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FINITE ELEMENT MODELING FOR HEAT TRANSFER OF FORCED CONVECTION IN INSULATED TUBE WITH EES ANALYTICAL VALIDATION AT DIFFERENT OPERATING CONDITIONS

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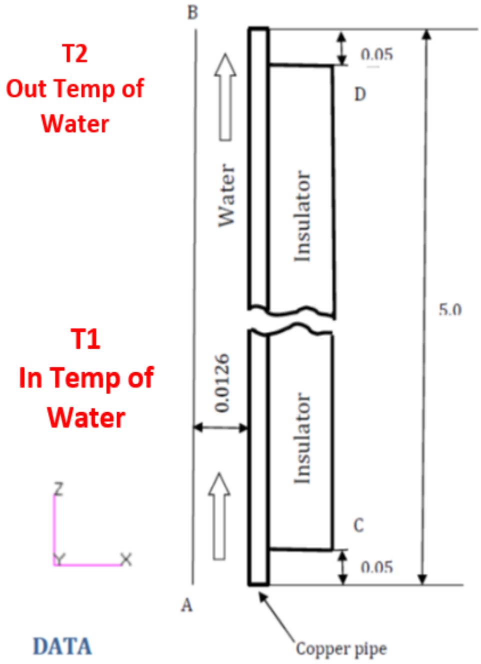
ABSTRACT

A copper pipe carrying boiling water from the boiler house to the floor above is insulated and sheltered in a duct to avoid exposing the pipe to cold weather. For renovation reasons the pipe's shelter has been temporarily removed, exposing the pipe to an extreme weather condition. It is critical to the plant operation for the water temperature at the pipe outlet to be maintained above 90oC. The Finite Element Model will be setup in Software Patran and the meshing will be done to execute accurate finite Element Analysis. The Finite Element solution was compared by an EES code in order to demonstrate different operation scenarios.



1. INTRODUCTION

The most popular FEA pre- and post-processing software in the world, is Patran offers solid modeling, meshing, analysis setup, and post-processing for a variety of solvers, including MSC Nastran, Patran offers a comprehensive collection of tools that simplify the development of analysis-ready models for thermal, linear, nonlinear, explicit dynamics, and other finite element solutions. Patran makes it simple for anyone to produce FE models, from geometry cleanup tools that help engineers deal with slivers and gaps in CAD to solid modeling tools that allow development of models from scratch. Surfaces and solids can readily be meshed using completely automated meshing processes, manual techniques that offer greater control, or a combination of both. Last but not least, the majority of popular FE solvers have loads, boundary conditions, and analysis setup built in, reducing the need to alter input decks.

In this problem we will Calculate the water temperature at point B under normal working conditions (Inshelter)

While the pipe is exposed to the extreme weather condition (outside the shelter), we will calculate the water temperate at the pipe outlet TB (at ambient temperature -60 oC)

Use the Patran graphic engine to plot the water temperature from point A to B (X-Y graph)

Use the Patran graphic engine to plot the insulator outside temperature from point C to D (X-Y graph) and will study the scenario What is the solution if Temperature at outlet at B drops lower than 90 C which is a process limiting factor.

2. METHODOLOGY

Data

- Mass flow rate is 0.04 – 0.16 Kg/m3, currently set to 0.04Kg/m3 to fulfill the plant requirements with the excess amount pumped back to the boiler house
- Normal ambient temperature (inside the shelter) 20oC Extraordinary ambient temperature (outside the shelter) 40 oC to -60 oC
- Water inlet temperature TA = 100oC
- Water thermal conductivity K = 0.65 W/m0K, mass density 1000 Kg/m3 Water specific heat Cp= 4200 J/Kg. 0K and dynamic viscosity = 0.001 Kg/m.s
- Properties of Material & dimensión of Tube & Insulation

Type K copper pipe nominal diameter	1”
Copper pipe inside diameter	0.0252 m
Copper pipe outside diameter	0.0286 m
Pipe wall thickness	0.0017 m
Pipe length	5 m
Pipe insulation thickness (3/8”)	0.0095 m
Pipe insulation length	4.9 m

Copper	*Insulator (Polyethylene)*
K = 401 W/m⁰K	K = 0.33 W/m⁰K
ρ = 8940 Kg/m^3	ρ = 24.0 Kg/m^3
C_p= 386 J/Kg.⁰K	C_p= 2000 J/Kg.⁰K
Convection Coefficients (inside the shelter)	
hac (air-copper) = 5 W/m$^{2.}$⁰K	
hap (air-polyethylene) = 5 W/m$^{2.}$⁰K	
Convection Coefficients (outside the shelter)	
hac (air-copper) = 30 W/m$^{2.}$⁰K (at sub-zero temp only)	
hap (air-polyethylene) = 30 W/m$^{2.}$⁰K (at sub-zero temp only)	

Procedure

- Creat the Geometry of the Model first by making the Analysis base don model and using “ prefernce to change the global tolerance to 0.0001 to acceot dimensions of 0.0017 mt & above
- Creat one curve with origin as start and [0 0 5] as End
- Creat three Surfaces to represent upper & lower portion of tuve thickness and middle insulation , use Surface XYZ and enter the coordinates as per the geometry
- Creat the material properties for Cu, Insulation and Water
- Creat the Properties of surfaces as Axi Sym 2D element
- Creat properties of Water curve as 1 D flow tube
- Creat the Tria mesh for Surface and bar2 for curve use the mesh seed as indicated in the problem
- Creat the boundary conditions as follows
- Inlet temp ant Node 1 of value 100 C
- Convection on three Surface outside edge with h=5 W/m0K and Temp 20 C
- Convection-2 on three surfaces outside edge to represent the extra ordinary outshelter conditions of h=30 W/mK and T =-60 C
- Coupled flow convection between the wáter curve 1 and the inside edge of surfaces with mass 0.04 Kg/sec and inlet the K/d*0.023=0.6 and 0.8,0.3 as Re & Pr powers
- Creat the following load Cases

1. InShelter with Convection and coupled and inlet Temp as boundary conditions
2. Outshelter with convection-2 , coupled and inlet Temp as boundary conditions
3. Higher insulation Case with convection 2 but insulation termal conductivity of K=0.1
4. Higher mass with convection 2 but mass flow rate 0.16 kg/sec

