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Heat transfer study of a triple row impingement channel at large impingement heights

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HEAT TRANSFER STUDY OF A TRIPLE ROW IMPINGEMENT CHANNEL AT LARGE IMPINGEMENT HEIGHTS

by

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ABSTRACT

Advanced cooling techniques are required to increase the Brayton cycle temperature ratio necessary for the increase of the overall cycle's efficiency. Current turbine components are cooled with an array of internal cooling channels in the midchord section of the blade, pin fin arrays at the trailing edge and impingement channels in the leading edge. Impingement channels provide the designer with high convective coefficients on the target surface. Increasing the heat transfer coefficient of these channels has been a subject of research for the past 20 years. In the current study, a triple row impingement channel is studied with a jet to target spacing of 6, 8 and 10. The effects of sidewalls are also analyzed. Temperature sensitive paint alongside thin foil heaters are used to obtain heat transfer distributions throughout the target and side walls of the three different channels. Thermal performances were also calculated for the two largest channels. It was found that the side walls provide a significant amount of cooling especially when the channels are mounted side by side so that their sidewalls behave as fins. Similar to literature it was found that an increase in Z/D decreases heat transfer coefficient and provides a more uniform profile. It was also found that the Z/D = 6 and 8 target wall heat transfer profiles are very similar, hinting to the fact that successful potential core impingement may have occurred at height of eight diameters. A Computational Fluid Dynamics, or CFD, study was also performed to provide better insight into the flow field that creates such characteristic heat transfer profiles. The Realizable k-ε solution with enhanced wall functions gave surface heat transfer coefficients 30% off from the experimental data.

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ACKNOWLEDGEMENTS

I would like to acknowledge my mentor and advisor Dr. Jay Kapat for all his support and encouragement. I would also like to thank my committee members Dr. Ali Gordon and Dr. Weiwei Deng**.**

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NOMENCLATURE

A_{cs}	Cross Sectional Area
A_h	Heater Surface Area (m^2)
Cp	Specific Heat at Constant Pressure (kJ/kg·K)
D	Jet Diameter (m)
D_{ch}	Channel Hydraulic Diameter (m)
f	Friction Factor
h	Heat Transfer Coefficient (HTC) (W/m^2K)
$\bar{h}$	Average Heat Transfer Coefficient (W/m^2K)
L	Channel Length (m)
$\dot{m}$	Mass Flow Rate (kg/s)
P	Static Pressure (kPa)

P_0	Total Pressure (kPa)
Pr	Prandtl Number
$q"$	Heat Flux (W/m^2)
Q	Total Heat Input (W)
R_h	Heater Resistance (ohm)
Re	Reynolds Number
SW	Side Wall
T	Temperature (K)
TW	Target Wall
V	Voltage Potential
x	Streamwise Location
y	Spanwise Location
z	Height from Target Wall
X	Streamwise Distance (m)
Y	Spanwise Distance (m)
Z	Impingement Height (m)
η	Thermal Performance Parameter
κ	Ratio of Specific Heats
ρ	Air Density (kg/m^3)

Subscripts

C	Cold
H	Hot

Carnot	Describing a Carnot cycle
e	Exit
eff	Effective
$loss$	Quantity Lost to the Environment
$reff$	Reference Value
w	Wall Value
0	Base Line Value

CHAPTER ONE: INTRODUCTION

1.1 Gas Turbine as a Heat Engine

Gas turbine is a form of heat engine where the hot reservoir is created by the combustion of fuel and the cold reservoir is the open atmosphere. It is well known that the maximum efficiency of any heat engine is denoted as the Carnot efficiency.

$$\eta_{Carnot} = 1 - \frac{T_C}{T_H}$$

A more accurate cycle is used to describe the processes inside a gas turbine – the Brayton Cycle. The Brayton cycle, as seen in Figure 1, is composed of four processes. In a gas turbine, air is drawn in at state 1; it is compressed until it reaches state 2. The compressed air is mixed with fuel and ignited as it passes through the combustor. The hot air then passes through the turbines where work is extracted. The process from state 4 to state 1 happens throughout the atmosphere; therefore, the Brayton cycle is an open loop cycle as the same air is not continuously being fed through the motor.

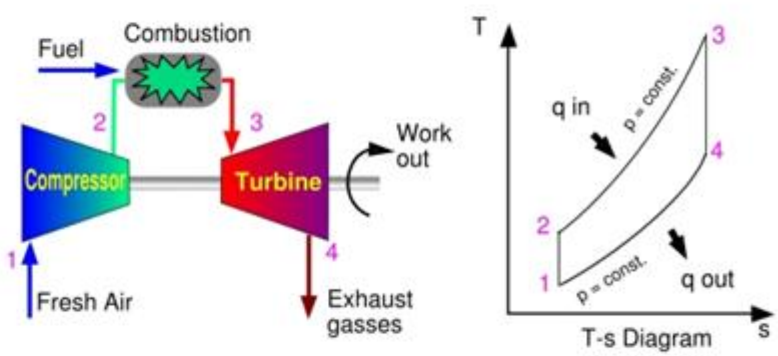


Figure 1: Brayton Cycle Flow Path and T-s Diagram (Adapted from UPTB Website)

The Brayton cycle has an isentropic efficiency similar to the carnot; the Brayton cycle efficiency is defined as

$$\eta_{Brayton} = 1 - \frac{T_4}{T_3} = 1 - \frac{1}{Pr^{\frac{k-1}{k}}}$$

It can be seen that increasing the temperature at which air enters the first turbine stage, T_3, increases the overall efficiency of the turbine. Moreover, increasing the pressure ratio, Pr, also aids in the increase of the efficiency. One of the hurdles of increasing T_3 is the fact that the post combustion gas is a few hundred degrees Celsius above the melting point of the super alloys used to make the turbine stator vanes and rotor blades. For this reason it is important to cool the hot components of the gas turbine in order to assure a reasonable life for the machine.

1.2 Cooling of Hot Components

The transition duct that connects the combustor to the first stage turbine, as well as the first stage of the turbine are the parts that are subject to the harshest thermal loadings and must therefore be cooled aggressively to maintain them in working conditions for a long period of time. Since the first stage guide vanes and rotor extrude into the flow, they are subject to the highest convection coefficients. These heat transfer coefficients can reach up to 4000 W/m^2K (Downs, 2009). Figure 2 shows the different magnitudes of convection coefficient around the blade. High heat transfer coefficients occur where the air stagnates into the leading edge of the airfoil. This high heat transfer region is not only caused by the lack of a thermal boundary layer to protect the airfoil but also because the effective heat transfer driving temperature is the recovery temperature. At the high Mach numbers that occur in turbines, the ratio of total to static temperatures is significant, causing the leading edge to have the highest effective heat load. Another

peak occurs on the suction side of the blade as the boundary layer created by the airfoil switches from being a laminar boundary layer into a turbulent one. Due to the nozzling effect of the turbine rotor and stators, the flow gathers speed toward the trailing edge of the airfoil; leading to higher convection coefficients on the pressure side of the airfoil.

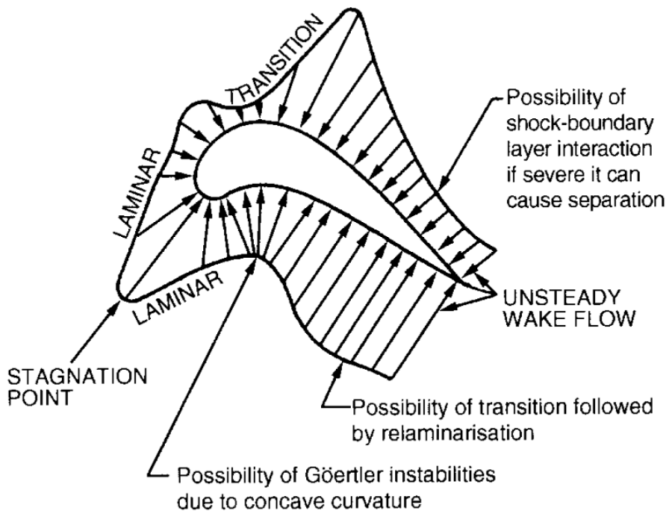


Figure 2: Thermal Loading Throughout a Turbine Blade (Daniels, 1982)

Simple convection channels were implemented in the early nineteen sixties; as years passed, the cooling techniques became more and more sophisticated, allowing the free stream temperature to increase to previously impossible levels. Currently the use of film cooling coupled with backside impingement leads the turbine cooling technology. The trend of allowable turbine inlet temperature is shown in Figure 3; from this figure, it can be seen that the allowable free stream temperature has increased around 600 degrees in the past 50 years. The addition of thermal barrier coatings also helps in the increase in allowable combustion temperatures by creating an extra resistance that the heat needs to move through as it moves from the combustion gasses into the coolant air. It is impotatnt to notice that, as seen in Figure 4, the increase in turbine inlet temperatures is done with the combined benefits of new alloys, TBC and cooling technologies.

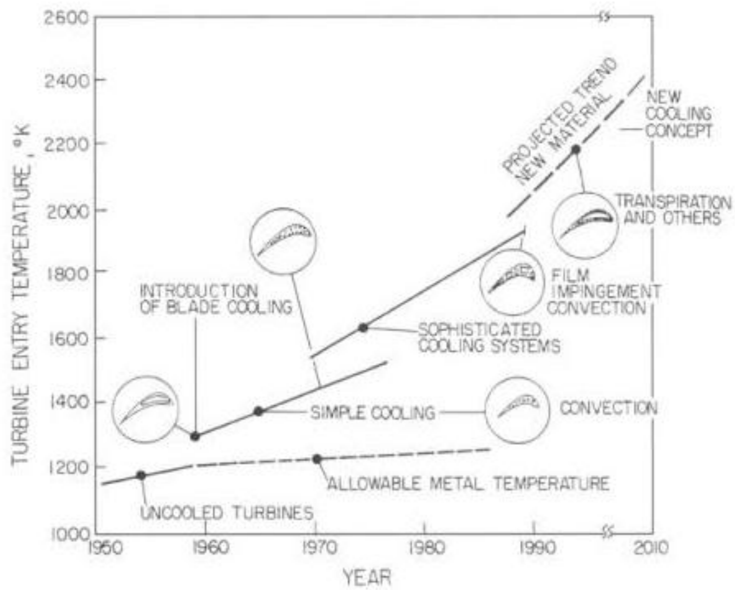


Figure 3: Allowable Turbine Inlet Temperature vs. Cooling Techniques over the Years (Clifford, 1985)

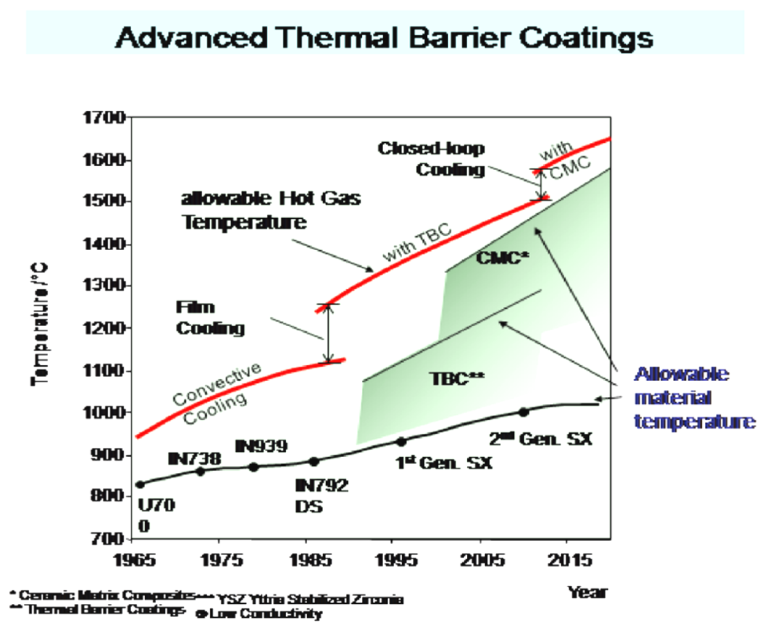


Figure 4: Turbine Inlet Temperature Increase with the help of TBC, New Super Alloys and Cooling Technologies (Kapat and Kiesow Lectures, 2010)

The cooling of inlet guide vanes can be done with the use of impingement inserts inside the airfoils. As air passes through the miniscule holes in the inserts, a jet is formed which then impinges on the wall of the airfoil producing one of the largest single phase heat transfer coefficients. This already impinged coolant air is then bled out as film

cooling as well as bled out through the trailing edge. Figure 5 shows a stator vane with the impingement insert in black, the film cooling extraction as well as the trailing edge bleed.

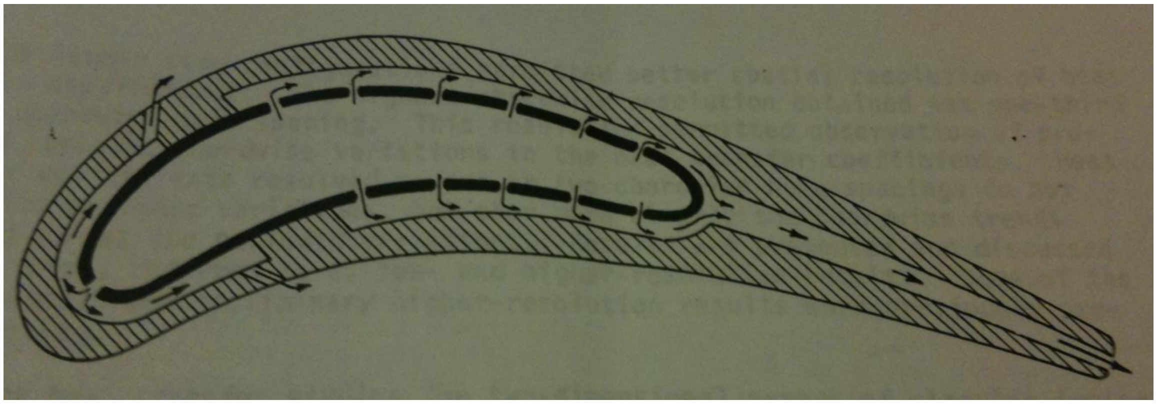


Figure 5: Turbine Stator Cooled with Impingement Coupled with Film Cooling (Florschuetz, 1980)

The cooling of turbine airfoils with the use of an impingement insert is only possible in stationary components as the rotating ones are subject to centrifugal loadings, making it unfeasible to cool them with this setup. Rotor blades are typically cooled with serpentine passages that have heat transfer enhancing features such as ribs, dimples and other turbulators; these serpentine passages are located in the mid chord of the blade. On the trailing edge, a bank of pins are used to obtain high convective coefficients in the thin region; the coolant is the bled out to compensate for the boundary layer created around the airfoil. Rows of impingement holes cool the leading edge. The spent air is then bled out through showerhead cooling. Figure 6 and Figure 7 show in detail the cooling channels around two similar airfoils airfoils.

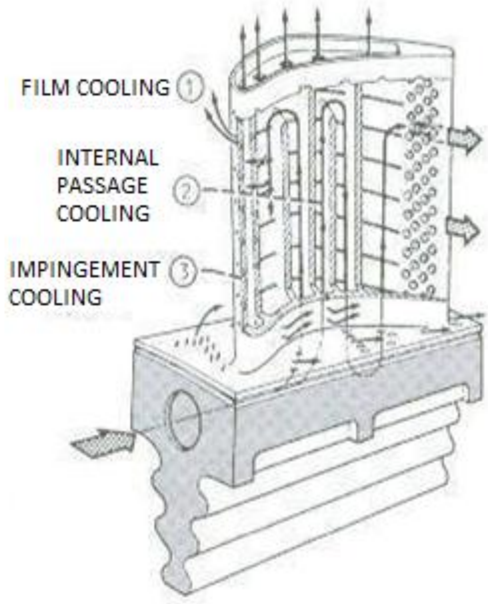


Figure 6: Rotor Blade Cooling Configuration (Gladden, 1988)

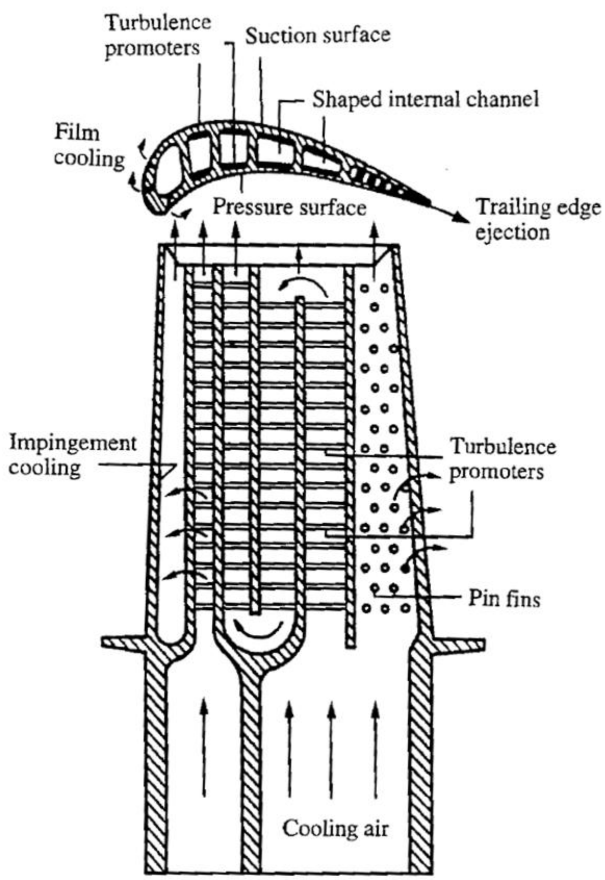


Figure 7: Cross-section of Turbine Airfoil with Cooling Channels (Han et al., 1984)

The coolant air is bled out from the later stages of the compressor. This air is expensive as it has been compressed and not under gown the heat addition by combustion. It is imperative that the minimum amount of coolant is used in these cooling configurations. The cooling must also be as uniform as possible to reduce thermal stresses within the blades, leading to a higher component life. Figure 8 shows freestream, metal and coolant temperatures of the flow, blade and coolant air. It can be seen that a decrease of 25degrees in the surface temperature of the blade can provide an airfoil with twice the working life. Impingement cooling has great potential to provide high heat transfer coefficients at a small flow rate. Impingement of a jet onto a surface provides high heat transfer coefficients due to a starting boundary layer as well as its high turbulence. When the jet is located around 3 diameters from the target surface, the heat transfer profile has two peaks; one located at the stagnation region and the other located between one and 3 diameters from the stagnation region. As the jet is moved away from the target wall, the secondary peak diminishes leaving a profile with a maximum at the stagnation region, decreasing radialy.

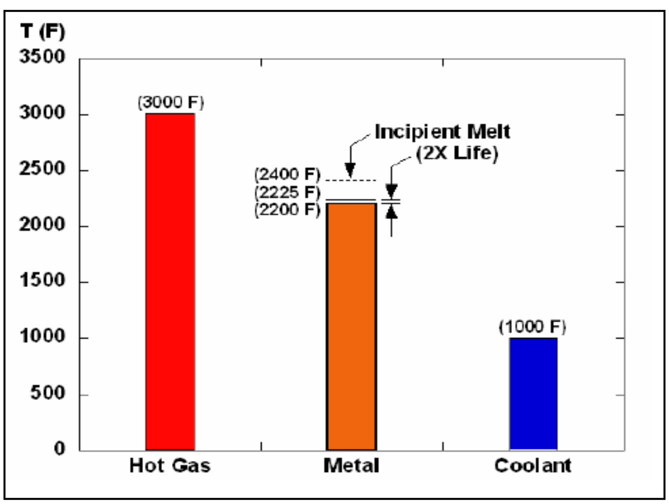


Figure 8: Relative Temperatures for Hot Gas, Metal Temperature and Coolant Temperature (Cardwell, 2005)

Figure 9 shows a diagram of a jet impinging on a target surface. The potential core is the part of the jet that has not been affected by the surrounding stagnant fluid. As the jet moves towards the target wall, its momentum diffuses into the surrounding fluid, decreasing the velocity at which it reaches the target wall and potentially decreasing the corresponding heat transfer coefficient. Studies have shown (Martin, 1973, for example) that the potential core may last anywhere between 7 to 10 diameters. The successful impingement of the potential core yields significantly higher heat transfer coefficients than a fully diffused jet; this comes, however, at a cost of higher pressure drop across the jet plate as well as a highly non uniform heat transfer profile.

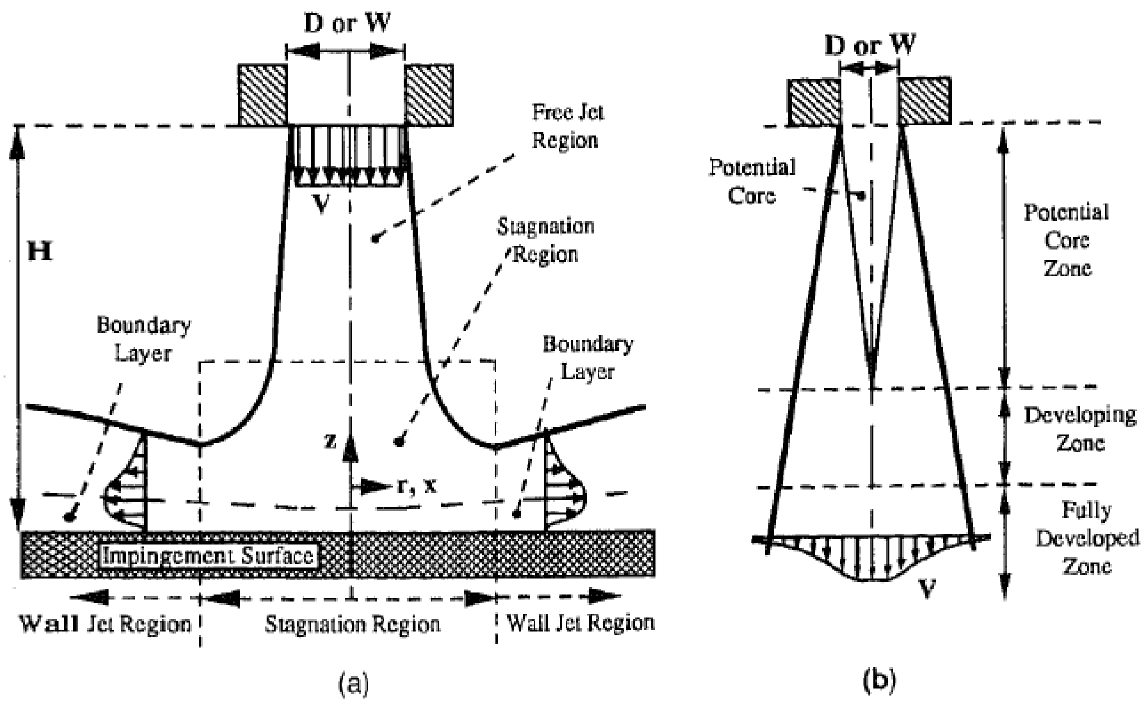


Figure 9: (a) The Development of the Wall Jet, (b) Jet Diffusion to Surroundings (Liu, 2006)

CHAPTER TWO: LITERATURE REVIEW

2.1 Impingement Literature Cornerstone

From the early days of simple convective cooling channels in turbine airfoils studies have been done on modes of enhancing heat transfer coefficients while maintaining a low pressure drop and minimum mass flow rate. Heat transfer characteristics of single round nozzle impingement were studied in the late 1960's and early 1970's. The collected works of many authors is combined into "*Heat and Mass Transfer between Impinging Gas Jets and Solid Surfaces*" by Holger Martin, 1977. The paper collects works from multiple authors who studied single round nozzle impingement effects on heat and mass transfer coefficients. In this compilation, non dimensional jet to target spacing was studied; they ranged from Z/D=1/2-10, providing plots of Sherwood number as a function of radius for four different jet to target spacings. The local Sherwood number was also given for a slot jet for H/S ranging from .5 to 20. Studies on impingement jet arrays were also gathered alongside an array of slot jets. Correlations were given for multiple setups present in the paper. Circular jet arrays and slot arrays are studied in detail with both analytical and experimental approaches. The paper also combines studies done on swirling jets, turbulence enhancers on the target surface, impingement on concave surfaces and angle of attack variations. Optimization studies were also done to find the optimal spacing for round and slot jet arrays.

Florschuetz studied the heat transfer characteristics of an array of jets impinging on a flat surface. This study was guided towards finding an optimal spacing for an array for jets used to cool the midchord of turbine airfoils similar to that found in Figure 5. His main contributions include a Nusselt number correlation as a function of jet to target

spacing, jet Reynolds number and other flow and geometric parameters. He found that an increase in hole spacing and channel height resulted in a decrease of heat transfer. He also provided a one dimensional jet mass flux and channel mass flux correlations

$$\frac{G_j}{G_{\bar{j}}} = \frac{\beta N_c \cosh\left(\beta\left(\frac{x}{x_n}\right)\right)}{\sinh\left(\beta N_c\right)}$$

$$\beta = \frac{C_D * \sqrt{2} * \pi/4}{\left(\frac{y_n}{d}\right)\left(\frac{z_n}{d}\right)}$$

$$x = x_n\left(i - \frac{1}{2}\right)$$

$$\frac{G_c}{G_j} = \frac{1}{\sqrt{2}C_D}\frac{\sinh\left(\beta\left(\frac{x}{x_n} - \frac{1}{2}\right)\right)}{\sinh\left(\beta\frac{x}{x_n}\right)}$$

His Nusselt number correlation takes the form of

$$Nu = A\left(\overline{Re_j}\right)^m \left\{1 - B\left[\left(\frac{z}{d}\right)\left(\frac{G_c}{G_j}\right)\right]^n\right\} * Pr^{1/3}$$

Where A, B and n are dependent by the two different types of arrays, inline or staggered.

Liu studied new techniques in temperature and pressure measurements of a single slot jet with the use of temperature sensitive paint or TSP and pressure sensitive paint or PSP. In his work, both measurement techniques are explained in detail. Since TSP is the only tool from that study currently used in this work, it will be explained further in the experimental setup section.

2.2 Relevant Impingement Channel Studies

Al-Aqal 2003 studied three different types of impingement channels. The use of TLC was implemented in this work to obtain heat transfer distributions for the target wall. The three different configurations varied the number of holes in the streamwise and spanwise directions. The first channel had a single row of 6 streamwise jets, the second consisted of 2 rows of 12 streamwise holes summing up to a total of 24 holes. The last channel is a triple spanwise row with 18 streamwise jets. This last geometry is the most similar to the one present in the current study. The third geometry will be used to compare results. There are differences however; the total width of the channel is of 16 diameters as opposed to 8 in this study. The streamwise jet spacing is also different; Al-Aqal used an X/D of 6.5 compared to X/D = 5 in this study. The jet to target plate spacings are similar on two occasions as he studied a Z/D=4, 6 and 8 while this work uses a Z/D = 6, 8 and 10. Average jet Reynolds numbers also fall within the range of this study as they range between 5000 and 33000. The author provides span averaged plots for all cases and Reynolds numbers convenient when comparing the results.

Ricklick 2009 studied a channel similar to the one found in this study. His channel was composed of a single row of 15 jets with a $Y_c/D = 4$, X/D = 5 and 15, and Z/D = 1, 3 and 5. Two channels were tested; one was pressure fed while the other was fed by suction. TSP was used to gather temperature data of all four wetted surfaces on the pressure channel and two surfaces on the suction channel. Since the maximum jet Mach number was less than 0.3, the flow was assumed to be incompressible leading to the conclusion that both channels contain identical flow patterns. Thin foil heaters were used to create the required heat flux for the channel. Besides channel geometry, Reynolds

numbers and heater geometry, Ricklicks' experimental setup is identical to the one presented in this work. The author also provided an ample comparison of his results to literature. He provided thermal performances of the entire channel at different Reynolds numbers and channel heights.

A small CFD study was also done. A paved mesh was created on the target wall with finer mesh near the impingement locations. The resulting y^+ at the wall was higher than one, yielding potentially faulty heat transfer values; however, this is acceptable since the CFD was used as a tool to better understand the flow physics and help understand the experimental heat transfer profiles.

2.3 Computational Studies on Impingement Channels

El-Gabry did a numerical study of jet impingement with cross flow. Two different turbulence models were compared in their ability to predict surface Nusselt number. The Yang-Shih and standard k-ε models were used to compute the flow generated by jets angled at 30, 60 and 90 degrees with cross flow. The computational results were compared to previous experimental work by El-Gabry. Comparisons to experimental results at Z/D = 1 and 2, 90° injection angle between Yang-Shih and standard k-ε. The error in the average Nu from the experimental results and both turbulence models were calculated. It was found that the Yang-Shih model behaved well at low Reynolds numbers with the average Nusselt number being 5% off from the experimental value while the standard k-ε was off my 9.4%. As jet Reynolds number was increased, the error of the standard k-ε model dropped to as low as 3.9% while the error from the Yang-shih model increased to -7.6%. The span average plots show the experimental data Nusselt number alongside the span averages of the results acquired by the Yang-Shih and

standard k-ε models. High Nusselt numbers occur at the impingement location decreasing thereafter after another impingement location is found. The frequencies of these variations are all the same for the experimental and the two numerical solutions. The amplitude of fluctuations between the impingement locations and the areas in between are much larger for both of the numerical results; however, the Yang-Shih model over predicts at the high Reynolds number for the Z/D=2 case. Since the amplitude of fluctuations is greater for the CFD solutions, it is important to note that even though the error in average Nusselt number is not great, the actual differences in the profile are much greater; upwards of 20% difference of heat transfer coefficients between the experimental and numerical heat transfer peaks. Other variations were studied (Injection angles, for example) but will not be discussed as their importance to the current study is minimal.

Zuckerman compared a much wider set of turbulence models in their ability to successfully predict Nusselt numbers caused by jet impingement. The models tested were k – ε, k-ω, Reynolds Stress Model, algebraic stress models, shear stress transport and lastly, the $\upsilon^2 f$ turbulence model. DNS runs are extremely time consuming to run; therefore, LES was run on its behalf to provide results for the unsteady turbulence models. The paper summarizes all the different models used, their computational cost, impingement heat transfer coefficient and their ability to predict the second peak in heat transfer. As expected DNS/LES provide the best prediction of both stagnation and secondary peak heat transfer coefficient; however, this comes at a large computational cost. The k – ε and k-ω provide poor heat transfer results for the stagnation region where they can have 30% error from the correct value. The Realizable k – ε model provides

better heat transfer results while still maintaining a low computational cost. The highest accuracy to cost ratio was achieved by the υ^2f model where it predicts the heat transfer coefficient for the surface with a minimum of 2% error while not being as expensive as the other unsteady models such as DNS and LES. Ideally, the CFD portion of this work would be run with the υ^2f model; however, since the code used to run the simulation, FLUENT, does not have the υ^2f model, a realizable $k - \varepsilon$ model will be used with enhanced wall functions for both thermal and velocity gradients.

CHAPTER THREE: EXPERIMENTAL SETUP AND TECHNIQUES

3.1 Temperature Measurements with TSP

Temperature sensitive paint, or TSP, provides the capability of measuring temperatures over the painted area. This measurement technique supersedes the advantages of other temperature measurement devices such as thermocouples because it provides the user with data over a large area rather than point temperatures given by thermocouples.

Uni-Coat TSP is purchased from ISSI. It is very robust to different working conditions. Calibration done on one batch of paint can be used for multiple cans as the product is highly consistent. The paint is calibrated in a dark booth; a painted coupon is placed on the hot side of a thermoelectric heat pump working on the Peltier effect; thermal paste is used to minimize contact resistance between the hot side and the TSP coupon. Calibrated thermocouples are placed in between the TSP and the thermoelectric heat pump. A reference temperature and picture are taken and the calibration commences. At least 5 or 6 data points should be taken to form the calibration. Intensity ratios are taken between the hot and cold pictures. They are then plotted versus their corresponding temperature.

