Investigation of The Natural Convection Heat Transfer in Deep Wellbore

By

Muhammad Amirul Asri Bin Ahmad Lukman

10303

A Project Dissertation Submitted in Partial Fulfillment of
The requirement for the
Bachelor of Engineering (Hons)
(Mechanical Engineering)

MAY 2011

Universiti Teknologi PETRONAS
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CERTIFICATION OF APPROVAL

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Approved by,

____

(Dr. Hussain H. Al-Kayiem)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
MAY 2011

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

(MUHAMMAD AMIRUL ASRI BIN AHMAD LUKMAN)

ABSTRACT

Radial heat transfer between the inner pipe fluid flow and the formation surrounding the oil wells occurs by overcoming various resistances in series. The major resistance is within the annular space between the wellbore tubing and the casing. The present work aims to predict the natural convection heat transfer coefficient in the annulus, which is hard to predict due to the large length-to-spacing ratio (aspect ratio). The approach to model natural convection heat transfer in this work is by analytical and numerical techniques. The annular space between the tubing and the casing is treated as a finite space bounded by walls and filled with fluid media (enclosures). Natural convection in such enclosures occurs as a result of buoyancy caused by a body force field with density variations within the annulus field. Correlations for inclined rectangular enclosures will be employed in the study. The flow field of such a case will be modeled and simulated for numerical analysis, using ANSYS-FLUENT – 12 software package. Some boundary parameters have been defined by the user and fed to the software. In order to verify the results, the predicted Nusselt numbers from both, analytical and numerical will be compared. The method of analysis is done first by doing the analytical simulation of the Nusselt correlation found in literature and comparing the result done in numerical analysis. Numerical simulation is then continued with various operational conditions and the analysis of the results. The variables interested are the difference of temperature between tubing and casing, density of air, velocity of air, and the Nusselt Number. The new functional correlations cover a wide range of oil well inclination angles. In terms of combined accuracy and continuity, these new functional correlations offer advantages in certain applications over those previously employed. As heat transfer is concerned, the convection heat transfer is the highest at the bottom of the long annulus. Comparing the analytical and numerical simulation, the difference is still clear that the theoretical analysis of the existing correlation does not agree with the numerical simulation. As a conclusion, the behavior of the natural convection heat transfer is better observed in the detail of the numerical simulation.

Keywords: Heat transfer Natural convection Casing annulus Numerical analysis Oil wells

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1
INTRODUCTION

1.1 Background of project

In a wellbore, the hot reservoir fluids enter a wellbore and flows to the surface causing it to lose heat immediately to the cooler surrounding formation. The surrounding rock gradually heats up, reducing the temperature difference and the heat transfer between the fluids and the rock. For constant mass flow rate, the earth surrounding the well reaches steady-state temperature distribution. Prediction of fluid temperatures in the wellbore as a function of depth and time is necessary to determine the fluid's physical properties and calculate pressure gradients.

There is a high thermal conducitivity and relatively small radial distance between the flowing fluids and the borehall wall, heat transfer in this region is considered as steady state. All the heat losst by the fluids instantaneously flows through the tubing, and through annulus that is to be analyzed. A cross section of a typical wellbore is shown in Fig. 1. Heat transfer within the annulus is primarily a result of convection while the heat transfer through the tubing and casing walls and through the cemented-filled annulus between the casing and borehole wall primarily results from conduction.

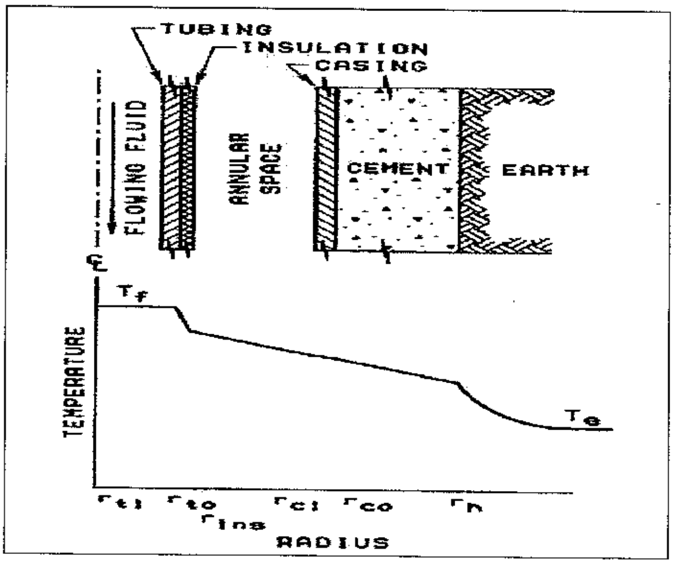

Figure 1 A representation of the Physical Problem[2]. (ti=inner tubing, t0=outer tubing, ci=inner casing, co=outer casing)

1.2 Problem Statement

Researches had been done to investigate the convective heat transfer by using empirical correlations for enclosure such as the annulus. The present correlations reported calculation of Nusselt number with low aspect ratio. In wellbore, deeper depths of high aspect ration of an annulus requires numerical simulation as there are no suitable empirical correlations yet to investigate the Nusselt number. Also, in deeper wellbore, the operational condition such as the temperature also affects the convective heat transfer in the annulus. Therefore, this project aims to mathematically and numerically simulate the result of varying operational conditions and also investigate Nusselt number at various depth of the well.

1.3 Objective

The objectives of this research are:

- To investigate the convective heat transfer in annulus of oil wells.
- Correlate the results.

In this project, it is important to know the scope of the study is in the investigation on natural convection heat transfer that occurs at the annulus of the wellbore.

1.4 Scope of the Work

The scope of work for semester one final year project is to research more on the analytical correlation to find the Nusselt number for a large aspect ratio. The equations will then be computed in mathematical software for analysis. The parameters will be changed and the result will be analyzed for further analysis by numerical simulation by using computational fluid dynamics. The first semester will emphasize on comparing the results of these methods of analysis.

For the second semester of the final year project, the research will focus on the numerical analysis with computational fluid dynamics. In this particular semester, the simulation of the wellbore natural convection heat transfer will be analyzed with various operational condtions. Investigation will also emphasize on the Nusselt number of various depth of the well.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

Incropera states that the Nusselt number is a parameter that is equal to the dimensionless temperature at the surface, and provides a measure of the convection heat transfer occurring at the surface. The Nusselt number is define by the equation $N_U = \frac{hL}{k_f}$ where h is the heat transfer coefficient, L is the length and k_f is the thermal conductivity. Incropera (2007) says that the Nusselt number is to the thermal boundary layer what the friction coefficient is to the velocity boundary layer. The equation $N_U = f(x^*, R_{eL,} P_r)$ implies that the Nusselt number must be some universal function of x^* which is the length, R_{eL} Rayleigh Number, and Pr Prandtl Number. When the function is known, it could be used to compute the value of Nu for different fluids and for different values of V and L. here, the local convection h may be determine from the value of Nu and the local heat flux may then be computed from the equation $q''_s = h(T_s - T_\infty)$ [Equation 2.1]

2.2 Nusselt Number Correlations

In the the project scope, it is found that Incropera comments the vertical rectangular cavity. According to Incropera[1]

In the vertical cavity, the vertical surfaces are heated and cooled, while the horizontal surfaces are adiabatic. As shown in figure 9.12, fluid motion is characterized by a recirculating or cellular flow fo which fluid ascends along the hot wall and descends along the cold wall.

Catton comes up with correlations in determining the Nusselt number for $1 \leq (H/L) \leq 10$ and the largest aspect ratio is for $10 \leq (H/L) \leq 40$.

New findings have been made by Hollands [8] for H/L>10 for $\theta = 90^\circ$ where:

$\overline{Nu}_{L90^\circ} = \max\{Nu_1, Nu_2, Nu_3\}$ [Equation 2.2] where

$$Nu_1 = 0.0605 Ra_L^{1/3} \quad \text{[Equation 2.3]}$$

$$Nu_2 = \left\{1 + \left[\frac{0.104 Ra_L^{0.293}}{1 + \left(6310 / Ra_L\right)^{1.36}}\right]^3\right\}^{1/3} \quad \text{[Equation 2.4]}$$

$$Nu_3 = 0.242\left(\frac{Ra_L}{H/L}\right)^{0.272} \quad \text{[Equation 2.5]}$$

And is valid for $10^3 < Ra_L < 10^7$; for $Ra_L \leq 10^3, \overline{Nu}_{L90^\circ} \approx 1$.

Hollands and coworkers also added correlations for $\theta = 0^\circ$,
where

$$\overline{Nu}_L = 1 + 1.44\left[1 - \frac{1708}{Ra_L \cos\theta}\right]\left\{1 - \frac{1708(\sin 1.8\theta)^{1.6}}{Ra_L \cos\theta}\right\} + \left[\left(\frac{Ra_L \cos\theta}{5830}\right)^{1/3} - 1\right]$$

[Equation 2.6]

Where if either of the terms in square bracket is negative, it must be set equal to zero. This equation is valid for $0 < Ra_L < 10^5$.

Raithby and Hollands recommends for natural convection between concentric cylinders and spheres are in the form of an effective thermal conductivity for use in the equations for conduction between concentric cylinders and spheres.

For concentric cylinders:

$$\frac{k_{eff}}{k} = 0.386\left(\frac{\Pr}{0.861 + \Pr}\right)^{1/4} Ra_{cyl}^{1/4} \qquad 10^2 < Ra_{cyl} < 10^7 \qquad \text{[Equation 2.7]}$$

where

$$Ra_{cyl} = \frac{\left[\ln\left(D_o / D_i\right)\right]^4}{L^3 (D_i^{-3/5} + D_0^{-3/5})^5} Ra_L \qquad \text{[Equation 2.8]}$$

And $L = (D_o - D_i)/2$ is the gap width.

2.3 Wellbore Heat Transfer

Brill and Mukherjee [4] says that for convection through the casing/tubing annulus,

$$T_{to} - T_{ci} = \frac{q}{2\pi\Delta L}\frac{1}{r_{ci}h_{an}}. \qquad \text{[Equation 2.9]}$$

In a study done by Herrera 1978, Wellbore heat loss Calculation Procedure is done by firstly calculation the heat transfer rate. The calculation continues with the calculation of the convection heat transfer coeffiecient, hc, and finally calculating the radiation heat transfer coefficient, hr.

Three modes of heat transfer are present in the casing annulus according to Willhite [7]. Heat is conducted through air contained in the annulus. Radiation and natural convection also occur. When a body is heated, radiant energy is emitted at a rate dependent on the temperature of the body. The amount of radiant energy transported between the tubing and casing depends on the view the surfaces have of each other an the emitting and absorbing characteristics of their surfaces. Heat transfer by natural convection in the annulus between the tubing and casing caused by fluid motion resulting from the variation of density with temperature. Hot fluid near the tubing wall is less dense than the fluid in the center of the annulus and tends to rise. Similarly, the fluid near the casing wall is cooler (and denser) than in the center of the annulus and tends to fall. Figure 2 is an interpretation of fluid motion in the casing annulus.

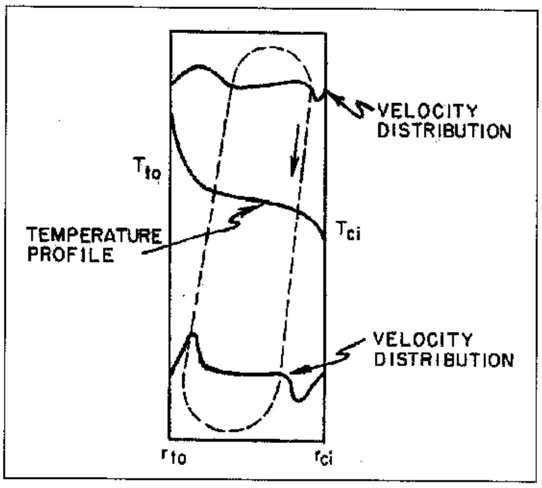

Figure 2 Natural convection in the annulus [7]

2.4 Dropkin and Sommerscales correlations

Dropkin and Sommerscales[3] have related the effective thermal conductivity of the annular fluid, khc, to the actual conductivity, kha, as follows:

$k_{hc} = k_{ha}(0.049)(Gr\,\mathrm{Pr})^{0.333}(\mathrm{Pr})^{0.074}$ [Equation 2.10]

Here, we know that the Nusselt Number is related by $Nu = \frac{k_{hc}}{k_{ha}}$ [Equation 2.11]

And Prandtl number is given by $\mathrm{Pr} = \frac{v}{\alpha}$ [Equation 2.12]

Where v is the air kinematic viscosity and α is the air thermal diffusivity.