Steps In Pictures

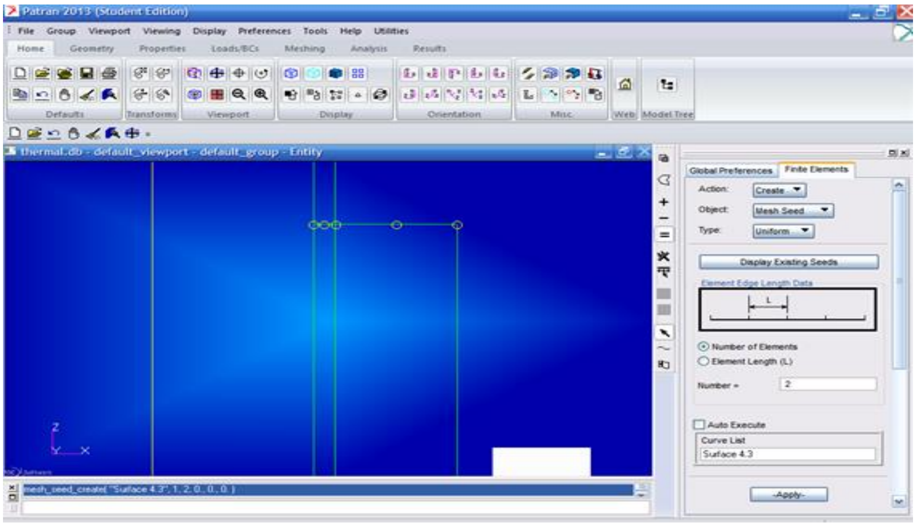


Fig1-Mesh Seeds

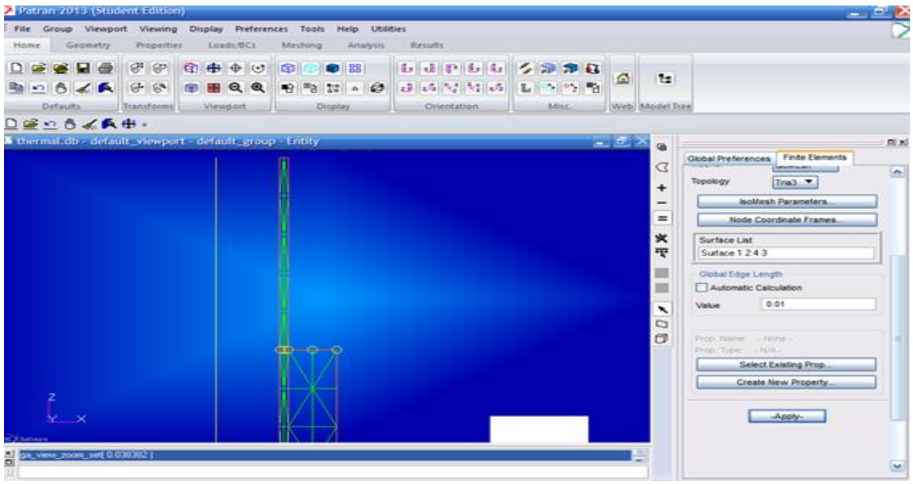


Fig2-Mesh in Tria3 element

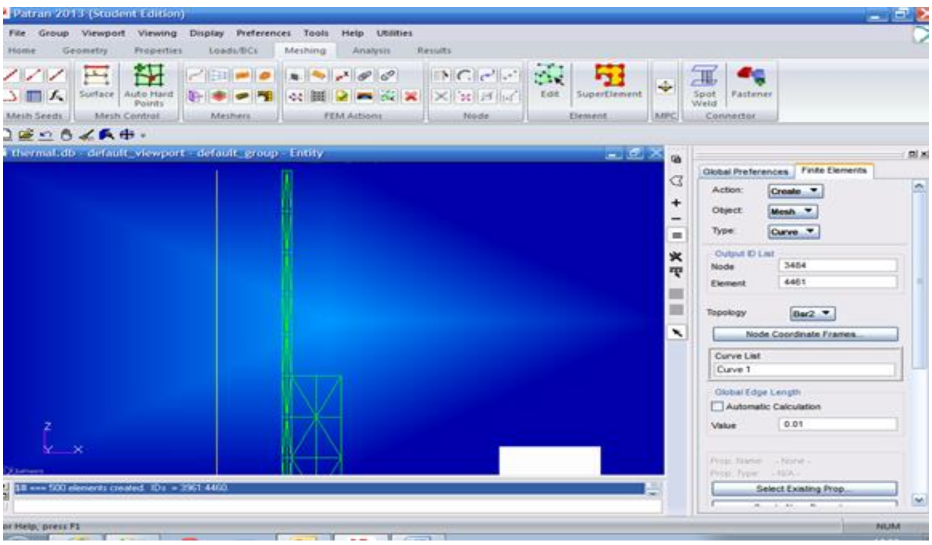


Fig3-Mesh in Bar2 Element

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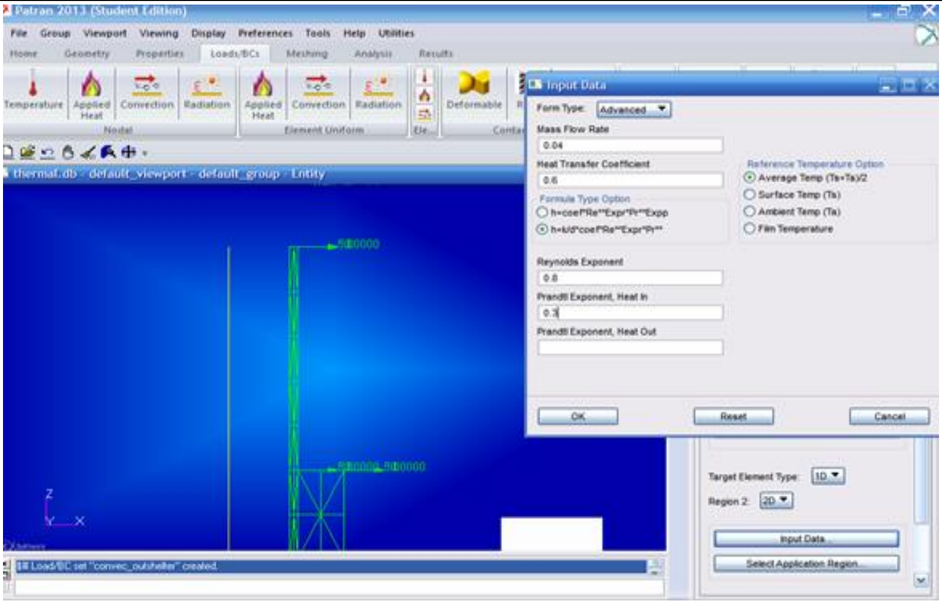

