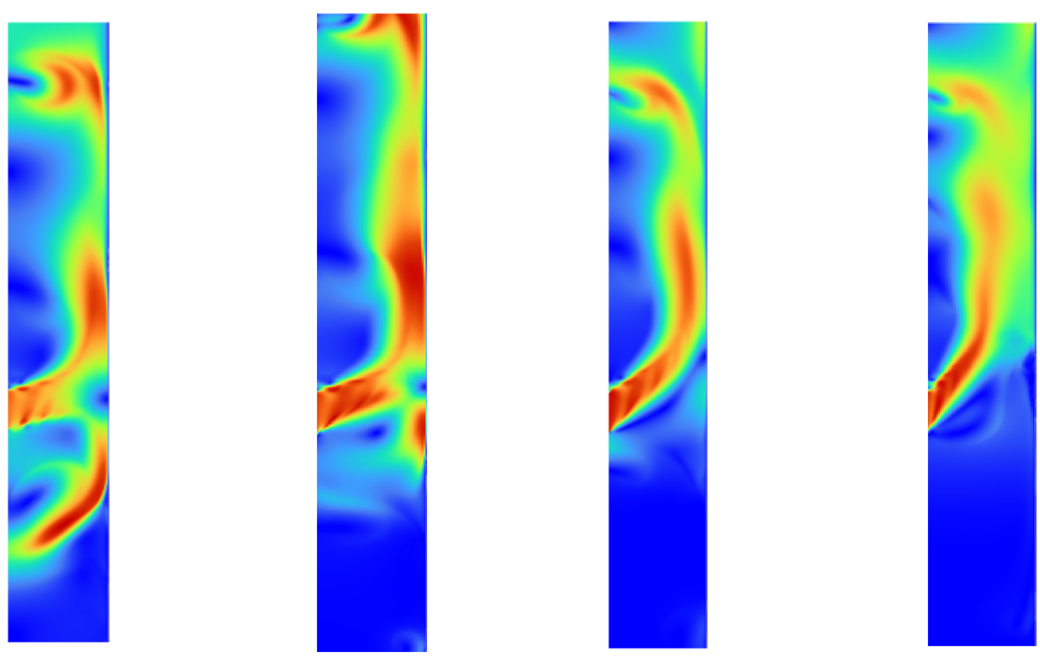
Velocity Vectors representation: As we can see in the below diagrams, there is a low-velocity region below the impingement. That region is the stagnation region, where velocity is almost zero and the kinetic energy get converted into static pressure. The formation of vortices is clearly visible in the diagrams, which later propagate with the flow.