The paint consists of fluorescent molecules suspended in a binder. These molecules, with a certain wavelength of light will be exited to a higher energy level. The molecules then can dissipate some of the energy by transferring it vibrationally to its neighboring binder particles and dissipate the remainder of the energy by radiating it as a photon as the molecule comes down to its original ground state. Since the amount of

energy that the particle can transmit to others through vibration is directly proportional on temperature and the total initial energy is fixed, by measuring the ratio of the intensity at a known temperature (reference picture) and intensity of the unknown temperature, feeding it through the correlation, the unknown temperature can be found to an uncertainty of 1 K. Figure 10 shows a simplified Jablonski diagram adapted from the suppliers website. The blue arrows signify the blue light used to excite the luminescent molecule, Tris(2,2'-bipyridyl) Ruthenium(II) Chloride Hexahydrate with a shellac binder, in our case. The shellac binder is impermeable to oxygen opposite of that found in PSP due to PSP relying on the presence of oxygen for it to function. Once the particle is excited, it can give off the energy in two different ways; one is by emitting it back out as another photon of the same energy and therefore wavelength. The second mode of the particle to lose its energy is through vibrational relaxation. This second process is directly dependent on the temperature, i.e. the higher the temperature, the higher the probability for it to lose energy to its surroundings. Once it loses some energy to the surrounding particles, it releases the remainder of the energy as a photon of less energy of that which excited it originally; hence why a long pass filter is installed in the CCD camera. For a more descriptive explanation of the way TSP works, refer to Liu, 2006.

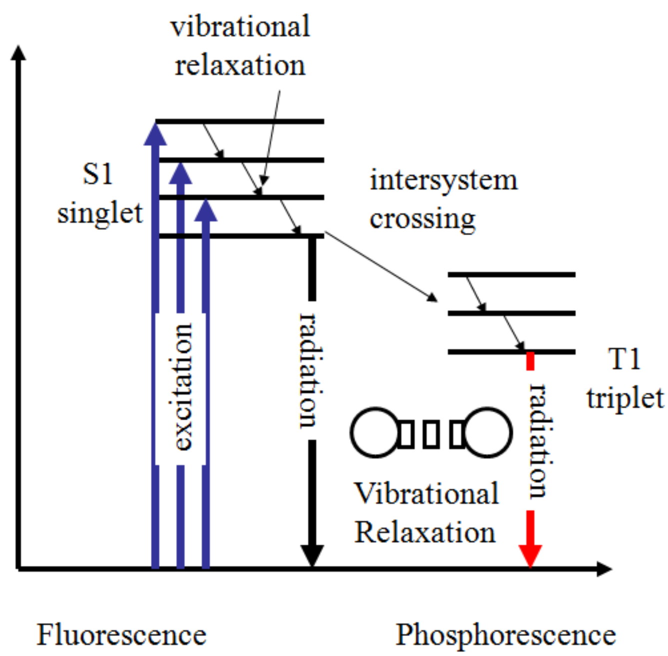


Figure 10: Simplified Jablonski Diagram (Adapted from ISSI Website)

Throughout the past two years, there have been numerous projects at CATER that have used TSP. Painting surfaces with TSP should be done carefully by someone who has experience with spray painting since every single can costs $500. A single can should be able to paint an area the size of an acrylic plate that is 36” wide and 24”tall.The sidewalls and the target wall of the impingement channel were painted with the use of less than one can. Painting on different surfaces is difficult; for example, when painting Rohacell, the paint canister can be held very close to the surface while spraying due to the surface being somewhat porous and rough; however, when painting straight onto metal heater strips, the can should be placed as far back as possible for the first run. Ideally for the first pass through, only a slight mist should be applied. If the can is being held too close to the surface the paint will run. Figure 11 shows a set of heater strips that has been painted too closely, leading the paint to drip down. Ideally, the paint would be applied to the surface in as many coats as possible. Of course, this would be time

demanding and impractical; therefore, with the knowledge that I have gained through the multiple TSP paintings on different surfaces, I have compiled a list of TSP dos and don’ts.

Dos:

- Clean the surface to be painted with acetone or break parts cleaner. Break parts cleaner is preferable over acetone as it does not leave an oily residual after cleaning.
- Paint the first coat as thin as possible. Most of the surface should not be covered. There should be an even mist of miniscule TSP circles. This will give the later coats something to attach to.
- When positioning the test section to paint, make sure to wipe it one last time as small dust particles may have attached to the surface.
- **Stop** if you see small bumps in the paint. This is caused by dust particles collecting all the paint around it while it is still wet due to surface tension. Clean the surface and repaint. This should be noticeable in the first few coats. If you see this pattern happening, do **not** continue thinking it will be covered by future coats. What will happen is the problem will get worse and worse; ultimately, the surface will have to be cleaned again and repainted.
- When painting test sections, try to paint the smallest section as possible. This will not only save paint but will make it very simple for the post processing code to crop out the unpainted areas.

- Let the finished painted surface to sit at least for 90 minutes after the last coat before baking. There have been problems when baking steel and acrylic test sections with the paint cracking while baking right after the last coat. Normally the finished surface is left to dry overnight and baked first thing in the morning.
- For test sections that are too large to be baked in the oven, the heat gun may be used. Carefully place a thermocouple in a central location with blue painters tape. The heating should be uniform and should not take more than 20 minutes of continuous blowing. When the thermocouple reaches 80-90 C, the plate can be assumed to be baked. To introduce a factor of safety in the baking, it does not hurt to bake it longer than it normally takes.
- Once the test section is mounted and ready to run, cover it with cloth that does not let any light through. This will protect the paint for further uses. This is especially important on test sections that can be used multiple times like the ones found in this study.
- When the test is running, turn **off** the LED lights. This light is the most damaging to the TSP as it degrades the quality of the fluorescent molecules.
- If there is a particular head of the TSP can that you prefer over others, you can remove it once the can is empty. It is difficult to get used to a single kind of nozzle, being able to transfer it from can to can is a must if painting consistency is to be kept.

Don’ts

- Do not clean a test section that has already been used with too much acetone. The acetone is volatile, evaporating quickly, cooling the test section rapidly. If this test section has had heaters attached to it and run previously, the acrylic will crack due to uneven stresses inside of it.
- If paint is dripping, stop painting immediately. Clean the surface and start over. Hold the can far from the surface in order for it not to drip.
- Do not use TSP to teach new apprentices, undergrads or graduate students how to paint. Regular spray paint is two orders of magnitude lower in cost while the painting process is exactly the same.
- Do not paint with the doors closed. The paint contains carcinogens that can harm the lungs. Always use a respirator and keep the room well ventilated. In-situ painting and baking has not been tried; however, it may be a real option if the test section is difficult to disassemble and easily accessible to painting and baking.
- If there is a can of paint that contains too little paint for the test section that needs to be painted, try to find a new can. The mixing of two different cans of TSP can be dangerous at times; however, it has been noticed over the years that ISSI provides a very robust and dependable product that does not vary significantly from batch to batch.

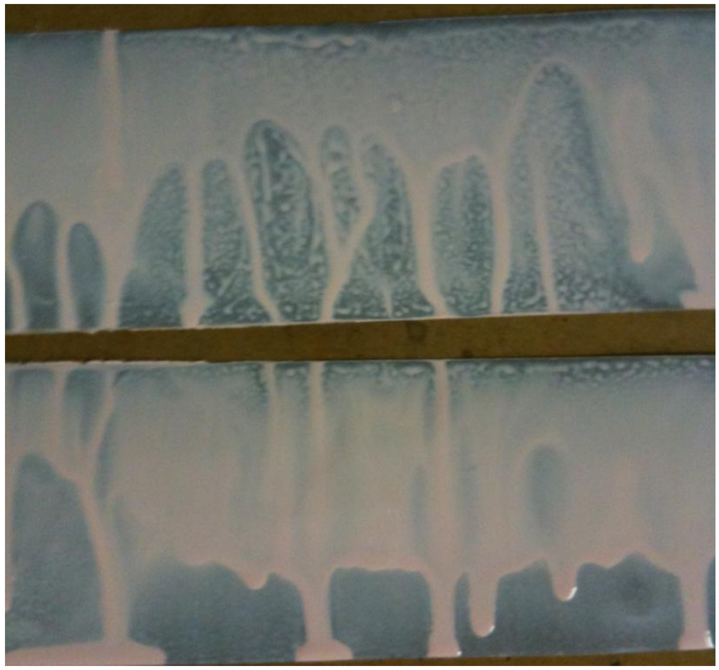


Figure 11: Heater Strips Painted with TSP Too Closely

3.2 Experimental Setup of Suction Channel

The impingement channel is fed under suction. As seen in Figure 12, air enters through the plenum; it crosses the jet plate as it gains speed to form the jets, which then impinge on the target wall. The flow then passes through a venturi flow meter and finally through the blower into the atmosphere. A bypass valve is used to control the flow rate of the impingement channel.

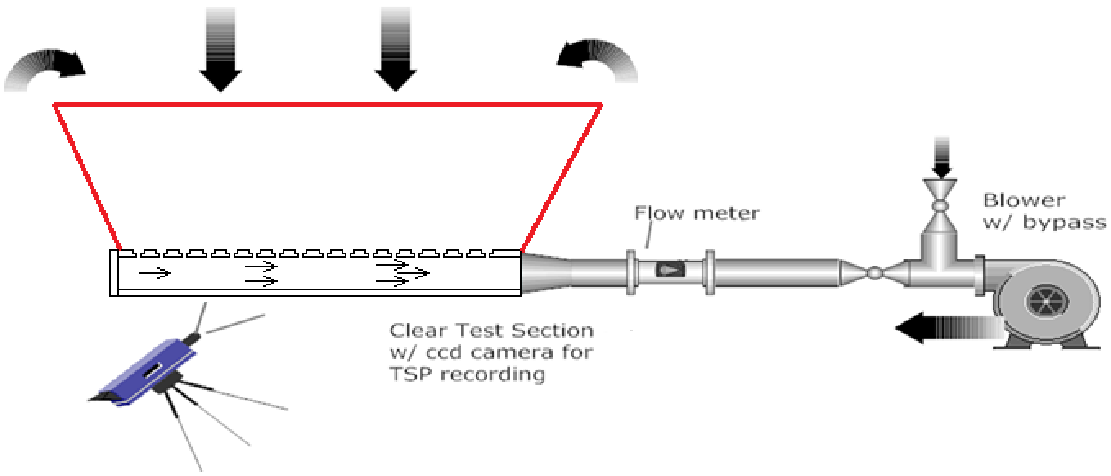


Figure 12: Flow Loop of Impingement Channel

The impingement channel consists of 15 streamwise rows of 3 spanwise jets each. The total width of the channel Y_c/D is of 8 diameters while the streamwise spacing between the rows is X/D=5; the spanwise distance between the holes is of Y/D=2. Figure 13shows the top view of the jet plate. The plate is counter bored to ensure that a nearly flat velocity profile of the jet is achieved. Figure 14 shows the front view of the channel. Z is denoted as the distance between the jet and target plates. Side walls are interchangeable to change the height of the channel to 6, 8 and 10 diameters. Two thirds of the streamwise rows can be covered to change the X/D from 5 to 15.

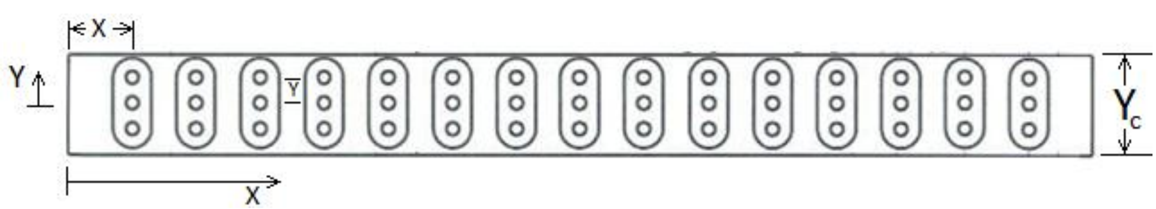


Figure 13: Top View of Jet Plate

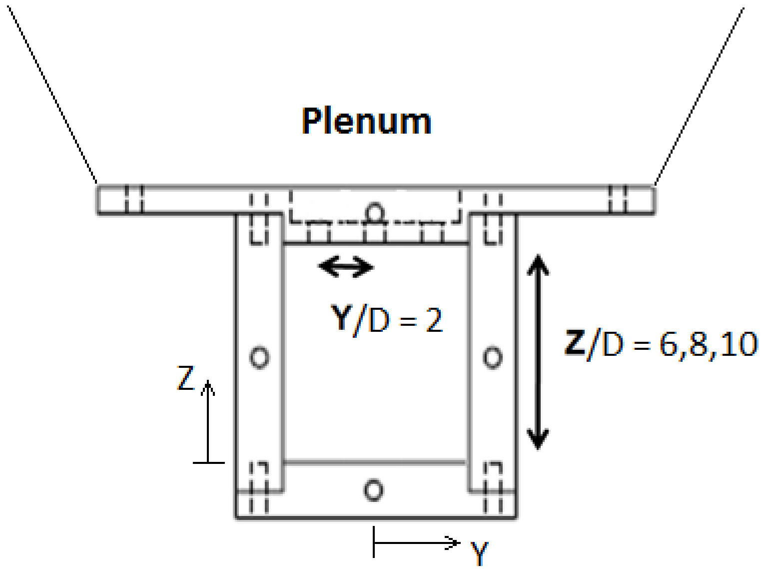


Figure 14: Front View of Impingement Channel

The target and sidewalls had heaters made specifically for them in a serpentine style. This was necessary to increase the resistance as the VARIACs used to power them only had a maximum current output of 20 amps. The heater strips are two diameters wide; at each end, copper tape with conductive adhesive was used to connect the leads to the power supply. The heater consists of 50 micron thick steel sheet sandwiched between two pieces of Kapton tape. The heater is attached to the painted surface with the use of double sided Kapton tape. The target test section can be seen in Figure 15; also seen in this figure are the two Teflon gaskets lined on the sides of the target plate. With the target wall bolted onto the sidewall, the gasket is compressed, generating a strong seal.

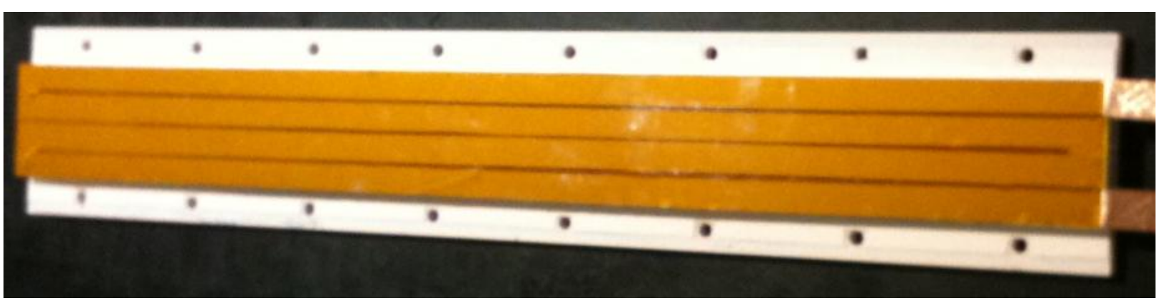


Figure 15: Target Wall Test Section with Heater Leads

For this study, the test matrix shown in Table 1 will be run. Target and side wall data will be taken at three different impingement heights at two different Reynolds numbers of 7500 and 15000 denoted by A and B respectively. A streamwise jet spacing study is also done by testing the target and side wall heat transfer at an X/D=15 for the low impingement height channel.

Table 1: Test Matrix

X/D	Z/D	Wall	Re
5	10	TW	7500
			15000
		SW	7500
			15000
	8	TW	7500
			15000
		SW	7500
			15000
	6	TW	7500
			15000
		SW	7500
			15000
15	6	TW	7500
			15000
		SW	7500
			15000

3.3 Data Processing and Reduction

As described previously, when taking temperature measurements with the use of TSP, reference temperatures are noted and a reference picture is taken. The experiment is the run; once the experiment reaches steady state, a new set of 4 pictures is taken. Given the calibration curve, temperatures are backed out.

$$TSP\ Calibration, T_{refpic} \rightarrow T_{profile}$$

Given the amount of heat generated inside the heater,

$$Q = I^2 R$$

Dividing by the heated area to get heat flux,

$$q" = \frac{Q}{A_h}$$

Heat loss tests were run to consider how much of the heat flux generated by the heaters goes through the backside instead of into the flow. It was found that 2.5% of the heat flux leaks out to the atmosphere through the acrylic. In order to account for this heat leakage, it must be subtracted from the calculated value to become

$$q"_{eff} = .975 * q"$$

Where A_h is the effective heated area given by

$$A_h = \left(\frac{X_C}{D} * \frac{Y_c}{D} * D^2\right) - A_{unheated}$$

Where $A_{unheated}$ is an estimate of how much unheated area is between the heater strips (~ 3% of the total area). $T_{ref} = \pm 1°C\ at\ 25°C \rightarrow 4\%$

To obtain heat transfer coefficient,

$$h = \frac{q"_{eff}}{T_{profile} - T_{ref}}$$

Where T_{ref} is the reference temperature. Typically set in literature to be the jet temperature.

To obtain the average Reynolds number for the jets, the total mass flow rate is used

$$Re_j = \frac{4\dot{m}_{Tot}}{\pi D_j \mu}$$

Where D_j is the jet diameter and μ is dynamic viscosity (1.983kg/m s at 300K)

Pressure measurements were taken at the sidewall after the last jet entered the channel. These pressure measurements were used to determine the thermal performance of the tallest two channels (Z/D = 8 and 10)

The thermal performance at constant pumping power is found by using the equation

$$\eta = \frac{\frac{h}{h_0}}{\left(\frac{f}{f_0}\right)^{1/3}} = \frac{\frac{h}{h_0}}{\left(\frac{P}{P_0}\right)^{1/3}}$$

Where h is the average heat transfer coefficient for the target wall of them impingement channel and h_o is the heat transfer coefficient obtained by passing the same amount of flow through a smooth duct; i.e. the Dittus-Boelter correlation. The friction factor f is found with the use of

$$f = \frac{(P_{pl} - P_{last\ jet})}{L} * \frac{2D_{ch}}{\rho V^2}$$

Where P_{pl} is the plenum static pressure, assumed to be atmospheric and $P_{last\ jet}$ is the pressure read after the last jet. V is the volumetric flow rate divided by the cross-sectional area of the duct after the last impingement row. The hydraulic diameter of the channel is set to be:

$$D_{ch} = \frac{4 * Y_c Z}{2(Y_c + Z)}$$

The baseline friction factor was calculated with the use of the Moody chart, the hydraulic diameter and the total mass flow rate though the channel. Thermal performance at constant pressure drop was also calculated with

$$\eta = \frac{\frac{h}{h_0}}{\left(\frac{f}{f_0}\right)} = \frac{\frac{h}{h_0}}{\left(\frac{P}{P_0}\right)}$$

3.4 Uncertainty Analysis

A simple uncertainty analysis was done to estimate the error in calculation of the heat transfer coefficient from the given outputs of the test data. From the bare basic measurements for voltage, area, current, temperature of thermocouples and temperature profiles of paint, a simple uncertainty analysis can be done to estimate the error for the calculated heat transfer coefficient. Figure 16 shows the different sources of error in the calculation of heat transfer coefficient. The effective uncertainty was calculated by taking the root of the sum of the squares of all the individual percentage errors. The experimental uncertainty for heat transfer coefficient was of 7.03%. This error may be reduced by acquiring higher temperatures of the TSP, reading current with a more accurate ammeter or reading reference temperatures with the use of a thermopile instead of a single thermocouple.

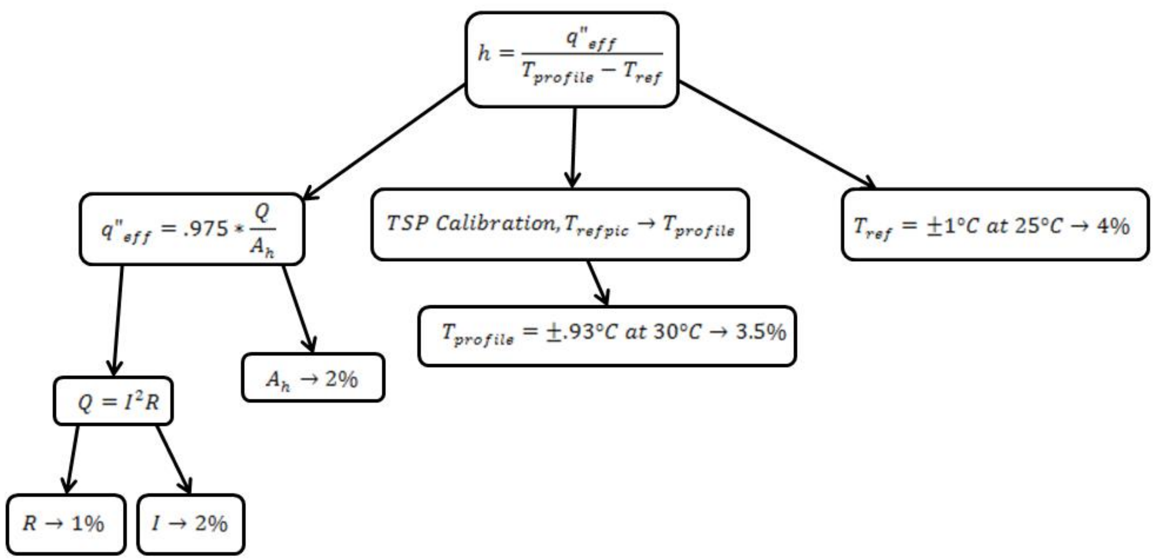


Figure 16: Heat Transfer Coefficient Uncertainty Tree

3.5 Lateral Conduction Analysis

To take into account the lateral conduction occurring inside the heater foil while the test is running, two simple 1D conduction and convection equations were used to quantify the amount of heat moving through the heater laterally and the amount of heat convecting into the air. The lateral conduction is expected to be at a maximum at the places where there are large spatial variations of surface temperature, which is why the Z/D = 6, X/D = 5 case at high Re is chosen to be studied. Figure 17 shows the temperature distribution of the aforementioned case. Four cold spots can be seen by their distinct blue and yellow color located at the stagnation regions. The maximum temperature gradient occurs between the third jet impingement and the middle region between jets. The temperature difference was seen to be of 13°C. The distance in between these two temperatures is of 2.5*D=.01875m. The corresponding heat flux between these two points was calculated to be 13000W/m^2 with k_{steel}~20W/m K. A region of 1cm by 1cm was then created and the amount of heat calculated through conduction and convection were compared. To acquire the amount of heat removed through conduction, a heat flux of 13000W/m^2 was imposed through an area of .01m by .00005m; this equaled to 0.0277 W . The amount of heat moved through convection was calculated by multiplying the heat flux used during the test by the area of the square .0001m^2; the resulting heat moving through the heater onto the air is .6 W. Since the heat moving through to the air is two orders of magnitudes larger than the heat moving laterally, the effective lateral conduction can be neglected.

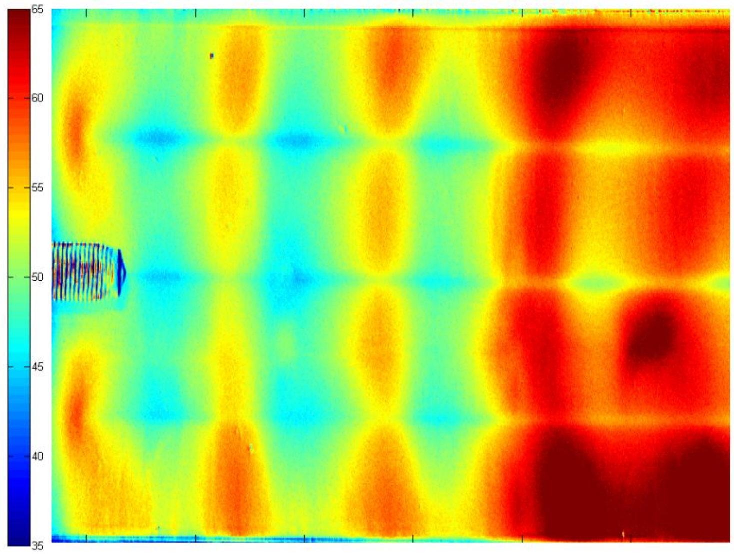


Figure 17: Temperature Profile of First Five Impingement Rows.

A second order approach was also taken to quantify the amount of lateral conduction in the heater. The temperature gradient was taken from high peaks in heat transfer caused by the second row of impingement of the same Z/D=6, X/D=5 channel at high Re. Figure 18 shows the high heat transfer coefficients created by the second row of jets. A quadratic curve fit was obtained by for this small region so that a continuous equation of heat transfer coefficients as a function of streamwise distance was quantified.

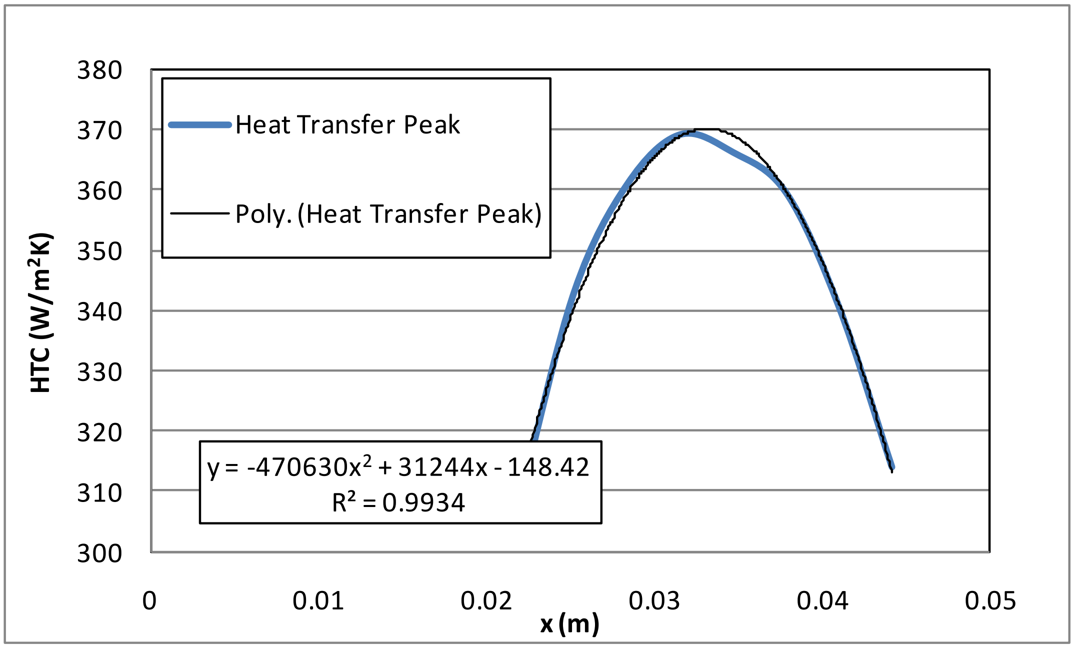


Figure 18: Detailed View of First Heat Transfer Peak with a Polynomial Curve Fit

The net heat gained by a differential volume from lateral conduction is the difference in the temperature gradient at the entrance and the exit multiplied by the thermal conductivity and cross sectional area. Using this method, shown in Figure 19, the net change in convective heat transfer due to lateral conduction can be studied.

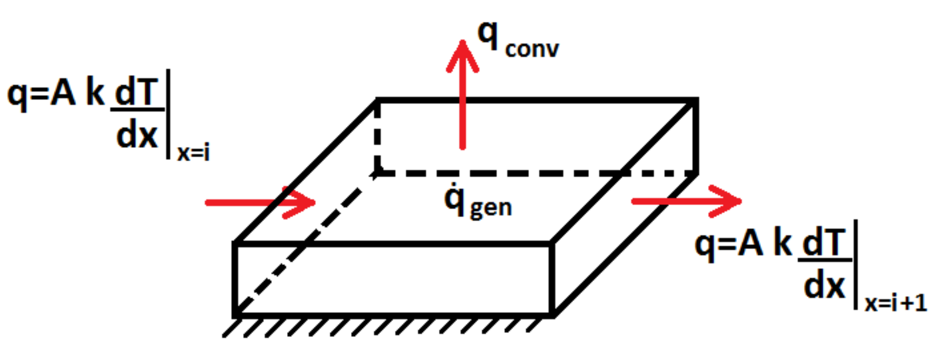


Figure 19: Control Volume Heat Transfer Analysis

By taking the difference between the out flowing heat trough the right side and the inflowing heat from the left side, a net gain or loss can be found. Figure 20 shows the

difference in magnitude between the out flowing heat through convection, seen in red and the net inflow of heat from lateral conduction in blue. From these calculations it was also found that the amount of heat moving through lateral conduction is tow orders of magnitude smaller than the amount of heat moving out through convection; leading to the belief that, even at high temperature gradients, lateral conduction does not play an important role in the ongoing heat transfer processes in the impingement channel. A more detailed calculation of this work can be seen in appendix A.

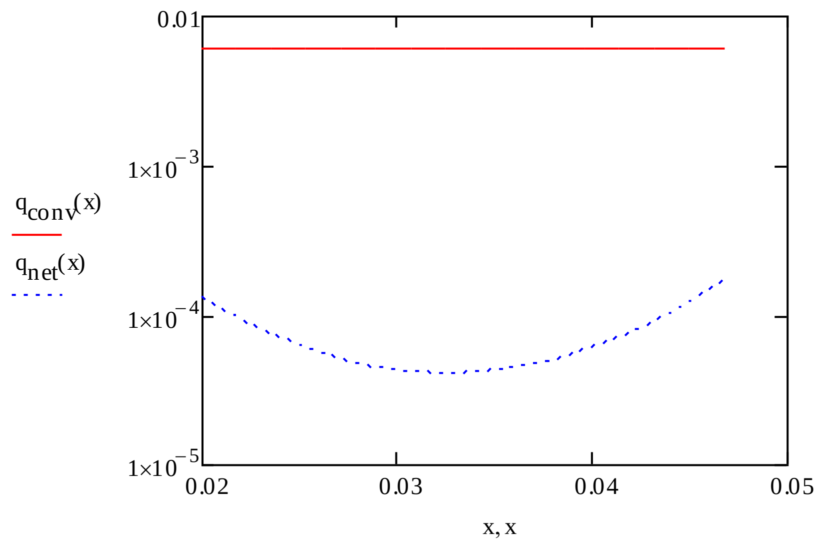


Figure 20: Heat Loss through Convection and Lateral Conduction

CHAPTER FOUR: HEAT TRANSFER RESULTS

4.1 Heat Transfer Validation

In order to obtain confidence in our experimental setup, an experiment was made to test something that has already been published in literature. A smooth channel was the obvious choice as it was easy to setup by taking off the end cap and blocking all the holes with smooth blue painters tape on the flow side and metal tape on the plenum side to ensure no leaks into the channel from the jet plate. The smooth channel has been studied widely and multiple correlations exist; one of these equations is the Dittus-Boelter correlation (Incropera, 2007). The test was run using the Z/D=6 side wall so that the hydraulic diameter was a minimum. Figure 21 shows the span averaged results versus non dimensional distance into the channel.