Rayleigh is a product of Grashof and Prandtl Number for free convection near a vertical wall as $Ra = Gr\,\mathrm{Pr}$ [Equation 2.12]

Computing these three relations in Dropkin and Sommerscales relations, we get:

$Nu = (0.049)(Gr\,\mathrm{Pr})^{0.333}(\frac{v}{\alpha})^{0.074}$ [Equation 2.13]

CHAPTER 3
METHODOLOGY

3.1 Analysis Technique

The analytical and numerical simulation will be used in this project to analyze the convection heat transfer in annulus. The analytical simulation will be based on the most suitable correlation recommended by Hollands and coworkers for aspect ratio H/L>10 for vertical enclosure. Then the analytical simulation will be computed from the correlations chosen in the literature review. The numerical simulation will follow by analyzing the varying paramaters by computational fluid dynamics. The results of these simulations will be compared and further analysis will be continued during the next phase of the convection heat transfer investigation in the annulus. When the analysis is focused on the numerical simulation, the results of the analysis will be analyzed with various operational conditions.

3.2 Required Software

The analytical model will be done by using Microsoft Excel software to ease the computing of the analytical results. All the correlations will be tabulated in the result section comparing the difference of results of different correlations used.
While for the numerical simulation, GAMBIT will be used to model the annulus while FLUENT will be used in the simulation of the results for further analysis.

3.3 Execution flow chart

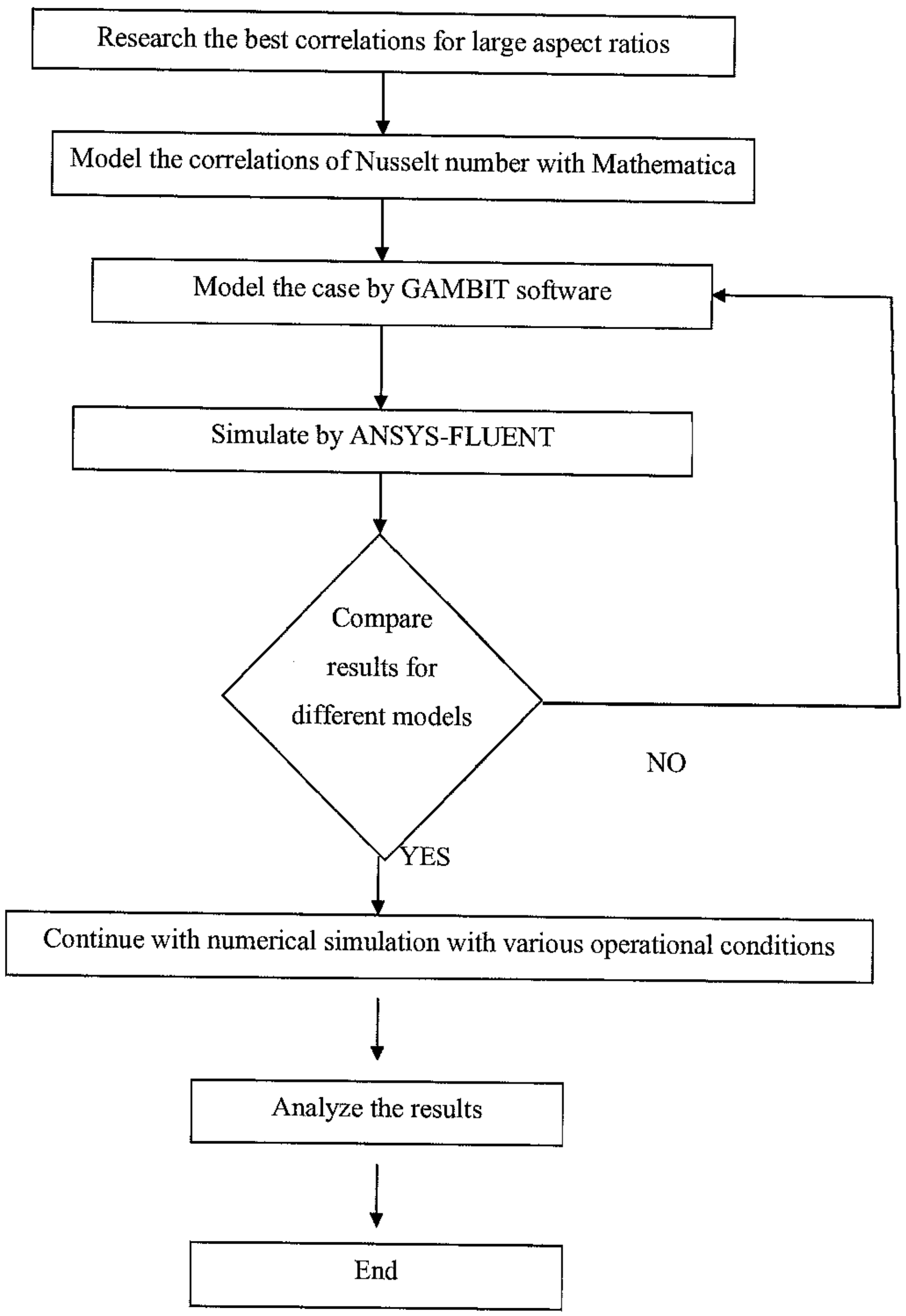

Figure 3.1 Execution flow chart

3.4 Gantt Chart

No	Details	Week 1	2	3	4	5	6		7	8	9	10	11	12	13	
1	Selection of Project Topic	■	■													
2	First meeting with supervisor	■	■													
3	Preliminary Research work															
	a) Research the correlations for Nusselt number			■	■	■	■									
	b) Research on the wellbore heat transfer			■	■	■	■									
4	Preliminary Report preparation				■											
5	Submission of Preliminary Report				●											
6	Progress report preparation					■	■		■	■						
7	Submission of Progress Report									●						
8	Seminar 2 (compulsory)									●						
9	Analytical Modelling of Solution									■	■	■	■	■	■	■
10	Modelling attempt by GAMBIT Software													■	■	■
11	Submission of Interim Report Final Draft															
12	Oral Presentation preparation												■	■		
13	Oral Presentation (Week 14)															

● Suggestion milestone ■ Process

Figure 3.2 Gantt chart for first semester

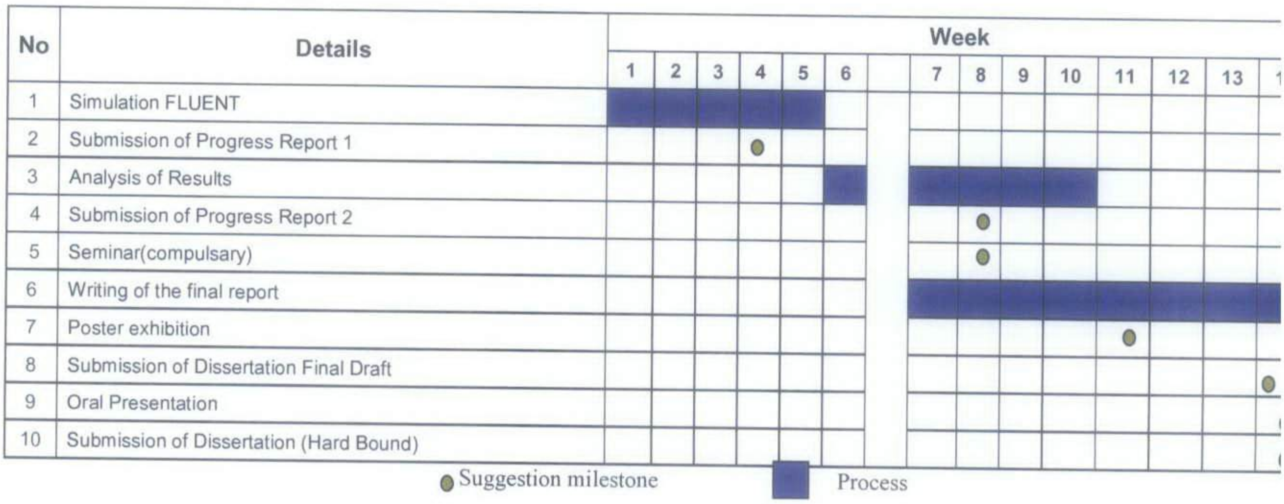

Figure 3.3 Gantt chart for second semester

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Analytical Model

These are the correlations that have been chosen for different cases in investigating the best correlations in the scope of study.

For Holland and coworkers[8],

H/L>10 for $\theta = 90^\circ$ where:

$$\overline{Nu}_{L90^\circ} = \max\{Nu_1, Nu_2, Nu_3\}$$

$$Nu_1 = 0.0605 Ra_L^{1/3}$$

$$Nu_2 = \left\{1 + \left[\frac{0.104 Ra_L^{0.293}}{1 + (6310/Ra_L)^{1.36}}\right]^3\right\}^{1/3}$$

$$Nu_3 = 0.242\left(\frac{Ra_L}{H/L}\right)^{0.272}$$

And is valid for $10^3 < Ra_L < 10^7$; for $Ra_L \leq 10^3, \overline{Nu}_{L90^\circ} \approx 1$.

While the other correlations from Petroleum Engineering industry proposed by Dropkin and Sommerscales[3] for heat transfer coefficients for natural convection in fluids between two vertical plates which is:

$$Nu = 0.049 Ra^{0.333}\left(\frac{\nu}{\alpha}\right)^{0.074}$$

The analysis starts by using the parameter of tubing insulation temperature and the casing temperature that is taken from real wellbore temperatures. The length annulus region is 0.042 meters with a height of 1500 m.

The table below shows the temperature of 10 segments that is divided from the total height of 1500 m. So, each segment will have a height of 150 m, width of 0.042 m and the tubing and casing temperatures for each segment are tabulated below. The table also shows the results of Nusselt Number for the analytical model.

Table 4.1 Results of Analytical Model

Segment	Tubing Temperature, Tt (K)	Casing Temperature, Tc (K)	Nusselt Number (Dropkin and Sommerscales)	Nusselt Number (Hollands)		
				1	2	3
1	304	297	1.67	2.13	2.28	0.48
2	306	299	1.65	2.11	2.26	0.47
3	308	300	1.71	2.19	2.35	0.49
4	309	302	1.63	2.08	2.22	0.47
5	310	304	1.53	1.96	2.08	0.45
6	311	305	1.53	1.95	2.07	0.44
7	313	307	1.51	1.93	2.05	0.44
8	313	309	1.31	1.68	1.74	0.39
9	314	310	1.31	1.67	1.73	0.39
10	314	312	1.03	1.32	1.28	0.32

4.2 Numerical Model

As up until the research made, a model of the case is made by using GAMBIT before the analysis is done in FLUENT. Below are pictures of the model done in GAMBIT in isometric view, front view, and top view.

Figure 4.1 Isometric View of the Model

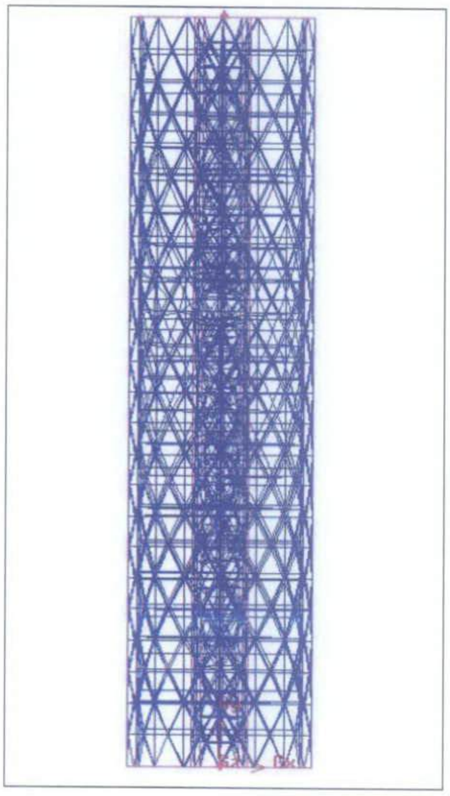

Figure 4.2 Front View of the model

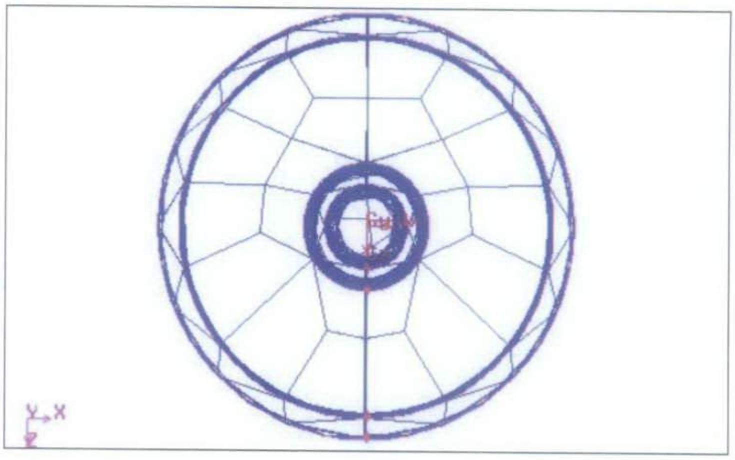

Figure 4.3 Top View of the model

The research is then continued with an analysis by modeling the annulus in a 2 dimension enclosure by segmenting it. The model is analyzed in such a way that it is viewed as an enclosure from the front view of the model. Below is a picture of how the model will look in front view.