Fig4-Coupled Boundary Coditions

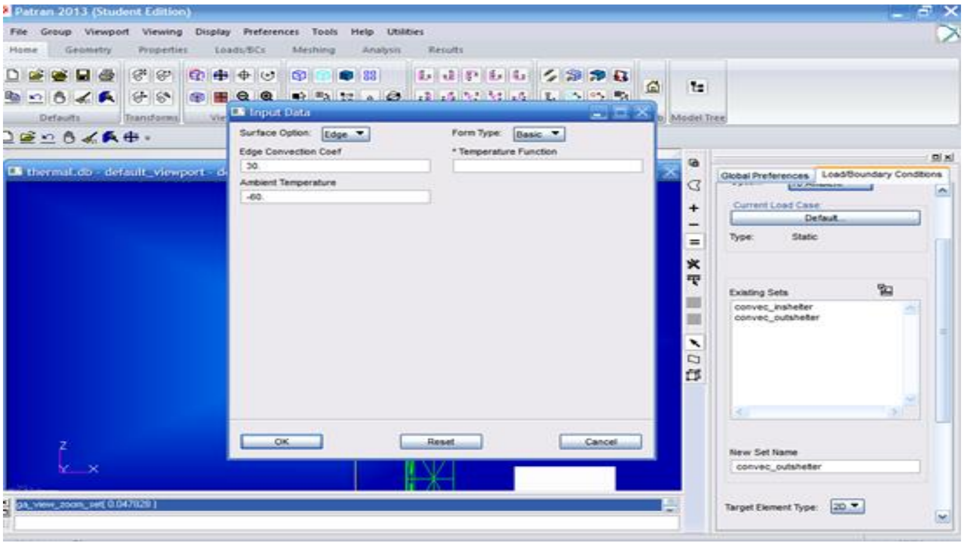

Fig5-Convection Boundary Conditions

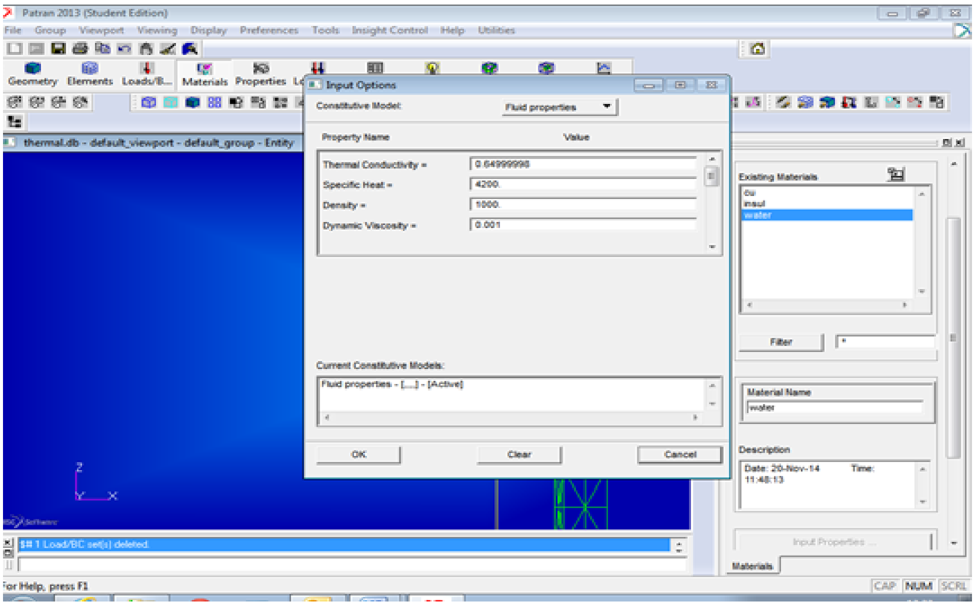

Fig6-Water Material defnition

3. CALCULATIONS

The thermal resistance of each (insulation) layer is calculated using the following equation:

$$R_{layer} = \frac{\ln(r_e / r_i)}{2\pi \cdot \lambda_k} \qquad [\text{m.K/W}]$$

Where:

r_e = the outer radius of that layer [m]

r_i = the inner radius of that layer [m]

λ_k = the thermal conductivity of that layer [W/m.K]

The total thermal resistance of a pipe, with or without insulation layer(s) and surface heat transfer resistances to inner fluid and extern 'air', can be calculated with following equation:

$$R_{l\,tot} = \frac{R_i}{2\pi\, r_1} + \sum_{k=1}^{n-1} \frac{\ln\left(\frac{r_{(k+1)}}{r_k}\right)}{2\pi\lambda_k} + \frac{R_e}{2\pi\, r_n} \qquad [\text{m.K/W}]$$

Where:

R_i = inner surface heat transfer resistance between fluid and material ($1/h_i$) [m^2.K/W]

R_e = outer surface heat transfer resistance between fluid and material ($1/h_i$) [m^2.K/W]

The heat flow passing through the pipe surface is calculated using the following equation:

$$\Phi_{l\,tot} = \frac{\theta_i - \theta_e}{R_{l\,tot}} \cdot L \qquad [\text{W}]$$