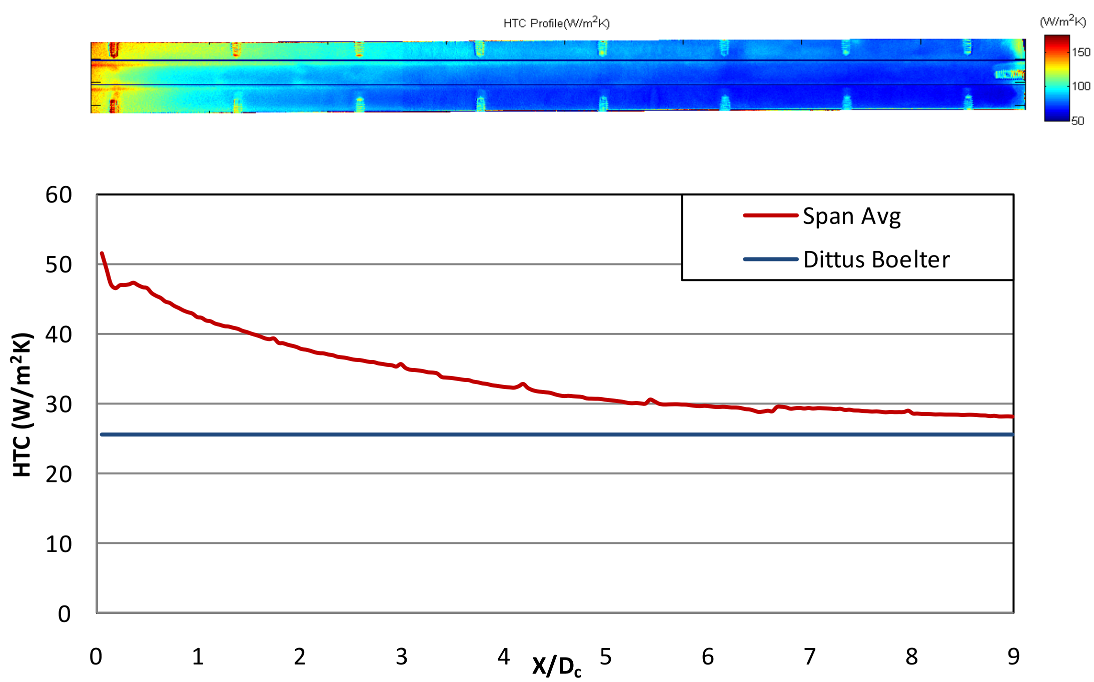


Figure 21: Validation Spanwise Averaged Results.

The plot shows decreasing heat transfer coefficient with increasing X/D_c due to the developing thermal boundary layer. The span average does not reach the Dittus-Boelter due to it not being fully developed in the limited space it is given. Typical flows can take up to 60 diameters to achieve a fully developed profile; with the current setup the maximum length of the channel was of 9 diameters. The profile; however, seems to have an asymptote at the Dittus-Boelter correlation value, leading to the belief that if the channel was longer, that value given by the correlation would be reached. One important factor to take into account in determining whether the experimental setup is validated is the fact that the Dittus-Boelter correlation has an uncertainty near 30%. Since the span average at high X/D_c is well within 30% from the calculated value, it is safe to assume that the current experimental setup is validated.

4.2 Heat Transfer Results

Heat transfer results are compared based on variations in channel height and average jet Reynolds number. As discussed earlier, there are numerous other parameters also affecting the heat transfer in these channels. As these parameters are changed, flow structures within the channel are expected to be altered as well, as discussed in the literature. Two of the major contributors to heat transfer in these channels are the successful jet impingement and the resulting cross flow. The same domain is captured in both the local and averaged results.

Figure 22 through Figure 25 highlights the heat transfer distribution for the cases with a jet to jet spacing of 5 diameters in the streamwise direction and of 2 in the spanwise direction. It is evident that the smallest channel height (Z/D=6) performs the best at all Reynolds numbers, on all surfaces. It is also interesting to note the similarity

in the target wall profiles between case 5.2.8A and B where the curves are very similar other than the obvious offset due to the change of the Reynolds number.   At this large spacing, we also see the degradation of the jets, a few diameters downstream of each impingement location. The downstream shifts of the peaks are evident after the second and third row of jets. Also evident in these plots, is the deflection of the impinging jet and the wall jets from the cross flow. The cross flow is forced to flow around the jet, deflecting the spread of the wall jet in the downstream direction. Impingement locations are also very evident at low X/D; however, as X/D and therefore the cross flow increase, the magnitude of the peaks start decreasing and eventually level out to pure internal flow.

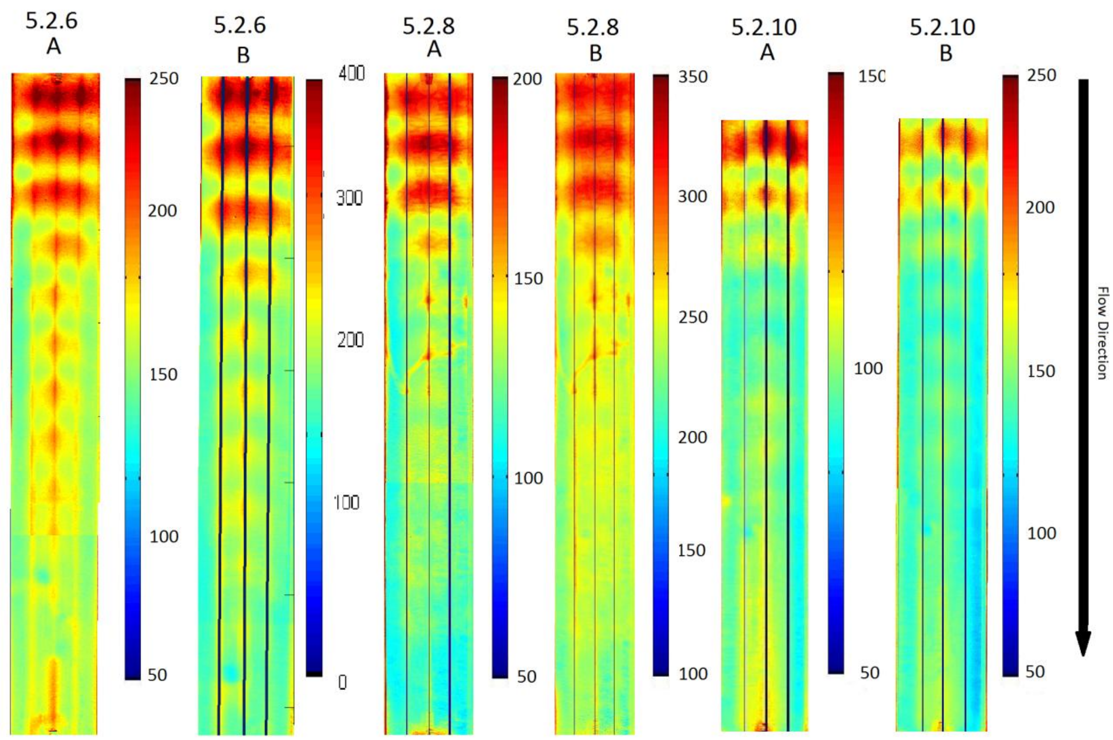


Figure 22: Target Wall Heat Transfer Coefficient Distributions

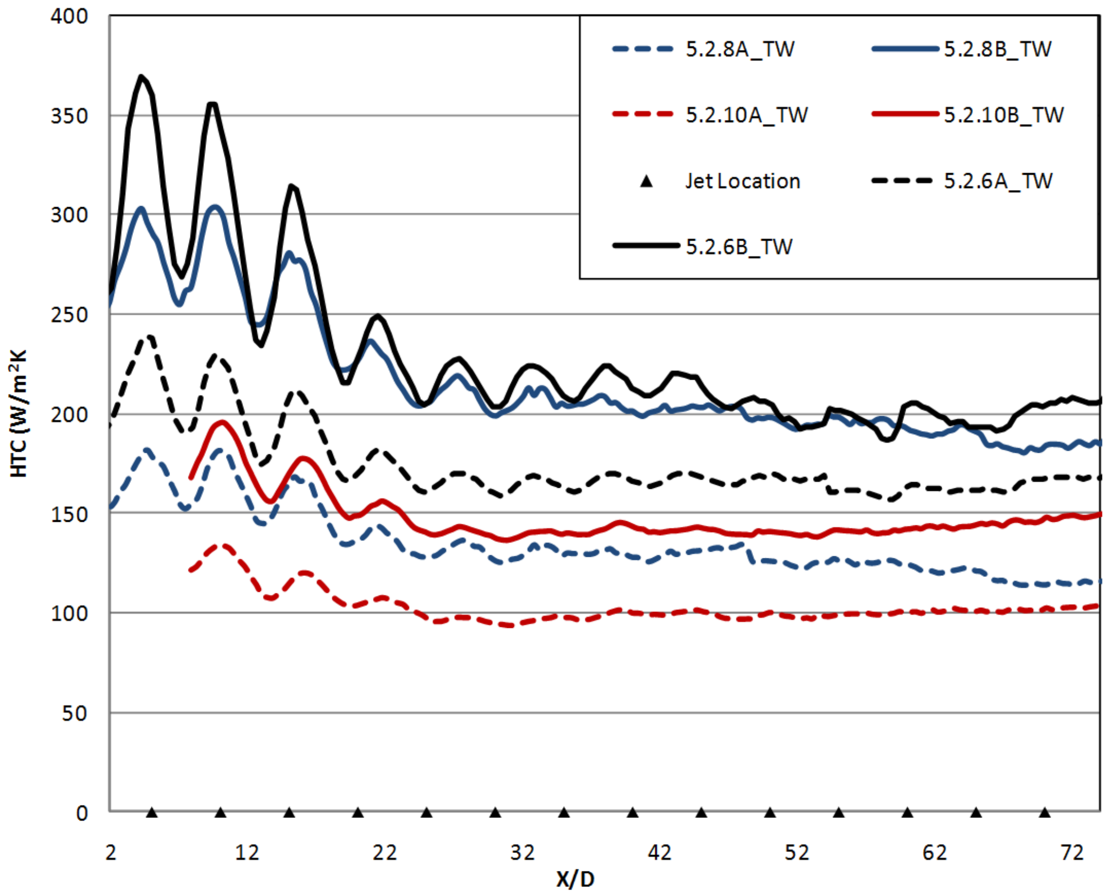


Figure 23: Span-averaged Target Wall Heat Transfer Distribution

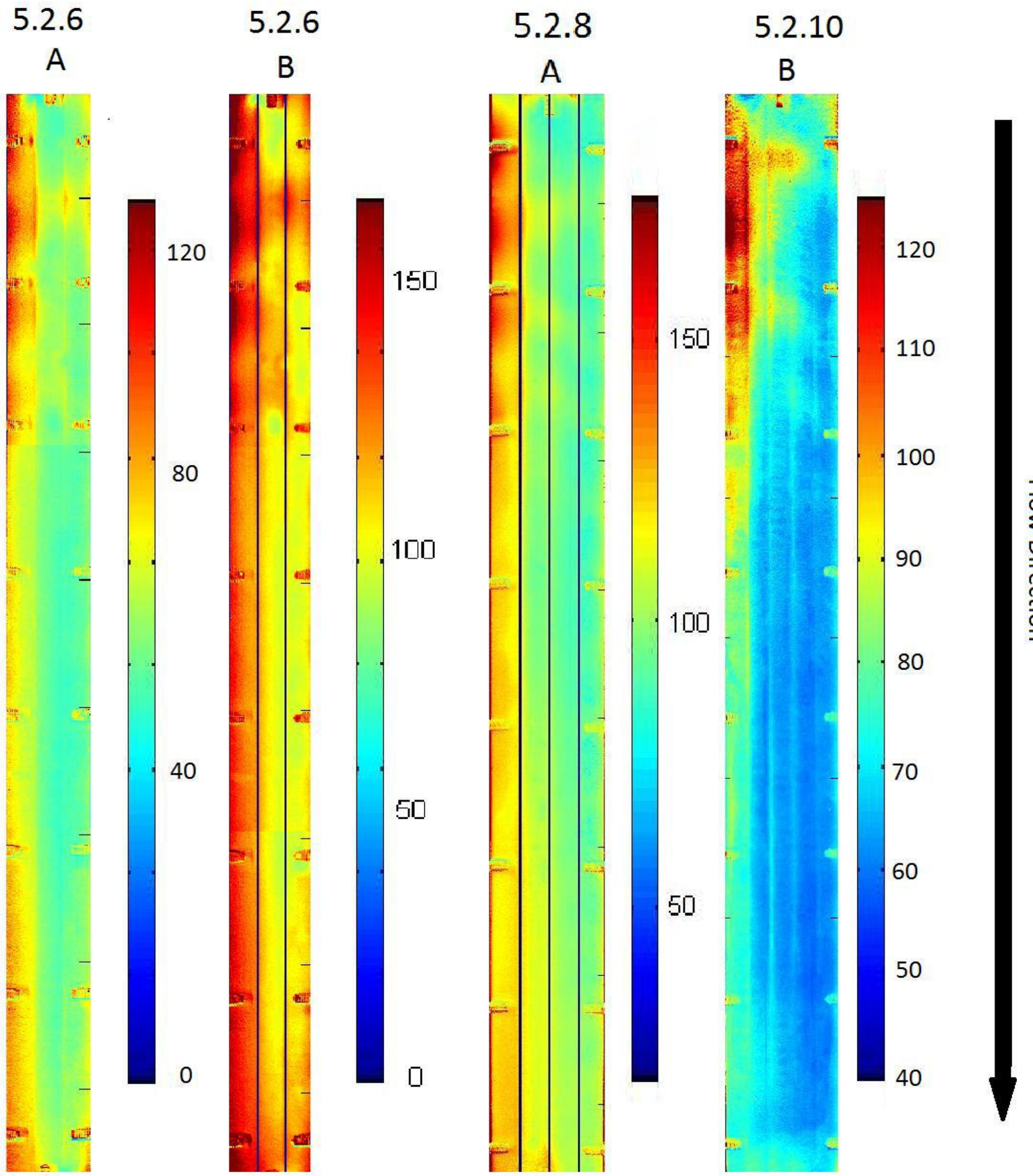


Figure 24: Side Wall Heat Transfer Coefficient Distributions

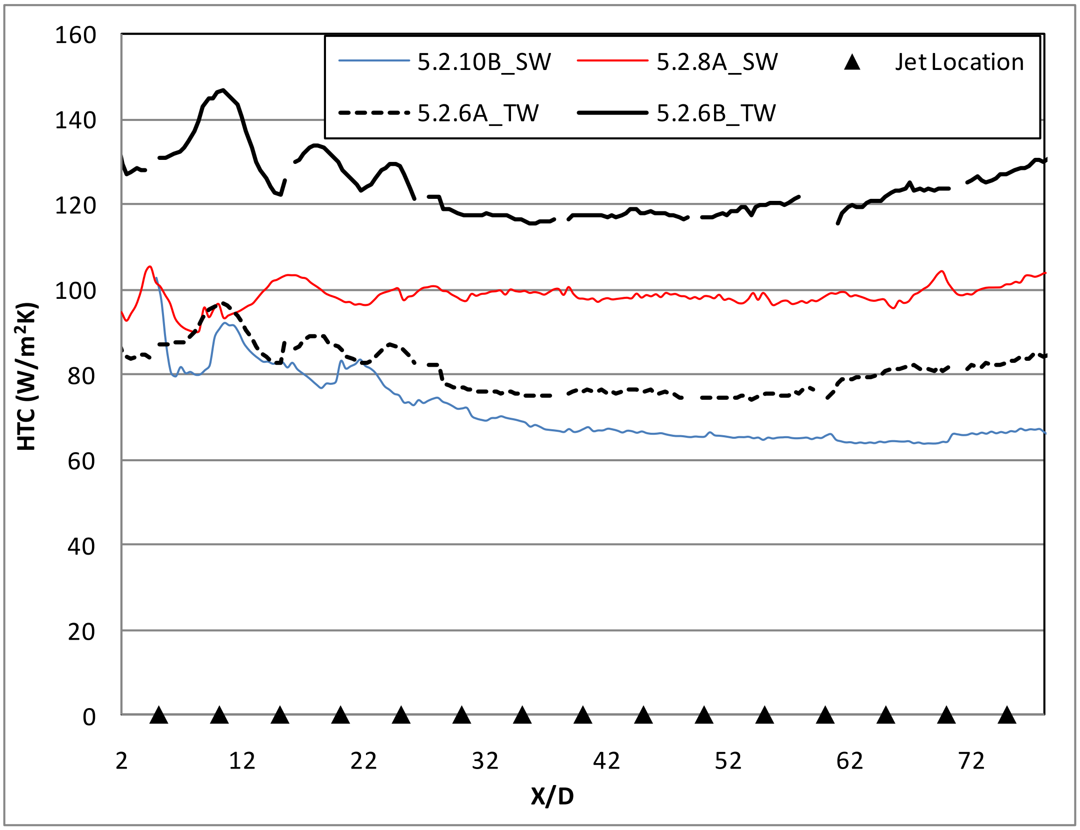


Figure 25: Span-averaged Side wall Heat Transfer Distribution

Figure 23 and Figure 25 show similar details, with impingement peaks clearly diminishing and shifting in the downstream direction. The cross flow clearly has some negative influence on these geometries when compared to the more traditional impingement highest on the order of 1 to 5 jet diameters. The heat transfer profiles of the target wall for all heights, seen in Figure 22 and Figure 24, show the rapid decay in heat transfer after the third jet. This can be explained by understanding that the first jet does not have any cross flow to deflect it, the second jet only has the first jet worth of momentum deflecting it downstream; however, since the channel is so tall, the momentum of the cross flow after the first and second jet are not enough to greatly disturb the incoming jets. After the third jet, however, the cross flow builds up enough momentum to greatly affect the integrity of the jets downstream, causing the span-

averaged heat transfer to rapidly drop. The point at which the crossflow starts taking a considerable effect occurs around X/D =35. The target wall profile of the Z/D=10 channel shows the outside jets on the second row of jet deflecting downstream. It can be conjectured that the bending of the outside jets downstream is caused by the wall jet created by the first row of jets separating from the side wall and deflecting the outside jets of the following rows of jets. The heat transfer profile for the Z/D case excludes the first jet due to shadows being present when the data was taken.

Also evident from this spanwise averaged data, is the increase in heat transfer with increases in Reynolds numbers, and decreases in impingement height. Results tend to be the closest from case to case at the first impingement jet. This is a reasonable result, as the effects of cross flow have little to no effect at the first few impingement locations. The impact of the jet would then be the driving force at these locations, and would be similar between cases except if the potential core is not reaching the target surface. The potential core of a jet tends to last between 6 and 10 diameters from its origin. It can be seen that the difference in heat transfer coefficient in the first two jets for the Z/D=8 and Z/D=10 channel is much different than the corresponding difference between the Z/D=6 and Z/D=8 heights. This decreased difference between the heights of the peaks may be attributed to the potential core reaching the target wall at the heights of 6 and 8 diameters, leading to similar profiles and may not be reaching the surface at the height of 10 diameters. The heat transfer values of the peaks diminish in the downstream direction. The range of fluctuation also drops, that is, the profile becomes more uniform at large X/D. This drop in fluctuation is more visible at the tallest channel height (Z/D=10) and less pronounced at the smallest channel. This is due to the jet in the small

channel having to travel a shorter distance to impinge on the target plate, leaving the crossflow less time for it to deflect the jet as opposed to the tall channel, where the jet has to travel almost twice the distance as the Z/D=6 channel for it to impinge on the target wall. This effect cannot be solely explained by the built up cross flow in the channel. Mixing loses also take part in the degradation of the stagnation size of the downstream jets. The mixing losses have much greater effect on the taller channels due to the same reason that the cross flow has a higher impact on them too, the jets have to travel a large distance before hitting the target plate, leading the stagnant or moving surrounding air to be a sink of its downward momentum for a longer time and distance than the respective smaller channels. The heat transfer coefficient of the side wall was also analyzed. Similar effects are expected on the side wall, due to the expected impact of the wall jet. As expected the strength of the cross flow is not enough to prevent wall jets from successfully impacting the side wall at small X/D jet locations; however, the crossflow takes dominance at around X/D=25. Also evident in these plots is the concentration of the wall jet impact to the bottom of the channel, on the order of 1-2 diameters in height. It is interesting to note that for the 5.2.10B case in Figure 24, as the first jet diffuses outward, it impacts the sidewall at a height of Z/D=6. The height at which the diffused jet affects the sidewall heat transfer coefficient decreases as the crossflow increases. The stagnation regions are also deflected in the downstream direction, similar to the target surface results. These effects are most evident in the 5.2.10B. Similar characteristics can be explained from the spanwise-averaged plots shown in Figure 25. These results again clearly show the effects of increasing the impingement height, and increases in Reynolds number. As the height is increased, the effect of the wall jet is significantly reduced,

partially due to the increased surface area, much of which is not affected by the wall jet. The diminishing effect of the cross flow accumulation is also evident in these plots, as the heat transfer peaks decrease in the downstream direction.

4.3 X/D Comparisons

The streamwise jet spacing was changed from X/D=5 to 15 by covering two out of three rows of jets. This was done by covering the impingement holes inside the channel with smooth blue painters tape and sealing the plenum side of the jet plate with metal tape to ensure no leakage. The profile is expected to be less uniform than the case where X/D=5 due to the large spreading of the high heat transfer peaks. Due to the large separation between the rows of jets, there is a lower amount of downward momentum than the equivalent X/D=5 geometry; for this reason, it is expected to see a lower heat transfer peak due to the jets momentum diffusing out faster to the stagnant air, decreasing the effective impingement velocity. Figure 26 shows the target wall heat transfer distribution. Similar to the X/D=5 profile, it can be seen that the heat transfer due to the jet impingement drastically reduces after the third jet. This phenomenon leads us to believe that, at both Reynolds numbers, the cross flow generated by the first three jets is powerful enough to effectively deflect the fourth jet downstream, diminishing its heat transfer performance. The similarity seen in Figure 26 between high and low Reynolds number implies that the downstream deflection of the jets is not dependent on the jet Reynolds numbers.

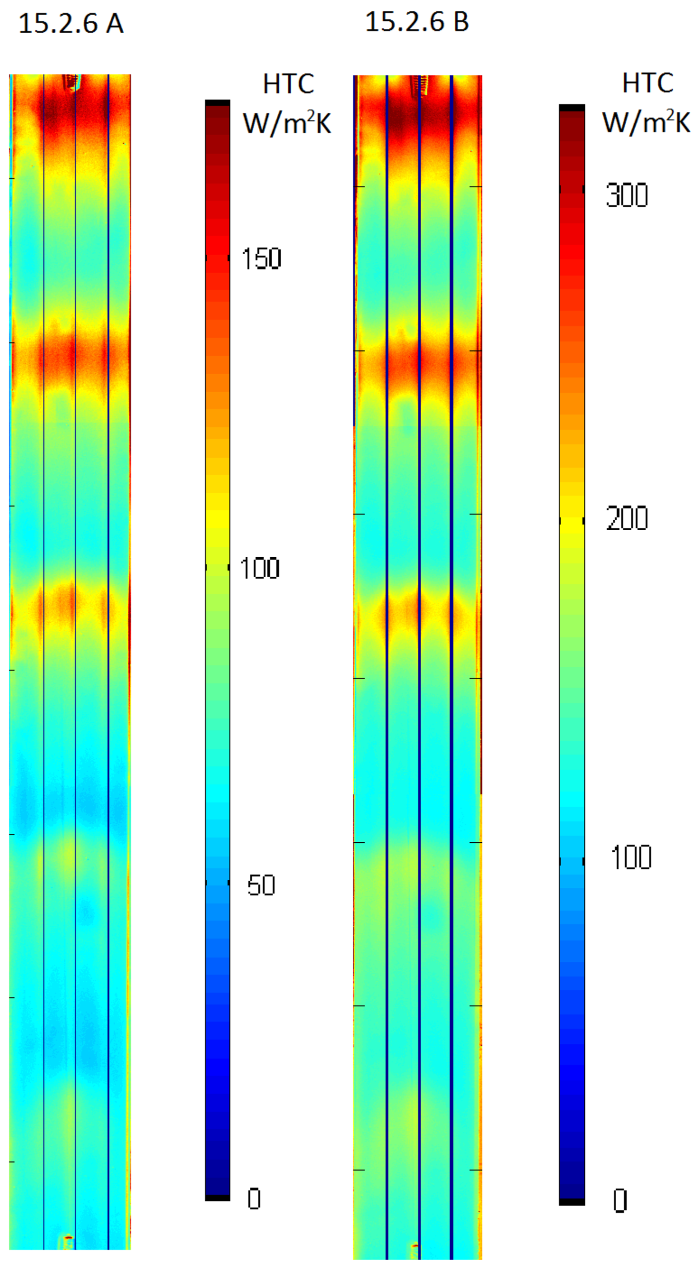


Figure 26: X/D=15 Target Wall Heat Transfer Profile

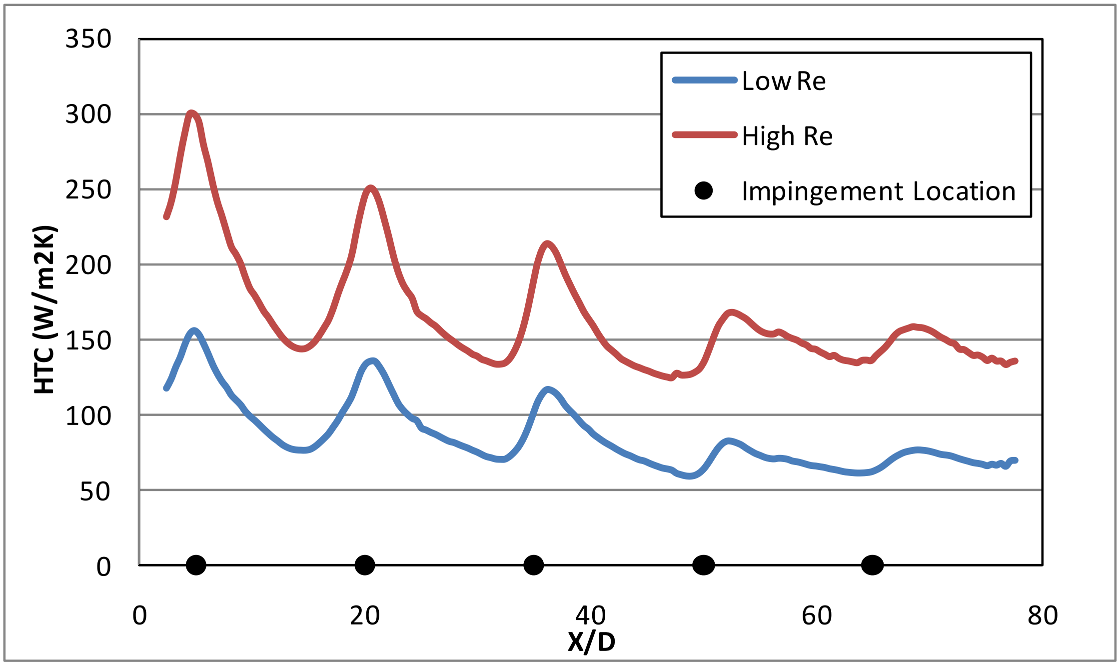


Figure 27: X/D=15 Span-averaged Target Wall Heat Transfer Distribution

On the span averaged plots seen in Figure 27, the downstream deflection of the jets is evident; however, as described previously, the shifts in the peaks of heat transfer occur at the same x/D for both Reynolds numbers. The amplitude of fluctuation of heat transfer coefficients for the high Reynolds number case is larger than that of the low Reynolds number. Both profiles seem to start to level off at the end of the impingement channel with the lowest span average being located just before the fourth jet at both Reynolds numbers.

A comparison of target wall heat transfer coefficients between X/D =15 and 5 is shown in Figure 28. At first glance, it is clearly visible that the X/D=15 average heat transfer coefficient is smaller than its X/D=5 counterpart. This is also noticed by Ricklick where he showed average HTC profiles for larger X/D to be smaller than those at lower X/D (Ricklick, 2009). This may occur due to there not being as high downward

momentum for the X/D=15 case as compared to the X/D=5 due to the lack of close jets. The stagnant air around the spaced out jets is taking away more of its momentum, decreasing the effective impingement Reynolds number. Also important to notice is the fact that since the X/D=5 case has three times the flow impinged into it, the cross flow velocity, and therefore Reynolds number, will be three times as large, increasing the heat transfer coefficient.

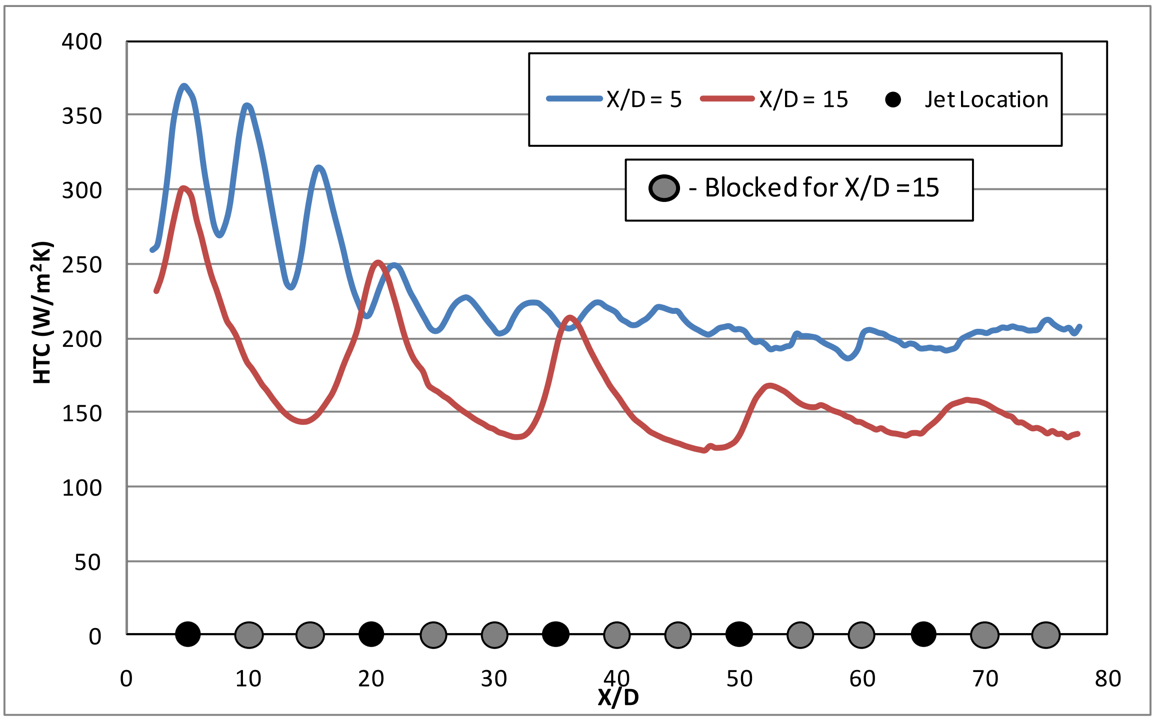


Figure 28: Target Wall Span-average Comparison of X/D=5 and 15 at High Re

The side walls also show similar patterns to their X/D=15 counterparts. Strong wall jet impingement can be seen on the side wall at low x/D and z/D. Figure 29 shows areas where the wall jet generated by the target wall impinges on the sidewall. Similar to the profile seen in Figure 24, the high heat transfer region reaches upward in the z direction up to a height of 4-5 diameters for the first jet. This high heat transfer stagnation region decreases as x/D increases to the point where the wall jet created by the last jet is negligible when coupled with pure channel flow.