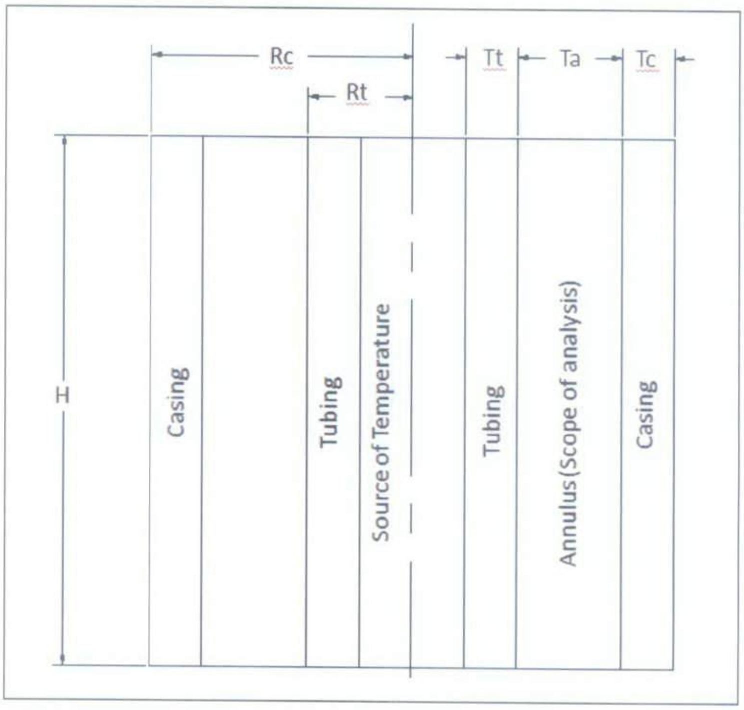

Figure 4.4 Front view of model with labels[Tc=Casing Thickness, Ta=Annulus Thickness, Tt=Tubing Thickness, Rt=Radius of tubing, Rc=Radius of Casing, H=Height of wellbore]

For the first model, the tubing and casing temperature will be set as tabulated in Table 4.1. As the height of the annulus of a wellbore is 1500 meters, the analysis will segment the height into 10 segments of height 150 meters each in an annulus of 0.042 m length. The tubing casing thickness where conduction occurs is set to be 0.0055 m and the casing thickness to be 0.01036 m. Below are the original data of the wellbore dimensions needed for the model.

Tubing Data

Outer diameter: 0.074 m

Inner diameter: 0.063 m

Tubing thickness: 0.0055 m

Casing Data

Outer diameter: 0.17872 m

Inner diameter: 0.158 m

Casing thickness: 0.01036 m

The model is meshed with a 6:1 ratio and iteration is done in FLUENT.

The results are listed below in these Appendices;

a) Appendix B : Velocity Vectors Coloured by Velocity Magnitude
b) Appendix C: Density versus Position
c) Appendix D: Velocity Magnitude versus Position
d) Appendix E: Nusselt Number versus Position
e) Appendix F: Calculation of Total Heat Transfer

4.3 Discussions

Results in listed in previous section will be discuss below according to Appendices Listed.

4.3.1 Velocity Vectors

The velocity vectors shown in Appendix B are divided into 7 sections where changes of velocity vector takes place in the 1500 meters annulus. Starting with Appendix B1 on the top of the annulus, the flow does not follow the circulation as depicted in Figure 2 [7]. This is due to the temperature at Segment 1 lower as compared to the other segments and the temperature results on the higher density of air in Appendix B1. While the annulus segment continues to a higher temperature, it is observed that the fluid still moves in opposite direction in Appendix B2 while the region near the casing loses its' velocity in upward direction and this is further confirmed by a newer segment as shown in Appendix B3. This behavior of the fluid velocity is due to the gravitational force that acts on to the fluid is bigger than buoyancy force that is suppose to move the air downwards near the casing. As the fluid flows continues in Appendix B4, the air near the tubing wall became slower until Appendix B5 shows that the fluid velocity starts to increase moving downwards opposing the buoyancy force near the tubing wall. The region near the casing wall starts to change its' direction downwards together with the fluid flowing near the tubing wall as shown in Appendix B6. This shows that the accumulation of fluid moving downwards increases that it adds more density to the fluid near the tubing wall eventhough the velocity is lower as it approaches the bottom of the annulus. Appendix B7 adds the prove that the usual flow for low aspect ratio in natural convection heat transfer does not apply for this high aspect ratio of annulus. As the fluid accumulates at the bottom of the annulus, the fluid near the casing region moves upwards because that is the only way the higher density of air can escape, but only until the point showed in Appendix B6.

4.3.2 Density

Fot the density analysis of the numerical simulation, the analysis is determined ad the mid section of each segment. For example, at height 75 meters, it is labeled h75 in the Appendix. In Appendix C1, we can see that density is higher at higher segment of the annulus. While in X-direction, it is observed that at height 525 meters, the density increases near the casing. At this point, the temperature still has the most effect on the density of the air. The lower the temperature, the higher the density of the fluid in each segment. This is different for segments at height 375 meters where the density does not increase very much and declines as it is nearest to the casing wall. As for Appendix C2, Density Decreases as the fluid moves to the lower segment of the annulus.

4.3.3 Velocity Magnitude

In Appendix D1, the trends of velocity seems to have a similar trend with Figure 2 [7]. At higher segments, the velocity profile shows that it has an opposite trend of the velocity.

Moving on to the analysis of velocity magnitude along the Y-direction, the velocity seems to decline from the bottom until the height of around 800 meters, the velocity starts to increase and fall down when it reaches the top of the annulus where no fluid flow is coming out.

4.3.4 Nusselt Number

The nusselt number for both the tubing wall and casing wall exhibits the same trend, where it increases as the temperature increases through lower segments [Appendix E4]. Appendix E3 shows that higher nusselt number occurs at the top of the annulus but it decreases when approaching the casing wall. As for the Nusselt Number at the Bottom of the Annulus, the Nusselt Number decreases from the tubing wall and has a constant value until it approaches the casing wall where the nusselt number increases.

4.3.5 Total Heat Transfer

Appendix F shows all the necessary calculation of Total Heat Transfer that will be further discuss in the next section.

4.3.6 Comparison of Nusselt Number for Analytical and Numerical Simulation

In Appendix G, table that shows the results segment by segment of the annulus and the total heat transfer rate, the nusselt number for analytical and numerical simulation is comparable and depicted in the graph below.

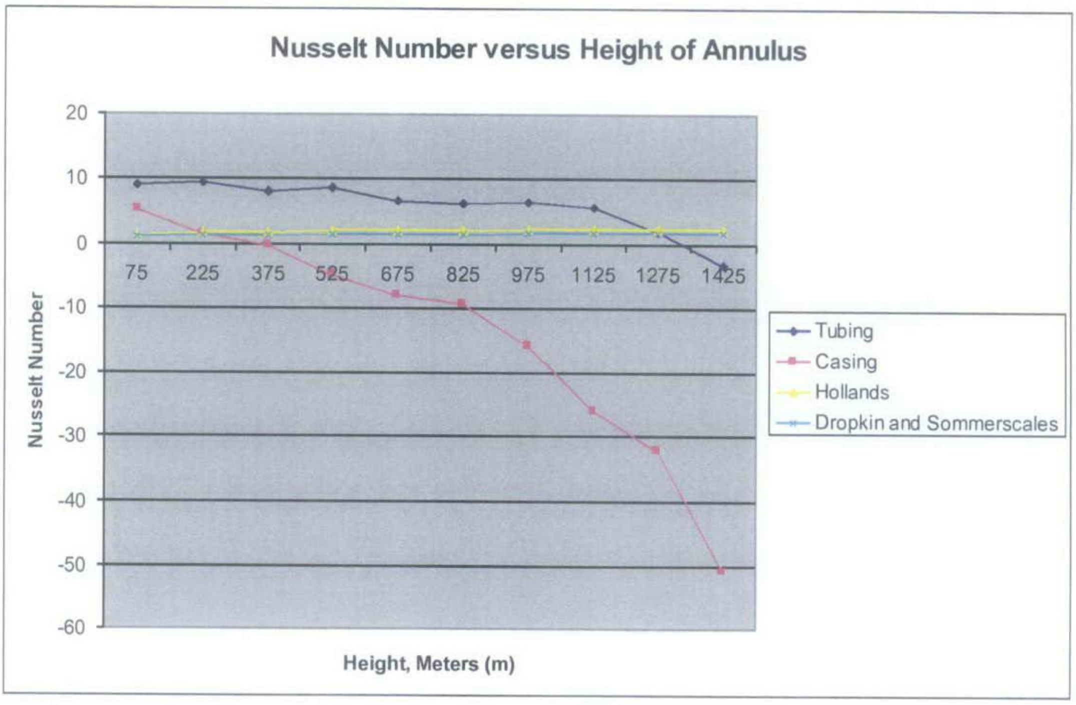

Figure 4.5 Graph of Nusselt Number of All Models versus the height of annulus

In the graph shown, the results between the analytical simulation does not differ very much and has almost the same trend. While for the Nusselt Number at Tubing has higher nusselt number but the same trend with the casing results. This shows that a higher convection heat transfer occurs near the tubing wall.

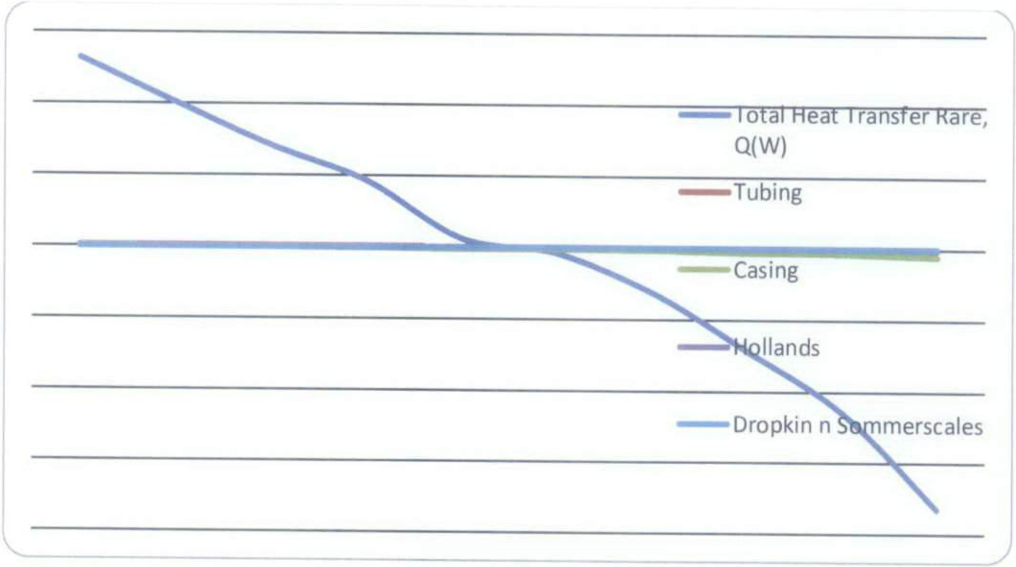

Figure 4.6 Total Heat Transfer Rate in comparison with Nusselt Number versus height of annulus

While the graph above, it shows that total heat transfer rate is the highest at the lowest segment of the annulus. It decreases and at about height of 750 meters the total heat transfer rate increases in negative value where heat is transferred from the annulus.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 Conclusion

From the research made so far, the correlation suggested by Hollands[8] and Dropkin and Sommerscales[3] agrees with each other.

It is used as a basis for the analytical simulation. The results obtain from this simulation will be compared to the numerical analysis that will be done by using computational fluid dynamics. As the numerical analysis done so far, it is observed that the behavior of the flow does not follow the natural convection heat transfer depicted by Willhite [7]. The flow is basically due to gravity and the gravitational force opposes the buoyancy force resulting in a reversed flow in the annulus.

As heat transfer is concerned, the convection heat transfer is the highest at the bottom of the long annulus. Comparing the analytical and numerical simulation, the difference is still clear that the theoretical analysis of the existing correlation does not agree with the numerical simulation.