The inner heat transfer Equation is

$$h_{int} = \frac{k}{d} * 0.023 * \mathrm{R_e^{0.8}} * \mathrm{P_r^{0.3}}$$

4. RESULTS

A-Inside Shelter

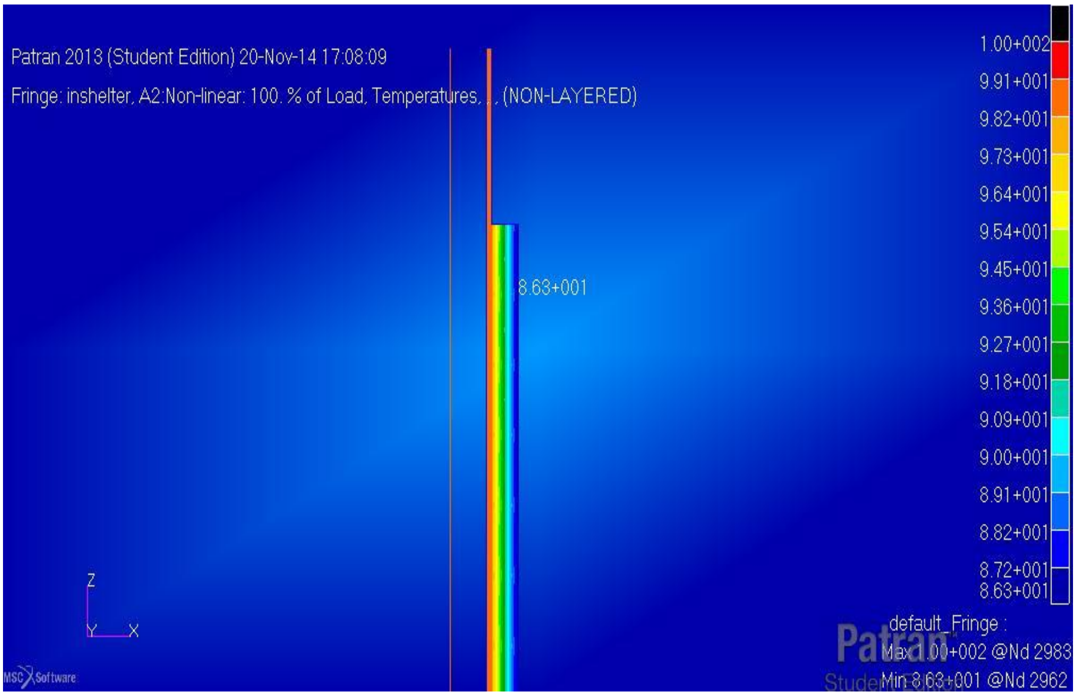

Fig7 Inside the Shelter the tube top section

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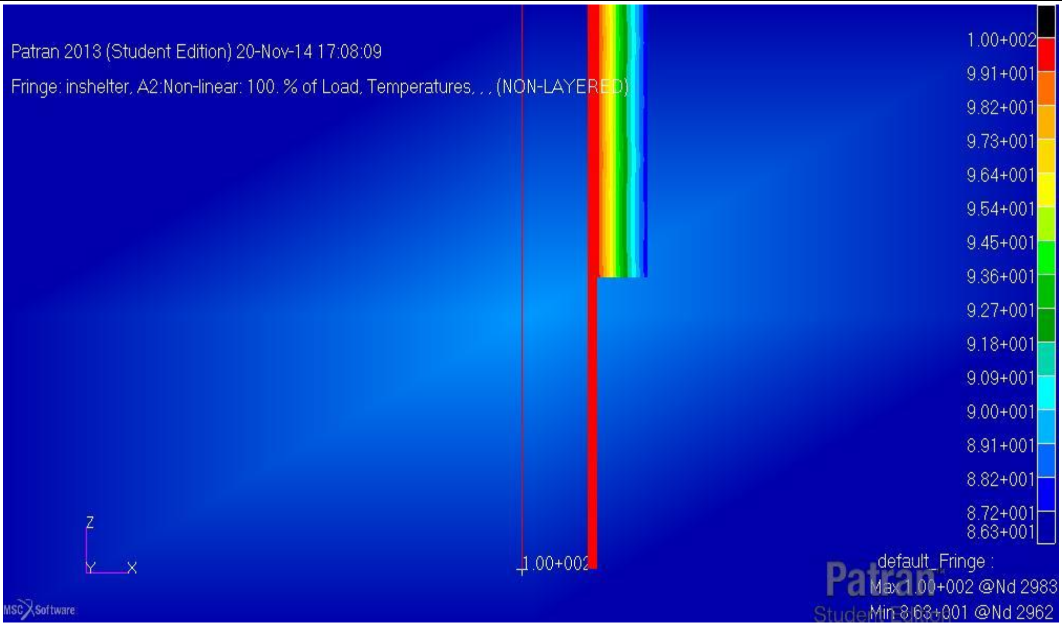