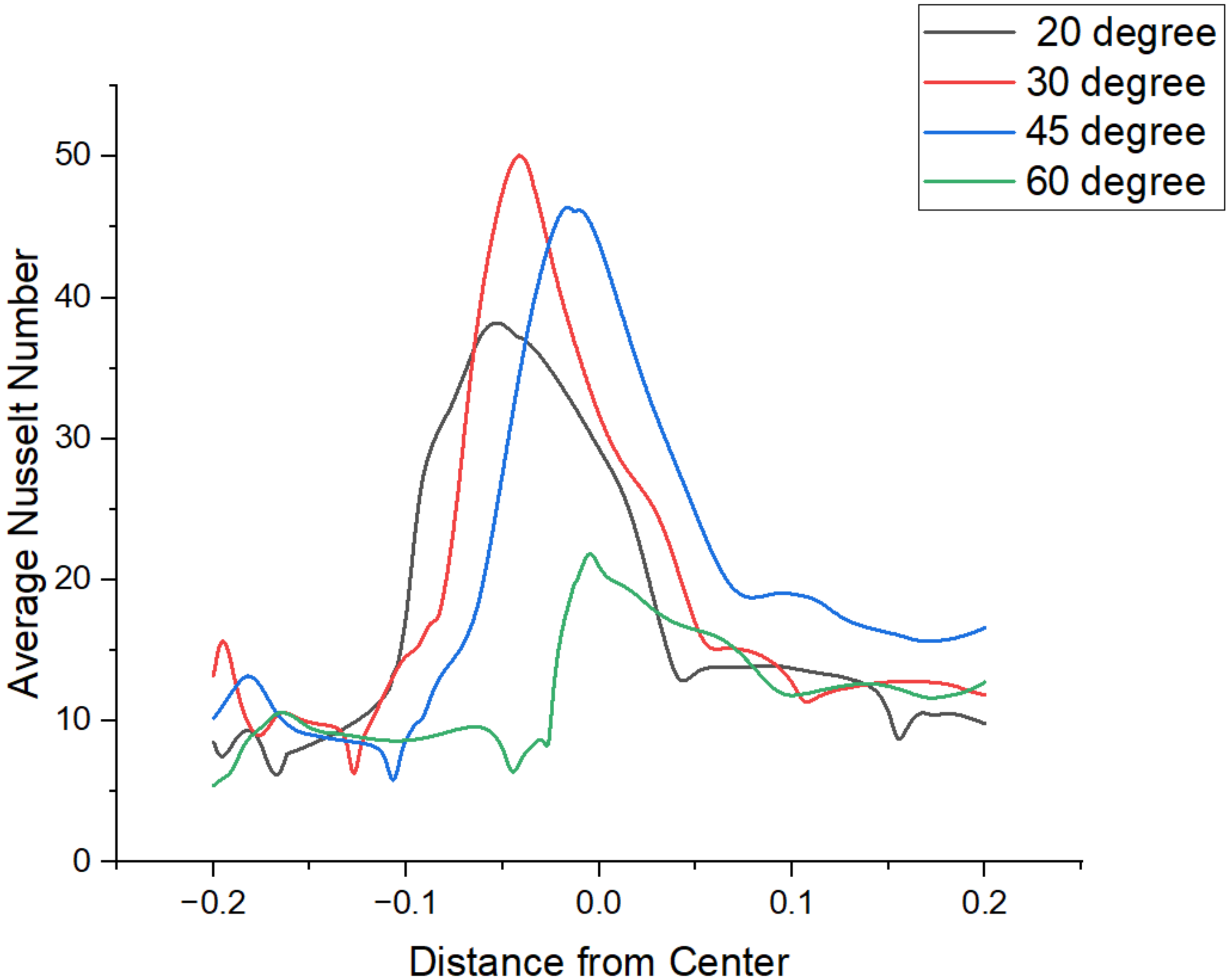


5.2 Nusselt Number vs Angle of Inclination of Impinging jet

Velocity contour at different angles: Angle of inclination of the impinging jet is varied. 20, 30, 45, and 60 degrees. The simulation was run until the steady-state had reached. It is observed that at a low angle of inclination, the air gets split into 2 regions: uphill and downhill. Due to the split, one-directional cooling gets reduced. As the angle of inclination increases, flow reduces to go in an uphill direction, but also the flow attachment to the surface decreases.