As a conclusion, the behavior of the natural convection heat transfer is better observed in the detail of the numerical simulation.

5.2 Recommendation

It is recommended that a variety of temperature variance in different wellbores should be analyzed numerically to see differences in its' heat transfer behavior. A 3 dimensional analysis can also be added in the future analysis of the natural convection heat transfer for deep wellbore. Besides that, the analysis can be done by validation of the wellbore by experimental work.

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$g = 9.8;$ "accelation owning to gravity, $\frac{m}{s^2}$";

$TH = 468;$ "tubing insulation temperature, ${}^0K$";

$TL = 300;$ "casing inside temperature, ${}^0K$";

$T := \frac{TH + TL}{2};$ "mean annuli temperature, ${}^0K$";

$\beta = \frac{1}{T};$ "air thermal expansion coefficient, $\frac{1}{{}^0K}$";

$L = 0.2;$

$\nu = (-1.1555)(10^{-14})(T^3) + (9.5728)(10^{-11})(T^2) + (3.7604)(10^{-8})T - (3.4484)(10^{-6});$ "air kinematic viscosity";

$\alpha = (9.1018)(10^{-11})(T^2) + (8.8197)(10^{-8})(T) - (1.0654)(10^{-5});$ "air thermal diffusivity";

$H = 110;$

$$Ra = \frac{g\beta(TH - TL)L^3}{\nu\alpha};$$

NU1Mechanic[Ra_] = 0.0605 (Ra)^(1/3);

$$NU2Mechanic[Ra\_] = \left(1 + \left(\frac{0.104\,Ra^{0.293}}{1 + (6310/Ra)\hat{}1.36}\right)\hat{}3\right)\hat{}(1/3);$$

$$NU3Mechanic[Ra\_] = 0.242\left(\frac{Ra}{\left(\frac{H}{L}\right)}\right)\hat{}0.272;$$

$$NUPetroleum[Ra\_] = 0.049\,Ra^{0.333}\left(\frac{\nu}{\alpha}\right)^{0.074}$$ "Petroleum Nusselt number"

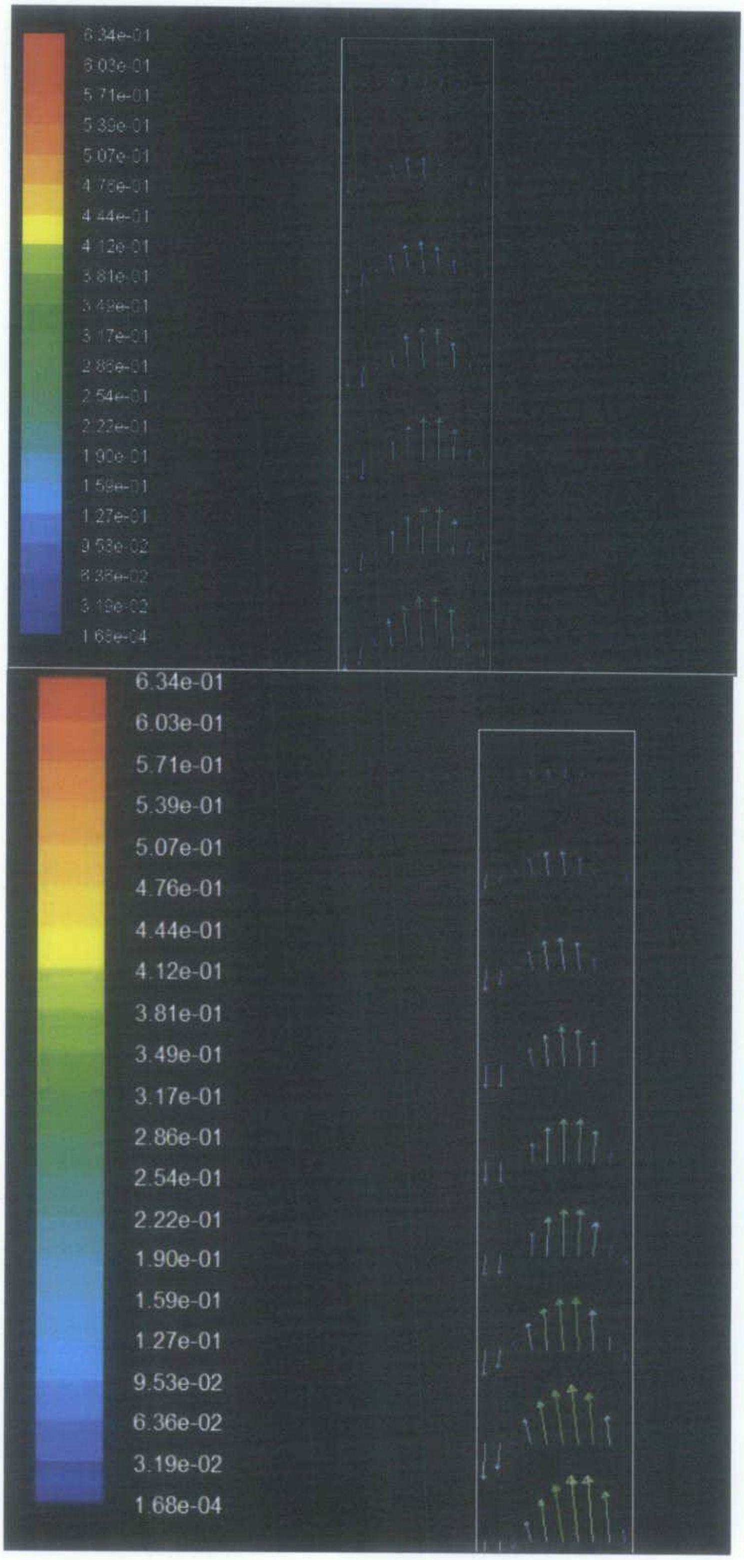
NU = Min[NU1Mechanic[Ra], NU2Mechanic[Ra], NU3Mechanic[Ra]] "The annuli Nusselt number"

Rayleigh = Ra " Rayleigh numer "