Fig8 Inside the Shelter the tube down section

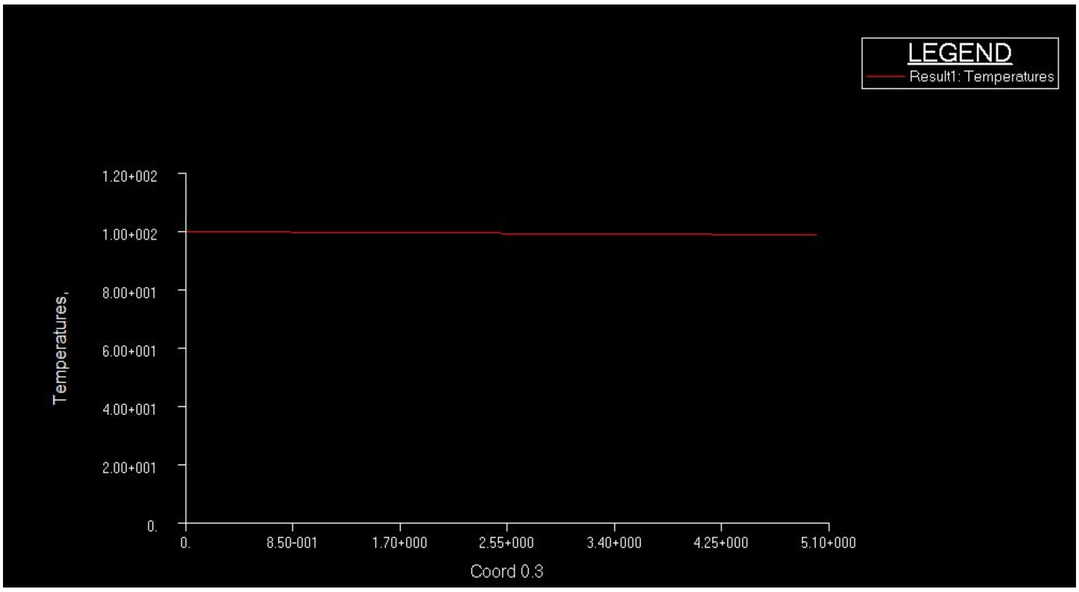

Fig 9 Temperature distribution along water tube axis inside Shelter

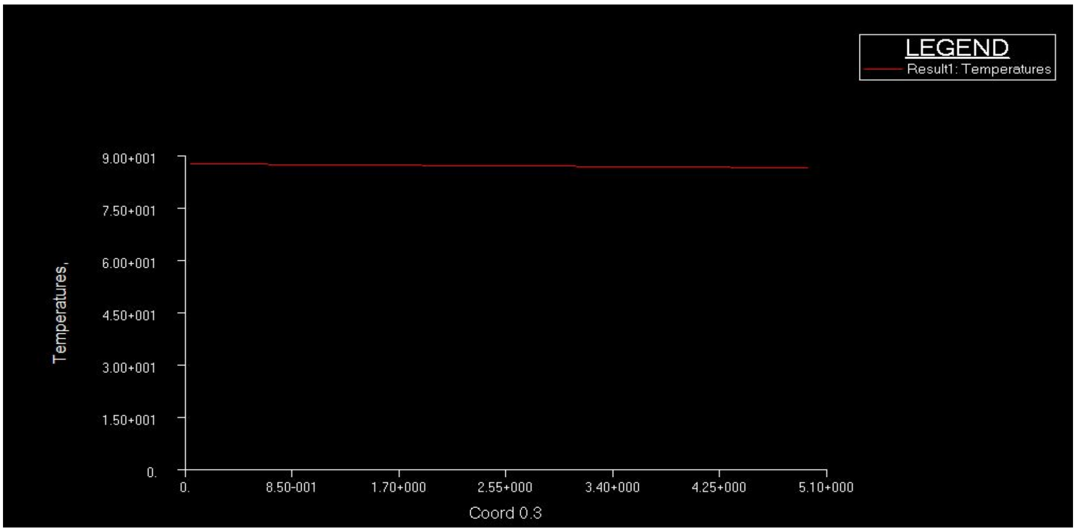

Fig 10 Temperature distribution along the outside of Insulation for tube inside shelter

