CFD MIDTERM

HEAT EXCHANGER DESIGN

TEAM 5

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DESIGN ASSUMPTIONS

1. The material properties of the air and oil remain constant with the exception of the air density, which was modeled as an ideal gas. The ANSYS Fluent database was used for the material properties of air and copper, and the material properties of the oil, inlet temperatures of the air and oil, and velocity of the inlet air were given in the problem statement. Additionally, a flow rate of 3.5 gpm was chosen for the oil.
2. Due to the geometric symmetry of the design, the exchanger was split into 24 parts of equal height and width and only one exterior (wall) unit and one interior unit was simulated. Due to the almost identical graphical results of the wall and interior units, plots are only shown for the interior units.

Material Properties

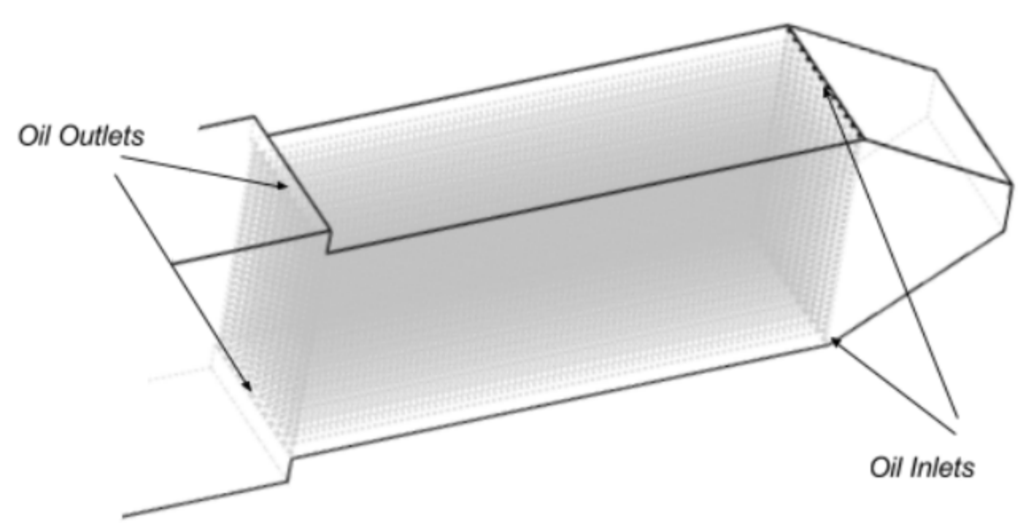
	Air	Oil	Copper	Aluminum
Density (lbm/ft3)	Ideal Gas	53.688	560.4595	169.7359
Specific Heat (btu/lb-r)	0.240388	0.5	0.091	0.2080402
Thermal Conductivity (btu/h-ft-r)	0.013986	0.15	224.007	116.9739
Viscosity (lbm/ft-s)	1.202e-05	0.0231		
Molecular weight (lb/lbmol)	28.966			
Phase	Gas	Liquid	Solid	Solid

These default properties from the Fulent library was used. Air was modeled as an ideal gas.

DESIGN CONCEPT

The heat exchanger was designed as a rectangular aluminum duct which fits exactly onto the air intake duct, and a total of 336 copper pipes parallel to the direction of airflow (*Figure 1* shows the complete exchanger).

Figure 1: Heat Exchanger Model



The copper pipes were arranged in 24 units containing 14 pipes each, equally spaced from each other in each direction (*Figure 2* shows a single unit). Each of the 24 units were connected to square pipes on either side, to serve as the oil inlet and outlet pipes for that unit. The heat exchanger was designed as a counter flow exchanger, with the air and oil flowing in opposite directions. Additionally, an exhaust valve was placed at the end of air duct. Figure 2 shows one modeled unit that had a one inch depth. Figure 3 shows a more detailed sketch of the copper pipes units and Figure 4 shows the assembly of the copper pipe units.