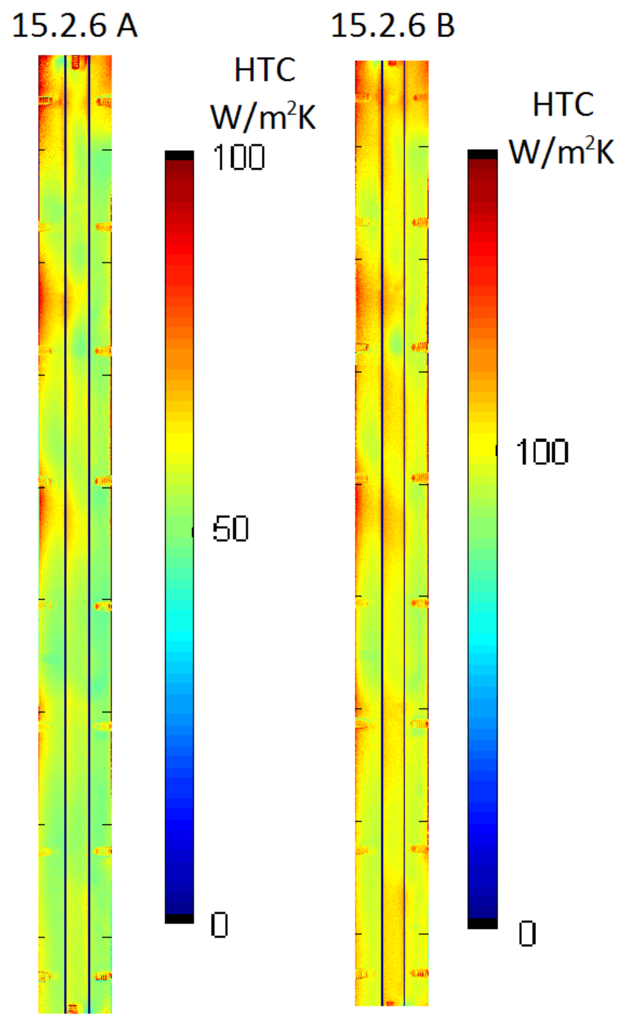


Figure 29: Side Wall Heat transfer Coefficient Profile

The span averaged plot, seen in Figure 30, shows a nearly flat profile with peaks located at the stagnation regions of the wall jets. Thw downstream deflection for the X/D=15 case is much more pronounced than the one for the X/D=5 case. This is due to the jet not being constrained by the wall jets generated by the previous and latter impingement locations. In the X/D=15 case, the wall jet is free to move downstream more so than the X/D=5 due to it not being disturbed by anything other than the cross flow.

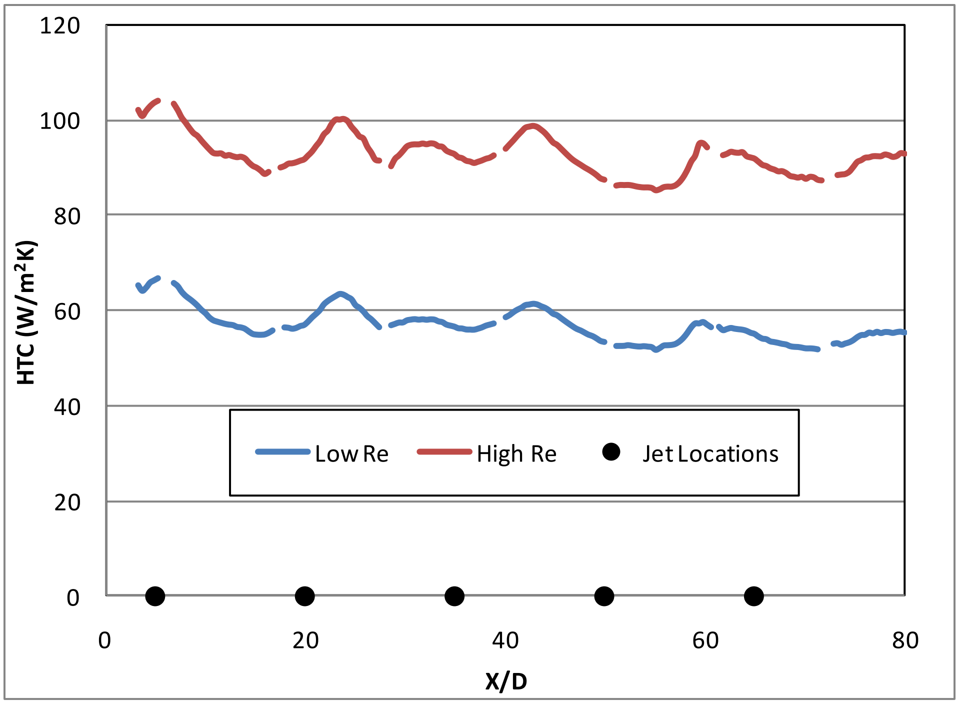


Figure 30: X/D=15 Side Wall Span-averaged Heat Transfer Coefficients

4.4 3D Comparison of the Heat Transfer Profiles

In order to further understand the target/sidewall interactions, both heat transfer profiles were positioned in an isometric view representative of the channel. One important thing to note is that both target and side wall profiles are not on the same scale. This form of data display is only qualitative way to describe the heat transfer profiles. Figure 31 shows the 3D profile of the X/D=5, Z/D=6 case. The both stagnation regions of the jet onto the target wall and the wall jet into the sidewall can be seen to occur at the same location for the first three streamwise rows. After the fourth and fifth row, the wall jet diminishes in magnitude. Also visible in this view is the increasing heat transfer at low z/D towards the end of the channel of the side wall. The constant input of mass and downward momentum into the channel causes the cross flow generated by the previous jets to be squeezed into the lower third of the channel, increasing the velocity and the heat transfer of the target wall.

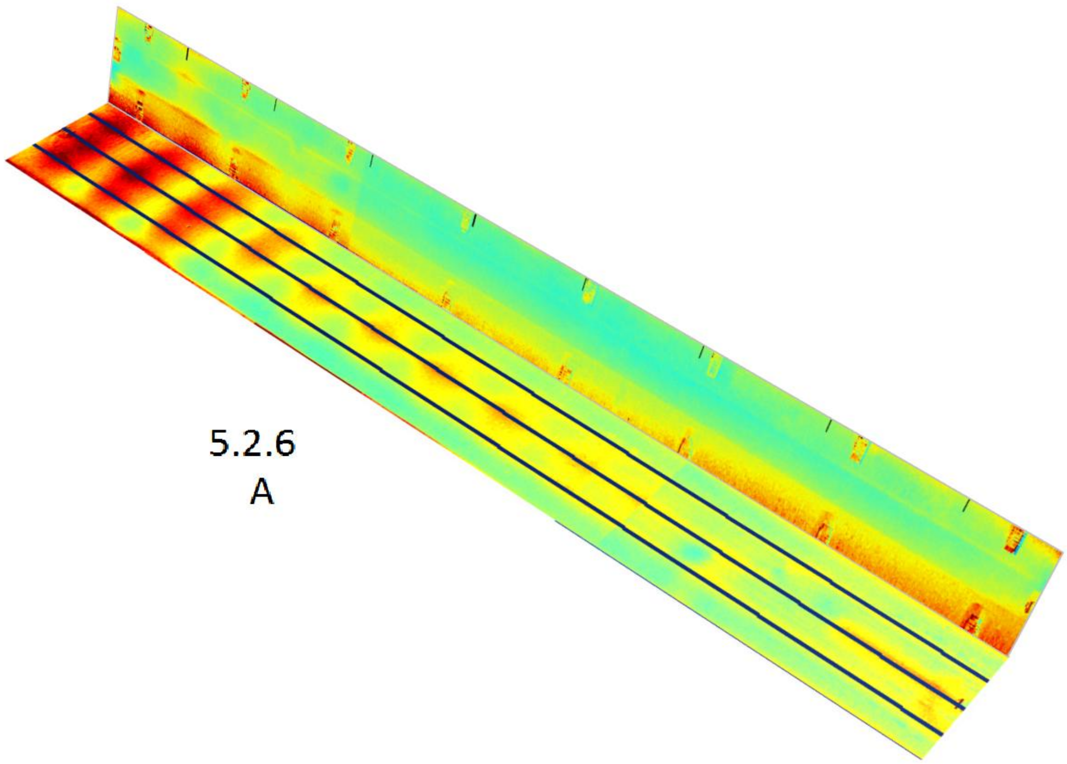


Figure 31: 3D Heat Transfer Profile for Z/D=6, X/D=5

Similar patterns are seen in the taller Z/D=8 channel seen in Figure 32. The wall jet generate by the third streamwise row of jets is been deflected downward more than its Z/D=6 counterpart. This can be attributed to the fact that the jet located at the Z/D=8 channel has lost much of its momentum and is more easily bent downstream by the cross flow generated by the first two jets. The Z/D=8 sidewall shows similar increasing heat transfer at high x/D; however, the increase is not as drastic as the one found in the Z/D=6 channel. This is caused due to the extra two diameters the jets have to cover to impinge on the surface; since the Z/D=8 channel is one third larger than the Z/D=6 one, the flow has to have more area to flow through. The last few jets only deflect the cross flow downward about 4 diameters; this leaves two diameters for the flow to pass through on the Z/D=6 channel, causing the velocity to increase rapidly and, therefore, increasing the heat transfer coefficient at the low z/D. Since the Z/D=8 channel has four remaining

diameters for the flow to move through, it does not deflect it as much as the Z/D=6 channel does only increasing the cross flow velocity, and resulting heat transfer coefficient, slightly over the area at low z/D and high x/D.

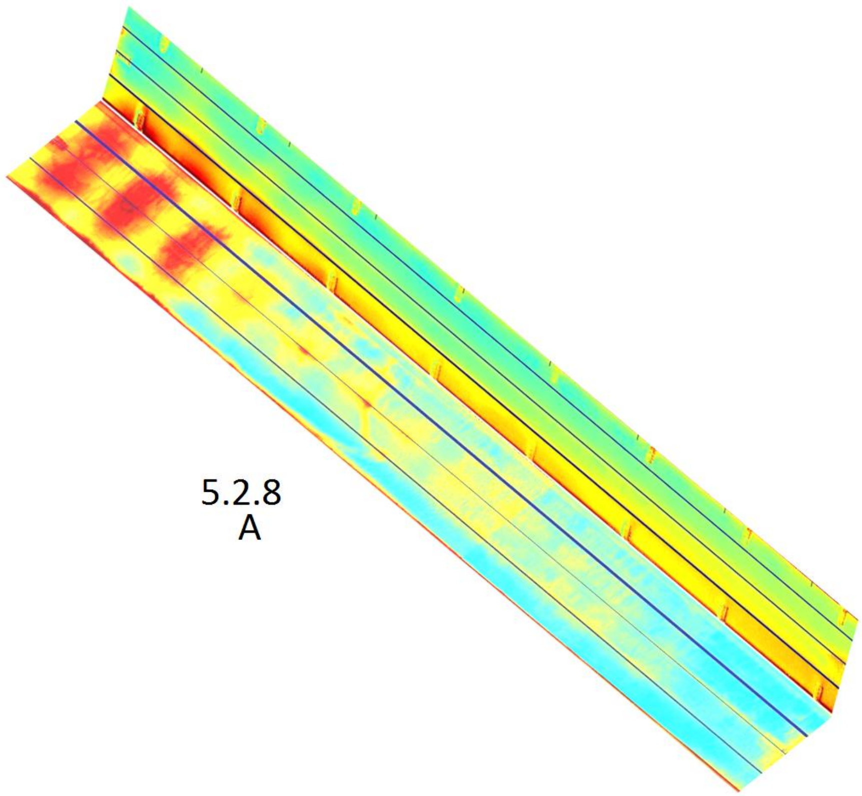


Figure 32: 3D Heat Transfer Profile for Z/D=8, X/D=5

The 3D heat transfer profile for Z/D=6 and x/D=15 channel, seen in Figure 33, shows similar details to those seen in the X/D=5 channels. The stagnation regions of the jet and wall jet occur at the same x location for the first three rows of jets; the wall jet generated by the fourth row of jets is deflected downstream only generating as small region of high convective coefficients at the side wall. The region located at the top right corner of the side wall is colored red, signifying high heat transfer; however, this area is generated by the heaters providing non uniform heat flux at this location. This region of high heat transfer coefficients also occur at x/D=0-4 of the target wall where the heater coil bends.

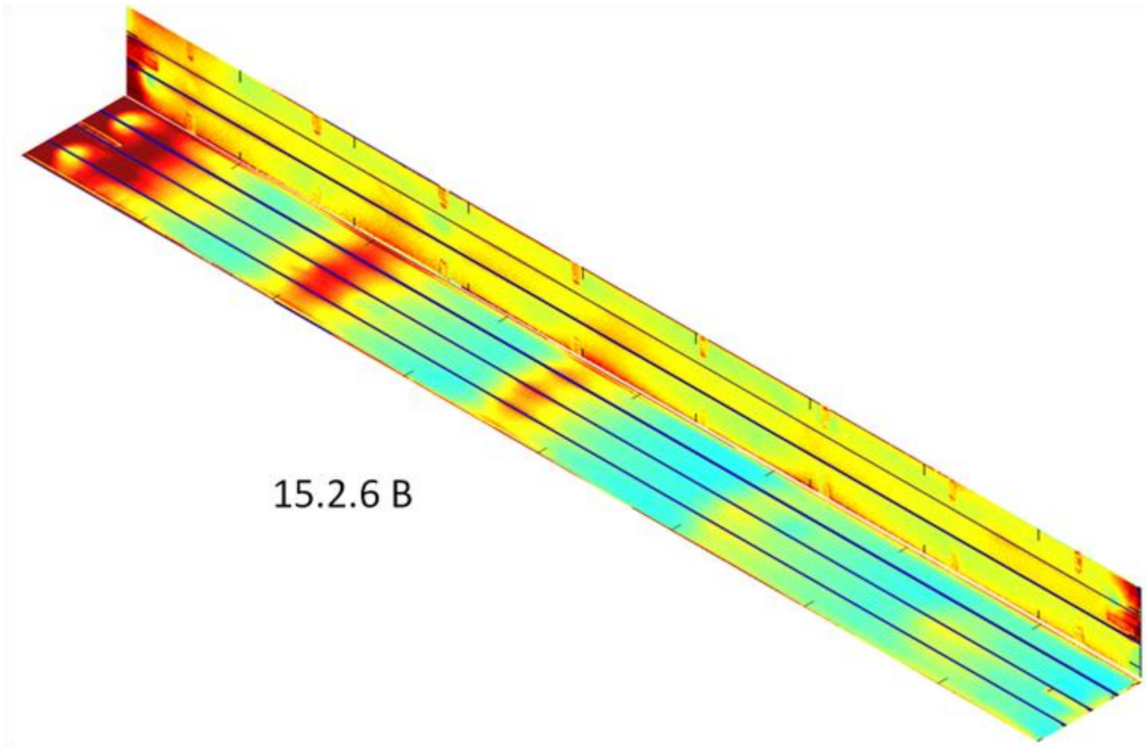


Figure 33: 3D Heat Transfer Profile for Z/D=6, X/D=15

4.5 Thermal Performance Calculations

Thermal performance calculations were done on the two tallest channels (Z/D=8 and 10). The pumping power was calculated for both channels at two Reynolds numbers. Figure 34 shows the ratio of pressures required to pull the same amount of flow through as smooth duct as opposed to through the jet plate. The Z/D=10 channel at high Reynolds number requires the largest pressure as seen in the Figure; however, in order to pull the same amount of flow rate through it requires a smaller pressure difference due to the large cross section.

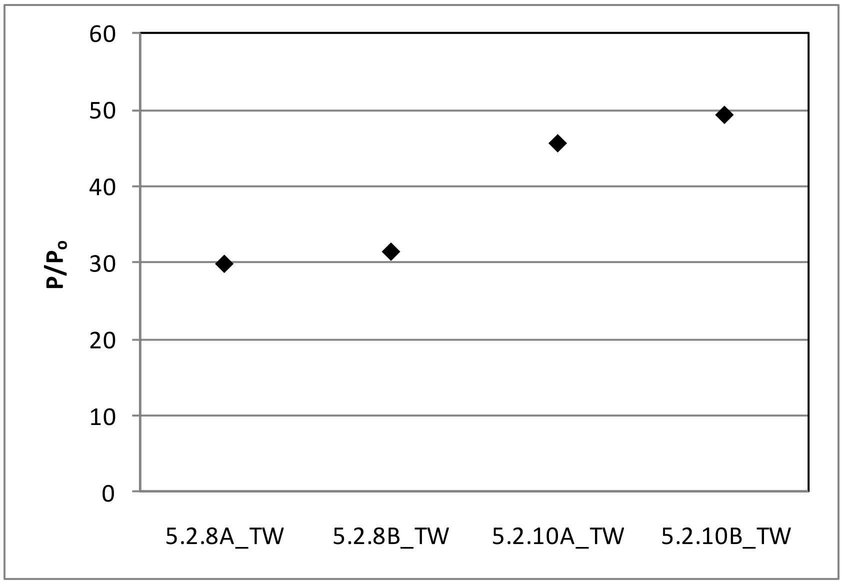


Figure 34: Pressure Drop Ratio with Respect to Smooth Channel

Next, the heat transfer enhancement was calculated. A total area averaged heat transfer coefficient was taken for the target wall and compared to the smooth channel Dittus-Boelter value while using the same total mass flow rate. Figure 35 shows an average heat transfer enhancement of four times that of a smooth channel. Similar trends were noticed in the literature (Ricklick, 2009) of decreasing heat transfer enhancement with an increase of jet Reynolds number. Ricklick also showed an increase in heat transfer enhancement with an increase of jet to target spacing similar to the one seen in Figure 35.

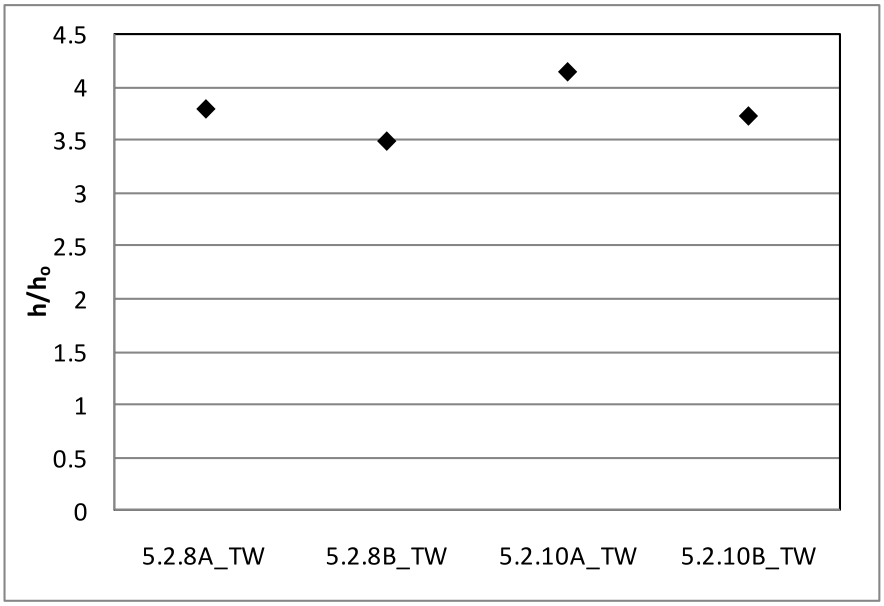


Figure 35: Heat Transfer Enhancement

Thermal performances at constant pressure drop were then calculated by dividing the heat transfer enhancement by the pressure increase. As seen in Figure 36, all the values fall well below 1, making the impingement channel an unfeasible mode of heat transfer enhancement when a constant pressure is supplied.

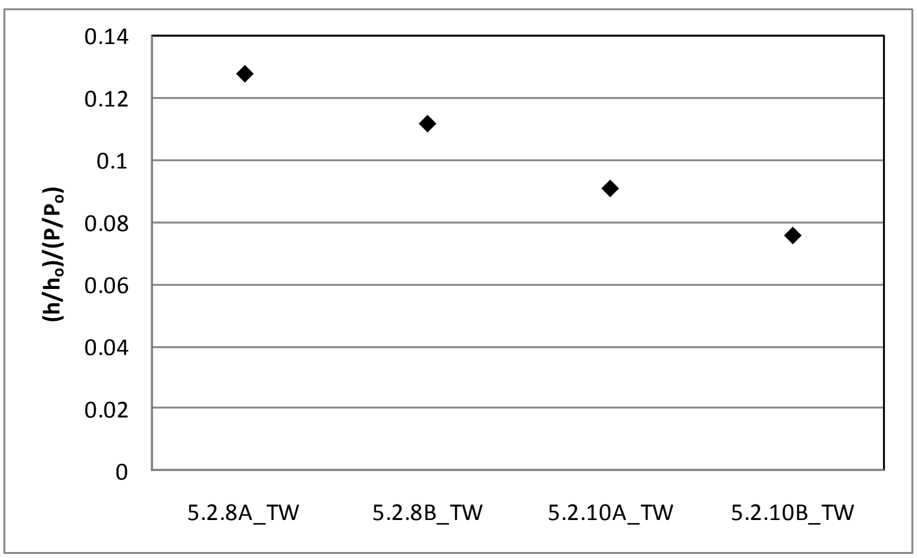


Figure 36: Thermal Performance at Constant Pressure Drop

The thermal performance at constant pumping drop was calculated in the same way that the constant pressure drop was calculated, the only difference being the pressure ratio term was raised to the one third power. As seen in Figure 37, the thermal performances at constant pumping power are all higher than unity; this signifies that if a surface needs to be cooled with the supply of a constant pumping power, the impingement channel is a feasible option. Similar to the figure, literature (Ricklick, 2009) showed a decrease of thermal performance with an increase of channel height and Reynolds number.

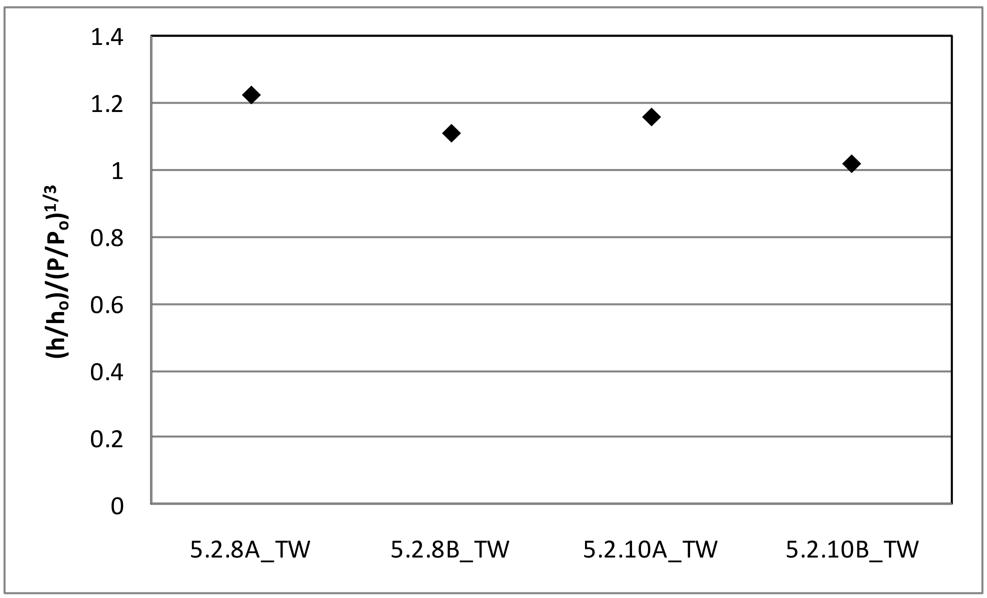


Figure 37: Thermal Performance at Constant Pumping Power

CHAPTER FIVE: COMPUTATIONAL FLUID DYNAMICS

5.1 Problem Setup

In order to further enhance the understanding of the heat transfer profiles showed previously, a computational study was performed. Even though CFD does not yield accurate quantitative results, it produces good qualitative data that can be used to explain the flow physics in the channel and therefore increase the understanding of the patterns seen previously. The channel was meshed with the use of GAMBIT. Due to the symmetry the channel was split in half in the streamwise direction. All horizontal surfaces (parallel to the target wall) were divided into 6 different regions that are later on going to be meshed individually. The six regions are seen in Figure 38; section 1 is located at the center of every jet, also referred to as "jet center". This region was created to reduce the squewness of the elements near the center of the jet by allowing the mesh to be completely linear with a squewness of zero. Section two complements section 1 to complete the impingement hole. The half impingement hole located at the symmetry wall contains the same exact region 2; however, it only has one half of the jet center. Section 3 was made in order to bring the polar geometry of the holes to match the cartesian aspect of the remainder of the channel. With the addition of section 3 to the channel, the only remaining sections are square or rectangular regions. Region 4 lies in between streamwise rows of jets. Section 5 is located at the entrance and the exit of the channel. These sections are not square in contrast with section 4. The last remaining section is located near the side wall of the channel extending from the beginning to the exit of the channel.

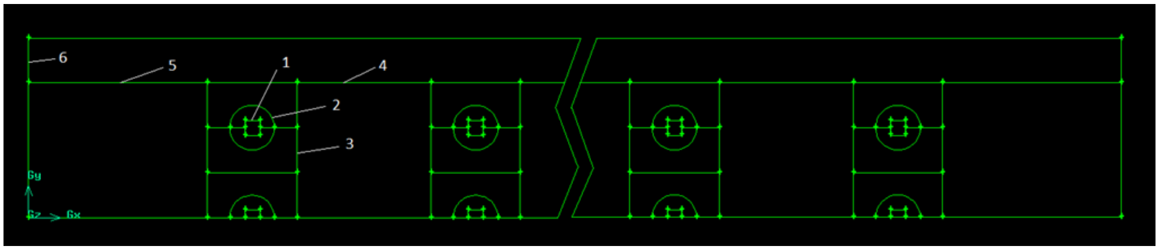


Figure 38: Horizontal Plane of Impingement Channel Geometry.

All the faces of sections 1 and 2 are linked throughout the channel and the plenum; however, in order to have greater control of the mesh in the plenum and the channel, the remaining sections 3, 4, 5 and 6 are not linked to every single similar face; instead they are only linked to similar faces in either the plenum or the channel.

Boundary layer spacing, number of rows and growth factor are placed around the channel. In order to maintain a y^+ of less than unity, the first cell spacing of the boundary layer inside the channel was set to be 0.00001 m (.01mm). This first cell spacing yielded y^+ values varying between zero and .9 at the target, side and front end wall. Figure 39 shows a contour of y^+ values on the heated walls. The maximum values occur near the impingement locations as expected due to large shear caused by the steep velocity gradient normal to the wall. On the downstream direction, the y^+ also increases due to the increase of flow rate and therefore the increased skin friction on the wall. At the impingement location of the first jet, the y^+ is close to zero due to the velocity having its direction mostly normal to the surface, yielding no shear.

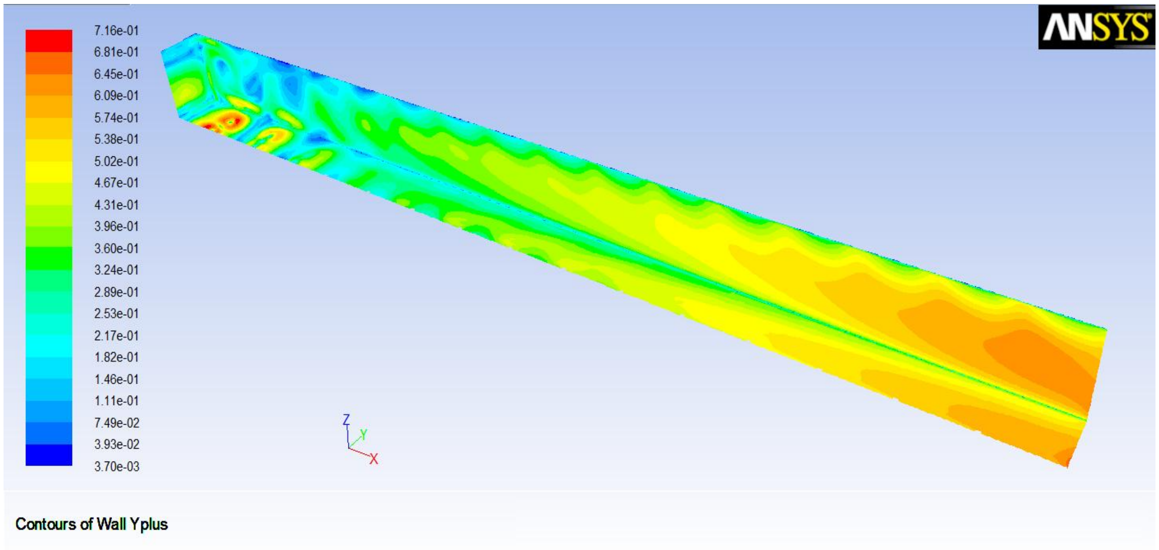


Figure 39: Target, Side and Front End Wall y^+ Values.

Once the faces were linked; edge meshes were created on the sides of the jet center. Section 2's inner edge was also meshed using a different parameter than the one used for the jet center in order to allow for more freedom when trying to refine the mesh. These two edge meshes is followed by meshing all of section 2 faces alongside all the jet centers. Once these were complete; section 3's inner edge was meshed with different parameters for the channel and plenum. Sections 4 and 5 sides that connected with the face made by section 6 were meshed so that their spacing was similar; again, the plenum and channel were meshed separately for increased control of mesh density in both of these areas. The upstream-most edge of section 6 was meshed so that the spacing is similar to the edge mesh in sections 4 and 5; this was done in order to have aspect ratios of the wall be as close as possible to unity. Sections 3, 4, 5 and 6 were meshed on both the channel and the plenum. With the entire target wall plane meshed; these surface meshes are coopered upwards to connect to the opposite wall. The vertical spacing has

also been set up differently between the channel and the plenum. The holes and the plenum were also coopered. The finished mesh was then exported as a *.msh file.

Boundary conditions were set in GAMBIT; once the mesh was imported into Fluent, values were set to every face depending on their location and purpose. Figure 40 shows the four different boundary conditions. Face 1 (blue) was set to be a mass flow inlet. The flow rate is half of the total flow rate at a given jet Reynolds number due to it being only half of the entire domain. Face 2 (yellow) is a symmetry plane; face 3 (red) is a pressure outlet at zero gauge pressure. The rest of the faces in the channel denoted by the number 4 (white) are set to walls. The target, side and front end wall had a heat flux applied to them equal to 10000W/m^2.

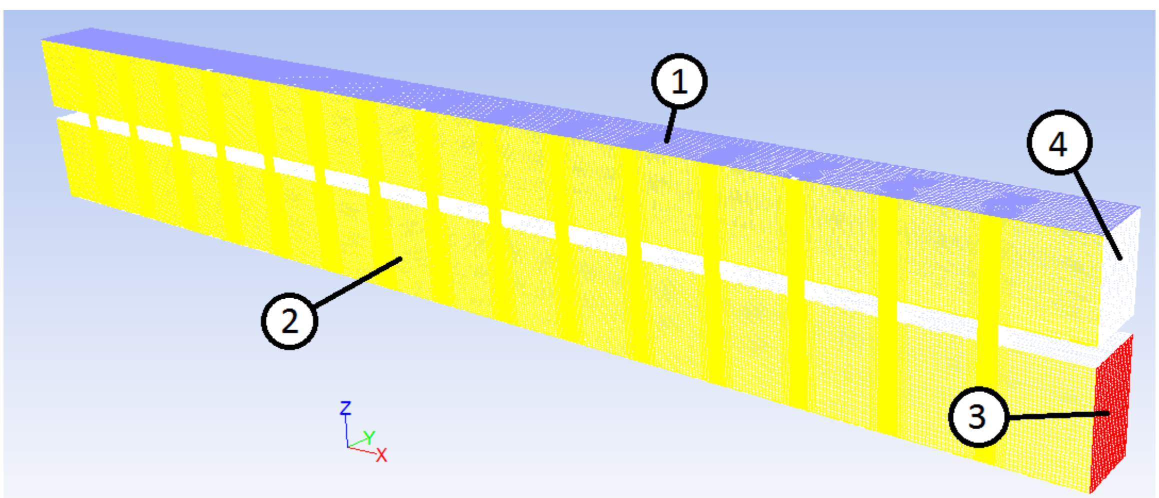


Figure 40: Finished Mesh with Boundary Conditions.