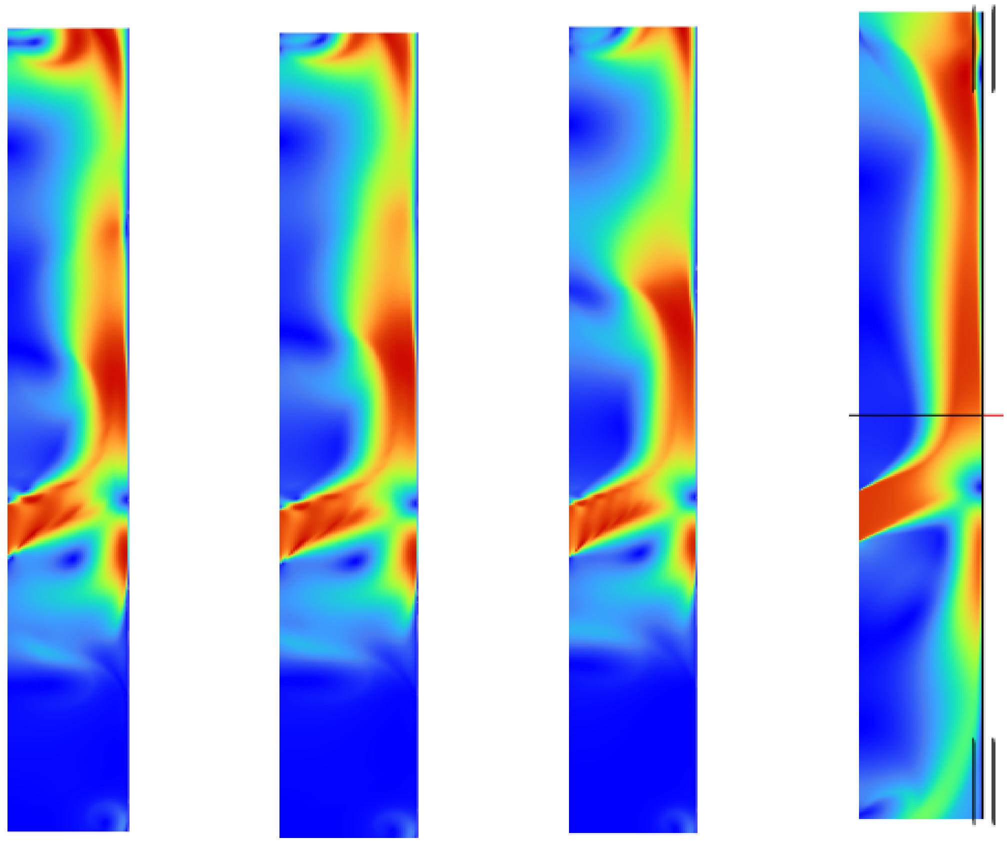
Angle (degree) 20 30 45 60



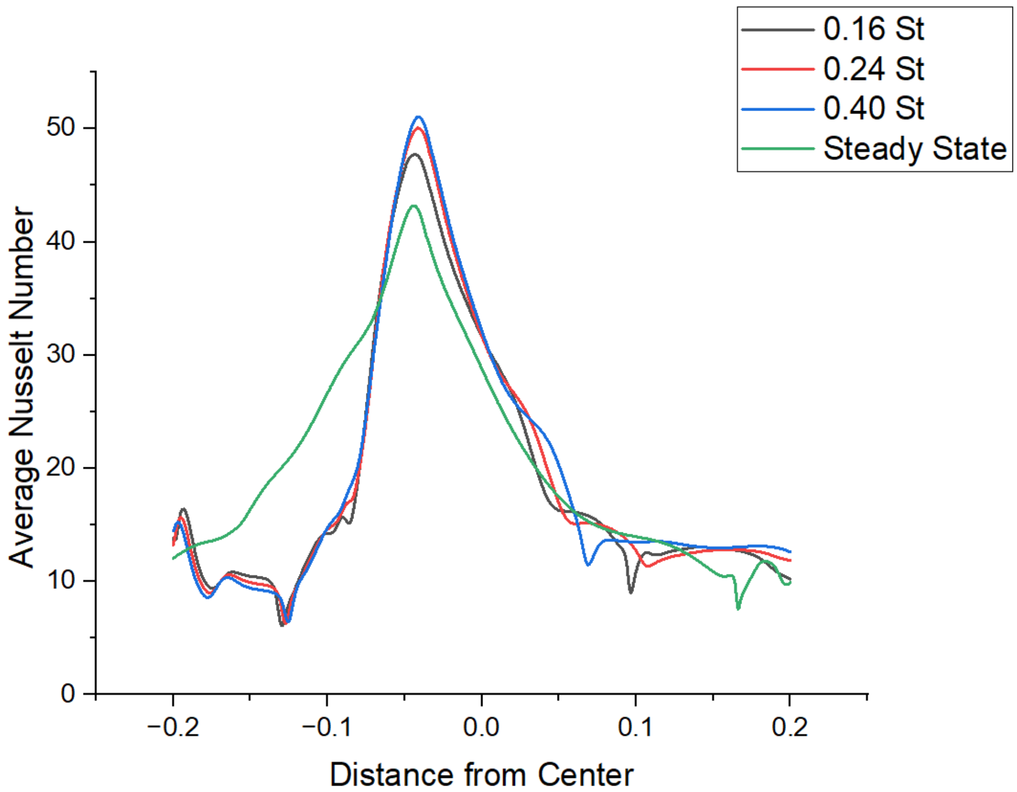
As we can see in the graph, the Maximum Nusselt number is observed at an angle of 30 degrees. Also, 60 degree gives a minimum nusselt number, which aligns with the fact that most of the flow get de-attached from the surface at a higher Inclination angle. Nusselt number at stagnation point also decreases at 20 degrees because of the separation of flow into 2 regions - uphill and downhill region.

5.3 Nusselt Number vs Strouhal Number

Velocity contours at different frequencies: We have found out that at 30 degrees of inclination, optimal heat transfer occurs. Now, on the optimal angle, i.e., 30 degrees, the frequency of pulsation of the impinging jet is varied, i.e., 20, 30, 50, and Steady-state. The simulation was run until the steady-state had reached. It is observed that as frequency increases, the heat transfer also increases. This is because of the fact that more frequency means more pulsation, which means more vortices form. As the number of vortices increases, it breaks the boundary layer, allowing more heat to be removed from the target surface.



Frequency(Hz) 20 30 50 Steady-State



As we can see in the graph, the Maximum Nusselt number is observed at a frequency of 50 degrees, and the minimum is obtained when the flow is steady. As the frequency is decreased from 50 to 20, we see a decline in nusselt number. This aligns with the fact that an increase in frequency leads to more number of pulses per second, which means more vortices formation that leads to greater heat transfer.

Chapter 6
Conclusion and Future Scope

Conclusions from the research are:

◦ Combining a shear stress transfer (SST) model with a transition intermittency model. At a reasonable computing time, the intermittency model best depicts the near-wall region..

◦ Thermal characteristics of impinging air-jet and inclined pulsating impinging air-jet were understood.

◦ Optimum heat transfer occurs at a 30-degree inclination.

◦ As the frequency is increased, the heat transfer increases as the nusselt number increases.

◦ As the angle of impingement increases beyond 30 degrees, the flow attachment to the wall decreases, resulting in a decrease in heat transfer.

Future Scope:

◦ Variation of Reynolds number and H/D ratio and their effect on Heat and fluid flow attributes can be further studied.

◦ Inclined pulsating jet has its application in cooling applications, like electronics cooling, reactor cooling, turbine cooling, and many more, which can be further explored.

Chapter 7
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