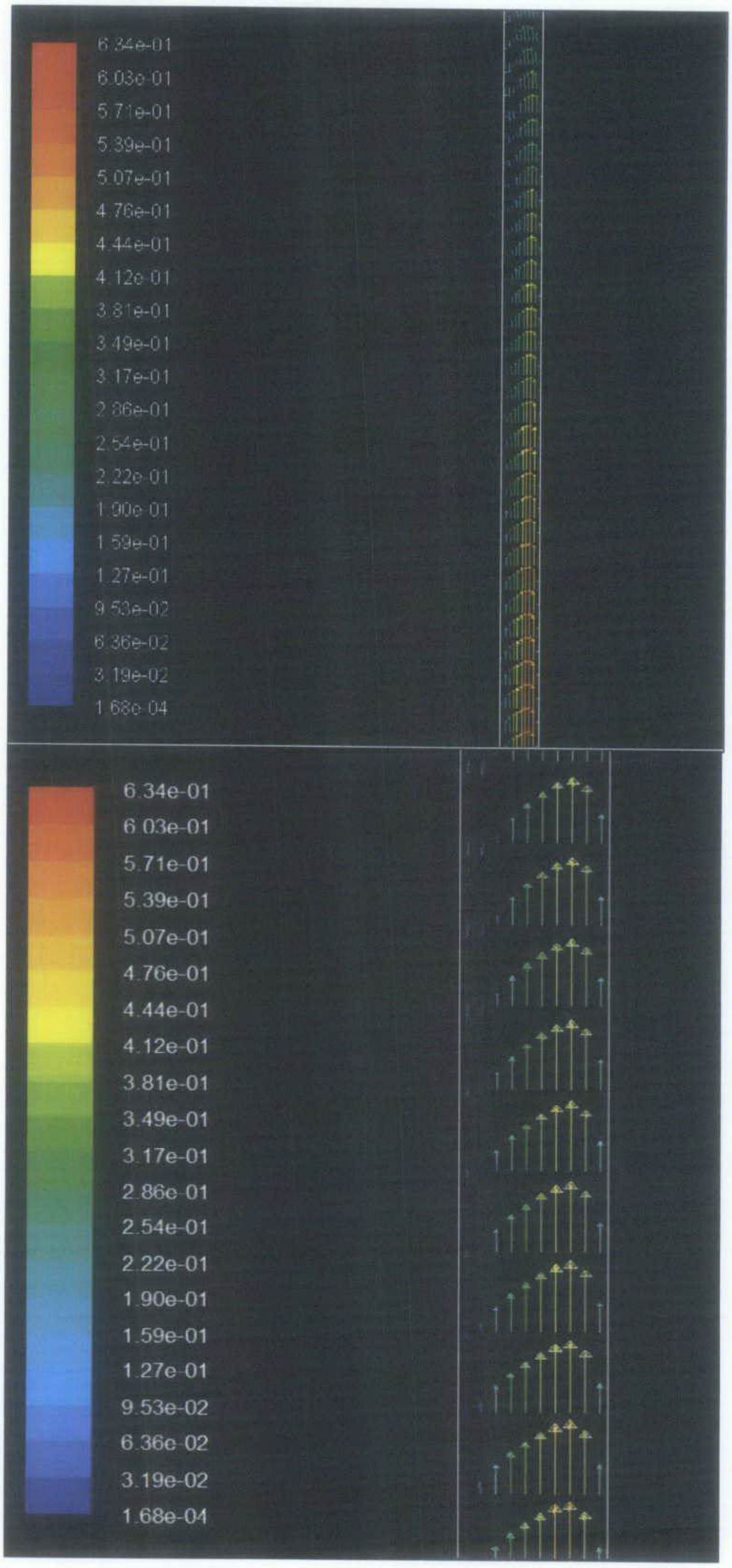
15.9355 Petroleum Nusselt number

5.02379 The annuli Nusselt number

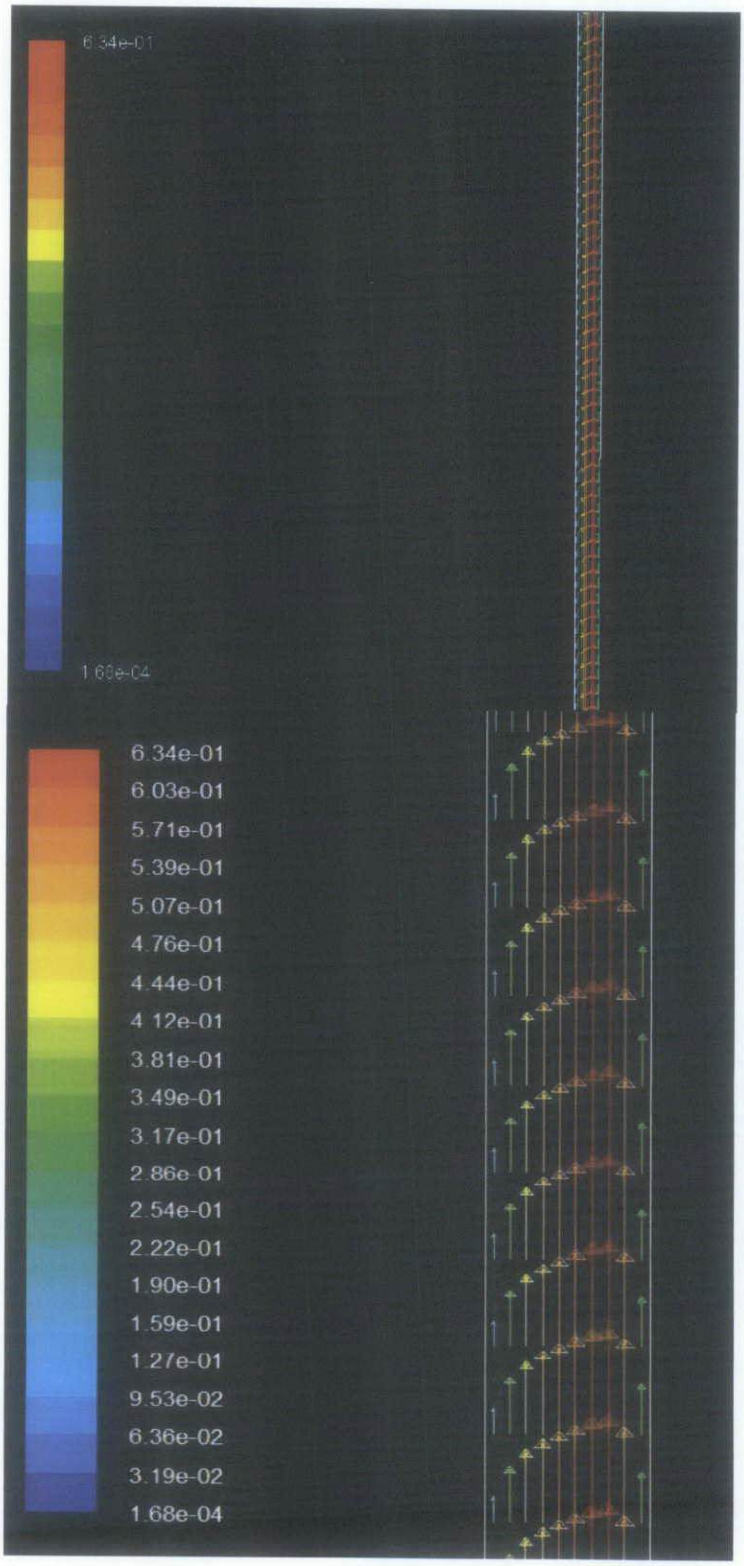
3.82886×10^7 Rayleigh numer



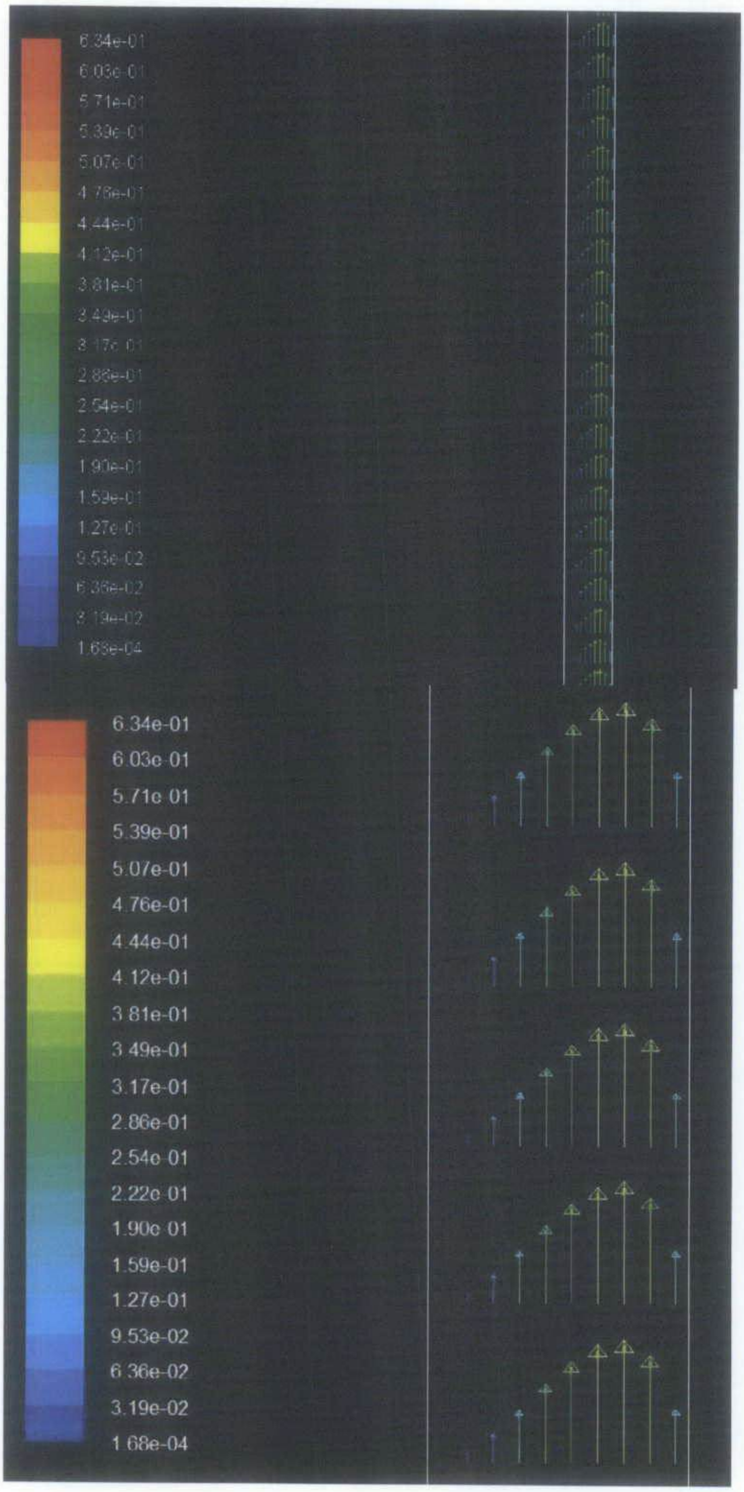
B1: Velocity Vector on Top of Annulus



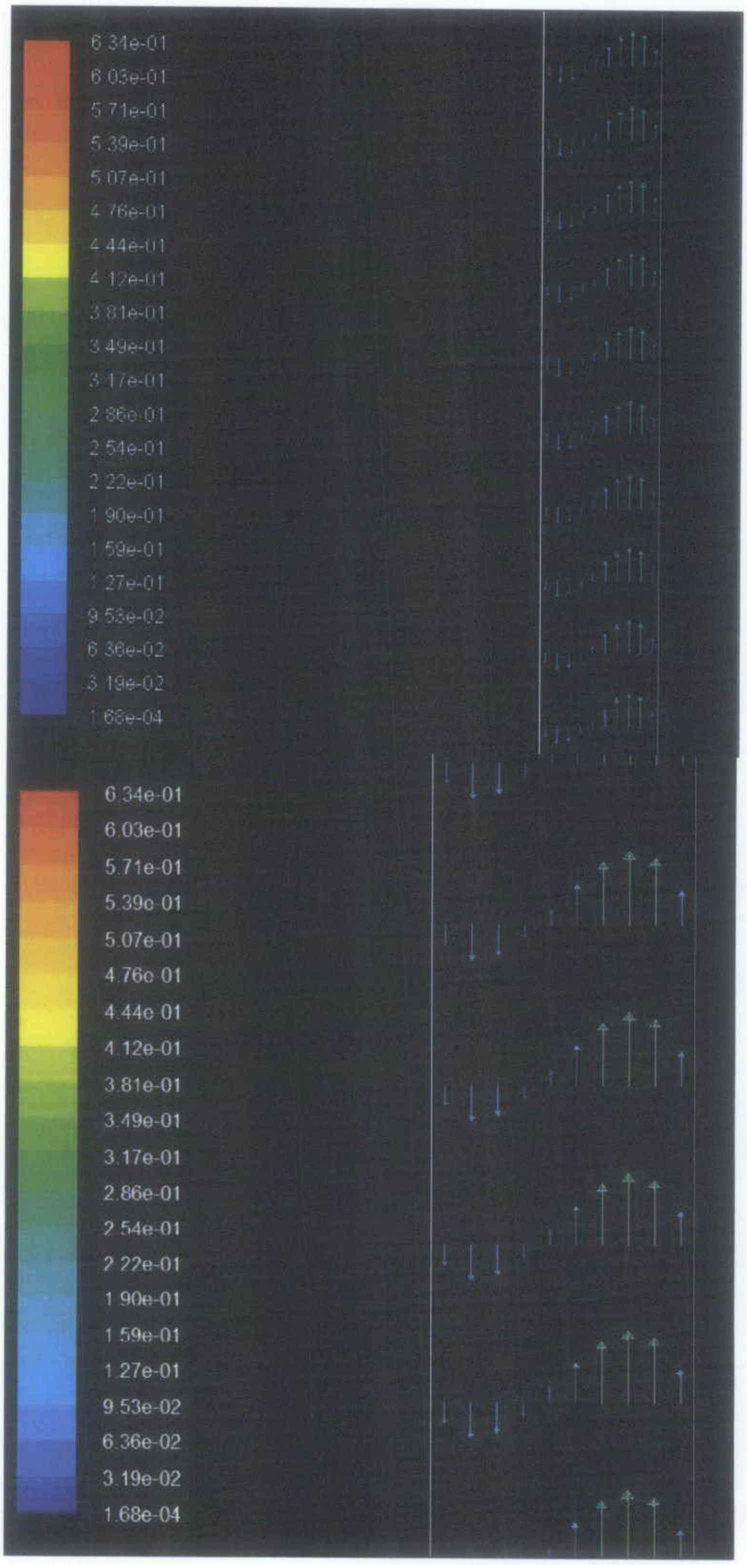
B2: Velocity Vector following Appendix B1



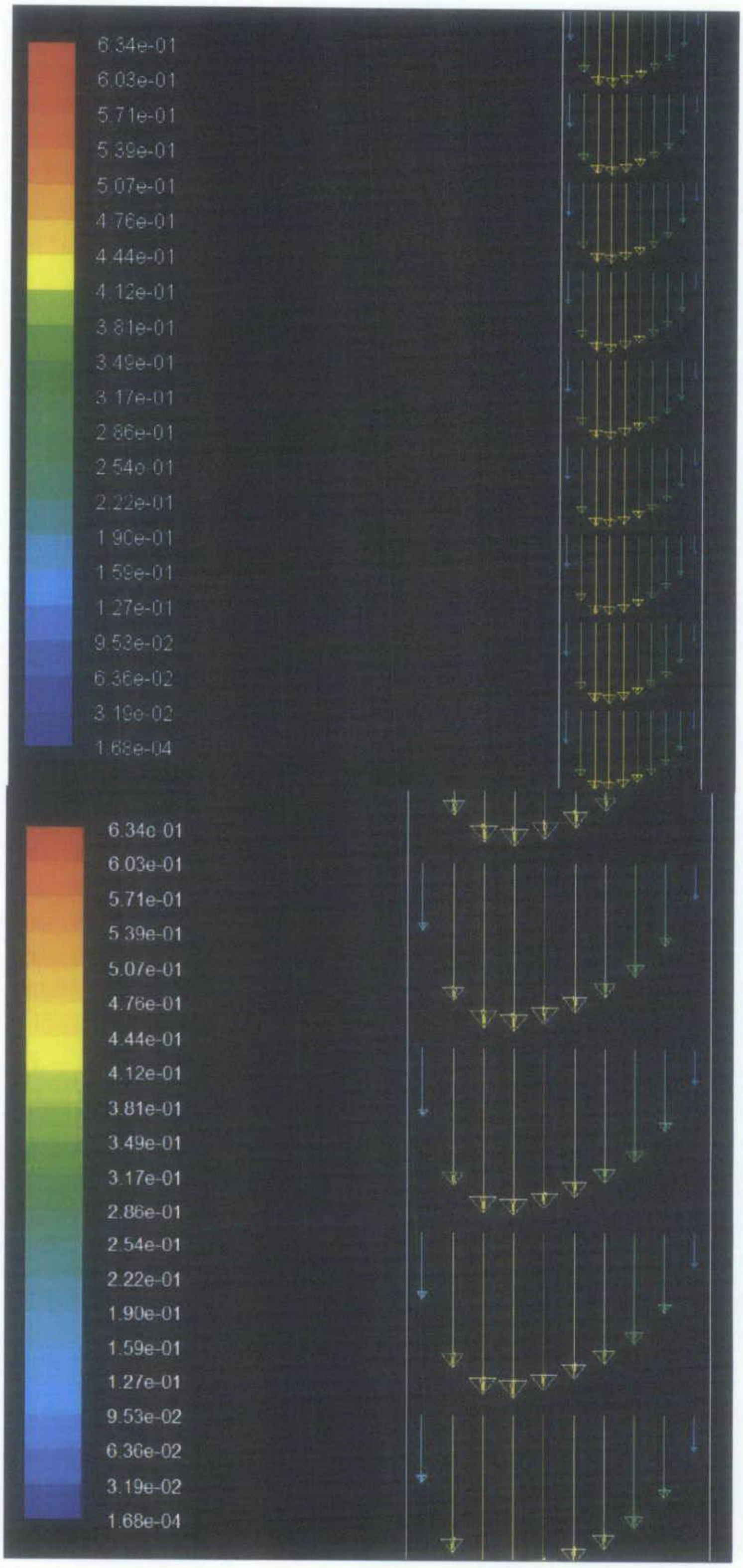
B3: Velocity Vector following Appendix B2