The model was imported into Fluent. It was scaled down by a factor of 1000 due to it being made in GAMBIT in millimeters. The energy model was turned on. The Realizable k-ε model was used with enhanced wall functions on both the pressure and thermal gradients. The boundary conditions were set as discussed previously; the mass flow inlet was set to the specific flow rate normal to the surface, the heat fluxes were set on the

heated walls, the outflow gauge pressure was set to zero. Two important reference values, characteristic length and reference temperature were set to be the diameter of the jet (.0075m) and 300K respectively. The spatial discretization parameters were set to second order upwind for momentum, turbulent kinetic energy, turbulent dissipation rate and energy. The under-relaxation factors were set to default. Four monitors were created to aid in the determination of convergence; two of them read Nusselt numbers at the stagnation region of the first and last jet; the remaining two read the exit velocity at the first and last jet. The continuity, x, y and x velocities, and energy equations residuals were set to be 1E-6, while k and ε residuals were set to 1E-4. The solution was initialized on the all zones at 1m/s in the positive x direction. The solution was set to autosave every 100 iterations while keeping only the two newest *.dat files. The calculation was then run for a maximum of 7000 iterations.

A grid independence study was done on the domain to find the optimal size of mesh that provides the correct solution while minimizing the compute time. Two monitors were set to check for grid independence; both of them were vertex maximum. One of them read the Nusselt number at the impingement location of the first center jet while the second one measures the velocity at the exit of the last jet. Four different mesh sizes were run to the convergence criterion explained before; their sizes were 900,000; 1.5 million, 2.8 million and 4.3 million cells.

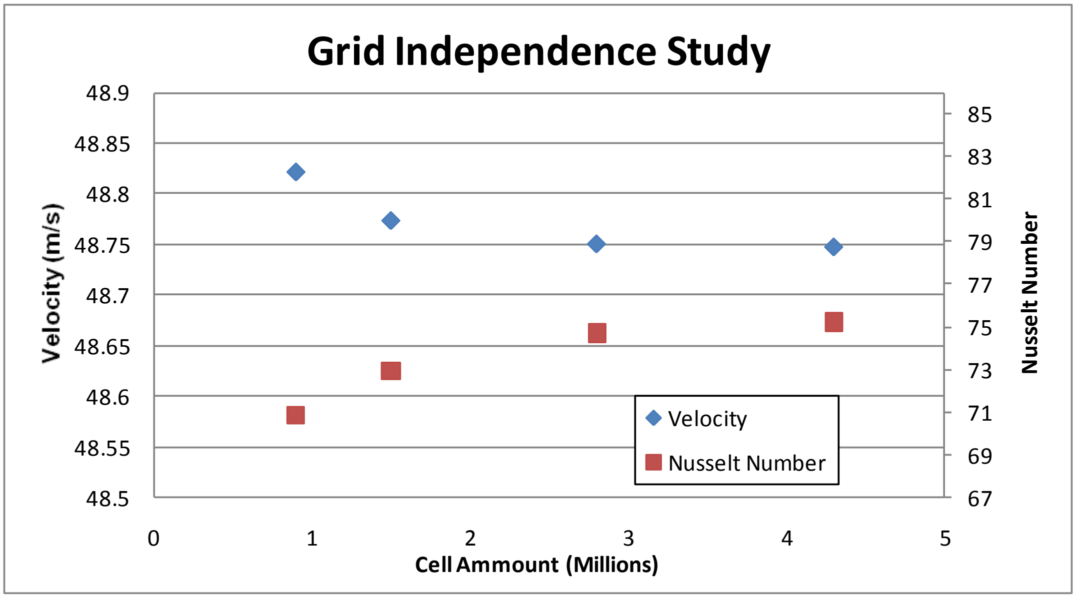


Figure 41: Grid Independence Study

It can be seen in Figure 41 that the difference between the 2.8 and 4.3 million cell meshes are very small, a difference of under .006% for velocity and .7% for Nusselt number. It can be safe to assume that the 2.8 million cell mesh is large enough to provide a mesh independent solution. The GAMBIT journal file used to create this mesh is attached to the appendix. The results shown hereafter are the ones obtained by the 2.8 million cell mesh.

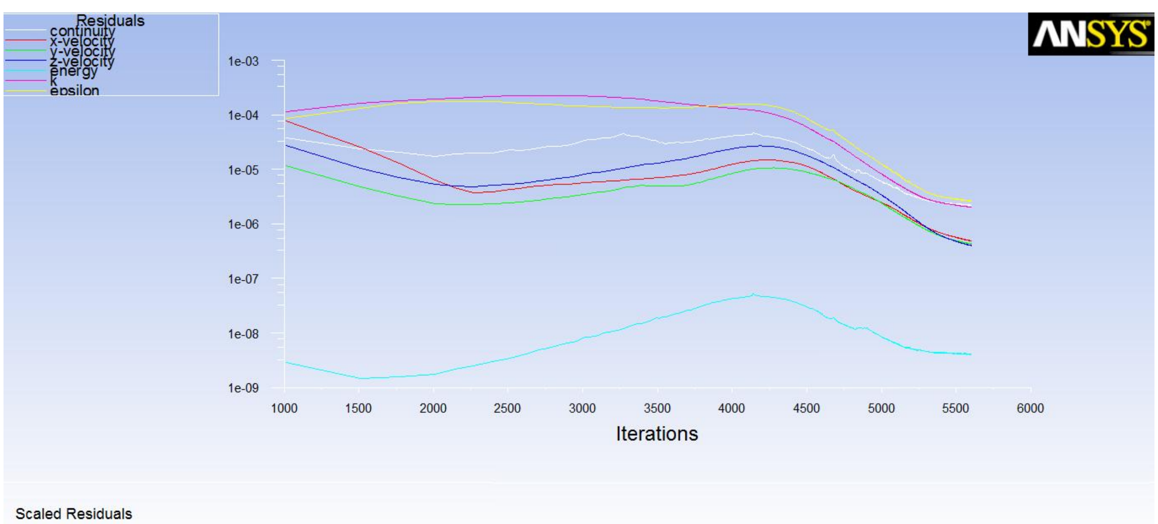


Figure 42: Residual Plots for the 2.6M Cell Run

For future reference, Figure 42 shows the residuals of the 2.6M cell calculation. Up until around 4400 iterations, the residuals were increasing; shortly thereafter, the residuals started decreasing until it converged just after 5500 iterations. All runs for the differently sized meshes had the same residual patters with the peak of residuals and point of convergence happening at different iterations.

5.2 CFD Results

As describe previously, all the results shown here are for the mesh containing 2.8 million elements. Figure 43 shows the total pressure contours. It can be seen that the plenum portion is at a constant total pressure. Once the jets form, since there are very small losses in the jets due to the wall friction; the total pressure still remains constant. Only when the jets enter the channel and start mixing with the cross flow is that they start losing the total pressure head. It is important to notice how the first two jets have the total pressure close to the plenum arriving at the target wall. This implies a successful impingement of the undisturbed potential core. As we move downstream, the total pressure is lost quite rapidly as the jets interact with the cross flow.

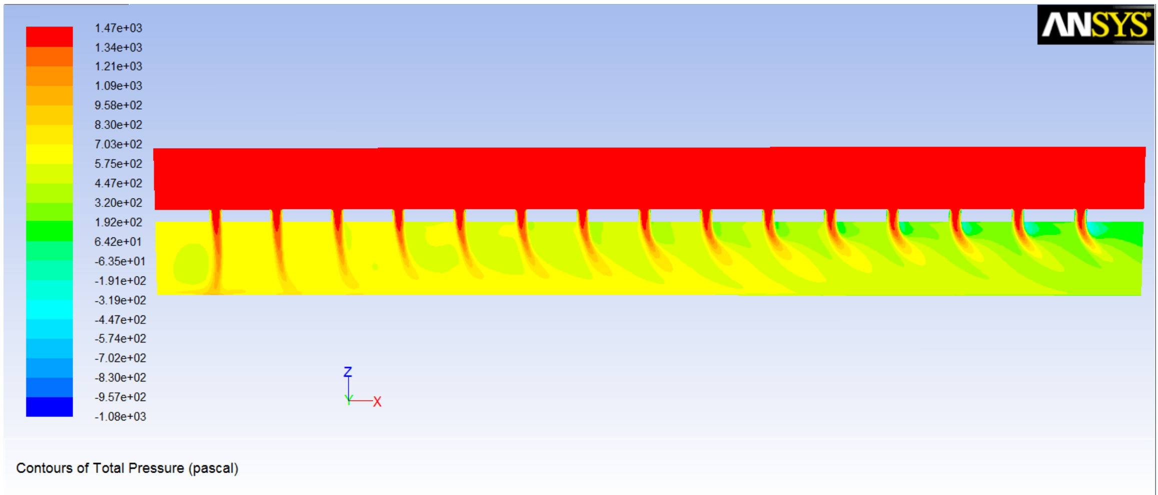


Figure 43: Total Pressure Contours

Similar details can be drawn out from Figure 44; it can be seen that the first three jets successfully impinge on the target wall while the rest of the downstream ones are deflected by the cross flow. As mentioned by Ricklick, the velocity magnitude of the last jet is larger than that of the first jet due to there being a lower static pressure at the end of the channel providing it with a steeper pressure gradient, hence higher velocity.

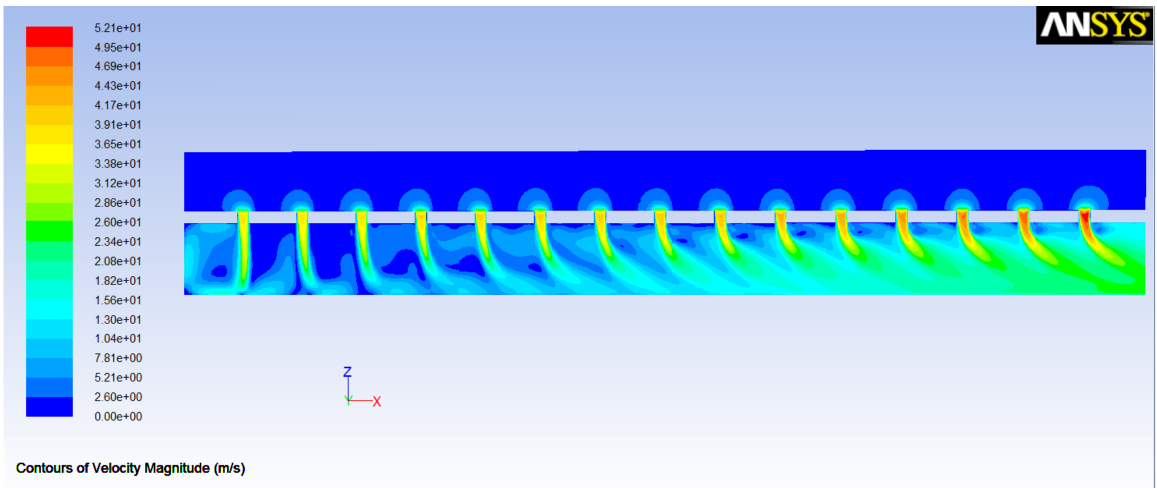


Figure 44: Velocity Magnitude Contours

Turbulent kinetic energy was plotted in Figure 45; it is expected to have the highest turbulent kinetic energy near the exit of the holes where the stagnant air is in contact with the fast moving jet. The mixing between the two regimes causes very energetic eddies to form potentially enhancing the target and side wall heat transfer coefficient. As cross flow builds up towards the end of the channel, the turbulent kinetic energy increases due to larger overall velocities and fluctuations between the cross flow and jets.

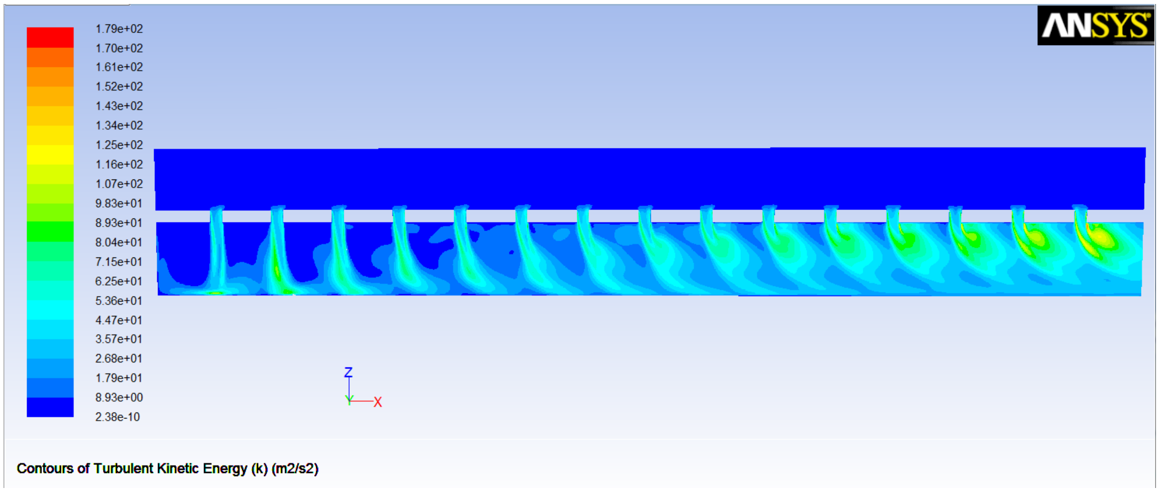


Figure 45: Turbulent Kinetic Energy Contours

As Ricklick showed in his work, the static temperature rise is quite small for such a small channel. It can be seen in Figure 46 that the driving temperature for heat transfer is that of the plenum. It is important to notice that a wall heat flux of 10000 W/m^2 was used as the boundary condition. Not even in the most powerful tests would we ever use heat fluxes that high; they normally range between 2500 to a maximum of 7000 W/m^2. A heat flux of 10000 W/m^2 will increase the temperature at a faster rate than what it is normally used in experimental testing.

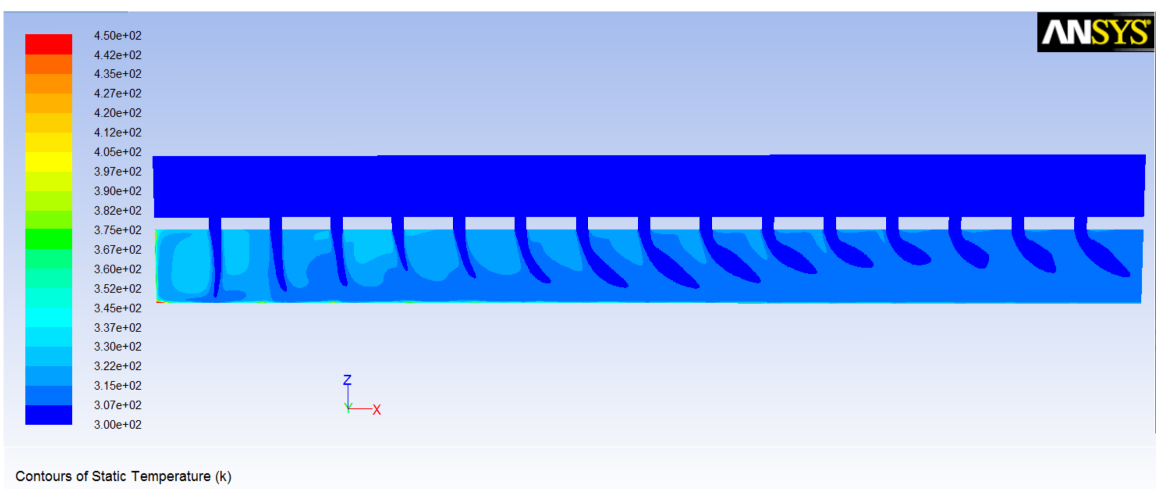


Figure 46: Static Temperature Contours

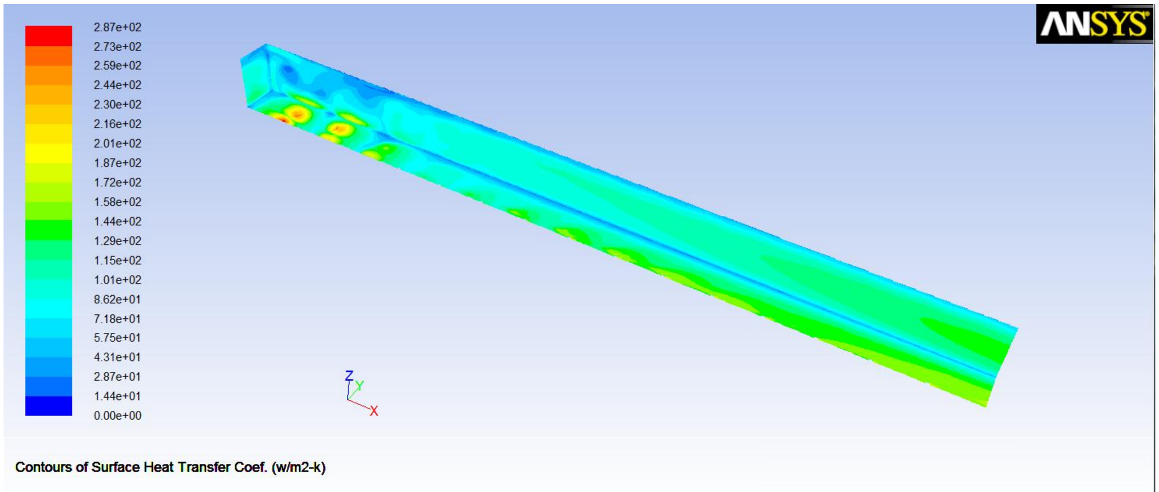


Figure 47: Target and Side Wall Heat Transfer Coefficient Contours

Figure 47 shows the target and sidewall heat transfer profiles. Peaks can be seen at the first three locations similar to that seen in Figure 22. The trend decreases rapidly to eventually become a slowly increasing heat transfer profile due to the increase of mass flow through the channel. The sidewall provides the same results; clear peaks in heat transfer where the wall jets impinge on the sidewall, seen in Figure 48 in more detail. The sidewall also shows a recirculation zone in between the first row of jets and the end wall. This is caused by the wall jet from the first row hitting the back wall, moving upwards in a circular pattern and coming back down when it encounters the first impingement row.

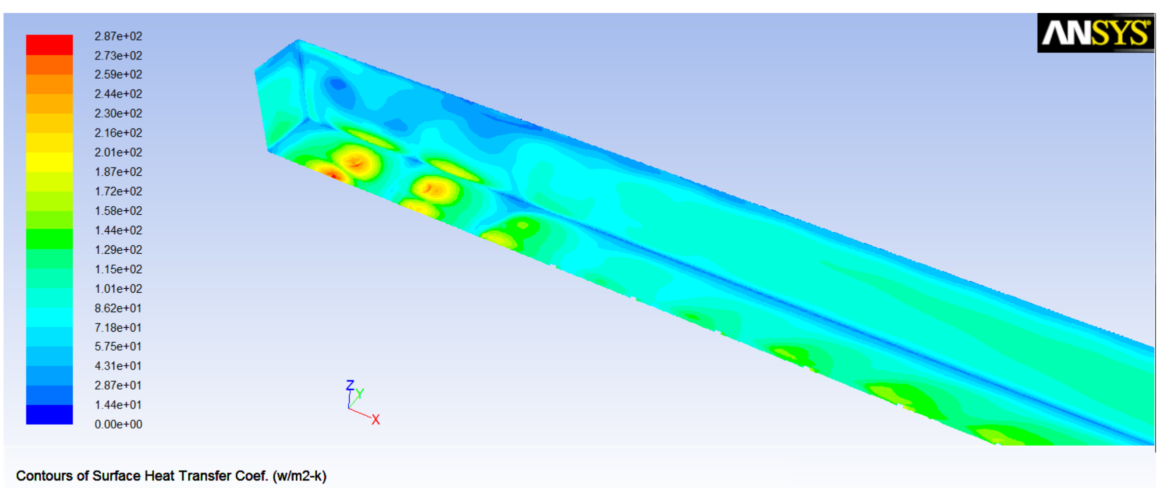


Figure 48: Closer View of First few Rows of Impingement HTC Contours

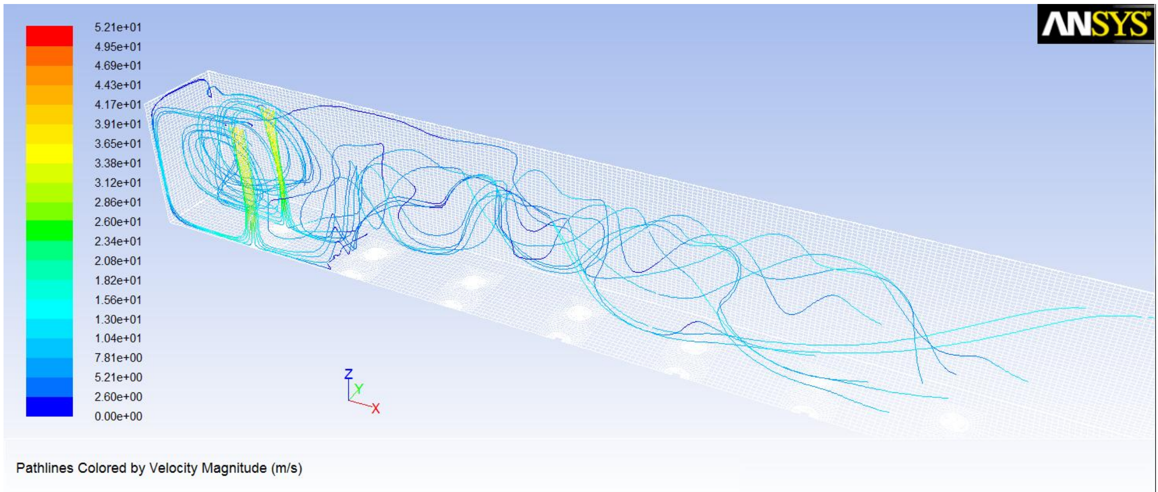


Figure 49: Pathlines Generating from the First Row of Jets

Figure 49 helps explain the low heat transfer region between the first row of jets and the end wall. Pathlines are generated at the exit of each hole in the first row. As the air impinges on the surface, half of it moves downstream and the other half movers upstream to this recirculation zone where it circulates for a period of time before reuniting with the remainder of the flow to move downstream. The wall jet that moves towards the second row of jets encounters the wall jet created by the second row of jets causing the pathlines to drastically move upwards. On the side of the channel, the pathlines behave erratically with no clear pattern, clearly signifying the highly turbulent and chaotic flow structure of this impingement channel.

CHAPTER SIX: CONCLUSIONS

It has been seen from this analysis, that the side walls provide significant heat transfer in an impingement channel, especially at the relatively smaller channel height. This is primarily the result of successful impact of the wall jet with the side walls. It was shown that the tallest channel (Z/D=10) has the most uniform profile with low heat transfer coefficients when compared to the other channels. The peaks of the Z/D=6 and 8 channels have a very similar profile which may indicate the successful impingement of the potential core of the jet on the target surface. As X/D increases, the peaks diminish and a positive slope profile is attained by the increase of cross flow velocity as more and more jets are introduced. Tall impingement channels provide the user with a heat transfer profile that is more uniform than those provided with the use of a smaller channel while still maintaining higher convective coefficients when compared to a smooth flow scenario. The downstream shift of the wall jets is found to be independent of Reynolds number and heavily dependent on streamwise position. It was also found that at X/D=15, the wall jets decay faster than their X/D=5 counterparts. From the 3D heat transfer profiles it was seen that the cross flow generated by multiple upstream jets is deflected downward, decreasing its effective flow area, increasing its velocity, hence providing higher convective coefficients at the side wall at high x/D and low z/D.

APPENDICES

Appendix A

Lateral Conduction Consideration

Thickness of foil heater

$t := 50\mu m$

Sample volume width

$\delta := 1mm$

Volume of sample volume

$V := \delta^2 \cdot t$

$k := 20 \frac{W}{m \cdot K}$

Heat flux

$q_{flux} := 6000 \frac{W}{m^2}$

Volumetric heat generation

$q_{vol} := \frac{q_{flux}}{t}$

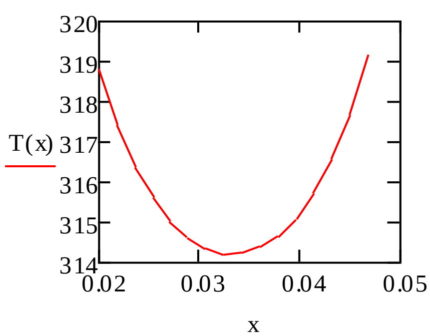
Temperature profile from the first row of impingement. ONLY valid for .02<x<.045

$$T(x) := 298K + \frac{q_{flux}}{\left(-470630x^2 + 31244x - 148.42\right)\frac{W}{m^2 K}}$$

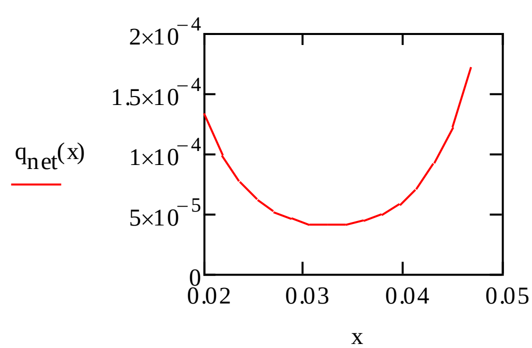
$N := 15$

$$x := \left(.02, \frac{.045 - .02}{N - 1} + .02 .. .047\right)$$

$A := \delta \cdot t$



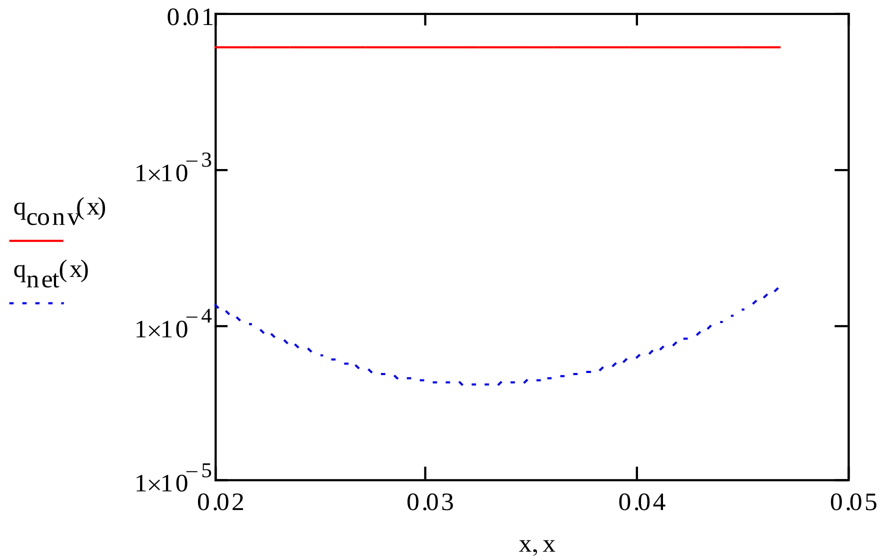
$$q_{net}(x) := A \cdot k \cdot \left(\frac{d}{dx} T\left(x + \frac{\delta}{m}\right) - \frac{d}{dx} T(x)\right) \frac{1}{m}$$



Now comparing the net heat gained by lateral conduction to heat generated and convected out,

$$q_{gen} := q_{vol} \cdot V = 6 \times 10^{-3} W$$

$$q_{conv}(x) := \delta^2 \cdot q_{flux} + q_{net}(x)$$



It can be seen that the lateral conduction into the sample volume is two orders of magnitude smaller than the heat removed by convection