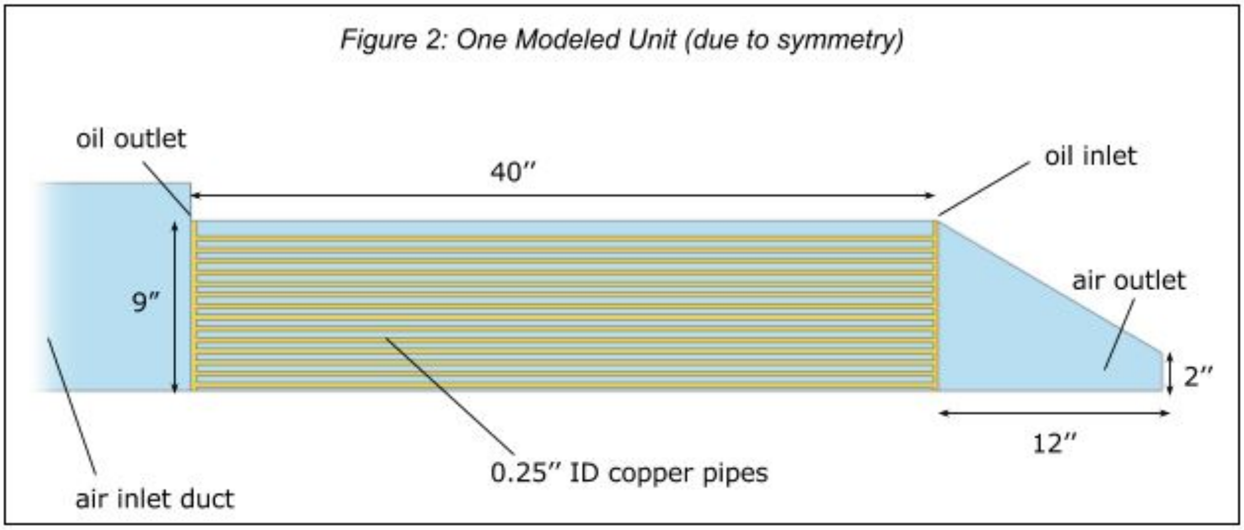


Figure 2: One Modeled Unit (due to symmetry)

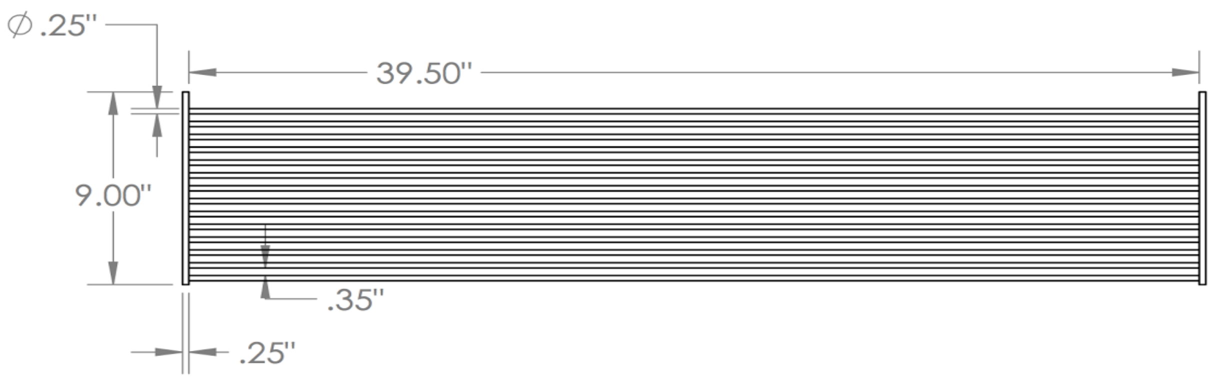


Figure 3: Dimensions of each copper tube segment

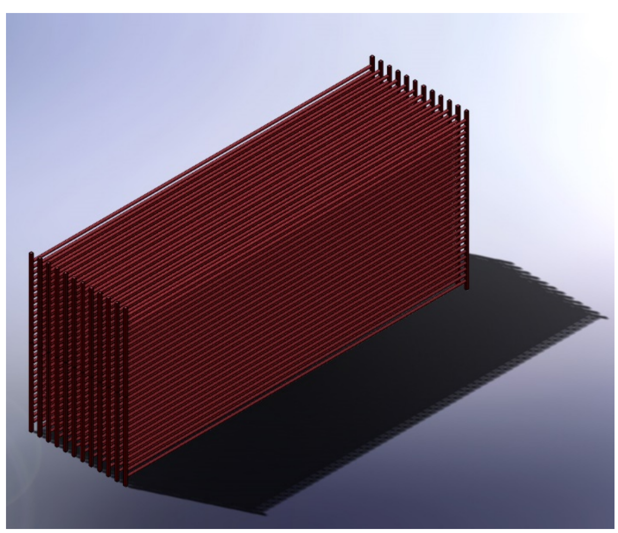


Figure 4: Assembly of all 24 segment of copper tubes

MESHING

The mesh of the duct is shown below. This unit was used for both the interior and wall units (by changing the boundary conditions of one side from "symmetry" to "wall")

A cross section of the mesh of the interior/exterior unit is shown below this unit was used for both the interior and wall units (by changing the boundary conditions of one side from "symmetry" to "wall"). The cells with a small element quality are due to the geometry of the circular pipes connecting to the square pipes, and are few in number.