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B-outside Shelter

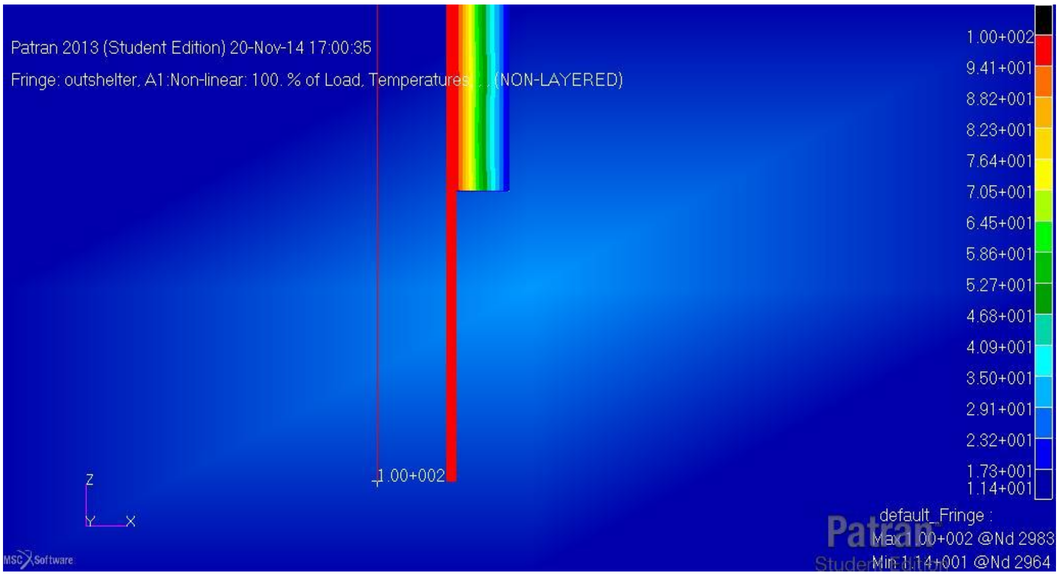

Fig 11 Outside Shelter tube bottom portion

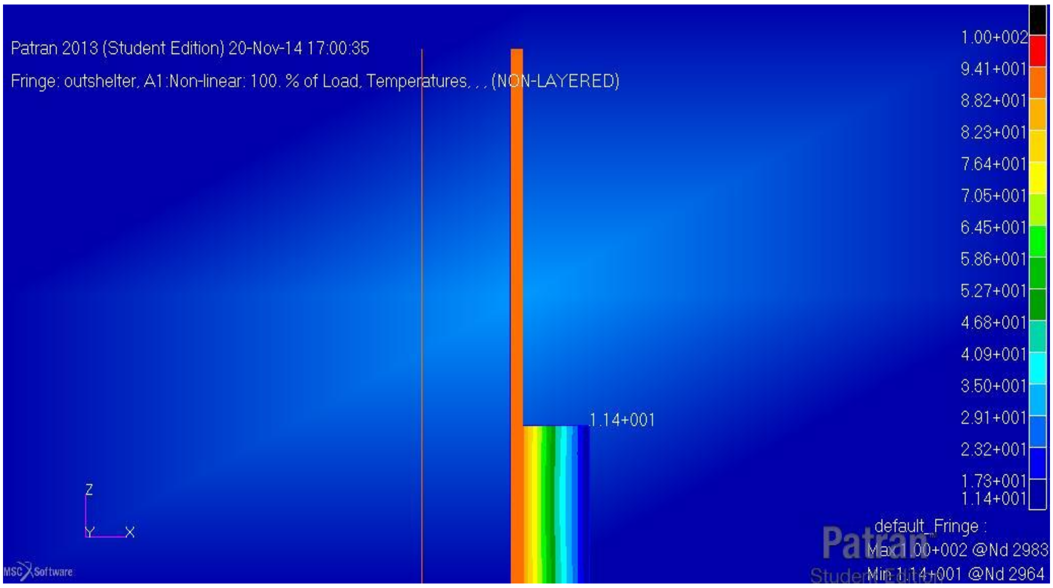

Fig 12 otside shelter Tube Top portion

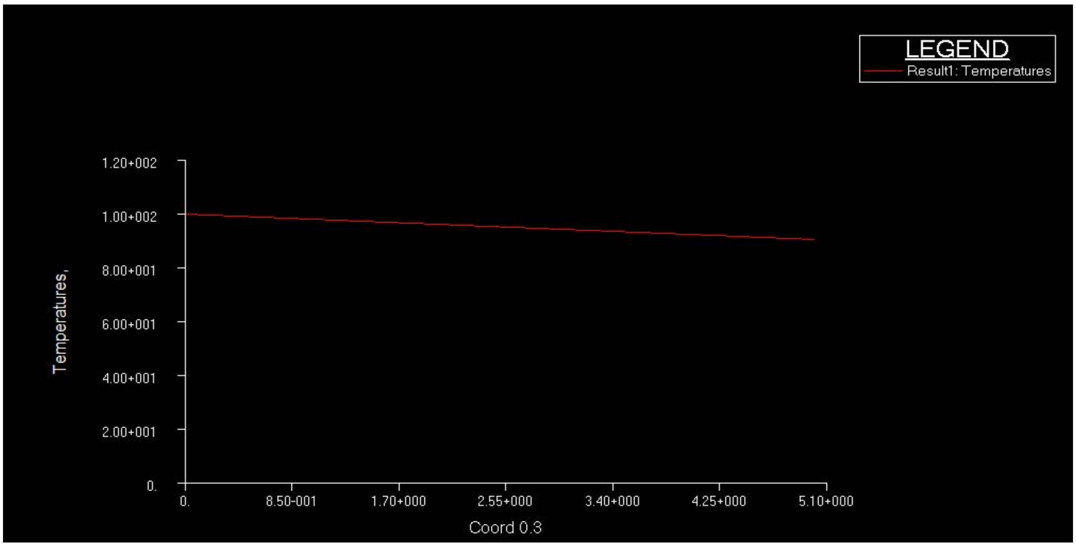

Fig13 Temperature distribution along water tube axis ouside Shelter

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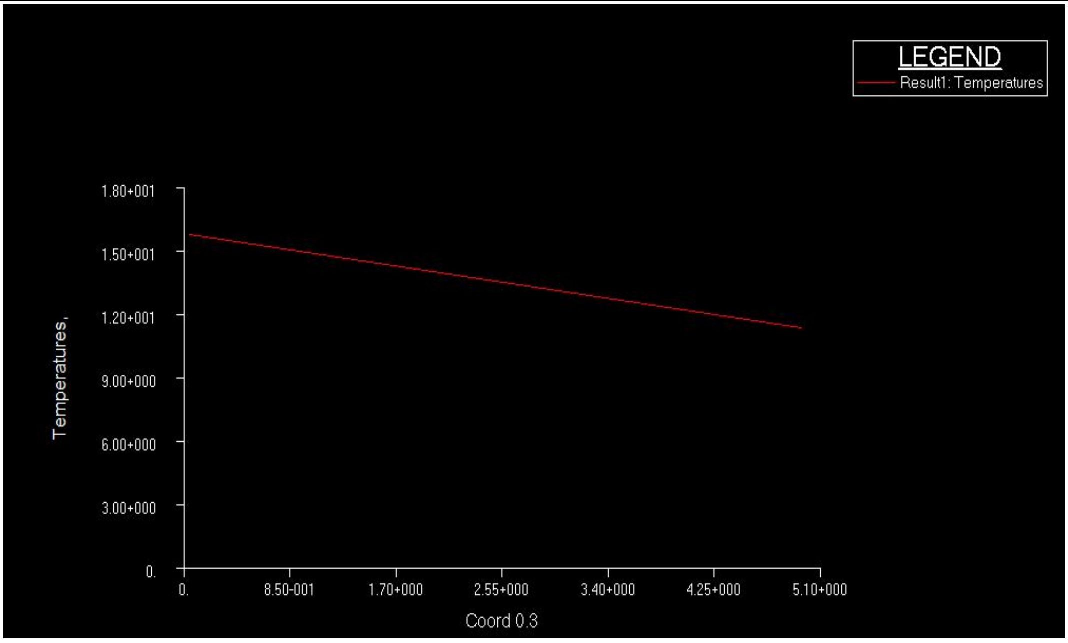