Appendix B

This is the journal file run on gambit to generate the geometry, faces, links, boundary layer, face and volume meshes, as well as the boundary conditions.

```
/set diameter
$d=7.5
$zc=6*($d)
$xc=80*($d)
$yc=4*($d)
$y=2*($d)
$x=5*($d)
$zp=5*($d)
$ztot=($zc)+($d)+($zp)
$jcf=(1/3)
$ocf=2

/Boundary layer constants
$first=0.1
$growth=1.2
$rows=4

/Meshing constants
$NumbNodes=5
$Numbtelnodes=6
$PLobnodes=5
$Chobnodes=5
$Plbenodes=($NumbNodes*(4)+$rows)
$plsqnodes=($NumbNodes*(3))
$Pllsnodes=($NumbNodes+$rows)

$Nojetcells=10
$Chzdnodes=($zc*$Nojetcells)/($d)
$Plzdnodes=($zp*$Nojetcells)/($d)

/Boundary layer constants for channel
$firstch=0.01
$growthch=1.2
$rowsch=8
$CHbenodes=($NumbNodes*(4)+$rowsch)
$CHlsnodes=($NumbNodes+$rowsch)

volume create "body" width ($xc) depth ($yc) height ($ztot) offset ($xc/2) ($yc/2) ($ztot/2) brick
volume create "cylinder" height ($ztot) radius1 ($d/2) radius3 ($d/2) offset ($x) 0 ($ztot/2) zaxis frustum
volume cmove "cylinder" multiple 1 offset 0 ($y) 0
volume cmove "cylinder" "volume.3" multiple 14 offset ($x) 0 0
volume create "jetplate" width ($xc) depth ($yc) height ($d)offset ($xc/2) ($yc/2) ($d/2+$zc) brick
volume split "body" volumes "jetplate" connected
volume split "jetplate" volumes "cylinder" "volume.3" "volume.4" "volume.5" \
  "volume.6" "volume.7" "volume.8" "volume.9" "volume.10" "volume.11" \
  "volume.12" "volume.13" "volume.14" "volume.15" "volume.16" "volume.17" \
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  "volume.18" "volume.19" "volume.20" "volume.21" "volume.22" "volume.23" \
  "volume.24" "volume.25" "volume.26" "volume.27" "volume.28" "volume.29" \
  "volume.30" "volume.31" connected
face create "jetcenter" width ($jcf*$d) height ($jcf*$d) offset ($x) 0 0 xyplane rectangle
face create "jetcircle" radius ($d/2) xyplane circle
face move "jetcircle" offset ($x) 0 0
face create "outbox" width ($ocf*$d) height ($ocf*$d) offset ($x) 0 0 xyplane rectangle
face split "outbox" connected faces "jetcircle" "jetcenter"
face split "jetcircle" connected faces "face.1"
face split "outbox" connected faces "face.1"
face cmove "jetcenter" "outbox" "jetcircle" "face.222" "face.223" multiple 1 offset 0 ($y) 0
face cmove "jetcenter" "outbox" "jetcircle" "face.222" "face.223" "face.224" "face.225" "face.226"
"face.227" "face.228" multiple 14 offset ($x) 0 0
volume delete "jetplate" lowertopology
face split "face.1" connected keeptool faces "jetcircle" "jetcenter" "outbox" \
  "face.222" "face.223" "face.224" "face.225" "face.226" "face.227" \
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  "face.243" "face.244" "face.245" "face.246" "face.247" "face.248" \
  "face.249" "face.250" "face.251" "face.252" "face.253" "face.254" \
  "face.255" "face.256" "face.257" "face.258" "face.259" "face.260" \
  "face.261" "face.262" "face.263" "face.264" "face.265" "face.266" \
  "face.267" "face.268" "face.269" "face.270" "face.271" "face.272" \
  "face.273" "face.274" "face.275" "face.276" "face.277" "face.278" \
  "face.279" "face.280" "face.281" "face.282" "face.283" "face.284" \
  "face.285" "face.286" "face.287" "face.288" "face.289" "face.290" \
  "face.291" "face.292" "face.293" "face.294" "face.295" "face.296" \
  "face.297" "face.298" "face.299" "face.300" "face.301" "face.302" \
  "face.303" "face.304" "face.305" "face.306" "face.307" "face.308" \
  "face.309" "face.310" "face.311" "face.312" "face.313" "face.314" \
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  "face.315" "face.316" "face.317" "face.318" "face.319" "face.320" \
  "face.321" "face.322" "face.323" "face.324" "face.325" "face.326" \
  "face.327" "face.328" "face.329" "face.330" "face.331" "face.332" \
  "face.333" "face.334" "face.335" "face.336" "face.337" "face.338" \
  "face.339" "face.340" "face.341" "face.342" "face.343" "face.344" \
  "face.345" "face.346" "face.347" "face.348" "face.349" "face.350" \
  "face.351" "face.352" "face.353" "face.354" "face.355" "face.356" \
  "face.357" "face.358" "face.359" "face.360" "face.361" "face.362" \
  "face.363" "face.364" "face.365" "face.366" "face.367" "face.368" offset 0 \
  0 $ztot

/THIS SPLITS THE TOP PLENUM FACE WITH THE FACES CREATED IN THE BOTTOM

face split "face.6" connected keeptool faces "jetcircle" "jetcenter" "outbox" \
  "face.222" "face.223" "face.224" "face.225" "face.226" "face.227" \
  "face.228" "face.229" "face.230" "face.231" "face.232" "face.233" \
  "face.234" "face.235" "face.236" "face.237" "face.238" "face.239" \
  "face.240" "face.241" "face.242" "face.243" "face.244" "face.245" \
  "face.246" "face.247" "face.248" "face.249" "face.250" "face.251" \
  "face.252" "face.253" "face.254" "face.255" "face.256" "face.257" \
  "face.258" "face.259" "face.260" "face.261" "face.262" "face.263" \
  "face.264" "face.265" "face.266" "face.267" "face.268" "face.269" \
  "face.270" "face.271" "face.272" "face.273" "face.274" "face.275" \
  "face.276" "face.277" "face.278" "face.279" "face.280" "face.281" \
  "face.282" "face.283" "face.284" "face.285" "face.286" "face.287" \
  "face.288" "face.289" "face.290" "face.291" "face.292" "face.293" \
  "face.294" "face.295" "face.296" "face.297" "face.298" "face.299" \
  "face.300" "face.301" "face.302" "face.303" "face.304" "face.305" \
  "face.306" "face.307" "face.308" "face.309" "face.310" "face.311" \
  "face.312" "face.313" "face.314" "face.315" "face.316" "face.317" \
  "face.318" "face.319" "face.320" "face.321" "face.322" "face.323" \
  "face.324" "face.325" "face.326" "face.327" "face.328" "face.329" \
  "face.330" "face.331" "face.332" "face.333" "face.334" "face.335" \
  "face.336" "face.337" "face.338" "face.339" "face.340" "face.341" \
  "face.342" "face.343" "face.344" "face.345" "face.346" "face.347" \
  "face.348" "face.349" "face.350" "face.351" "face.352" "face.353" \
  "face.354" "face.355" "face.356" "face.357" "face.358" "face.359" \
  "face.360" "face.361" "face.362" "face.363" "face.364" "face.365" \
  "face.366" "face.367" "face.368"

/THIS MOVES THE FACES THAT WE ARE USING TO PLIT THE BOTTOM PLENUM SURFACE

face move "jetcircle" "jetcenter" "outbox" "face.222" "face.223" "face.224" \
  "face.225" "face.226" "face.227" "face.228" "face.229" "face.230" \
  "face.231" "face.232" "face.233" "face.234" "face.235" "face.236" \
  "face.237" "face.238" "face.239" "face.240" "face.241" "face.242" \
  "face.243" "face.244" "face.245" "face.246" "face.247" "face.248" \
  "face.249" "face.250" "face.251" "face.252" "face.253" "face.254" \
  "face.255" "face.256" "face.257" "face.258" "face.259" "face.260" \
  "face.261" "face.262" "face.263" "face.264" "face.265" "face.266" \
  "face.267" "face.268" "face.269" "face.270" "face.271" "face.272" \
  "face.273" "face.274" "face.275" "face.276" "face.277" "face.278" \
  "face.279" "face.280" "face.281" "face.282" "face.283" "face.284" \
  "face.285" "face.286" "face.287" "face.288" "face.289" "face.290" \
  "face.291" "face.292" "face.293" "face.294" "face.295" "face.296" \
  "face.297" "face.298" "face.299" "face.300" "face.301" "face.302" \
```

```
  "face.303" "face.304" "face.305" "face.306" "face.307" "face.308" \
  "face.309" "face.310" "face.311" "face.312" "face.313" "face.314" \
  "face.315" "face.316" "face.317" "face.318" "face.319" "face.320" \
  "face.321" "face.322" "face.323" "face.324" "face.325" "face.326" \
  "face.327" "face.328" "face.329" "face.330" "face.331" "face.332" \
  "face.333" "face.334" "face.335" "face.336" "face.337" "face.338" \
  "face.339" "face.340" "face.341" "face.342" "face.343" "face.344" \
  "face.345" "face.346" "face.347" "face.348" "face.349" "face.350" \
  "face.351" "face.352" "face.353" "face.354" "face.355" "face.356" \
  "face.357" "face.358" "face.359" "face.360" "face.361" "face.362" \
  "face.363" "face.364" "face.365" "face.366" "face.367" "face.368" offset 0 \
  0 -$zp

/SPLITS THE BOTTOM FACE OF THE PLENUM WITH THE FACES THAT ARE USED TO SPLIT

face split "face.114" connected keeptool faces "jetcircle" "jetcenter" \
  "outbox" "face.222" "face.223" "face.224" "face.225" "face.226" "face.227" \
  "face.228" "face.229" "face.230" "face.231" "face.232" "face.233" \
  "face.234" "face.235" "face.236" "face.237" "face.238" "face.239" \
  "face.240" "face.241" "face.242" "face.243" "face.244" "face.245" \
  "face.246" "face.247" "face.248" "face.249" "face.250" "face.251" \
  "face.252" "face.253" "face.254" "face.255" "face.256" "face.257" \
  "face.258" "face.259" "face.260" "face.261" "face.262" "face.263" \
  "face.264" "face.265" "face.266" "face.267" "face.268" "face.269" \
  "face.270" "face.271" "face.272" "face.273" "face.274" "face.275" \
  "face.276" "face.277" "face.278" "face.279" "face.280" "face.281" \
  "face.282" "face.283" "face.284" "face.285" "face.286" "face.287" \
  "face.288" "face.289" "face.290" "face.291" "face.292" "face.293" \
  "face.294" "face.295" "face.296" "face.297" "face.298" "face.299" \
  "face.300" "face.301" "face.302" "face.303" "face.304" "face.305" \
  "face.306" "face.307" "face.308" "face.309" "face.310" "face.311" \
  "face.312" "face.313" "face.314" "face.315" "face.316" "face.317" \
  "face.318" "face.319" "face.320" "face.321" "face.322" "face.323" \
  "face.324" "face.325" "face.326" "face.327" "face.328" "face.329" \
  "face.330" "face.331" "face.332" "face.333" "face.334" "face.335" \
  "face.336" "face.337" "face.338" "face.339" "face.340" "face.341" \
  "face.342" "face.343" "face.344" "face.345" "face.346" "face.347" \
  "face.348" "face.349" "face.350" "face.351" "face.352" "face.353" \
  "face.354" "face.355" "face.356" "face.357" "face.358" "face.359" \
  "face.360" "face.361" "face.362" "face.363" "face.364" "face.365" \
  "face.366" "face.367" "face.368"

/COPIES THE FACES THAT WE USED TO SPLIT TO BOTTOM OF THE PLENUM TO THE TOP OF
THE CHANNEL

face cmove "jetcircle" "jetcenter" "outbox" "face.222" "face.223" "face.224" \
  "face.225" "face.226" "face.227" "face.228" "face.229" "face.230" \
  "face.231" "face.232" "face.233" "face.234" "face.235" "face.236" \
  "face.237" "face.238" "face.239" "face.240" "face.241" "face.242" \
  "face.243" "face.244" "face.245" "face.246" "face.247" "face.248" \
  "face.249" "face.250" "face.251" "face.252" "face.253" "face.254" \
  "face.255" "face.256" "face.257" "face.258" "face.259" "face.260" \
  "face.261" "face.262" "face.263" "face.264" "face.265" "face.266" \
  "face.267" "face.268" "face.269" "face.270" "face.271" "face.272" \
  "face.273" "face.274" "face.275" "face.276" "face.277" "face.278" \
  "face.279" "face.280" "face.281" "face.282" "face.283" "face.284" \
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 "face.285" "face.286" "face.287" "face.288" "face.289" "face.290" \
 "face.291" "face.292" "face.293" "face.294" "face.295" "face.296" \
 "face.297" "face.298" "face.299" "face.300" "face.301" "face.302" \
 "face.303" "face.304" "face.305" "face.306" "face.307" "face.308" \
 "face.309" "face.310" "face.311" "face.312" "face.313" "face.314" \
 "face.315" "face.316" "face.317" "face.318" "face.319" "face.320" \
 "face.321" "face.322" "face.323" "face.324" "face.325" "face.326" \
 "face.327" "face.328" "face.329" "face.330" "face.331" "face.332" \
 "face.333" "face.334" "face.335" "face.336" "face.337" "face.338" \
 "face.339" "face.340" "face.341" "face.342" "face.343" "face.344" \
 "face.345" "face.346" "face.347" "face.348" "face.349" "face.350" \
 "face.351" "face.352" "face.353" "face.354" "face.355" "face.356" \
 "face.357" "face.358" "face.359" "face.360" "face.361" "face.362" \
 "face.363" "face.364" "face.365" "face.366" "face.367" "face.368" multiple 1 offset 0 \
 0 -$d
```

/NAME OF COPIED NEW FACES

```
/"face.1104" "face.1105" "face.1106" "face.1107" "face.1108" "face.1109" "face.1110" /"face.1111"
"face.1112" "face.1113" "face.1114" "face.1115" "face.1116" "face.1117" /"face.1118" "face.1119"
"face.1120" "face.1121" "face.1122" "face.1123" "face.1124" /"face.1125" "face.1126" "face.1127"
"face.1128" "face.1129" "face.1130" "face.1131" /"face.1132" "face.1133" "face.1134" "face.1135"
"face.1136" "face.1137" "face.1138" /"face.1139" "face.1140" "face.1141" "face.1142" "face.1143"
"face.1144" "face.1145" /"face.1146" "face.1147" "face.1148" "face.1149" "face.1150" "face.1151"
"face.1152" /"face.1153" "face.1154" "face.1155" "face.1156" "face.1157" "face.1158" "face.1159"
/"face.1160" "face.1161" "face.1162" "face.1163" "face.1164" "face.1165" "face.1166" /"face.1167"
"face.1168" "face.1169" "face.1170" "face.1171" "face.1172" "face.1173" /"face.1174" "face.1175"
"face.1176" "face.1177" "face.1178" "face.1179" "face.1180" /"face.1181" "face.1182" "face.1183"
"face.1184" "face.1185" "face.1186" "face.1187" /"face.1188" "face.1189" "face.1190" "face.1191"
"face.1192" "face.1193" "face.1194" /"face.1195" "face.1196" "face.1197" "face.1198" "face.1199"
"face.1200" "face.1201" /"face.1202" "face.1203" "face.1204" "face.1205" "face.1206" "face.1207"
"face.1208" /"face.1209" "face.1210" "face.1211" "face.1212" "face.1213" "face.1214" "face.1215"
/"face.1216" "face.1217" "face.1218" "face.1219" "face.1220" "face.1221" "face.1222" /"face.1223"
"face.1224" "face.1225" "face.1226" "face.1227" "face.1228" "face.1229" /"face.1230" "face.1231"
"face.1232" "face.1233" "face.1234" "face.1235" "face.1236" /"face.1237" "face.1238" "face.1239"
"face.1240" "face.1241" "face.1242" "face.1243" /"face.1244" "face.1245" "face.1246" "face.1247"
"face.1248" "face.1249" "face.1250" /"face.1251" "face.1252" "face.1253"
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/THIS SPLITS THE TOP OF THE CHANNEL WITH THE NEW COPIED FACES

```
face split "face.209" connected keeptool faces "face.1104" "face.1105" "face.1106" "face.1107"
"face.1108" "face.1109" "face.1110" "face.1111" "face.1112" "face.1113" "face.1114" "face.1115"
"face.1116" "face.1117" "face.1118" "face.1119" "face.1120" "face.1121" "face.1122" "face.1123"
"face.1124" "face.1125" "face.1126" "face.1127" "face.1128" "face.1129" "face.1130" "face.1131"
"face.1132" "face.1133" "face.1134" "face.1135" "face.1136" "face.1137" "face.1138" "face.1139"
"face.1140" "face.1141" "face.1142" "face.1143" "face.1144" "face.1145" "face.1146" "face.1147"
"face.1148" "face.1149" "face.1150" "face.1151" "face.1152" "face.1153" "face.1154" "face.1155"
"face.1156" "face.1157" "face.1158" "face.1159" "face.1160" "face.1161" "face.1162" "face.1163"
"face.1164" "face.1165" "face.1166" "face.1167" "face.1168" "face.1169" "face.1170" "face.1171"
"face.1172" "face.1173" "face.1174" "face.1175" "face.1176" "face.1177" "face.1178" "face.1179"
"face.1180" "face.1181" "face.1182" "face.1183" "face.1184" "face.1185" "face.1186" "face.1187"
"face.1188" "face.1189" "face.1190" "face.1191" "face.1192" "face.1193" "face.1194" "face.1195"
"face.1196" "face.1197" "face.1198" "face.1199" "face.1200" "face.1201" "face.1202" "face.1203"
"face.1204" "face.1205" "face.1206" "face.1207" "face.1208" "face.1209" "face.1210" "face.1211"
"face.1212" "face.1213" "face.1214" "face.1215" "face.1216" "face.1217" "face.1218" "face.1219"
"face.1220" "face.1221" "face.1222" "face.1223" "face.1224" "face.1225" "face.1226" "face.1227"
```

"face.1228" "face.1229" "face.1230" "face.1231" "face.1232" "face.1233" "face.1234" "face.1235" "face.1236" "face.1237" "face.1238" "face.1239" "face.1240" "face.1241" "face.1242" "face.1243" "face.1244" "face.1245" "face.1246" "face.1247" "face.1248" "face.1249" "face.1250" "face.1251" "face.1252" "face.1253"

/THIS UNITES THE RECTANGLE OUTSIDE FACES AND THE SEMICIRCLE SO THAT IT MAKES A RECTANGLE WIHOUT THE CENTERJET

face unite faces "jetcircle" "face.223" real
face unite faces "face.222" "outbox" real
face unite faces "face.228" "face.226" real
face unite faces "face.225" "face.227" real
face unite faces "face.231" "face.233" real
face unite faces "face.232" "face.230" real
face unite faces "face.236" "face.238" real
face unite faces "face.237" "face.235" real
face unite faces "face.241" "face.243" real
face unite faces "face.242" "face.240" real
face unite faces "face.248" "face.246" real
face unite faces "face.245" "face.247" real
face unite faces "face.253" "face.251" real
face unite faces "face.252" "face.250" real
face unite faces "face.256" "face.258" real
face unite faces "face.257" "face.255" real
face unite faces "face.263" "face.261" real
face unite faces "face.260" "face.262" real
face unite faces "face.268" "face.266" real
face unite faces "face.265" "face.264" real
face unite faces "face.265" "face.267" real
face unite faces "face.273" "face.271" real
face unite faces "face.272" "face.270" real
face unite faces "face.276" "face.278" real
face unite faces "face.277" "face.275" real
face unite faces "face.281" "face.283" real
face unite faces "face.282" "face.280" real
face unite faces "face.286" "face.288" real
face unite faces "face.287" "face.285" real
face unite faces "face.291" "face.293" real
face unite faces "face.292" "face.290" real
face unite faces "face.296" "face.298" real
face unite faces "face.297" "face.295" real
face unite faces "face.301" "face.303" real
face unite faces "face.302" "face.300" real
face unite faces "face.306" "face.308" real
face unite faces "face.307" "face.305" real
face unite faces "face.316" "face.318" real
face unite faces "face.312" "face.310" real
face unite faces "face.311" "face.313" real
face unite faces "face.315" "face.317" real
face unite faces "face.321" "face.323" real
face unite faces "face.322" "face.320" real
face unite faces "face.326" "face.328" real
face unite faces "face.327" "face.325" real
face unite faces "face.331" "face.333" real
face unite faces "face.332" "face.330" real
face unite faces "face.336" "face.338" real

```
face unite faces "face.337" "face.335" real
face unite faces "face.347" "face.345" real
face unite faces "face.346" "face.348" real
face unite faces "face.342" "face.340" real
face unite faces "face.341" "face.343" real
face unite faces "face.356" "face.358" real
face unite faces "face.357" "face.355" real
face unite faces "face.352" "face.350" real
face unite faces "face.351" "face.353" real
face unite faces "face.361" "face.363" real
face unite faces "face.366" "face.368" real
face unite faces "face.360" "face.362" real
face unite faces "face.365" "face.367" real


/SPLITTING ALL THE FACES OF THE CIRCLES IN THE BOTTOM OF THE PLENUM

face split "face.912" connected keeptool faces "face.222"
face split "face.117" connected keeptool faces "face.228"
face split "face.117" connected keeptool faces "face.225"

face split "face.922" connected keeptool faces "face.232"
face split "face.124" connected keeptool faces "face.236"
face split "face.124" connected keeptool faces "face.237"

face split "face.932" connected keeptool faces "face.242"
face split "face.131" connected keeptool faces "face.248"
face split "face.131" connected keeptool faces "face.245"

face split "face.942" connected keeptool faces "face.252"
face split "face.138" connected keeptool faces "face.256"
face split "face.138" connected keeptool faces "face.257"

face split "face.952" connected keeptool faces "face.260"
face split "face.145" connected keeptool faces "face.268"
face split "face.145" connected keeptool faces "face.265"

face split "face.962" connected keeptool faces "face.272"
face split "face.152" connected keeptool faces "face.276"
face split "face.152" connected keeptool faces "face.277"

face split "face.972" connected keeptool faces "face.282"
face split "face.159" connected keeptool faces "face.286"
face split "face.159" connected keeptool faces "face.287"

face split "face.982" connected keeptool faces "face.292"
face split "face.166" connected keeptool faces "face.296"
face split "face.166" connected keeptool faces "face.297"

face split "face.992" connected keeptool faces "face.302"
face split "face.173" connected keeptool faces "face.306"
face split "face.173" connected keeptool faces "face.307"

face split "face.1002" connected keeptool faces "face.312"
face split "face.180" connected keeptool faces "face.316"
face split "face.180" connected keeptool faces "face.315"
```

face split "face.1012" connected keeptool faces "face.322"
face split "face.187" connected keeptool faces "face.326"
face split "face.187" connected keeptool faces "face.327"

face split "face.1022" connected keeptool faces "face.332"
face split "face.194" connected keeptool faces "face.336"
face split "face.194" connected keeptool faces "face.337"

face split "face.1032" connected keeptool faces "face.342"
face split "face.201" connected keeptool faces "face.346"
face split "face.201" connected keeptool faces "face.347"

face split "face.1042" connected keeptool faces "face.352"
face split "face.208" connected keeptool faces "face.356"
face split "face.208" connected keeptool faces "face.357"

face split "face.1052" connected keeptool faces "face.360"
face split "face.215" connected keeptool faces "face.366"
face split "face.215" connected keeptool faces "face.365"

/THIS UNITES THE RECTANGLE OUTSIDE FACES AND THE SEMICIRCLE SO THAT IT MAKES A RECTANGLE WIHOUT THE CENTERJET

face unite faces "face.1104" "face.1108" real
face unite faces "face.1107" "face.1106" real
face unite faces "face.1113" "face.1111" real
face unite faces "face.1112" "face.1110" real
face unite faces "face.1118" "face.1116" real
face unite faces "face.1117" "face.1115" real
face unite faces "face.1123" "face.1121" real
face unite faces "face.1122" "face.1120" real
face unite faces "face.1128" "face.1126" real
face unite faces "face.1127" "face.1125" real
face unite faces "face.1133" "face.1131" real
face unite faces "face.1132" "face.1130" real
face unite faces "face.1138" "face.1136" real
face unite faces "face.1137" "face.1135" real
face unite faces "face.1143" "face.1141" real
face unite faces "face.1142" "face.1140" real
face unite faces "face.1148" "face.1146" real
face unite faces "face.1147" "face.1145" real
face unite faces "face.1153" "face.1151" real
face unite faces "face.1152" "face.1150" real
face unite faces "face.1158" "face.1156" real
face unite faces "face.1157" "face.1155" real
face unite faces "face.1163" "face.1161" real
face unite faces "face.1162" "face.1160" real
face unite faces "face.1168" "face.1166" real
face unite faces "face.1167" "face.1165" real
face unite faces "face.1173" "face.1171" real
face unite faces "face.1172" "face.1170" real
face unite faces "face.1178" "face.1176" real
face unite faces "face.1177" "face.1175" real
face unite faces "face.1183" "face.1181" real

```
face unite faces "face.1182" "face.1180" real
face unite faces "face.1186" "face.1188" real
face unite faces "face.1187" "face.1185" real
face unite faces "face.1193" "face.1191" real
face unite faces "face.1192" "face.1190" real
face unite faces "face.1198" "face.1196" real
face unite faces "face.1197" "face.1195" real
face unite faces "face.1203" "face.1201" real
face unite faces "face.1202" "face.1200" real
face unite faces "face.1206" "face.1208" real
face unite faces "face.1207" "face.1205" real
face unite faces "face.1213" "face.1211" real
face unite faces "face.1212" "face.1210" real
face unite faces "face.1216" "face.1218" real
face unite faces "face.1217" "face.1215" real
face unite faces "face.1221" "face.1223" real
face unite faces "face.1222" "face.1220" real
face unite faces "face.1228" "face.1226" real
face unite faces "face.1227" "face.1225" real
face unite faces "face.1233" "face.1231" real
face unite faces "face.1232" "face.1230" real
face unite faces "face.1238" "face.1236" real
face unite faces "face.1237" "face.1235" real
face unite faces "face.1243" "face.1241" real
face unite faces "face.1242" "face.1240" real
face unite faces "face.1248" "face.1246" real
face unite faces "face.1247" "face.1245" real
face unite faces "face.1253" "face.1251" real
face unite faces "face.1252" "face.1250" real

/SPLITTING ALL THE FACES OF THE CIRCLES IN THE TOP OF THE CHANNEL

face split "face.1257" connected keeptool faces "face.1107"
face split "face.115" connected keeptool faces "face.1113"
face split "face.115" connected keeptool faces "face.1112"

face split "face.1267" connected keeptool faces "face.1117"
face split "face.122" connected keeptool faces "face.1123"
face split "face.122" connected keeptool faces "face.1122"

face split "face.1277" connected keeptool faces "face.1127"
face split "face.129" connected keeptool faces "face.1133"
face split "face.129" connected keeptool faces "face.1132"

face split "face.1287" connected keeptool faces "face.1137"
face split "face.136" connected keeptool faces "face.1143"
face split "face.136" connected keeptool faces "face.1142"

face split "face.1297" connected keeptool faces "face.1147"
face split "face.143" connected keeptool faces "face.1153"
face split "face.143" connected keeptool faces "face.1152"

face split "face.1307" connected keeptool faces "face.1157"
face split "face.150" connected keeptool faces "face.1163"
face split "face.150" connected keeptool faces "face.1162"
```

```
face split "face.1317" connected keeptool faces "face.1167"
face split "face.157" connected keeptool faces "face.1173"
face split "face.157" connected keeptool faces "face.1172"

face split "face.1327" connected keeptool faces "face.1177"
face split "face.164" connected keeptool faces "face.1183"
face split "face.164" connected keeptool faces "face.1182"

face split "face.1337" connected keeptool faces "face.1187"
face split "face.171" connected keeptool faces "face.1193"
face split "face.171" connected keeptool faces "face.1192"

face split "face.1347" connected keeptool faces "face.1197"
face split "face.178" connected keeptool faces "face.1203"
face split "face.178" connected keeptool faces "face.1202"

face split "face.1357" connected keeptool faces "face.1207"
face split "face.185" connected keeptool faces "face.1213"
face split "face.185" connected keeptool faces "face.1212"

face split "face.1367" connected keeptool faces "face.1217"
face split "face.192" connected keeptool faces "face.1221"
face split "face.192" connected keeptool faces "face.1222"

face split "face.1377" connected keeptool faces "face.1227"
face split "face.199" connected keeptool faces "face.1233"
face split "face.199" connected keeptool faces "face.1232"

face split "face.1387" connected keeptool faces "face.1237"
face split "face.206" connected keeptool faces "face.1243"
face split "face.206" connected keeptool faces "face.1242"

face split "face.1397" connected keeptool faces "face.1247"
face split "face.213" connected keeptool faces "face.1253"
face split "face.213" connected keeptool faces "face.1252"


face split "face.1452" connected keeptool faces "face.224"
face split "face.1456" connected keeptool faces "face.234"
face split "face.1460" connected keeptool faces "face.244"
face split "face.1464" connected keeptool faces "face.254"
face split "face.1468" connected keeptool faces "face.264"
face split "face.1472" connected keeptool faces "face.274"
face split "face.1476" connected keeptool faces "face.284"
face split "face.1480" connected keeptool faces "face.294"
face split "face.1484" connected keeptool faces "face.304"
face split "face.1488" connected keeptool faces "face.314"
face split "face.1492" connected keeptool faces "face.324"
face split "face.1496" connected keeptool faces "face.334"
face split "face.1500" connected keeptool faces "face.344"
face split "face.1504" connected keeptool faces "face.354"
face split "face.1508" connected keeptool faces "face.364"

/DELETING ALL THE FACES USED TO MAKE THE CUTS

face delete "jetcircle" "face.222" "face.228" "face.225" "jetcenter" \
```

```
  "face.224" "face.231" "face.232" "face.236" "face.237" "face.229" \
  "face.1456" "face.241" "face.242" "face.239" "face.248" "face.244" \
  "face.245" "face.253" "face.249" "face.252" "face.254" "face.256" \
  "face.257" "face.263" "face.259" "face.260" "face.268" "face.264" \
  "face.265" "face.273" "face.272" "face.269" "face.276" "face.277" \
  "face.274" "face.281" "face.282" "face.286" "face.279" "face.287" \
  "face.284" "face.291" "face.292" "face.296" "face.297" "face.289" \
  "face.294" "face.301" "face.299" "face.302" "face.306" "face.307" \
  "face.304" "face.311" "face.312" "face.316" "face.315" "face.309" \
  "face.314" "face.321" "face.322" "face.326" "face.327" "face.319" \
  "face.324" "face.331" "face.332" "face.329" "face.336" "face.334" \
  "face.337" "face.341" "face.342" "face.339" "face.346" "face.344" \
  "face.347" "face.351" "face.352" "face.349" "face.356" "face.354" \
  "face.357" "face.361" "face.359" "face.360" "face.366" "face.364" \
  "face.365" lowertopology
face delete "face.1104" "face.1105" "face.1107" "face.1113" "face.1112" \
  "face.115" "face.234" "face.1118" "face.1114" "face.1117" "face.1123" \
  "face.1122" "face.122" "face.1138" "face.1128" "face.1127" "face.1124" \
  "face.1133" "face.1132" "face.129" "face.1134" "face.1137" "face.1143" \
  "face.136" "face.1142" "face.1148" "face.1144" "face.1147" "face.1153" \
  "face.143" "face.1152" "face.1158" "face.1154" "face.1157" "face.1163" \
  "face.150" "face.1162" "face.1168" "face.1164" "face.1167" "face.1173" \
  "face.157" "face.1172" "face.1178" "face.1174" "face.1177" "face.1183" \
  "face.164" "face.1182" "face.1186" "face.1184" "face.1187" "face.1193" \
  "face.171" "face.1192" "face.1198" "face.1194" "face.1197" "face.1203" \
  "face.178" "face.1202" "face.1206" "face.1204" "face.1207" "face.1213" \
  "face.185" "face.1212" "face.1216" "face.1214" "face.1217" "face.1221" \
  "face.192" "face.1222" "face.1228" "face.1224" "face.1227" "face.1233" \
  "face.199" "face.1232" "face.1238" "face.1234" "face.1237" "face.1243" \
  "face.206" "face.1242" "face.1248" "face.1244" "face.1247" "face.1253" \
  "face.213" "face.1252" lowertopology
face delete "face.1109" "face.1119" "face.1129" "face.1139" "face.1149" "face.1159" \
  "face.1169" "face.1179" "face.1189" "face.1199" "face.1209" "face.1219" \
  "face.1229" "face.1239" "face.1249" lowertopology


face create "CP1" width 600 height 7.5 offset 300 (22.5+($d)/2) 0 xyplane rectangle

face create "CP2" width 600 height 7.5 offset 300 (22.5+($d)/2) ($zc) xyplane rectangle

face create "CP3" width 600 height 7.5 offset 300 (22.5+($d)/2) ($zc+$d) xyplane rectangle

face create "CP4" width 600 height 7.5 offset 300 (22.5+($d)/2) ($zc+$d+$zp) xyplane rectangle

face split "face.6" connected faces "CP4"
face split "face.114" connected faces "CP3"
face split "face.209" connected faces "CP2"
face split "face.1" connected faces "CP1"


/****************************************************************************
/**************************GEOMETRY IS FINISHED*******************************
/****************************************************************************


face modify "face.912" side "vertex.6437" "vertex.6436"
```

```
face modify "face.1600" side "vertex.7302" "vertex.7303"
face modify "face.117" side "vertex.6446" "vertex.6447"
face modify "face.646" side "vertex.3312"
face modify "face.646" side "vertex.3313"
face modify "face.647" side "vertex.3432" "vertex.3433"
face modify "face.372" side "vertex.2040" "vertex.2041"
face modify "face.376" side "vertex.2100" "vertex.2101"
face modify "face.377" side "vertex.2221" "vertex.2220"

/ LINKING ALL THE JET CENTERS

face link "face.1450" "face.640" edges "edge.6949" "edge.3518" vertices \
  "vertex.6437" "vertex.3253" reverse
face link "face.1450" "face.1257" edges "edge.6949" "edge.7340" vertices \
  "vertex.6437" "vertex.6797" reverse
face link "face.1257" "face.370" edges "edge.7340" "edge.2139" vertices \
  "vertex.6797" "vertex.2041" reverse
face link "face.1257" "face.1454" edges "edge.7340" "edge.6975" vertices \
  "vertex.6797" "vertex.6461" reverse
face link "face.1454" "face.649" edges "edge.6975" "edge.3519" vertices \
  "vertex.6461" "vertex.3255" reverse
face link "face.1454" "face.1267" edges "edge.6975" "edge.7377" vertices \
  "vertex.6461" "vertex.6831" reverse
face link "face.1267" "face.379" edges "edge.7377" "edge.2141" vertices \
  "vertex.6831" "vertex.2043" reverse
face link "face.1267" "face.1458" edges "edge.7377" "edge.7001" vertices \
  "vertex.6831" "vertex.6485" reverse
face link "face.1458" "face.659" edges "edge.7001" "edge.3520" vertices \
  "vertex.6485" "vertex.3257" reverse
face link "face.1458" "face.1277" edges "edge.7001" "edge.7414" vertices \
  "vertex.6485" "vertex.6865" reverse
face link "face.1277" "face.389" edges "edge.7414" "edge.2143" vertices \
  "vertex.6865" "vertex.2045" reverse
face link "face.1277" "face.1462" edges "edge.7414" "edge.7027" vertices \
  "vertex.6865" "vertex.6509" reverse
face link "face.1462" "face.669" edges "edge.7027" "edge.3521" vertices \
  "vertex.6509" "vertex.3259" reverse
face link "face.1462" "face.1287" edges "edge.7027" "edge.7451" vertices \
  "vertex.6509" "vertex.6899" reverse
face link "face.1287" "face.399" edges "edge.7451" "edge.2145" vertices \
  "vertex.6899" "vertex.2047" reverse
face link "face.1287" "face.1466" edges "edge.7451" "edge.7053" vertices \
  "vertex.6899" "vertex.6533" reverse
face link "face.1466" "face.679" edges "edge.7053" "edge.3522" vertices \
  "vertex.6533" "vertex.3261" reverse
face link "face.1466" "face.1297" edges "edge.7053" "edge.7488" vertices \
  "vertex.6533" "vertex.6933" reverse
face link "face.1297" "face.409" edges "edge.7488" "edge.2147" vertices \
  "vertex.6933" "vertex.2049" reverse
face link "face.1297" "face.1470" edges "edge.7488" "edge.7079" vertices \
  "vertex.6933" "vertex.6557" reverse
face link "face.1470" "face.689" edges "edge.7079" "edge.3523" vertices \
  "vertex.6557" "vertex.3263" reverse
face link "face.1470" "face.1307" edges "edge.7079" "edge.7525" vertices \
  "vertex.6557" "vertex.6967" reverse
face link "face.1307" "face.419" edges "edge.7525" "edge.2149" vertices \
```