DUCT

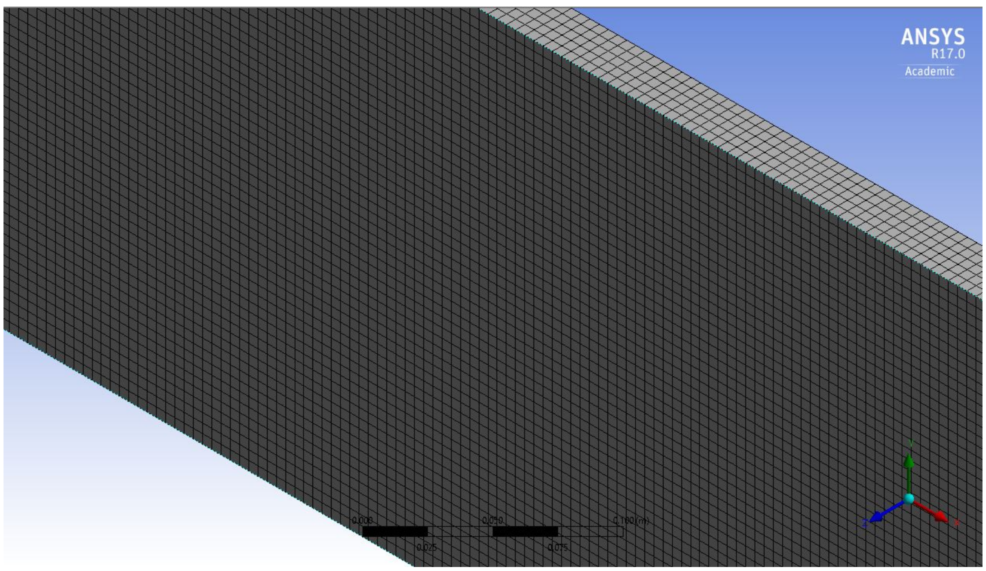


Figure 5: Mesh of the Duct

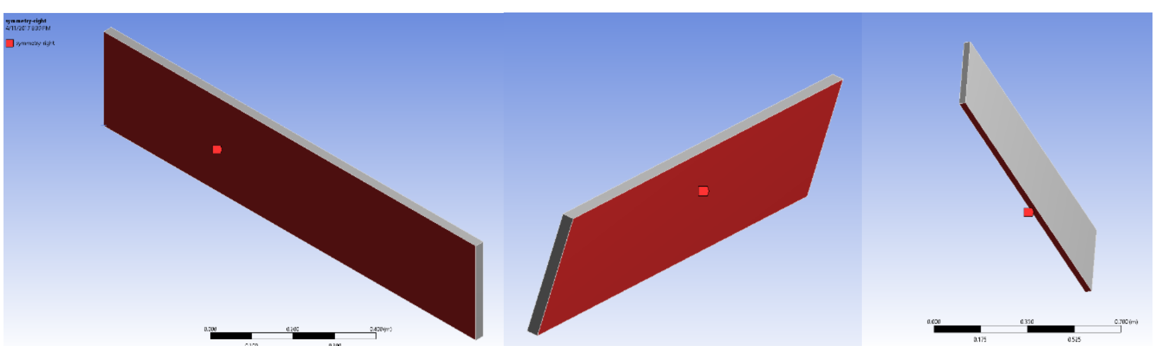
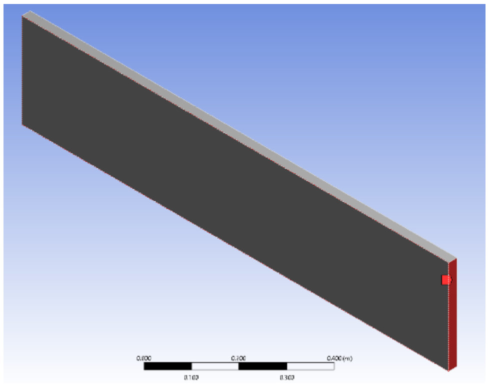