Fig14 Temperature distribution along the outside of Insulation outside shelter

Temperature at outlet 90.4 C

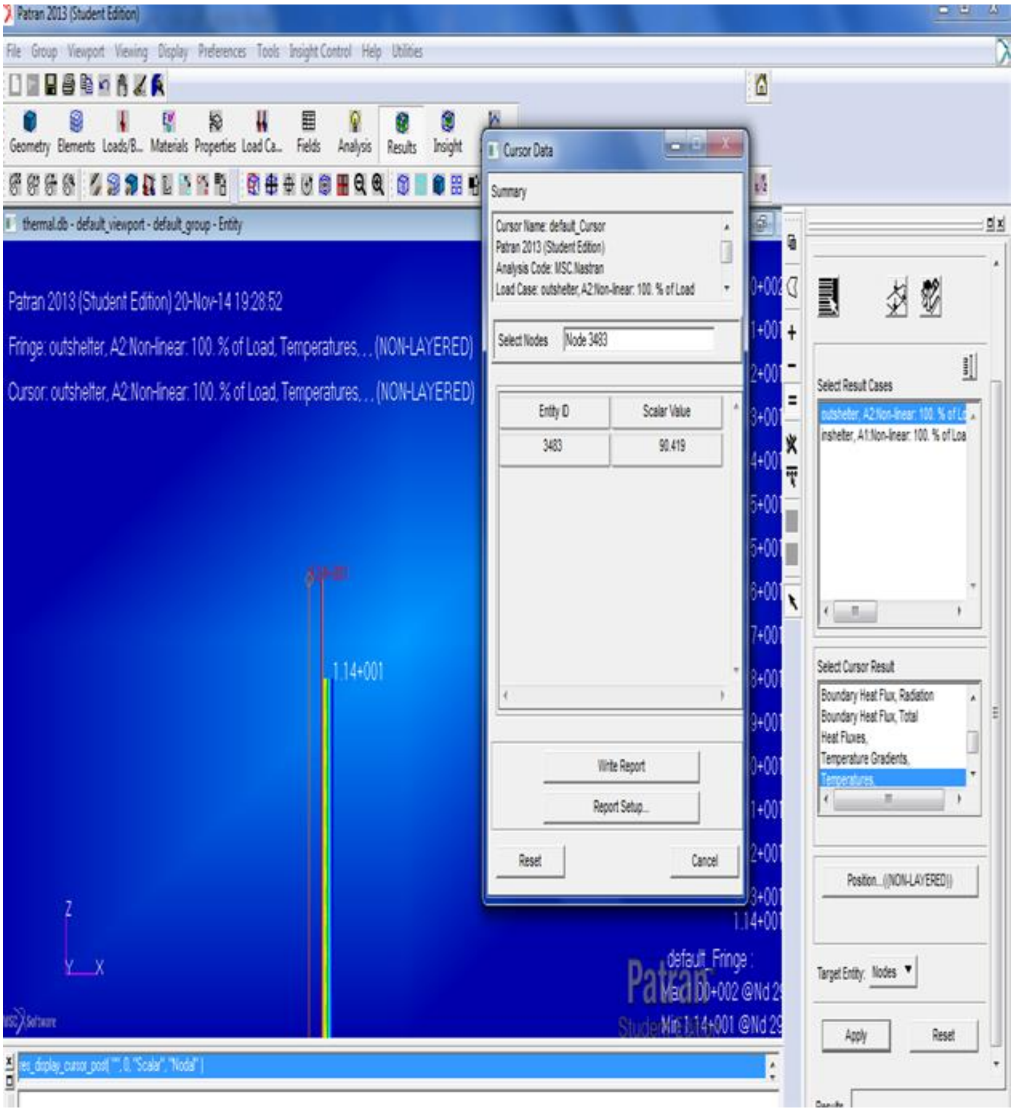

Fig 15 Indicate temperature crossed 90c

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To accommodate for drop below 90C

- The water lost heat to outside environment is equal to (Mass X specific heat X Delta T), so to compensate for more heat transfer due to drop of outside air Temperature **,** we increase the mass flow rate and it proved to be a solution with extra pumping cost .

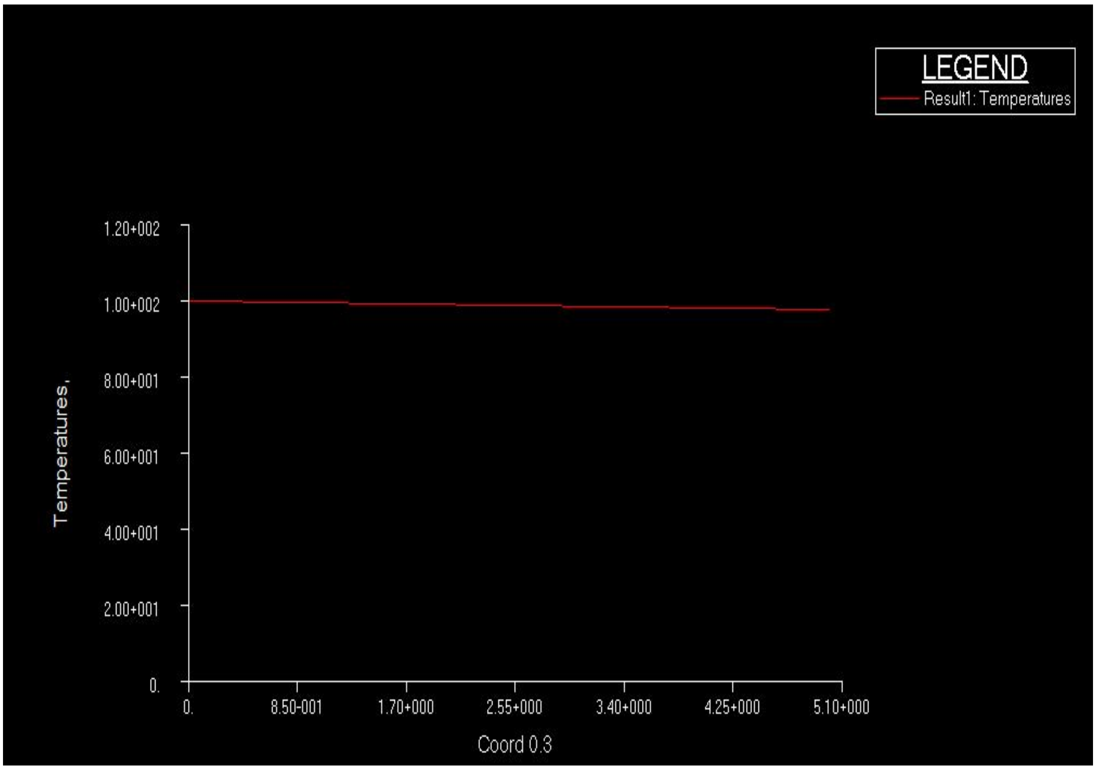

Fig 16 Water temp distribution when mass increased to 0.16 Kg/sec

- The other option but non practical is to use a more resistance Insulator either by increasing Insulator Thickness or using higher resistance material , trailing is the effect of decreasing the insulation thermal conductivity from 0.33 to 0.1 , this option is not practical