```
  "vertex.6967" "vertex.2051" reverse
face link "face.1307" "face.1474" edges "edge.7525" "edge.7105" vertices \
  "vertex.6967" "vertex.6581" reverse
face link "face.1474" "face.1317" edges "edge.7105" "edge.7562" vertices \
  "vertex.6581" "vertex.7001" reverse
face link "face.1474" "face.699" edges "edge.7105" "edge.3524" vertices \
  "vertex.6581" "vertex.3265" reverse
face link "face.1317" "face.429" edges "edge.7562" "edge.2151" vertices \
  "vertex.7001" "vertex.2053" reverse
face link "face.1317" "face.1478" edges "edge.7562" "edge.7131" vertices \
  "vertex.7001" "vertex.6605" reverse
face link "face.1478" "face.1327" edges "edge.7131" "edge.7599" vertices \
  "vertex.6605" "vertex.7035" reverse
face link "face.1478" "face.709" edges "edge.7131" "edge.3525" vertices \
  "vertex.6605" "vertex.3267" reverse
face link "face.1327" "face.439" edges "edge.7599" "edge.2153" vertices \
  "vertex.7035" "vertex.2055" reverse
face link "face.1327" "face.1482" edges "edge.7599" "edge.7157" vertices \
  "vertex.7035" "vertex.6629" reverse
face link "face.1482" "face.719" edges "edge.7157" "edge.3526" vertices \
  "vertex.6629" "vertex.3269" reverse
face link "face.1482" "face.1337" edges "edge.7157" "edge.7636" vertices \
  "vertex.6629" "vertex.7069" reverse
face link "face.1337" "face.449" edges "edge.7636" "edge.2155" vertices \
  "vertex.7069" "vertex.2057" reverse
face link "face.1337" "face.1486" edges "edge.7636" "edge.7183" vertices \
  "vertex.7069" "vertex.6653" reverse
face link "face.1486" "face.1347" edges "edge.7183" "edge.7673" vertices \
  "vertex.6653" "vertex.7103" reverse
face link "face.1347" "face.459" edges "edge.7673" "edge.2157" vertices \
  "vertex.7103" "vertex.2059" reverse
face link "face.1486" "face.729" edges "edge.7183" "edge.3527" vertices \
  "vertex.6653" "vertex.3271" reverse
face link "face.1347" "face.1490" edges "edge.7673" "edge.7209" vertices \
  "vertex.7103" "vertex.6677" reverse
face link "face.1490" "face.1357" edges "edge.7209" "edge.7710" vertices \
  "vertex.6677" "vertex.7137" reverse
face link "face.1490" "face.739" edges "edge.7209" "edge.3528" vertices \
  "vertex.6677" "vertex.3273" reverse
face link "face.1357" "face.469" edges "edge.7710" "edge.2159" vertices \
  "vertex.7137" "vertex.2061" reverse
face link "face.1357" "face.1494" edges "edge.7710" "edge.7235" vertices \
  "vertex.7137" "vertex.6701" reverse
face link "face.1494" "face.1367" edges "edge.7235" "edge.7747" vertices \
  "vertex.6701" "vertex.7171" reverse
face link "face.1494" "face.749" edges "edge.7235" "edge.3529" vertices \
  "vertex.6701" "vertex.3275" reverse
face link "face.1367" "face.479" edges "edge.7747" "edge.2161" vertices \
  "vertex.7171" "vertex.2063" reverse
face link "face.1367" "face.1498" edges "edge.7747" "edge.7261" vertices \
  "vertex.7171" "vertex.6725" reverse
face link "face.1498" "face.1377" edges "edge.7261" "edge.7784" vertices \
  "vertex.6725" "vertex.7205" reverse
face link "face.1377" "face.489" edges "edge.7784" "edge.2163" vertices \
  "vertex.7205" "vertex.2065" reverse
face link "face.1498" "face.759" edges "edge.7261" "edge.3530" vertices \
```

```
  "vertex.6725" "vertex.3277" reverse
face link "face.1377" "face.1502" edges "edge.7784" "edge.7287" vertices \
  "vertex.7205" "vertex.6749" reverse
face link "face.1502" "face.1387" edges "edge.7287" "edge.7821" vertices \
  "vertex.6749" "vertex.7239" reverse
face link "face.1387" "face.499" edges "edge.7821" "edge.2165" vertices \
  "vertex.7239" "vertex.2067" reverse
face link "face.1387" "face.1506" edges "edge.7821" "edge.7313" vertices \
  "vertex.7239" "vertex.6773" reverse
face link "face.1502" "face.769" edges "edge.7287" "edge.3531" vertices \
  "vertex.6749" "vertex.3279" reverse
face link "face.1506" "face.1397" edges "edge.7313" "edge.7858" vertices \
  "vertex.6773" "vertex.7273" reverse
face link "face.1506" "face.779" edges "edge.7313" "edge.3532" vertices \
  "vertex.6773" "vertex.3281" reverse
face link "face.1397" "face.509" edges "edge.7858" "edge.2167" vertices \
  "vertex.7273" "vertex.2069" reverse

/LINKING ALL THE COMPLETE JETCENTERS


face link "face.1452" "face.644" edges "edge.7891" "edge.3773" vertices \
  "vertex.7303" "vertex.3433"
face link "face.1452" "face.115" edges "edge.7891" "edge.7364" vertices \
  "vertex.7303" "vertex.6819"
face link "face.1452" "face.1456" edges "edge.7891" "edge.7900" vertices \
  "vertex.7303" "vertex.7311"
face link "face.1456" "face.654" edges "edge.7900" "edge.3774" vertices \
  "vertex.7311" "vertex.3435"
face link "face.1456" "face.122" edges "edge.7900" "edge.7401" vertices \
  "vertex.7311" "vertex.6853"
face link "face.1456" "face.1460" edges "edge.7900" "edge.7909" vertices \
  "vertex.7311" "vertex.7319"
face link "face.1460" "face.1464" edges "edge.7909" "edge.7918" vertices \
  "vertex.7319" "vertex.7327"
face link "face.1460" "face.129" edges "edge.7909" "edge.7438" vertices \
  "vertex.7319" "vertex.6887"
face link "face.1460" "face.664" edges "edge.7909" "edge.3775" vertices \
  "vertex.7319" "vertex.3437"
face link "face.1464" "face.674" edges "edge.7918" "edge.3776" vertices \
  "vertex.7327" "vertex.3439"
face link "face.1464" "face.136" edges "edge.7918" "edge.7475" vertices \
  "vertex.7327" "vertex.6921"
face link "face.1464" "face.1468" edges "edge.7918" "edge.7927" vertices \
  "vertex.7327" "vertex.7335"
face link "face.1472" "face.1468" edges "edge.7936" "edge.7927" vertices \
  "vertex.7343" "vertex.7335"
face link "face.1468" "face.143" edges "edge.7927" "edge.7512" vertices \
  "vertex.7335" "vertex.6955"
face link "face.1468" "face.684" edges "edge.7927" "edge.3777" vertices \
  "vertex.7335" "vertex.3441"
face link "face.1472" "face.694" edges "edge.7936" "edge.3778" vertices \
  "vertex.7343" "vertex.3443"
face link "face.1472" "face.150" edges "edge.7936" "edge.7549" vertices \
  "vertex.7343" "vertex.6989"
face link "face.1472" "face.1476" edges "edge.7936" "edge.7945" vertices \
```

```
  "vertex.7343" "vertex.7351"
face link "face.1476" "face.1480" edges "edge.7945" "edge.7954" vertices \
  "vertex.7351" "vertex.7359"
face link "face.1476" "face.157" edges "edge.7945" "edge.7586" vertices \
  "vertex.7351" "vertex.7023"
face link "face.1476" "face.704" edges "edge.7945" "edge.3779" vertices \
  "vertex.7351" "vertex.3445"
face link "face.1480" "face.714" edges "edge.7954" "edge.3780" vertices \
  "vertex.7359" "vertex.3447"
face link "face.1480" "face.164" edges "edge.7954" "edge.7623" vertices \
  "vertex.7359" "vertex.7057"
face link "face.1480" "face.1484" edges "edge.7954" "edge.7963" vertices \
  "vertex.7359" "vertex.7367"
face link "face.1484" "face.171" edges "edge.7963" "edge.7660" vertices \
  "vertex.7367" "vertex.7091"
face link "face.1484" "face.724" edges "edge.7963" "edge.3781" vertices \
  "vertex.7367" "vertex.3449"
face link "face.1480" "face.1488" edges "edge.7954" "edge.7972" vertices \
  "vertex.7359" "vertex.7375"
face link "face.1488" "face.178" edges "edge.7972" "edge.7697" vertices \
  "vertex.7375" "vertex.7125"
face link "face.1488" "face.734" edges "edge.7972" "edge.3782" vertices \
  "vertex.7375" "vertex.3451"
face link "face.1488" "face.1492" edges "edge.7972" "edge.7981" vertices \
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  "vertex.7383" "vertex.7159"
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  "vertex.7391" "vertex.7399"
face link "face.1500" "face.1504" edges "edge.7999" "edge.8008" vertices \
  "vertex.7399" "vertex.7407"
face link "face.1504" "face.1508" edges "edge.8008" "edge.8017" vertices \
  "vertex.7407" "vertex.7415"
face link "face.1500" "face.199" edges "edge.7999" "edge.7808" vertices \
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face link "face.1500" "face.764" edges "edge.7999" "edge.3785" vertices \
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face link "face.1508" "face.784" edges "edge.8017" "edge.3787" vertices \
  "vertex.7415" "vertex.3461"
face link "face.1504" "face.206" edges "edge.8008" "edge.7845" vertices \
  "vertex.7407" "vertex.7261"
face link "face.1508" "face.213" edges "edge.8017" "edge.7882" vertices \
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/linking the jetcenters of the bottom of the channel. one of them has to be reversed but the otherones are not
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face link "face.115" "face.374" edges "edge.7364" "edge.2394" vertices \
  "vertex.6819" "vertex.2221" reverse

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face link "face.444" "face.454" edges "edge.2408" "edge.2410" vertices \
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  "vertex.2241" "vertex.2243"
face link "face.484" "face.494" edges "edge.2416" "edge.2418" vertices \
  "vertex.2243" "vertex.2245"
face link "face.494" "face.504" edges "edge.2418" "edge.2420" vertices \
  "vertex.2245" "vertex.2247"
face link "face.504" "face.514" edges "edge.2420" "edge.2422" vertices \
  "vertex.2247" "vertex.2249"

/UP TO THIS POINT, ALL THE FACES ARE CONNCTED SUCCESSFULLY.
/LINKING THE FIRST THREE JET TELEPHONES



/face link "face.912" "face.117" edges "edge.6950" "edge.6960" vertices \
/  "vertex.6437" "vertex.6446" reverse
/face link "face.912" "face.1600" edges "edge.6950" "edge.7890" vertices \
/  "vertex.6437" "vertex.7303" reverse
face link "face.912" "face.372" edges "edge.6950" "edge.2168" vertices \
  "vertex.6437" "vertex.2041"
face link "face.117" "face.376" edges "edge.6959" "edge.2304" vertices \
  "vertex.6447" "vertex.2101" reverse
face link "face.1600" "face.377" edges "edge.7890" "edge.2423" vertices \
  "vertex.7303" "vertex.2221" reverse
face link "face.372" "face.382" edges "edge.2168" "edge.2169" vertices \
  "vertex.2041" "vertex.2043"
face link "face.377" "face.387" edges "edge.2423" "edge.2424" vertices \
  "vertex.2221" "vertex.2223"
face link "face.376" "face.386" edges "edge.2304" "edge.2306" vertices \
  "vertex.2101" "vertex.2103"
face link "face.387" "face.397" edges "edge.2424" "edge.2425" vertices \
  "vertex.2223" "vertex.2225"
face link "face.386" "face.396" edges "edge.2306" "edge.2308" vertices \
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  "vertex.2103" "vertex.2105"
face link "face.382" "face.392" edges "edge.2169" "edge.2170" vertices \
  "vertex.2043" "vertex.2045"
face link "face.382" "face.392" edges "edge.2169" "edge.2170" vertices \
  "vertex.2043" "vertex.2045"
face link "face.382" "face.392" edges "edge.2169" "edge.2170" vertices \
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face link "face.382" "face.392" edges "edge.2169" "edge.2170" vertices \
  "vertex.2043" "vertex.2045"
face link "face.397" "face.407" edges "edge.2425" "edge.2426" vertices \
  "vertex.2225" "vertex.2227"
face link "face.392" "face.402" edges "edge.2170" "edge.2171" vertices \
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face link "face.396" "face.406" edges "edge.2290" "edge.2291" vertices \
  "vertex.2104" "vertex.2106"
face link "face.407" "face.417" edges "edge.2426" "edge.2427" vertices \
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  "vertex.2231" "vertex.2233"
face link "face.437" "face.447" edges "edge.2429" "edge.2430" vertices \
  "vertex.2233" "vertex.2235"
face link "face.447" "face.457" edges "edge.2430" "edge.2431" vertices \
  "vertex.2235" "vertex.2237"
face link "face.457" "face.467" edges "edge.2431" "edge.2432" vertices \
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face link "face.467" "face.477" edges "edge.2432" "edge.2433" vertices \
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face link "face.406" "face.416" edges "edge.2291" "edge.2292" vertices \
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face link "face.416" "face.426" edges "edge.2292" "edge.2293" vertices \
  "vertex.2108" "vertex.2110"
face link "face.426" "face.436" edges "edge.2293" "edge.2294" vertices \
  "vertex.2110" "vertex.2112"
face link "face.436" "face.446" edges "edge.2294" "edge.2295" vertices \
  "vertex.2112" "vertex.2114"
face link "face.446" "face.456" edges "edge.2295" "edge.2296" vertices \
  "vertex.2114" "vertex.2116"
face link "face.456" "face.466" edges "edge.2296" "edge.2297" vertices \
  "vertex.2116" "vertex.2118"
face link "face.466" "face.476" edges "edge.2297" "edge.2298" vertices \
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  "vertex.2122" "vertex.2124"
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face link "face.502" "face.512" edges "edge.2181" "edge.2182" vertices \
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/LINKING THE TELEPHONES OF THE BOTTOM OF THE PLENUM

face link "face.912" "face.922" edges "edge.6950" "edge.6976" vertices \
  "vertex.6437" "vertex.6461"
face link "face.922" "face.932" edges "edge.6976" "edge.7002" vertices \
  "vertex.6461" "vertex.6485"
face link "face.932" "face.942" edges "edge.7002" "edge.7028" vertices \
  "vertex.6485" "vertex.6509"
face link "face.942" "face.952" edges "edge.7028" "edge.7054" vertices \
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face link "face.952" "face.962" edges "edge.7054" "edge.7080" vertices \
  "vertex.6533" "vertex.6557"
face link "face.962" "face.972" edges "edge.7080" "edge.7106" vertices \
  "vertex.6557" "vertex.6581"
face link "face.972" "face.982" edges "edge.7106" "edge.7132" vertices \
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face link "face.982" "face.992" edges "edge.7132" "edge.7158" vertices \
  "vertex.6605" "vertex.6629"
face link "face.992" "face.1002" edges "edge.7158" "edge.7184" vertices \
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face link "face.1600" "face.1602" edges "edge.7890" "edge.7899" vertices \
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face link "face.1608" "face.1610" edges "edge.7926" "edge.7935" vertices \
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face link "face.1624" "face.1626" edges "edge.7998" "edge.8007" vertices \
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face link "face.1626" "face.1628" edges "edge.8007" "edge.8016" vertices \
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/LINKING ALL THE TELEPHONES OF THE TOP OF THE CHANNEL

face link "face.912" "face.1510" edges "edge.6950" "edge.7339" vertices \
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face link "face.117" "face.1512" edges "edge.6959" "edge.7349" vertices \
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face link "face.1600" "face.1514" edges "edge.7890" "edge.7363" vertices \
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face link "face.1516" "face.1522" edges "edge.7376" "edge.7413" vertices \
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face link "face.1522" "face.1528" edges "edge.7413" "edge.7450" vertices \
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face link "face.1528" "face.1534" edges "edge.7450" "edge.7487" vertices \
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face link "face.1546" "face.1552" edges "edge.7561" "edge.7598" vertices \
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face link "face.1564" "face.1570" edges "edge.7672" "edge.7709" vertices \
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face link "face.1570" "face.1576" edges "edge.7709" "edge.7746" vertices \
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face link "face.1576" "face.1582" edges "edge.7746" "edge.7783" vertices \
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face link "face.1582" "face.1588" edges "edge.7783" "edge.7820" vertices \
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face link "face.1588" "face.1594" edges "edge.7820" "edge.7857" vertices \
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face link "face.1518" "face.1524" edges "edge.7387" "edge.7424" vertices \
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face link "face.1536" "face.1542" edges "edge.7498" "edge.7535" vertices \
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face link "face.1560" "face.1566" edges "edge.7646" "edge.7683" vertices \
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face link "face.1566" "face.1572" edges "edge.7683" "edge.7720" vertices \
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face link "face.1572" "face.1578" edges "edge.7720" "edge.7757" vertices \
  "vertex.7146" "vertex.7180"
face link "face.1578" "face.1584" edges "edge.7757" "edge.7794" vertices \
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face link "face.1584" "face.1590" edges "edge.7794" "edge.7831" vertices \
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face link "face.1590" "face.1596" edges "edge.7831" "edge.7868" vertices \
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face link "face.1514" "face.1520" edges "edge.7363" "edge.7400" vertices \
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face link "face.1520" "face.1526" edges "edge.7400" "edge.7437" vertices \
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face link "face.1526" "face.1532" edges "edge.7437" "edge.7474" vertices \
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face link "face.1538" "face.1544" edges "edge.7511" "edge.7548" vertices \
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face link "face.1544" "face.1550" edges "edge.7548" "edge.7585" vertices \
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face link "face.1568" "face.1574" edges "edge.7696" "edge.7733" vertices \
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  "vertex.7159" "vertex.7193"
face link "face.1580" "face.1586" edges "edge.7770" "edge.7807" vertices \
  "vertex.7193" "vertex.7227"
face link "face.1586" "face.1592" edges "edge.7807" "edge.7844" vertices \
  "vertex.7227" "vertex.7261"
face link "face.1592" "face.1598" edges "edge.7844" "edge.7881" vertices \
  "vertex.7261" "vertex.7295"

/LINKING ALL THE TELEPHONES OF THE TOP OF THE PLENUM

face link "face.912" "face.642" edges "edge.6950" "edge.3489" vertices \
  "vertex.6437" "vertex.3253" reverse
/face link "face.642" "face.647" edges "edge.3489" "edge.3744" vertices \
/  "vertex.3253" "vertex.3433"
face link "face.117" "face.646" edges "edge.6959" "edge.3638" vertices \
  "vertex.6447" "vertex.3313"
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face link "face.776" "face.786" edges "edge.3679" "edge.3681" vertices \
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face link "face.777" "face.787" edges "edge.3770" "edge.3772" vertices \
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face link "face.647" "face.1600" edges "edge.3685" "edge.6963" vertices \
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/LINKING OUTBOXES ON THE PLENUM

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face modify "face.918" side "vertex.4405" "vertex.4404"

/face link "face.911" "face.915" edges "edge.4778" "edge.4898" vertices \
/  "vertex.4374" "vertex.4434"
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face link "face.911" "face.641" edges "edge.4779" "edge.3578" vertices \
  "vertex.4405" "vertex.3283" reverse
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face link "face.685" "face.695" edges "edge.3837" "edge.3838" vertices \
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face link "face.1040" "face.1050" edges "edge.4805" "edge.4807" vertices \
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/LINKING THE TOP OF THE CHANEL OUTBOXES

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face modify "face.1263" side "vertex.6322" "vertex.6321"
face modify "face.1260" side "vertex.6397" "vertex.6396"
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/face link "face.371" "face.375" edges "edge.2053" "edge.2336" vertices \
/  "vertex.1955" "vertex.2135"
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/LINKING THE BOTTOM OF THE CHANEL OUTBOXES

face link "face.375" "face.385" edges "edge.2440" "edge.2443" vertices \
  "vertex.2251" "vertex.2253"
face link "face.385" "face.395" edges "edge.2443" "edge.2446" vertices \
  "vertex.2253" "vertex.2255"
face link "face.395" "face.405" edges "edge.2446" "edge.2449" vertices \
  "vertex.2255" "vertex.2257"
face link "face.405" "face.415" edges "edge.2449" "edge.2452" vertices \
  "vertex.2257" "vertex.2259"
face link "face.415" "face.425" edges "edge.2452" "edge.2455" vertices \
  "vertex.2259" "vertex.2261"
face link "face.425" "face.435" edges "edge.2455" "edge.2458" vertices \
  "vertex.2261" "vertex.2263"
face link "face.435" "face.445" edges "edge.2458" "edge.2461" vertices \
  "vertex.2263" "vertex.2265"
face link "face.445" "face.455" edges "edge.2461" "edge.2464" vertices \
  "vertex.2265" "vertex.2267"
face link "face.455" "face.465" edges "edge.2464" "edge.2467" vertices \
```