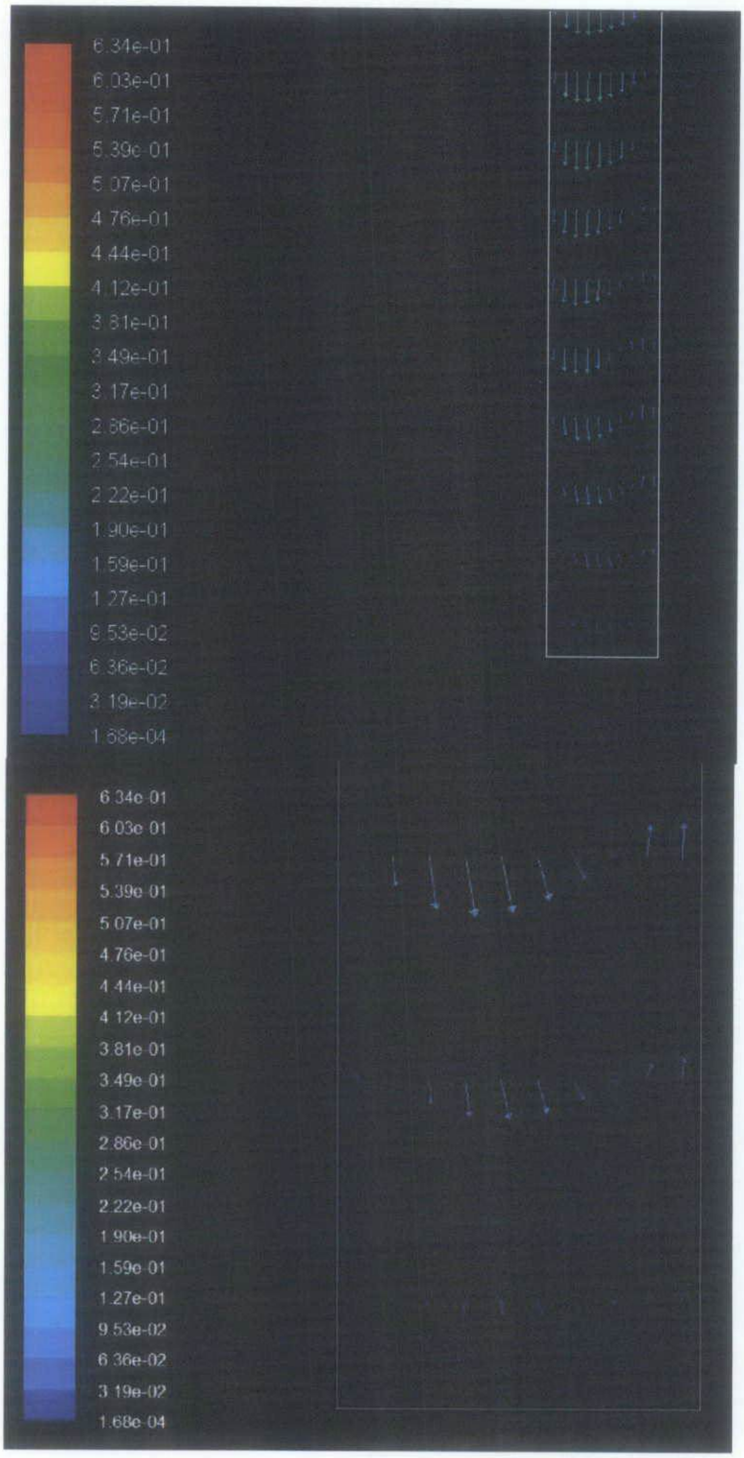
B4:Velocity Vector following Appendix B3



B5:Velocity Vector following Appendix B4



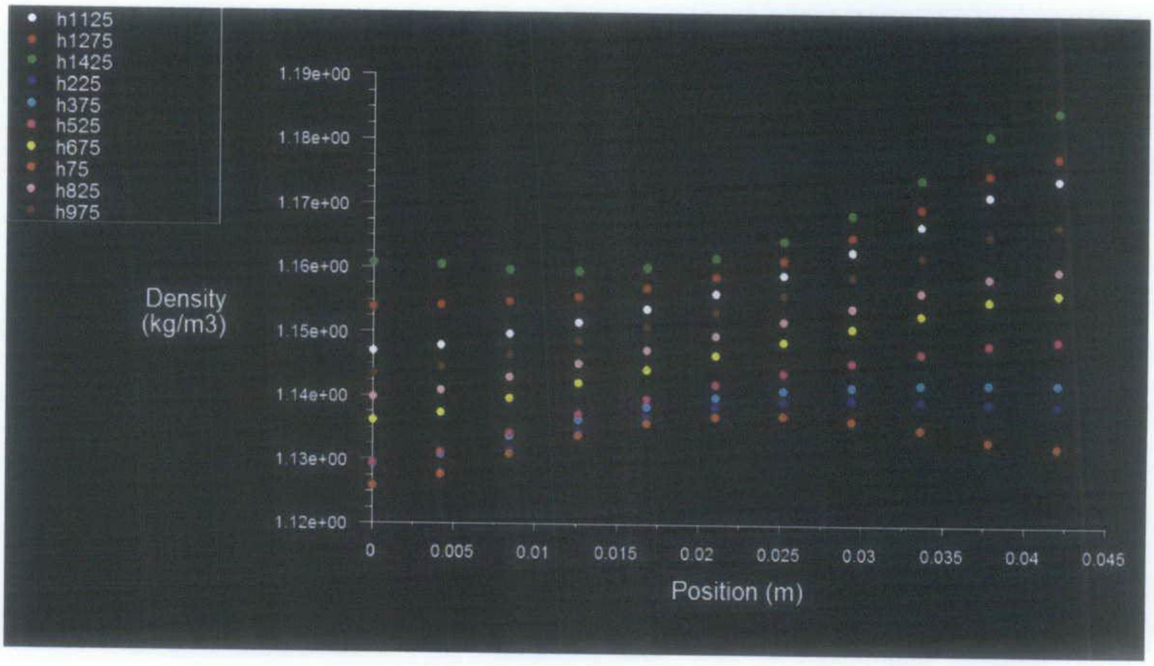
B6:Velocity Vector following Appendix B5



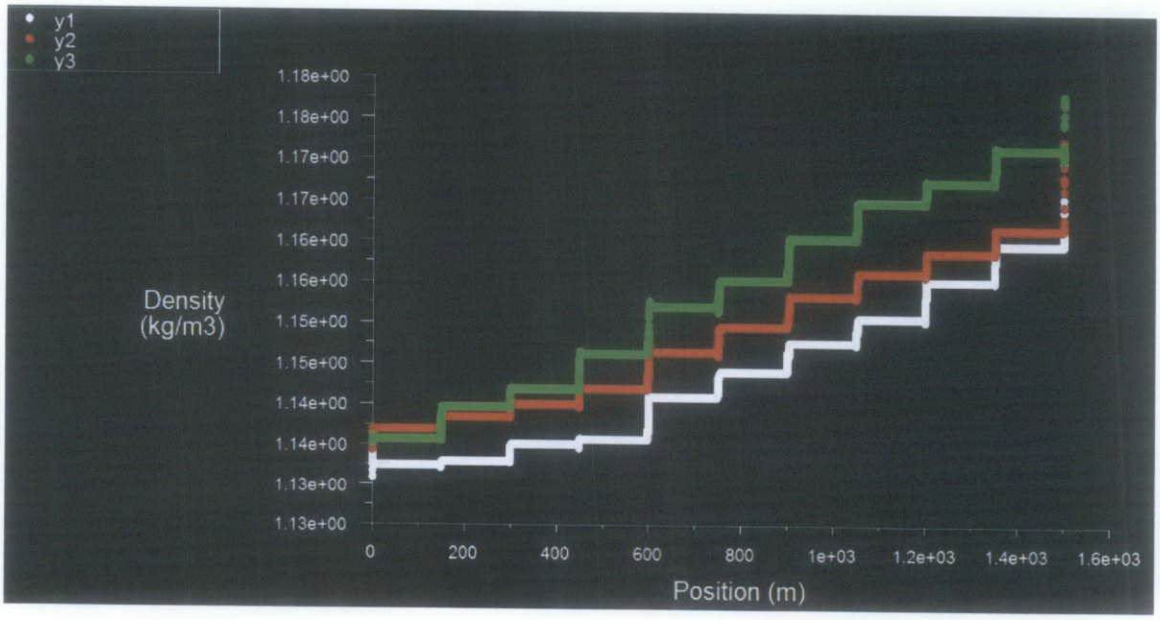
B7: Velocity Vector following Appendix B6 (Bottom of Annulus)

APPENDIX C

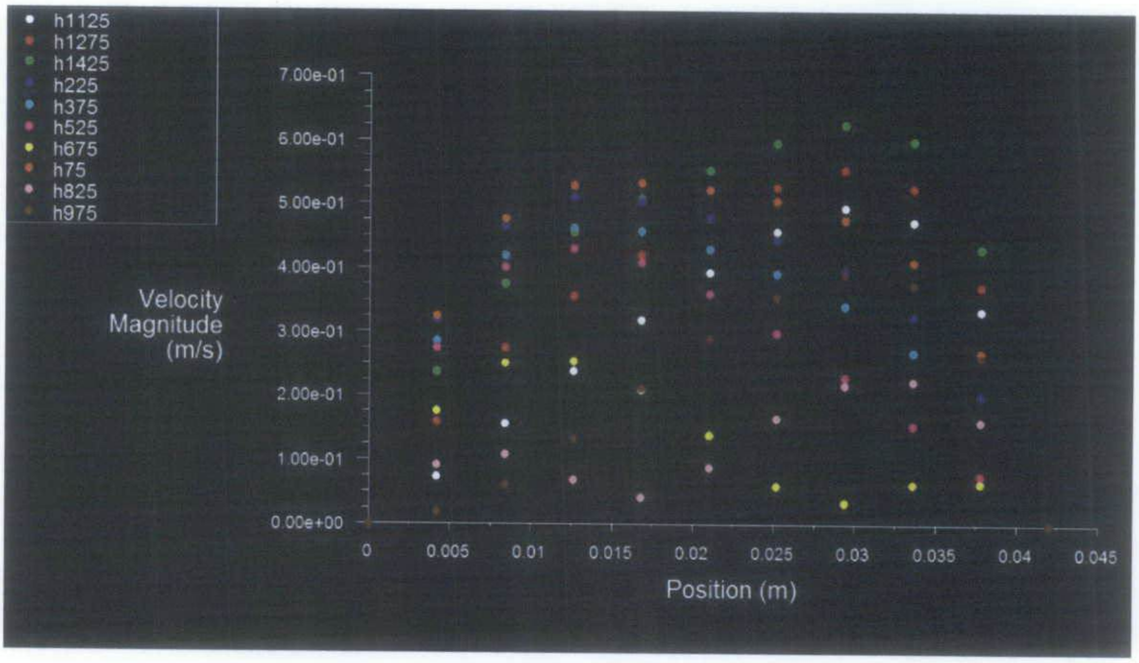
Density versus Position



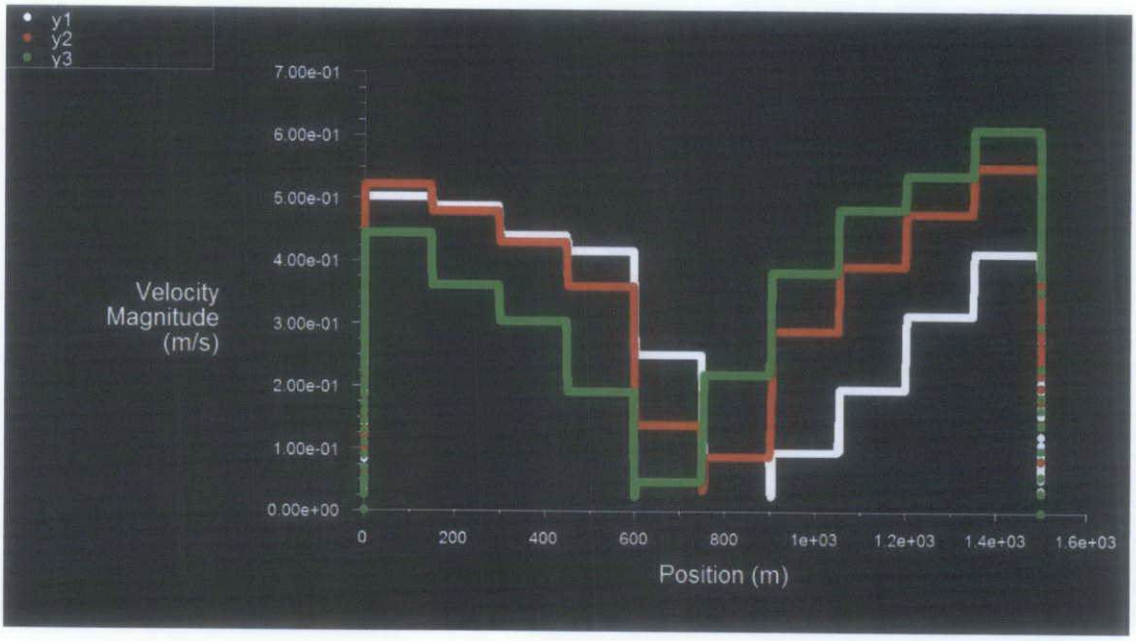
C1: Density Variation of Fluid



C2: Density of Fluid Along Y-direction



D1: Velocity Magnitude of Fluid Along X-direction



D2: Velocity Magnitude of Fluid Along Y-Direction [y1=Region near Tubing wall, y2=Mid-Section of annulus, y3=Region near Casing wall]