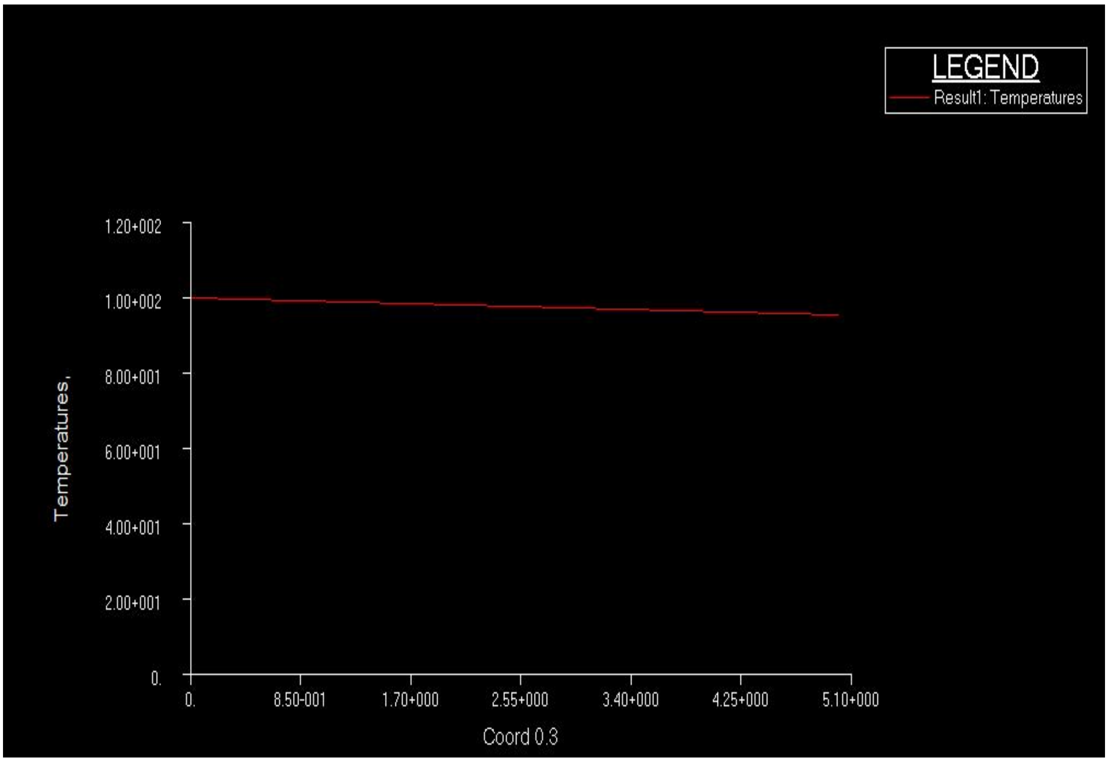

Fig 17 Water temp distribution when insulation Resistance increased

Analytical solution

A model in Engineering Equation solver was created EES is an iterative software that could solve a group of equations together , the main idea is use and approximation solution by considering the average of water in and out temperature for heat transfer with Air , the model will give less accurate results but could be used as indication of the main parameters affecting the problem and accordingly utilize FEA analysis of Nastran to get a more accurate results

$$Q_{in} = -Q_{out}$$

$$m.c_p.\Delta T = -L.\frac{\left(\frac{T_2 + T_1}{2}\right) - T_a}{R_{tot}}$$

$$\frac{T_{water} - T_{insurf}}{R_{conV-in}} = \frac{T_{insurf} - T_{outsurf}}{R_{insul} + R_{Cu}}$$

$$\frac{T_{outsurf} - T_{air}}{R_{Conv-Out}} = \frac{T_{insurf} - T_{outsurf}}{R_{insul} + R_{Cu}}$$

Program Code

```
v=4*mass/(1000*3.14*(0.0252*0.0252))
Re=1000*v*0.0252/0.001
hin=(401/0.0252)*0.023*((Re)^0.8)*1.8^0.3
Rin=1/(2*3.14*0.0126*hin)
Rout=1/(2*3.14*0.0126*hout)
Rcu=ln(0.0143/0.0126)/(2*3.14*401)
Rinsu=ln(r_insu/0.0143)/(2*3.14*Kins)
r_insu=0.0143+thick
Rtot=Rinsu+Rcu+Rin+Rout
T2=-((((T2+T1)/2)-Ta)/(mass*Rtot*4200))*5+T1
T1=100
Tis1=((Rinsu+Rcu)*(T1-Tis1)/Rin)+Tos1
Tos1=(Rout*((T1-Tis1)/Rin))+Ta


Tis2=((Rinsu+Rcu)*(T2-Tis2)/Rin)+Tos2
Tos2=(Rout*((T2-Tis2)/Rin))+Ta
```

Formatted Equation " Code in formatted shape"

$$v = 4 \cdot \frac{mass}{1000 \cdot 3.14 \cdot 0.0252 \cdot 0.0252}$$

$$Re = 1000 \cdot v \cdot \frac{0.0252}{0.001}$$

$$hin = \frac{401}{0.0252} \cdot 0.023 \cdot Re^{0.8} \cdot 1.8^{0.3}$$

$$Rin = \frac{1}{2 \cdot 3.14 \cdot 0.0126 \cdot hin}$$

$$Rout = \frac{1}{2 \cdot 3.14 \cdot 0.0126 \cdot hout}$$

$$Rcu = \frac{\ln\left[\frac{0.0143}{0.0126}\right]}{2 \cdot 3.14 \cdot 401}$$

$$Rinsu = \frac{\ln\left[\frac{r_{insu}}{0.0143}\right]}{2 \cdot 3.14 \cdot Kins}$$

$$r_{insu} = 0.0143 + thick$$

$$Rtot = Rinsu + Rcu + Rin + Rout$$

$$T2 = -\left[\frac{\frac{T2 + T1}{2} - Ta}{mass \cdot Rtot \cdot 4200}\right] \cdot 5 + T1$$

$$T1 = 100$$

$$Tis1 = \left[Rinsu + Rcu\right] \cdot \left[\frac{T1 - Tis1}{Rin}\right] + Tos1$$

$$Tos1 = Rout \cdot \left[\frac{T1 - Tis1}{Rin}\right] + Ta$$

$$Tis2 = \left[Rinsu + Rcu\right] \cdot \left[\frac{T2 - Tis2}{Rin}\right] + Tos2$$

$$Tos2 = Rout \cdot \left[\frac{T2 - Tis2}{Rin}\right] + Ta$$

Parametric table with different parameters change options , like increasing mass flow rate from 0.04 to 0.16 Kg/Sec and increasing the thickness of insulation or increasing its resistanc

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Parametric Table: Table 1

	thick	Ta	hout	Kins	T2	Tos1	Tos2	mass
Run 1	0.019	-60	30	0.33	94.36	21.28	18.41	0.04
Run 2	0.019	20	5	0.33	99.19	88.88	88.19	0.04
Run 3	0.0095	-60	30	0.33	98.23	41.03	39.91	0.16
Run 4	0.0095	20	5	0.33	99.79	92.91	92.71	0.16
Run 5	0.0095	-60	30	0.33	93.02	41.02	36.61	0.04
Run 6	0.0095	20	5	0.33	99.15	92.91	92.13	0.04
Run 7	0.0095	-60	30	0.1	96.18	-5.316	-6.621	0.04
Run 8	0.0095	20	5	0.1	99.29	80.56	80.02	0.04

Terms desc.

Thick is thickness of insulation

Tos1 is insulation outer temperature at inlet

Tos2 is insulation outer temperature at exit

T2 is outlet water temp

hout is air outside heat transfer coefficient

Ta is outside air temperature

5. CONCLUSION

The Finite Element Model was setup in Patran for the flow across an Insulated Pipe with cold ambient conditions and a design Target to not to exceed 90c and the problem parameters of mass and insulation characteristic was setup the meshing strategy and boundary conditions with executed and the software gave the solution “stable” that exceeded the design parameters different design alternative of mass and insulation increase was introduced to Patran System and the Solution was also validated Analytical through conducting an Analytical Model with Engineering Equation solver .

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