```
  "vertex.2267" "vertex.2269"
face link "face.465" "face.475" edges "edge.2467" "edge.2470" vertices \
  "vertex.2269" "vertex.2271"
face link "face.475" "face.485" edges "edge.2470" "edge.2473" vertices \
  "vertex.2271" "vertex.2273"
face link "face.485" "face.495" edges "edge.2473" "edge.2476" vertices \
  "vertex.2273" "vertex.2275"
face link "face.495" "face.505" edges "edge.2476" "edge.2479" vertices \
  "vertex.2275" "vertex.2277"
face link "face.505" "face.515" edges "edge.2479" "edge.2482" vertices \
  "vertex.2277" "vertex.2279"
face link "face.378" "face.388" edges "edge.2245" "edge.2248" vertices \
  "vertex.2135" "vertex.2141"
face link "face.388" "face.398" edges "edge.2248" "edge.2251" vertices \
  "vertex.2141" "vertex.2147"
face link "face.398" "face.408" edges "edge.2251" "edge.2254" vertices \
  "vertex.2147" "vertex.2153"
face link "face.408" "face.418" edges "edge.2254" "edge.2257" vertices \
  "vertex.2153" "vertex.2159"
face link "face.418" "face.428" edges "edge.2257" "edge.2260" vertices \
  "vertex.2159" "vertex.2165"
face link "face.428" "face.438" edges "edge.2260" "edge.2263" vertices \
  "vertex.2165" "vertex.2171"
face link "face.438" "face.448" edges "edge.2263" "edge.2266" vertices \
  "vertex.2171" "vertex.2177"
face link "face.448" "face.458" edges "edge.2266" "edge.2269" vertices \
  "vertex.2177" "vertex.2183"
face link "face.458" "face.468" edges "edge.2269" "edge.2272" vertices \
  "vertex.2183" "vertex.2189"
face link "face.468" "face.478" edges "edge.2272" "edge.2275" vertices \
  "vertex.2189" "vertex.2195"
face link "face.478" "face.488" edges "edge.2275" "edge.2278" vertices \
  "vertex.2195" "vertex.2201"
face link "face.488" "face.498" edges "edge.2278" "edge.2281" vertices \
  "vertex.2201" "vertex.2207"
face link "face.498" "face.508" edges "edge.2281" "edge.2284" vertices \
  "vertex.2207" "vertex.2213"
face link "face.508" "face.518" edges "edge.2284" "edge.2287" vertices \
  "vertex.2213" "vertex.2219"
face link "face.371" "face.380" edges "edge.2185" "edge.2188" vertices \
  "vertex.2071" "vertex.2073"
face link "face.380" "face.390" edges "edge.2188" "edge.2191" vertices \
  "vertex.2073" "vertex.2075"
face link "face.390" "face.400" edges "edge.2191" "edge.2194" vertices \
  "vertex.2075" "vertex.2077"
face link "face.400" "face.410" edges "edge.2194" "edge.2197" vertices \
  "vertex.2077" "vertex.2079"
face link "face.410" "face.420" edges "edge.2197" "edge.2200" vertices \
  "vertex.2079" "vertex.2081"
face link "face.420" "face.430" edges "edge.2200" "edge.2203" vertices \
  "vertex.2081" "vertex.2083"
face link "face.430" "face.440" edges "edge.2203" "edge.2206" vertices \
  "vertex.2083" "vertex.2085"
face link "face.440" "face.450" edges "edge.2206" "edge.2209" vertices \
  "vertex.2085" "vertex.2087"
face link "face.450" "face.460" edges "edge.2209" "edge.2212" vertices \
```

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  "vertex.2087" "vertex.2089"
face link "face.460" "face.470" edges "edge.2212" "edge.2215" vertices \
  "vertex.2089" "vertex.2091"
face link "face.470" "face.480" edges "edge.2215" "edge.2218" vertices \
  "vertex.2091" "vertex.2093"
face link "face.480" "face.490" edges "edge.2218" "edge.2221" vertices \
  "vertex.2093" "vertex.2095"
face link "face.490" "face.500" edges "edge.2221" "edge.2224" vertices \
  "vertex.2095" "vertex.2097"
face link "face.500" "face.510" edges "edge.2224" "edge.2227" vertices \
  "vertex.2097" "vertex.2099"

/TOP SIDE BOX beginning of channel

face link "face.1649" "face.1633" edges "edge.97" "edge.3533" vertices \
  "vertex.4374" "vertex.3162" reverse

/TOP SIDE BOXES

face link "face.1650" "face.1651" edges "edge.4749" "edge.4751" vertices \
  "vertex.4376" "vertex.4378"
face link "face.1652" "face.1653" edges "edge.4753" "edge.4755" vertices \
  "vertex.4380" "vertex.4382"
face link "face.1653" "face.1654" edges "edge.4755" "edge.4757" vertices \
  "vertex.4382" "vertex.4384"
face link "face.1654" "face.1655" edges "edge.4757" "edge.4759" vertices \
  "vertex.4384" "vertex.4386"
face link "face.1655" "face.1656" edges "edge.4759" "edge.4761" vertices \
  "vertex.4386" "vertex.4388"
face link "face.1656" "face.114" edges "edge.4761" "edge.4763" vertices \
  "vertex.4388" "vertex.4390"
face link "face.114" "face.1657" edges "edge.4763" "edge.4765" vertices \
  "vertex.4390" "vertex.4392"
face link "face.1657" "face.1658" edges "edge.4765" "edge.4767" vertices \
  "vertex.4392" "vertex.4394"
face link "face.1658" "face.1659" edges "edge.4767" "edge.4769" vertices \
  "vertex.4394" "vertex.4396"
face link "face.1659" "face.1660" edges "edge.4769" "edge.4771" vertices \
  "vertex.4396" "vertex.4398"
face link "face.1660" "face.1661" edges "edge.4771" "edge.4773" vertices \
  "vertex.4398" "vertex.4400"
face link "face.1661" "face.1662" edges "edge.4773" "edge.4775" vertices \
  "vertex.4400" "vertex.4402"
face link "face.1650" "face.1634" edges "edge.4900" "edge.8036" vertices \
  "vertex.4481" "vertex.3464" reverse
face link "face.1634" "face.1635" edges "edge.8036" "edge.8037" vertices \
  "vertex.3464" "vertex.3466"
face link "face.1635" "face.1636" edges "edge.8037" "edge.8038" vertices \
  "vertex.3466" "vertex.3468"
face link "face.1636" "face.1637" edges "edge.8038" "edge.8039" vertices \
  "vertex.3468" "vertex.3470"
face link "face.1637" "face.1638" edges "edge.8039" "edge.8040" vertices \
  "vertex.3470" "vertex.3472"
face link "face.1638" "face.1639" edges "edge.8040" "edge.8041" vertices \
  "vertex.3472" "vertex.3474"
face link "face.1639" "face.6" edges "edge.8041" "edge.8042" vertices \
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  "vertex.3474" "vertex.3476"
face link "face.6" "face.1640" edges "edge.8042" "edge.8043" vertices \
  "vertex.3476" "vertex.3478"
face link "face.1640" "face.1641" edges "edge.8043" "edge.8044" vertices \
  "vertex.3478" "vertex.3480"
face link "face.1641" "face.1642" edges "edge.8044" "edge.8045" vertices \
  "vertex.3480" "vertex.3482"
face link "face.1642" "face.1643" edges "edge.8045" "edge.8046" vertices \
  "vertex.3482" "vertex.3484"
face link "face.1643" "face.1644" edges "edge.8046" "edge.8047" vertices \
  "vertex.3484" "vertex.3486"
face link "face.1644" "face.1645" edges "edge.8047" "edge.8048" vertices \
  "vertex.3486" "vertex.3488"
face link "face.1645" "face.1646" edges "edge.8048" "edge.8049" vertices \
  "vertex.3488" "vertex.3490"
face link "face.1651" "face.1652" edges "edge.4751" "edge.4753" vertices \
  "vertex.4378" "vertex.4380"

/TOP SIDE BOX END OF CHANNEL

face link "face.1647" "face.1663" edges "edge.8050" "edge.99" vertices \
  "vertex.7433" "vertex.7435" reverse

/TOP SIDE BOX BACK OF CHANNEL

face link "face.1648" "face.1664" edges "edge.12" "edge.8069" vertices \
  "vertex.8" "vertex.84" reverse

/BOTTOM SIDE BOX

face link "face.1665" "face.1681" edges "edge.6773" "edge.2048" vertices \
  "vertex.6291" "vertex.1950" reverse
face link "face.1680" "face.1696" edges "edge.8071" "edge.8105" vertices \
  "vertex.7436" "vertex.7438" reverse
face link "face.1666" "face.1667" edges "edge.6894" "edge.6896" vertices \
  "vertex.6397" "vertex.6399"
face link "face.1667" "face.1668" edges "edge.6896" "edge.6898" vertices \
  "vertex.6399" "vertex.6401"
face link "face.1668" "face.1669" edges "edge.6898" "edge.6900" vertices \
  "vertex.6401" "vertex.6403"
face link "face.1669" "face.1670" edges "edge.6900" "edge.6902" vertices \
  "vertex.6403" "vertex.6405"
face link "face.1670" "face.1671" edges "edge.6902" "edge.6904" vertices \
  "vertex.6405" "vertex.6407"
face link "face.1671" "face.209" edges "edge.6904" "edge.6906" vertices \
  "vertex.6407" "vertex.6409"
face link "face.209" "face.1672" edges "edge.6906" "edge.6908" vertices \
  "vertex.6409" "vertex.6411"
face link "face.1672" "face.1673" edges "edge.6908" "edge.6910" vertices \
  "vertex.6411" "vertex.6413"
face link "face.1673" "face.1674" edges "edge.6910" "edge.6912" vertices \
  "vertex.6413" "vertex.6415"
face link "face.1674" "face.1675" edges "edge.6912" "edge.6914" vertices \
  "vertex.6415" "vertex.6417"
face link "face.1675" "face.1676" edges "edge.6914" "edge.6916" vertices \
  "vertex.6417" "vertex.6419"
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face link "face.1676" "face.1677" edges "edge.6916" "edge.6918" vertices \
  "vertex.6419" "vertex.6421"
face link "face.1677" "face.1678" edges "edge.6918" "edge.6920" vertices \
  "vertex.6421" "vertex.6423"
face link "face.1666" "face.1682" edges "edge.6894" "edge.8090" vertices \
  "vertex.6397" "vertex.2251" reverse
face link "face.1682" "face.1683" edges "edge.8090" "edge.8091" vertices \
  "vertex.2251" "vertex.2253"
face link "face.1683" "face.1684" edges "edge.8091" "edge.8092" vertices \
  "vertex.2253" "vertex.2255"
face link "face.1684" "face.1685" edges "edge.8092" "edge.8093" vertices \
  "vertex.2255" "vertex.2257"
face link "face.1685" "face.1686" edges "edge.8093" "edge.8094" vertices \
  "vertex.2257" "vertex.2259"
face link "face.1686" "face.1687" edges "edge.8094" "edge.8095" vertices \
  "vertex.2259" "vertex.2261"
face link "face.1687" "face.1688" edges "edge.8095" "edge.8096" vertices \
  "vertex.2261" "vertex.2263"
face link "face.1688" "face.1" edges "edge.8096" "edge.8097" vertices \
  "vertex.2263" "vertex.2265"
face link "face.1" "face.1689" edges "edge.8097" "edge.8098" vertices \
  "vertex.2265" "vertex.2267"
face link "face.1689" "face.1690" edges "edge.8098" "edge.8099" vertices \
  "vertex.2267" "vertex.2269"
face link "face.1690" "face.1691" edges "edge.8099" "edge.8100" vertices \
  "vertex.2269" "vertex.2271"
face link "face.1691" "face.1692" edges "edge.8100" "edge.8101" vertices \
  "vertex.2271" "vertex.2273"
face link "face.1692" "face.1693" edges "edge.8101" "edge.8102" vertices \
  "vertex.2273" "vertex.2275"
face link "face.1693" "face.1694" edges "edge.8102" "edge.8103" vertices \
  "vertex.2275" "vertex.2277"
face link "face.1679" "face.1695" edges "edge.89" "edge.2227" vertices \
  "vertex.6320" "vertex.2039" reverse

//////////////////////////////////////////////////////////////////
///////////////////MESHING BEGINS HERE/////////////////////
//////////////////////////////////////////////////////////////////

/..............................................................
/................BOUNDARY LAYERS BEGINS HERE..................
/..............................................................



/BOUNDARY LAYER FOR THE bottom of plenum
blayer create first $first growth $growth  rows $rows transition 1 trows 0 \
  uniform
blayer attach "b_layer.1" face "face.2" "face.2" "face.2" "face.2" "face.2" \
  "face.2" "face.2" "face.2" "face.2" "face.2" "face.2" "face.2" "face.2" \
  "face.2" "face.2" "face.2" "face.2" "face.2" "face.2" "face.2" "face.2" \
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  "edge.4748" "edge.106" "edge.6946" "edge.6947" "edge.107" "edge.4749" \
  "edge.4750" "edge.116" "edge.6972" "edge.6973" "edge.117" "edge.4751" \
  "edge.4752" "edge.126" "edge.6998" "edge.6999" "edge.127" "edge.4753" \
  "edge.4754" "edge.136" "edge.7024" "edge.7025" "edge.137" "edge.4755" \
  "edge.4756" "edge.146" "edge.7050" "edge.7051" "edge.147" "edge.4757" \
  "edge.4758" "edge.156" "edge.7076" "edge.7077" "edge.157" "edge.4759" \
  "edge.4760" "edge.166" "edge.7102" "edge.7103" "edge.167" "edge.4761" \
  "edge.4762" "edge.176" "edge.7128" "edge.7129" "edge.177" "edge.4763" \
  "edge.4764" "edge.186" "edge.7154" "edge.7155" "edge.187" "edge.4765" \
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  "edge.4770" "edge.216" "edge.7232" "edge.7233" "edge.217" "edge.4771" \
  "edge.4772" "edge.226" "edge.7258" "edge.7259" "edge.227" "edge.4773" \
  "edge.4774" "edge.236" "edge.7284" "edge.7285" "edge.237" "edge.4775" \
  "edge.4776" "edge.246" "edge.7310" "edge.7311" "edge.247" "edge.4777" add

/MESHING THE PLENUM

blayer create first $first growth $growth rows $rows transition 1 trows 0 \
  uniform
blayer attach "b_layer.2" face "face.4" "face.4" "face.5" "face.110" \
  "face.110" edge "edge.99" "edge.8069" "edge.100" "edge.8052" "edge.98" add

blayer create first $first growth $growth rows $rows transition 1 trows 0 \
  uniform
blayer attach "b_layer.4" face "face.1649" "face.1664" "face.1664" \
  "face.1664" "face.1663" edge "edge.8052" "edge.98" "edge.100" "edge.8069" \
  "edge.99" add

blayer create first $first growth $growth rows $rows transition 1 trows 0 \
  uniform
blayer attach "b_layer.4" face "face.2" "face.2" "face.2" "face.2" "face.2" \
  "face.2" "face.2" "face.2" "face.2" "face.2" "face.2" "face.2" "face.2" \
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  "edge.3477" "edge.3478" "edge.3479" "edge.3480" "edge.3487" "edge.11" \
  "edge.3482" "edge.3483" "edge.3484" "edge.3485" "edge.3486" "edge.8051" \
  "edge.12" "edge.10" "edge.8034" add

blayer create first $first growth $growth rows $rows transition 1 trows 0 \
  uniform
blayer attach "b_layer.5" face "face.1663" "face.1664" "face.1664" \
  "face.1664" "face.1649" edge "edge.99" "edge.8069" "edge.100" "edge.98" \
  "edge.8052" add

/BOUNDARY LAYER OF THE HOLES

blayer create first $first growth $growth rows $rows transition 1 trows 0 \
  uniform
blayer attach "b_layer.1" face "face.642" edge "edge.3534" add

blayer create first $first growth $growth rows $rows transition 1 trows 0 \
  uniform
blayer attach "b_layer.7" face "face.117" "face.1600" edge "edge.4824" \
  "edge.110" add


/BONDARY LAYER OF THE CHANNEL
////////////////////////////////////////////////////////////////////////////////
////////////////////TARGET WALL BOUNDARY LAYER/////////////////////////////////
////////////////////////////////////////////////////////////////////////////////

                        ////////////////
                        //BBB////L//////
                        //B//B///L//////
                        //B//B///L//////
                        //BBB////L//////
                        //B//B///L//////
                        //B//B///L//////
                        //BBB////LLLLL//
                        ////////////////

blayer create first $firstch growth $growthch rows $rowsch transition 1 trows 0 \
  uniform
blayer attach "b_layer.8" face "face.103" "face.103" "face.103" "face.103" \
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  "face.104" "face.104" edge "edge.2048" "edge.2049" "edge.2050" "edge.2051" \
  "edge.2052" "edge.2053" "edge.2054" "edge.2055" "edge.2056" "edge.2057" \
  "edge.2058" "edge.2059" "edge.2060" "edge.2061" "edge.2062" "edge.2063" \
  "edge.2064" "edge.2065" "edge.2066" "edge.2072" "edge.2067" "edge.2068" \
  "edge.2069" "edge.2070" "edge.2071" "edge.2084" "edge.2078" "edge.2073" \
  "edge.2074" "edge.2075" "edge.2076" "edge.2077" "edge.2079" "edge.2080" \
  "edge.2081" "edge.2082" "edge.2083" "edge.2090" "edge.2096" "edge.2085" \
  "edge.2086" "edge.2087" "edge.2088" "edge.2089" "edge.2091" "edge.2092" \
  "edge.2093" "edge.2094" "edge.2095" "edge.2102" "edge.2108" "edge.2097" \
  "edge.2098" "edge.2099" "edge.2100" "edge.2101" "edge.2103" "edge.2104" \
  "edge.2105" "edge.2106" "edge.2107" "edge.2114" "edge.2120" "edge.2109" \
  "edge.2110" "edge.2111" "edge.2112" "edge.2113" "edge.2115" "edge.2116" \
  "edge.2117" "edge.2118" "edge.2119" "edge.2126" "edge.2132" "edge.2121" \
  "edge.2122" "edge.2123" "edge.2124" "edge.2125" "edge.2127" "edge.2128" \
  "edge.2129" "edge.2130" "edge.2131" "edge.2133" "edge.2134" "edge.2136" \
  "edge.2137" "edge.1" "edge.2135" "edge.8088" "edge.3" "edge.4" "edge.8105" \
  "edge.2" add

///////////////////////////////////////////////////////////////////////////////

blayer create first $firstch growth $growthch rows $rowsch transition 1 trows 0 \
  uniform
blayer attach "b_layer.9" face "face.1681" "face.1696" "face.1696" \
  "face.1696" "face.1695" edge "edge.2" "edge.8105" "edge.4" "edge.3" \
  "edge.8088" add

//
blayer create first $firstch growth $growthch rows $rowsch transition 1 trows 0 \
  uniform
blayer attach "b_layer.10" face "face.103" "face.103" "face.103" \
  "face.103" "face.103" "face.103" "face.103" "face.103" "face.103" \
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  "face.106" "face.104" "face.104" edge "edge.6743" "edge.101" \
  "edge.7336" "edge.7337" "edge.102" "edge.6744" "edge.6745" "edge.111" \
  "edge.7373" "edge.7374" "edge.112" "edge.6746" "edge.6747" "edge.121" \
  "edge.7410" "edge.7411" "edge.122" "edge.6748" "edge.6749" "edge.131" \
  "edge.7447" "edge.7448" "edge.132" "edge.6750" "edge.6751" "edge.141" \
  "edge.7484" "edge.7485" "edge.142" "edge.6752" "edge.6755" "edge.6753" \
  "edge.151" "edge.6754" "edge.7521" "edge.7522" "edge.152" "edge.161" \
```

```
  "edge.6756" "edge.6757" "edge.7558" "edge.7559" "edge.162" "edge.171" \
  "edge.7595" "edge.7596" "edge.172" "edge.6758" "edge.6759" "edge.181" \
  "edge.7632" "edge.7633" "edge.182" "edge.6760" "edge.6761" "edge.191" \
  "edge.7669" "edge.7670" "edge.192" "edge.6762" "edge.6763" "edge.6767" \
  "edge.6765" "edge.201" "edge.7706" "edge.7707" "edge.202" "edge.6764" \
  "edge.211" "edge.6766" "edge.7743" "edge.7744" "edge.212" "edge.6769" \
  "edge.221" "edge.6768" "edge.7780" "edge.7781" "edge.222" "edge.6771" \
  "edge.231" "edge.6770" "edge.7817" "edge.7818" "edge.232" "edge.241" \
  "edge.7854" "edge.7855" "edge.242" "edge.6772" "edge.89" "edge.8070" \
  "edge.91" "edge.92" "edge.8087" "edge.90" add

blayer create first $first growth $growth rows $rows transition 1 trows 0 \
  uniform
blayer attach "b_layer.11" face "face.4" "face.5" "face.2" "face.5" \
  "face.110" "face.2" edge "edge.8" "edge.8" "edge.6" "edge.7" "edge.7" \
  "edge.5" add
blayer create first $firstch growth $growthch rows $rowsch transition 1 trows 0 \
  uniform
blayer attach "b_layer.12" face "face.106" "face.104" "face.103" "face.105" \
  edge "edge.87" "edge.87" "edge.85" "edge.88" add

/.........................................................................
/.........................BOUNDARY LAYERS ENDS HERE........................
/.........................................................................

edge picklink "edge.6948" "edge.6949"
edge mesh "edge.6949" "edge.6948" successive ratio1 1 intervals $NumbNodes
edge picklink "edge.6950"
edge mesh "edge.6950" successive ratio1 1 intervals ($NumbNodes*2)
face mesh "face.1450" map

edge picklink "edge.6963" "edge.6947"
edge mesh "edge.6947" "edge.6963" successive ratio1 1 intervals ($Numbtelnodes+$rows)

face mesh "face.912" map
edge picklink "edge.6961" "edge.6960" "edge.7889" "edge.7890"
edge mesh "edge.7890" "edge.7889" "edge.6960" "edge.6961" successive ratio1 1 \
  intervals ($NumbNodes)
edge picklink "edge.6959" "edge.7891"
edge mesh "edge.7891" "edge.6959" successive ratio1 1 intervals ($NumbNodes*2)
face mesh "face.1452" map
face mesh "face.1600" "face.117" map

/blayer create first $first growth $growth rows $rows transition 1 trows 0 \
/  uniform
/blayer attach "b_layer.12" face "face.2" "face.110" "face.5" "face.110" \
/  "face.2" "face.4" "face.5" "face.4" edge "edge.5" "edge.5" "edge.7" \
/  "edge.7" "edge.6" "edge.6" "edge.8" "edge.8" add

/Meshing constants
/$NumbNodes=5
/$Numbtelnodes=6
/$PLobnodes=5
/$Chobnodes=5
/$Plbenodes=($NumbNodes*(4)+$rows)
/$plsqnodes=($NumbNodes*(3))
```

```
/$Pllsnodes=($NumbNodes+$rows)
/$Nojetcells=10

edge picklink "edge.3686" "edge.3402"
edge mesh "edge.3686" "edge.3402" successive ratio1 1 intervals ($PLobnodes)
edge picklink "edge.6744" "edge.6864"
edge mesh "edge.6864" "edge.6744" successive ratio1 1 intervals 5
face link "face.1260" "face.375" edges "edge.6923" "edge.2440" vertices \
  "vertex.6397" "vertex.2251" reverse
face modify "face.915" side "vertex.4479" "vertex.4480"
face mesh "face.915" "face.918" "face.911" map size 1
face mesh "face.1260" "face.1263" "face.1256" map size 1
edge picklink "edge.8068" "edge.8053"
edge mesh "edge.8068" "edge.8053" successive ratio1 1 intervals ($Plbenodes)
edge picklink "edge.8086" "edge.8071"
edge mesh "edge.8071" "edge.8086" successive ratio1 1 intervals ($CHbenodes)
edge delete "edge.8053" "edge.8068" keepsettings onlymesh
edge mesh "edge.8053" "edge.8068" successive ratio1 1 intervals ($Plbenodes)
edge delete "edge.8090" keepsettings onlymesh
edge picklink "edge.8090"
edge mesh "edge.8090" successive ratio1 1 intervals ($plsqnodes)
edge delete "edge.8054" keepsettings onlymesh
edge picklink "edge.8054"
edge mesh "edge.8054" successive ratio1 1 intervals ($plsqnodes)
face mesh "face.1647" "face.1679" "face.1678" "face.1646" "face.1633" \
  "face.1665" map
edge delete "edge.98" "edge.8087" keepsettings onlymesh
edge picklink "edge.8087" "edge.98"
edge mesh "edge.98" successive ratio1 1 intervals ($Pllsnodes)
edge mesh "edge.8087" successive ratio1 1 intervals ($CHlsnodes)
face mesh "face.1648" "face.1680" map

///////////////////////////////////
//////COOPERING ALL THE JETS////////
///////////////////////////////////

volume mesh "volume.3" cooper source "face.1600" "face.1452" "face.117" \
  "face.1514" "face.1512" "face.115" intervals ($Nojetcells)
volume mesh "volume.5" cooper source "face.1456" "face.1602" "face.124" \
  "face.1518" "face.1520" "face.122" intervals ($Nojetcells)
volume mesh "volume.7" cooper source "face.1460" "face.1604" "face.131" \
  "face.1526" "face.1524" "face.129" intervals ($Nojetcells)
volume mesh "volume.9" cooper source "face.1464" "face.1606" "face.138" \
  "face.1532" "face.1530" "face.136" intervals ($Nojetcells)
volume mesh "volume.11" cooper source "face.1468" "face.1608" "face.145" \
  "face.1538" "face.143" "face.1536" intervals ($Nojetcells)
volume mesh "volume.13" cooper source "face.1472" "face.1610" "face.152" \
  "face.1544" "face.1542" "face.150" intervals ($Nojetcells)
volume mesh "volume.15" cooper source "face.1476" "face.1612" "face.159" \
  "face.1550" "face.1548" "face.157" intervals ($Nojetcells)
volume mesh "volume.17" cooper source "face.1480" "face.1614" "face.166" \
  "face.1556" "face.1554" "face.164" intervals ($Nojetcells)
volume mesh "volume.19" cooper source "face.1484" "face.1616" "face.173" \
  "face.1562" "face.171" "face.1560" intervals ($Nojetcells)
volume mesh "volume.21" cooper source "face.1488" "face.1618" "face.180" \
  "face.1568" "face.1566" "face.178" intervals ($Nojetcells)
```

```
volume mesh "volume.23" cooper source "face.1492" "face.1620" "face.187" \
  "face.1574" "face.1572" "face.185" intervals ($Nojetcells)
volume mesh "volume.25" cooper source "face.1496" "face.1622" "face.194" \
  "face.1578" "face.1580" "face.192" intervals ($Nojetcells)
volume mesh "volume.27" cooper source "face.1624" "face.1500" "face.201" \
  "face.1586" "face.1584" "face.199" intervals ($Nojetcells)
volume mesh "volume.29" cooper source "face.1504" "face.1626" "face.208" \
  "face.1592" "face.1590" "face.206" intervals ($Nojetcells)
volume mesh "volume.31" cooper source "face.1628" "face.1508" "face.215" \
  "face.1596" "face.1598" "face.213" intervals ($Nojetcells)
volume mesh "volume.30" cooper source "face.1506" "face.1052" "face.1594" \
  "face.1397" intervals ($Nojetcells)
volume mesh "volume.28" cooper source "face.1502" "face.1042" "face.1588" \
  "face.1387" intervals ($Nojetcells)
volume mesh "volume.26" cooper source "face.1498" "face.1032" "face.1582" \
  "face.1377" intervals ($Nojetcells)
volume mesh "volume.24" cooper source "face.1494" "face.1022" "face.1576" \
  "face.1367" intervals ($Nojetcells)
volume mesh "volume.22" cooper source "face.1490" "face.1012" "face.1570" \
  "face.1357" intervals ($Nojetcells)
volume mesh "volume.20" cooper source "face.1486" "face.1002" "face.1564" \
  "face.1347" intervals ($Nojetcells)
volume mesh "volume.18" cooper source "face.1482" "face.992" "face.1558" \
  "face.1337" intervals ($Nojetcells)
volume mesh "volume.16" cooper source "face.1478" "face.982" "face.1552" \
  "face.1327" intervals ($Nojetcells)
volume mesh "volume.14" cooper source "face.1474" "face.972" "face.1546" \
  "face.1317" intervals ($Nojetcells)
volume mesh "volume.12" cooper source "face.1470" "face.962" "face.1540" \
  "face.1307" intervals ($Nojetcells)
volume mesh "volume.10" cooper source "face.1466" "face.952" "face.1534" \
  "face.1297" intervals ($Nojetcells)
volume mesh "volume.8" cooper source "face.1462" "face.942" "face.1528" \
  "face.1287" intervals ($Nojetcells)
volume mesh "volume.6" cooper source "face.1458" "face.932" "face.1522" \
  "face.1277" intervals ($Nojetcells)
volume mesh "volume.4" cooper source "face.1454" "face.922" "face.1516" \
  "face.1267" intervals ($Nojetcells)
volume mesh "cylinder" cooper source "face.1450" "face.912" "face.1510" \
  "face.1257" intervals ($Nojetcells)

window modify invisible mesh

volume mesh "volume.34" cooper source "face.1649" "face.1650" "face.1651" \
  "face.1652" "face.1653" "face.1654" "face.1655" "face.1664" "face.1639" \
  "face.1638" "face.1637" "face.1636" "face.1635" "face.1634" "face.1633" \
  "face.1648" "face.1610" "face.1608" "face.1606" "face.1604" "face.1602" \
  "face.1600" "face.1472" "face.962" "face.1468" "face.952" "face.1464" \
  "face.942" "face.1460" "face.932" "face.1456" "face.922" "face.1452" \
  "face.912" "face.915" "face.918" "face.911" "face.925" "face.928" \
  "face.920" "face.935" "face.938" "face.930" "face.945" "face.948" \
  "face.940" "face.955" "face.958" "face.950" "face.965" "face.968" \
  "face.960" "face.694" "face.689" "face.684" "face.679" "face.674" \
  "face.669" "face.664" "face.659" "face.654" "face.649" "face.644" \
  "face.640" "face.697" "face.696" "face.692" "face.687" "face.686" \
  "face.682" "face.677" "face.676" "face.672" "face.667" "face.666" \
```

```
  "face.662" "face.657" "face.656" "face.652" "face.647" "face.646" \
  "face.642" "face.695" "face.698" "face.690" "face.685" "face.688" \
  "face.680" "face.675" "face.678" "face.670" "face.665" "face.668" \
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  "face.1662" "face.1663" "face.788" "face.1656" "face.1474" "face.159" \
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  "face.1508" "face.1052" "face.1504" "face.1042" "face.1500" "face.1032" \
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  "face.1484" "face.992" "face.1480" "face.982" "face.1476" "face.972" \
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  "face.995" "face.998" "face.990" "face.1005" "face.1008" "face.1000" \
  "face.1015" "face.1018" "face.1010" "face.1025" "face.1028" "face.1020" \
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  "face.1050" "face.114" "face.1058" "face.774" "face.769" "face.764" \
  "face.759" "face.754" "face.749" "face.744" "face.739" "face.734" \
  "face.729" "face.724" "face.719" "face.714" "face.709" "face.704" \
  "face.699" "face.777" "face.776" "face.772" "face.767" "face.766" \
  "face.762" "face.757" "face.756" "face.752" "face.747" "face.746" \
  "face.742" "face.737" "face.736" "face.732" "face.727" "face.726" \
  "face.722" "face.717" "face.716" "face.712" "face.707" "face.706" \
  "face.702" "face.779" "face.784" "face.787" "face.775" "face.778" \
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  "face.750" "face.745" "face.748" "face.740" "face.735" "face.738" \
  "face.730" "face.725" "face.728" "face.720" "face.715" "face.718" \
  "face.710" "face.705" "face.708" "face.700" "face.782" "face.786" \
  "face.785" "face.6" "face.780" "face.1055" "face.215" "face.1506" \
  "face.208" "face.1502" "face.201" "face.1498" "face.194" "face.1494" \
  "face.187" "face.1490" "face.180" "face.1486" "face.173" "face.1482" \
  "face.166" intervals ($Plzdnodes)

volume delete "body" onlymesh
volume mesh "body" cooper source "face.1689" "face.1690" "face.1691" \
  "face.1692" "face.1693" "face.1681" "face.1682" "face.1683" "face.1684" \
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  "face.1367" "face.185" "face.1572" "face.1357" "face.178" "face.1566" \
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  "face.1287" "face.129" "face.1524" "face.1277" "face.122" "face.1518" \
  "face.1267" "face.115" "face.1512" "face.1257" "face.1380" "face.1383" \
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  "face.1315" "face.1310" "face.1313" "face.1305" "face.1300" "face.1303" \
  "face.1295" "face.1290" "face.1293" "face.1285" "face.1280" "face.1283" \
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  "face.1256" "face.209" "face.374" "face.370" "face.384" "face.379" \
  "face.394" "face.389" "face.404" "face.399" "face.414" "face.409" \
```

```
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  "face.1510" "face.1403" "face.518" "face.1588" "face.1592" "face.1594" \
  "face.1694" "face.1695" "face.1598" "face.1679" "face.1678" "face.515" \
  "face.516" "face.510" "face.500" "face.508" "face.505" "face.213" \
  "face.1596" "face.1397" "face.206" "face.1590" "face.1387" "face.517" \
  "face.514" "face.512" "face.502" "face.506" "face.507" "face.509" \
  "face.499" "face.504" "face.1400" "face.1395" "face.1385" "face.1390" \
  "face.1393" intervals ($Chzdnodes)


/////////////////////////////////////////////////////////////
///////////////BOUNDARY CONDITIONS////////////////////////
/////////////////////////////////////////////////////////////

physics create "Symmetry" btype "SYMMETRY" face "face.2" "face.103" \
  "face.211" "face.204" "face.197" "face.190" "face.183" "face.176" \
  "face.169" "face.162" "face.155" "face.148" "face.141" "face.134" \
  "face.127" "face.120" "face.112"
physics create "Wall" btype "SYMMETRY" face "face.110" "face.5" "face.1649" \
  "face.1664" "face.918" "face.915" "face.911" "face.925" "face.1650" \
  "face.928" "face.920" "face.935" "face.938" "face.930" "face.1652" \
  "face.1651" "face.948" "face.945" "face.940" "face.1653" "face.1654" \
  "face.958" "face.955" "face.950" "face.1655" "face.965" "face.968" \
  "face.960" "face.978" "face.975" "face.970" "face.1656" "face.114" \
  "face.985" "face.988" "face.980" "face.995" "face.998" "face.990" \
  "face.1657" "face.1005" "face.1008" "face.1000" "face.1658" "face.1015" \
  "face.1018" "face.1010" "face.1659" "face.1028" "face.1025" "face.1020" \
  "face.1035" "face.1660" "face.1038" "face.1030" "face.1045" "face.1661" \
  "face.1048" "face.1040" "face.1055" "face.1662" "face.1058" "face.1050" \
  "face.1663" "face.4" "face.1395" "face.1679" "face.1403" "face.1400" \
  "face.1680" "face.1385" "face.1678" "face.1393" "face.1390" "face.1375" \
  "face.1677" "face.1383" "face.1380" "face.1676" "face.1365" "face.1373" \
  "face.1370" "face.1675" "face.1355" "face.1363" "face.1360" "face.1674" \
  "face.1345" "face.1353" "face.1350" "face.1673" "face.1335" "face.1343" \
  "face.1340" "face.1672" "face.1325" "face.1333" "face.1330" "face.209" \
  "face.1315" "face.1323" "face.1320" "face.1671" "face.1305" "face.1313" \
  "face.1310" "face.1670" "face.1295" "face.1303" "face.1300" "face.1669" \
```

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  "face.1285" "face.1293" "face.1290" "face.1668" "face.1275" "face.1283" \
  "face.1280" "face.1667" "face.1265" "face.1273" "face.1270" "face.1666" \
  "face.1256" "face.1263" "face.1260" "face.1665" "face.214" "face.91" \
  "face.207" "face.85" "face.200" "face.79" "face.193" "face.73" "face.186" \
  "face.67" "face.179" "face.61" "face.172" "face.55" "face.165" "face.49" \
  "face.158" "face.43" "face.151" "face.37" "face.144" "face.31" "face.137" \
  "face.25" "face.130" "face.19" "face.123" "face.13" "face.116" "face.8"
physics modify "Wall" btype "WALL" face "face.110" "face.5" "face.1649" \
  "face.1664" "face.918" "face.915" "face.911" "face.925" "face.1650" \
  "face.928" "face.920" "face.935" "face.938" "face.930" "face.1652" \
  "face.1651" "face.948" "face.945" "face.940" "face.1653" "face.1654" \
  "face.958" "face.955" "face.950" "face.1655" "face.965" "face.968" \
  "face.960" "face.978" "face.975" "face.970" "face.1656" "face.114" \
  "face.985" "face.988" "face.980" "face.995" "face.998" "face.990" \
  "face.1657" "face.1005" "face.1008" "face.1000" "face.1658" "face.1015" \
  "face.1018" "face.1010" "face.1659" "face.1028" "face.1025" "face.1020" \
  "face.1035" "face.1660" "face.1038" "face.1030" "face.1045" "face.1661" \
  "face.1048" "face.1040" "face.1055" "face.1662" "face.1058" "face.1050" \
  "face.1663" "face.4" "face.1395" "face.1679" "face.1403" "face.1400" \
  "face.1680" "face.1385" "face.1678" "face.1393" "face.1390" "face.1375" \
  "face.1677" "face.1383" "face.1380" "face.1676" "face.1365" "face.1373" \
  "face.1370" "face.1675" "face.1355" "face.1363" "face.1360" "face.1674" \
  "face.1345" "face.1353" "face.1350" "face.1673" "face.1335" "face.1343" \
  "face.1340" "face.1672" "face.1325" "face.1333" "face.1330" "face.209" \
  "face.1315" "face.1323" "face.1320" "face.1671" "face.1305" "face.1313" \
  "face.1310" "face.1670" "face.1295" "face.1303" "face.1300" "face.1669" \
  "face.1285" "face.1293" "face.1290" "face.1668" "face.1275" "face.1283" \
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  "face.1256" "face.1263" "face.1260" "face.1665" "face.214" "face.91" \
  "face.207" "face.85" "face.200" "face.79" "face.193" "face.73" "face.186" \
  "face.67" "face.179" "face.61" "face.172" "face.55" "face.165" "face.49" \
  "face.158" "face.43" "face.151" "face.37" "face.144" "face.31" "face.137" \
  "face.25" "face.130" "face.19" "face.123" "face.13" "face.116" "face.8"
physics create "Heat Fluxes" btype "WALL" face "face.104" "face.106" \
  "face.370" "face.379" "face.389" "face.372" "face.382" "face.392" \
  "face.371" "face.380" "face.390" "face.378" "face.388" "face.398" \
  "face.376" "face.386" "face.396" "face.374" "face.384" "face.394" \
  "face.377" "face.387" "face.397" "face.375" "face.385" "face.395" \
  "face.1681" "face.1682" "face.1683" "face.1684" "face.1696" "face.402" \
  "face.412" "face.422" "face.432" "face.442" "face.400" "face.410" \
  "face.420" "face.430" "face.440" "face.408" "face.418" "face.428" \
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  "face.446" "face.404" "face.414" "face.424" "face.434" "face.444" \
  "face.407" "face.417" "face.427" "face.437" "face.447" "face.405" \
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  "face.1686" "face.1687" "face.452" "face.462" "face.472" "face.482" \
  "face.492" "face.1693" "face.450" "face.460" "face.470" "face.480" \
  "face.490" "face.1692" "face.458" "face.468" "face.478" "face.488" \
  "face.498" "face.1" "face.456" "face.466" "face.476" "face.486" "face.496" \
  "face.454" "face.464" "face.474" "face.484" "face.494" "face.457" \
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  "face.518" "face.502" "face.512" "face.1695" "face.500" "face.510" \
  "face.1694" "face.508" "face.506" "face.516" "face.504" "face.514" \
  "face.507" "face.517" "face.515" "face.505"
physics create "Mass flow inlet" btype "SYMMETRY" face "face.640" "face.649" \
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  "face.659" "face.642" "face.652" "face.662" "face.672" "face.641" \
  "face.650" "face.660" "face.670" "face.648" "face.658" "face.668" \
  "face.678" "face.646" "face.656" "face.666" "face.676" "face.644" \
  "face.654" "face.664" "face.674" "face.647" "face.657" "face.667" \
  "face.677" "face.645" "face.655" "face.665" "face.675" "face.1633" \
  "face.1634" "face.1635" "face.1636" "face.1637" "face.1648" "face.679" \
  "face.689" "face.699" "face.682" "face.692" "face.702" "face.712" \
  "face.680" "face.690" "face.700" "face.710" "face.688" "face.698" \
  "face.708" "face.718" "face.6" "face.686" "face.696" "face.706" "face.716" \
  "face.684" "face.694" "face.704" "face.714" "face.687" "face.697" \
  "face.707" "face.717" "face.685" "face.695" "face.705" "face.715" \
  "face.1640" "face.1638" "face.1639" "face.719" "face.729" "face.739" \
  "face.749" "face.722" "face.732" "face.742" "face.752" "face.762" \
  "face.720" "face.730" "face.740" "face.750" "face.760" "face.728" \
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  "face.769" "face.779" "face.772" "face.782" "face.770" "face.780" \
  "face.778" "face.776" "face.786" "face.774" "face.784" "face.777" \
  "face.787" "face.775" "face.785" "face.1647" "face.1646"
physics create "Outflow" btype "OUTFLOW" face "face.105"
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