X Position, (m)	Velocity Magnitude, (m/s)									
	H75	H225	H375	H525	H675	H825	H975	H1125	H1275	H1425
0	0	0	0	0	0	0	0	0	0	0
0.0042	0.325	0.319	0.285	0.276	0.176	0.091	0.018	0.073	0.159	0.236
0.0084	0.477	0.466	0.421	0.401	0.251	0.108	0.061	0.155	0.274	0.376
0.0126	0.528	0.510	0.463	0.431	0.253	0.069	0.132	0.239	0.357	0.456
0.0168	0.533	0.504	0.458	0.409	0.209	0.042	0.213	0.319	0.422	0.508
0.0210	0.522	0.479	0.431	0.361	0.139	0.088	0.290	0.394	0.478	0.553
0.0252	0.505	0.445	0.392	0.299	0.059	0.165	0.355	0.457	0.526	0.597
0.0294	0.476	0.398	0.342	0.229	0.033	0.217	0.392	0.494	0.554	0.626
0.0336	0.411	0.325	0.269	0.154	0.063	0.224	0.374	0.473	0.525	0.600
0.0378	0.268	0.201	0.160	0.076	0.065	0.160	0.261	0.335	0.372	0.432
0.0420	0	0	0	0	0	0	0	0	0	0

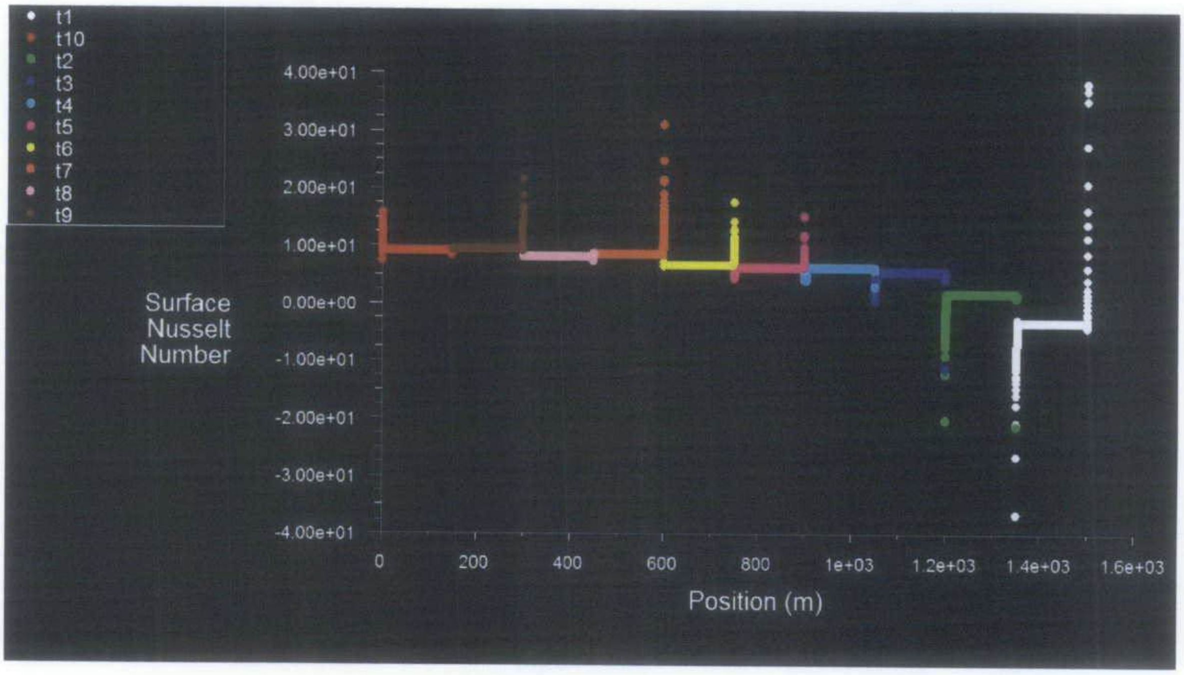
D3: Table of Velocity Magnitude of Fluid Along X-direction

Height Position, (m)	Velocity, (m/s)		
	Y1	Y2	Y3
75	0.502495	0.521709	0.44358
225	0.488212	0.47863	0.361737
375	0.441868	0.430574	0.305205
525	0.416142	0.36063	0.191791
675	0.251859	0.138957	0.048043
825	0.088337	0.08792	0.22044
975	0.096515	0.29036	0.382902
1125	0.196813	0.393955	0.483784
1275	0.31571	0.477758	0.539492
1425	0.416021	0.55304	0.612802

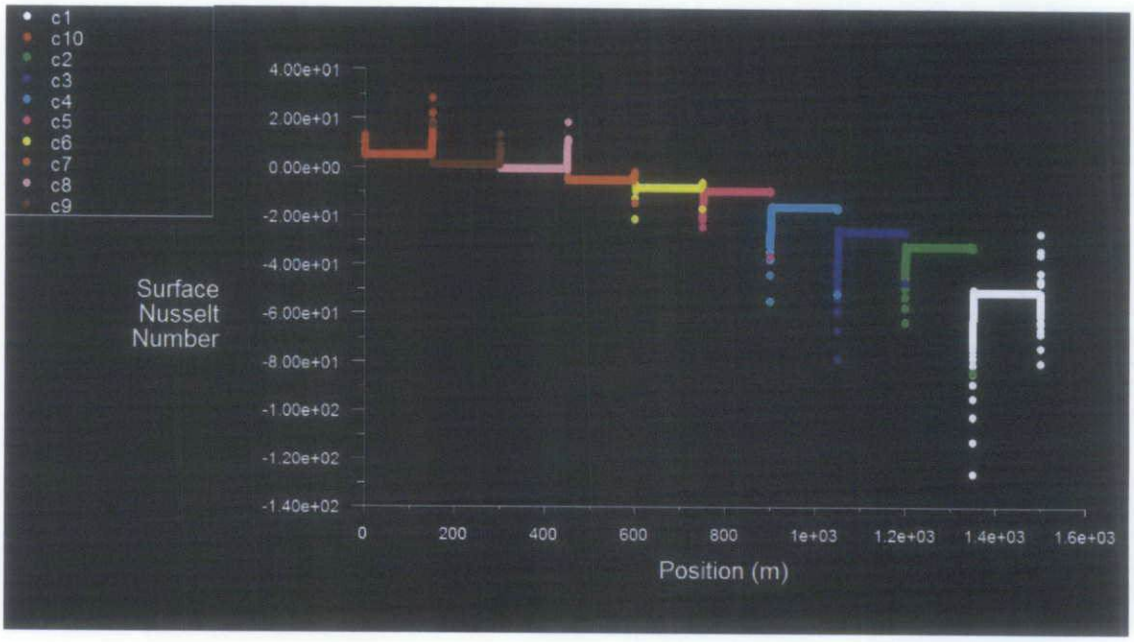
D4: Table of Velocity Magnitude of Fluid Along Y-Direction

APPENDIX E

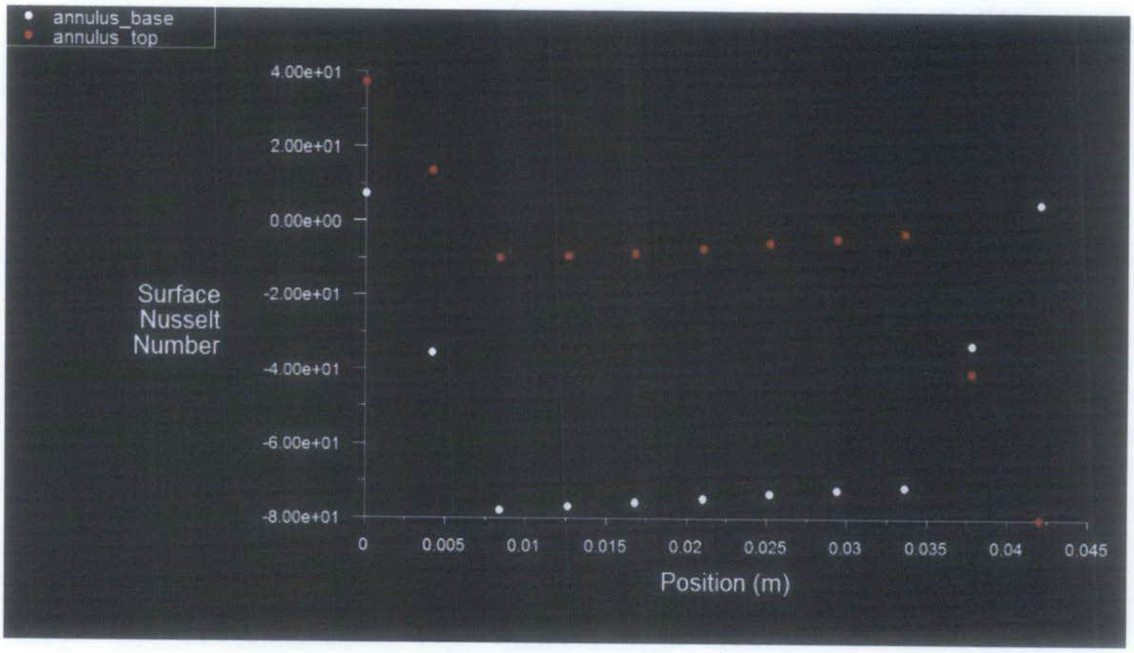
Nusselt Number versus Position



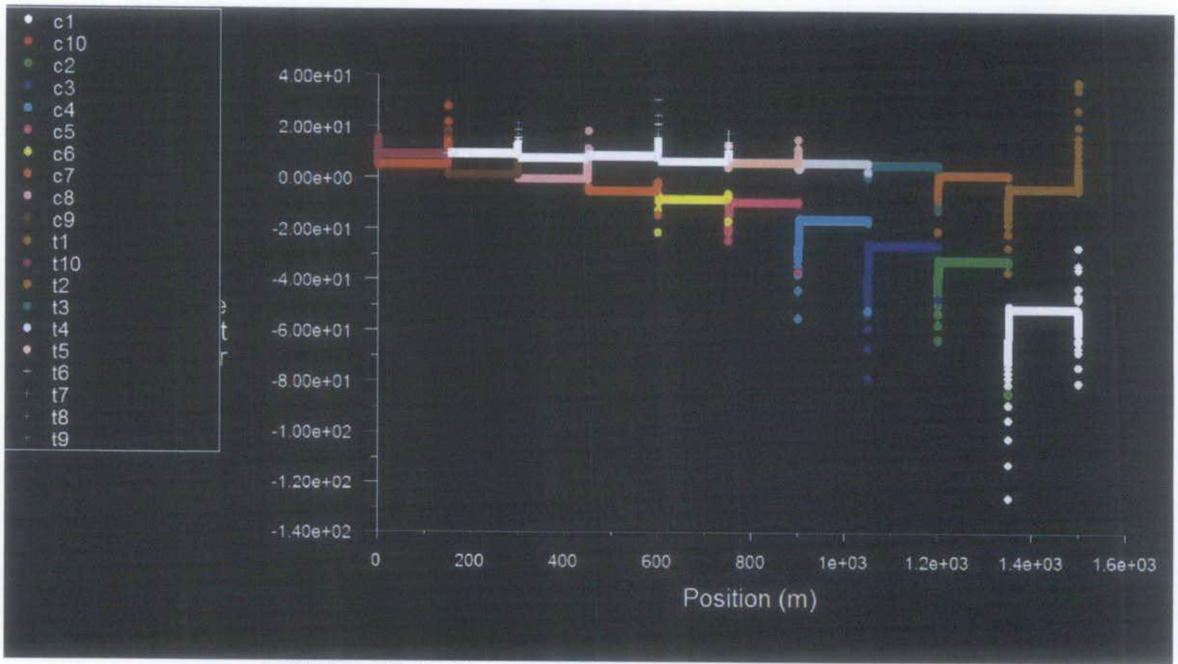
E1: Nusselt Number along tubing wall



E2: Nusselt Number along casing wall



E3: Nusselt Number along the top and bottom of annulus



E4: Nusselt Number along tubing and casing wall

Total Heat Transfer Rate at Casing (w)

c1	-1641.3626
c10	461.83318
c2	-1265.6304
c3	-1121.9861
c4	-797.16433
c5	-542.59095
c6	-495.04571
c7	-327.3022
c8	-26.206963
c9	113.29404
Net	-5642.1621

Total Heat Transfer Rate at Tubing (w)

t1	-184.80122
t10	857.57734
t2	120.37725
t3	407.9948
t4	486.67825
t5	503.87513
t6	559.35018
t7	791.37965
t8	734.05493
t9	894.04933
Net	5170.5356

Net Heat Transfer Rate of Tubing and Casing (w)

c1	-1641.3626
c10	461.84619
c2	-1265.6476
c3	-1121.9992
c4	-797.17168
c5	-542.59261
c6	-495.04424
c7	-327.29749
c8	-26.199571
c9	113.30377
t1	-184.80826
t10	857.58558
t2	120.37242
t3	407.99161

t4	486.67655
t5	503.87457
t6	559.35152
t7	791.38443
t8	734.06079
t9	894.05676
Net	-471.61908

Total Heat Transfer Rate for Segment 1	(w)
c1	-1641.3626
t1	-184.80826
Net	-1826.1709

Total Heat Transfer Rate for Segment 2	(w)
c2	-1265.6476
t2	120.37242
Net	-1145.2752

Total Heat Transfer Rate for Segment 3	(w)
c3	-1121.9992
t3	407.99161
Net	-714.00761

Total Heat Transfer Rate for Segment 4	(w)
c4	-797.17168
t4	486.67655
Net	-310.49513

Total Heat Transfer Rate for Segment 5	(w)
c5	-542.59261
t5	503.87457
Net	-38.718039

Total Heat Transfer Rate for Segment 6 (w)

c6	-495.04424
t6	559.35152
Net	64.307276

Total Heat Transfer Rate for Segment 7 (w)

c7	-327.29749
t7	791.38443
Net	464.08694

Total Heat Transfer Rate for Segment 8 (w)

c8	-26.199571
t8	734.06079
Net	707.86122

Total Heat Transfer Rate for Segment 9 (w)

c9	113.30377
t9	894.05676
Net	1007.3605

Total Heat Transfer Rate for Segment 10 (w)

c10	461.84619
t10	857.58558
Net	1319.4318

Net Heat Transfer Rate for Annulus	(w)
annulus_base	-0.91168681
annulus_top	-0.07450611
c1	-1641.3626
c10	461.84619
c2	-1265.6476
c3	-1121.9992
c4	-797.17168
c5	-542.59261
c6	-495.04424
c7	-327.29749
c8	-26.199571
c9	113.30377
t1	-184.80826
t10	857.58558
t2	120.37242
t3	407.99161
t4	486.67655
t5	503.87457
t6	559.35152
t7	791.38443
t8	734.06079
t9	894.05676
Net	-472.60527

APPENDIX G

Comparison of Nusselt Number for Analytical and Numerical Simulation

Segment	Height, Meters (M)	Average Temperature, T (K)	Total Heat Transfer Rate, Q(W)	Nusselt Number			
				Tubing (Numerical)	Casing (Numerical)	Hollands	Dropkin and Sommerscales
1	1425	300.5	-1826.17	-3.2028	-50.9338	2.2822	1.6671
2	1275	302.5	-1145.28	1.8967	-32.0909	2.2583	1.6506
3	1125	304	-714.01	5.7116	-25.9725	2.3483	1.7129
4	975	305.5	-310.50	6.4832	-15.7674	2.2230	1.6263
5	825	307	-38.72	6.3588	-9.4038	2.0846	1.5337
6	675	308	64.31	6.7222	-8.1145	2.0733	1.5263
7	525	310	464.09	8.7255	-4.8362	2.0510	1.5116
8	375	311	707.86	8.1423	-0.3735	1.7374	1.3144
9	225	312	1007.36	9.5111	1.4092	1.7271	1.3081
10	75	313	1319.43	9.1256	5.2842	1.2815	1.0335

FLUENT
Version: 2d, dp, dbns imp, lam (2d, double precision, density-based implicit, laminar)
Release: 6.3.26
Title:

Models

Model	Settings
Space	2D
Time	Steady
Viscous	Laminar
Heat Transfer	Enabled
Solidification and Melting	Disabled
Radiation	None
Species Transport	Disabled
Coupled Dispersed Phase	Disabled
Pollutants	Disabled
Pollutants	Disabled
Soot	Disabled

FLUENT
Version: 2d, dp, dbns imp, lam (2d, double precision, density-based implicit, laminar)
Release: 6.3.26
Title:

Material Properties

Material: wood (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	700
Cp (Specific Heat)	j/kg-k	constant	2310
Thermal Conductivity	w/m-k	constant	0.17299999

Material: steel (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	8030
Cp (Specific Heat)	j/kg-k	constant	502.48001
Thermal Conductivity	w/m-k	constant	16.27

Material: air (fluid)

Property	Units	Method	Value(s)

Density	kg/m3	incompressible-ideal-gas	#f
Cp (Specific Heat)	j/kg-k	constant	1006.43
Thermal Conductivity	w/m-k	constant	0.0242
Viscosity	kg/m-s	constant	1.7894001e-05
Molecular Weight	kg/kgmol	constant	28.966
L-J Characteristic Length	angstrom	constant	3.711
L-J Energy Parameter	k	constant	78.6
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: aluminum (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	2719
Cp (Specific Heat)	j/kg-k	constant	871
Thermal Conductivity	w/m-k	constant	202.4

FLUENT
Version: 2d, dp, dbns imp, lam (2d, double precision, density-based implicit, laminar)
Release: 6.3.26
Title:

Boundary Conditions

Zones

name	id	type
fluid	2	fluid
annulus_base	3	wall
annulus_top	4	wall
c10	5	wall

```
c9                  6    wall
c8                  7    wall
c7                  8    wall
c6                  9    wall
c5                  10   wall
c4                  11   wall
c3                  12   wall
c2                  13   wall
c1                  14   wall
t10                 15   wall
t9                  16   wall
t8                  17   wall
t7                  18   wall
t6                  19   wall
t5                  20   wall
t4                  21   wall
t3                  22   wall
t2                  23   wall
t1                  24   wall
default-interior    26   interior
```

```
Boundary Conditions
      fluid

         Condition                                 Value
         ---------------------------------------------------------------
-----------------------------------------------------------------------
-----------------------------------------------------------------------
------
         Material Name                             air
         Specify source terms?                     no
         Source Terms                              ((mass) (x-momentum)
(y-momentum) (energy))
         Specify fixed values?                     no
         Fixed Values                              ((x-velocity (inactive
. #f) (constant . 0) (profile  )) (y-velocity (inactive . #f) (constant
. 0) (profile  )) (temperature (inactive . #f) (constant . 0) (profile
)))
         Motion Type                               0
         X-Velocity Of Zone (m/s)                  0
         Y-Velocity Of Zone (m/s)                  0
         Rotation speed (rad/s)                    0
         X-Origin of Rotation-Axis (m)             0
         Y-Origin of Rotation-Axis (m)             0
         Deactivated Thread                        no
         Porous zone?                              no
         X-Component of Direction-1 Vector         1
         Y-Component of Direction-1 Vector         0
         Direction-1 Viscous Resistance (1/m2)     0
         Direction-2 Viscous Resistance (1/m2)     0
         Direction-1 Inertial Resistance (1/m)     0
         Direction-2 Inertial Resistance (1/m)     0
```

C0 Coefficient for Power-Law	0
C1 Coefficient for Power-Law	0
Porosity	1
Solid Material Name	aluminum

annulus_base

Condition	Value
Wall Thickness (m)	0
Heat Generation Rate (w/m3)	0
Material Name	wood
Thermal BC Type	0
Temperature (k)	300
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

annulus_top

Condition	Value
Wall Thickness (m)	0
Heat Generation Rate (w/m3)	0
Material Name	wood
Thermal BC Type	0
Temperature (k)	300
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Define wall velocity components?	no

X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

c10

Condition	Value
Wall Thickness (m)	0.01036
Heat Generation Rate (w/m3)	0
Material Name	steel
Thermal BC Type	0
Temperature (k)	312
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

c9

Condition	Value
Wall Thickness (m)	0.01036
Heat Generation Rate (w/m3)	0
Material Name	steel
Thermal BC Type	0
Temperature (k)	310
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Wall Motion	0

Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

c8

Condition	Value
Wall Thickness (m)	0.01036
Heat Generation Rate (w/m3)	0
Material Name	steel
Thermal BC Type	0
Temperature (k)	309
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

c7

Condition	Value
Wall Thickness (m)	0.01036
Heat Generation Rate (w/m3)	0
Material Name	steel
Thermal BC Type	0
Temperature (k)	307
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

c6

Condition	Value
Wall Thickness (m)	0.01036
Heat Generation Rate (w/m3)	0
Material Name	steel
Thermal BC Type	0
Temperature (k)	305
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
Rotation Speed (rad/s)	0

X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

c5

Condition	Value
Wall Thickness (m)	0.01036
Heat Generation Rate (w/m3)	0
Material Name	steel
Thermal BC Type	0
Temperature (k)	304
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

c4

Condition	Value
Wall Thickness (m)	0.01036
Heat Generation Rate (w/m3)	0
Material Name	steel
Thermal BC Type	0
Temperature (k)	302
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1

Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

c3

Condition	Value
Wall Thickness (m)	0.01036
Heat Generation Rate (w/m3)	0
Material Name	steel
Thermal BC Type	0
Temperature (k)	300
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

c2

Condition	Value
Wall Thickness (m)	0.01036
Heat Generation Rate (w/m3)	0
Material Name	steel
Thermal BC Type	0
Temperature (k)	299
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0

Free Stream Temperature (k)	300
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

c1

Condition	Value
Wall Thickness (m)	0.01036
Heat Generation Rate (w/m3)	0
Material Name	steel
Thermal BC Type	0
Temperature (k)	297
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

t10

Condition	Value
Wall Thickness (m)	0.0055
Heat Generation Rate (w/m3)	0
Material Name	steel
Thermal BC Type	0
Temperature (k)	314
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

t9

Condition	Value
Wall Thickness (m)	0.0055
Heat Generation Rate (w/m3)	0
Material Name	steel
Thermal BC Type	0
Temperature (k)	314
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
Rotation Speed (rad/s)	0

X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

t8

Condition	Value
Wall Thickness (m)	0.0055
Heat Generation Rate (w/m3)	0
Material Name	steel
Thermal BC Type	0
Temperature (k)	313
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

t7

Condition	Value
Wall Thickness (m)	0.0055
Heat Generation Rate (w/m3)	0
Material Name	steel
Thermal BC Type	0
Temperature (k)	313
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1

Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

t6

Condition	Value
Wall Thickness (m)	0.0055
Heat Generation Rate (w/m3)	0
Material Name	steel
Thermal BC Type	0
Temperature (k)	311
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

t5

Condition	Value
Wall Thickness (m)	0.0055
Heat Generation Rate (w/m3)	0
Material Name	steel
Thermal BC Type	0
Temperature (k)	310
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0

Free Stream Temperature (k)	300
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

t4

Condition	Value
Wall Thickness (m)	0.0055
Heat Generation Rate (w/m3)	0
Material Name	steel
Thermal BC Type	0
Temperature (k)	309
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

t3

Condition	Value
Wall Thickness (m)	0.0055
Heat Generation Rate (w/m3)	0
Material Name	steel
Thermal BC Type	0
Temperature (k)	308
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

t2

Condition	Value
Wall Thickness (m)	0.0055
Heat Generation Rate (w/m3)	0
Material Name	steel
Thermal BC Type	0
Temperature (k)	306
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
Rotation Speed (rad/s)	0

X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

t1

Condition	Value
Wall Thickness (m)	0.0055
Heat Generation Rate (w/m3)	0
Material Name	steel
Thermal BC Type	0
Temperature (k)	304
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

default-interior

Condition	Value

```
FLUENT
Version: 2d, dp, dbns imp, lam (2d, double precision, density-based
implicit, laminar)
Release: 6.3.26
Title:

Solver Controls
---------------

   Equations

      Equation   Solved
      -----------------
      Flow       yes

   Numerics

      Numeric                                Enabled
      ---------------------------------------------
      Absolute Velocity Formulation          yes

   Relaxation

      Variable   Relaxation Factor
      -----------------------------
      Solid      1

   Linear Solver

                 Solver     Termination    Residual Reduction
      Variable   Type       Criterion      Tolerance
      --------------------------------------------------------
      Flow       F-Cycle    0.1

   Discretization Scheme

      Variable   Scheme
      ------------------------------
      Flow       Second Order Upwind

   Time Marching

      Parameter         Value
      -------------------------
      Solver            Implicit
      Courant Number    5

   Solution Limits

      Quantity                      Limit
      ---------------------------------
      Minimum Absolute Pressure     1
      Maximum Absolute Pressure     5e+10
      Minimum Temperature           1
      Maximum Temperature           5000
```