Figure 6 : Symmetries in the Duct



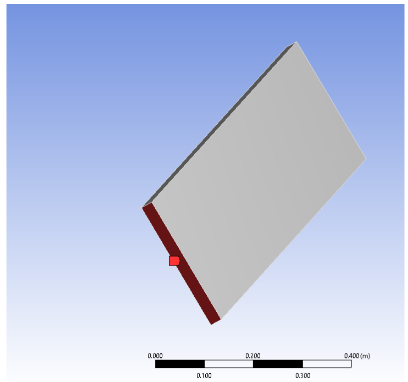


Figure 7 : Velocity Inlet *Fig 8 : Pressure Outlet*

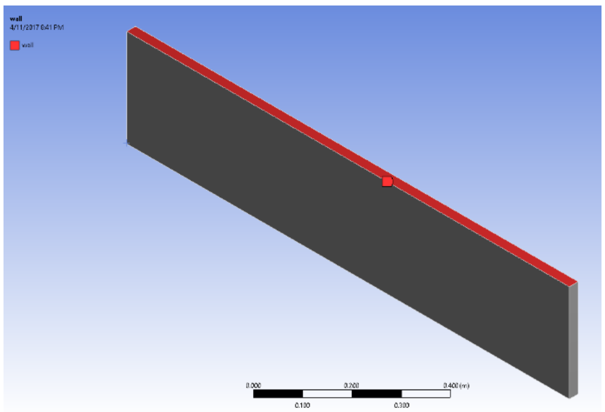
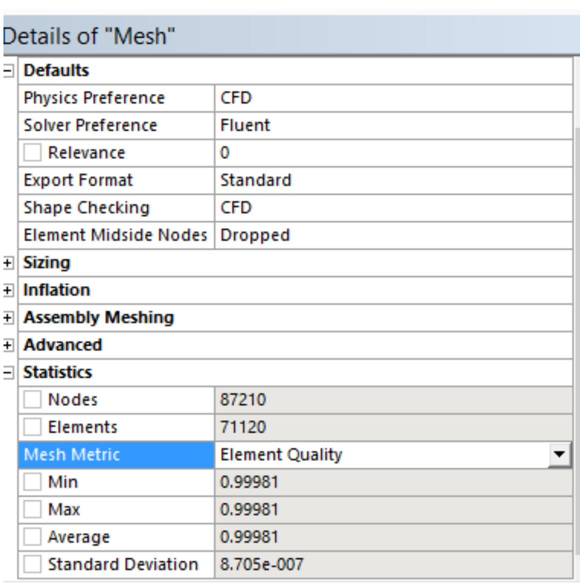


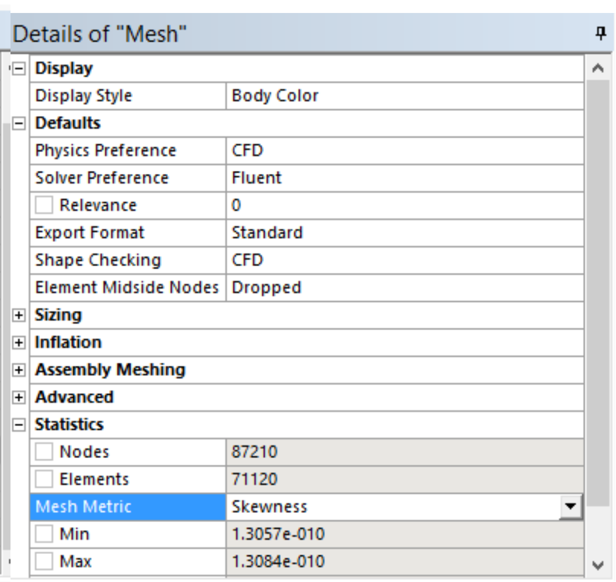
Figure 9: Wall

These boundary conditions were applied when simulating the duct.



Details of "Mesh"

Defaults	
Physics Preference	CFD
Solver Preference	Fluent
Relevance	0
Export Format	Standard
Shape Checking	CFD
Element Midside Nodes	Dropped
Sizing	
Inflation	
Assembly Meshing	
Advanced	
Statistics	
Nodes	87210
Elements	71120
Mesh Metric	Element Quality
Min	0.99981
Max	0.99981
Average	0.99981
Standard Deviation	8.705e-007



Details of "Mesh"

Display	
Display Style	Body Color
Defaults	
Physics Preference	CFD
Solver Preference	Fluent
Relevance	0
Export Format	Standard
Shape Checking	CFD
Element Midside Nodes	Dropped
Sizing	
Inflation	
Assembly Meshing	
Advanced	
Statistics	
Nodes	87210
Elements	71120
Mesh Metric	Skewness
Min	1.3057e-010
Max	1.3084e-010

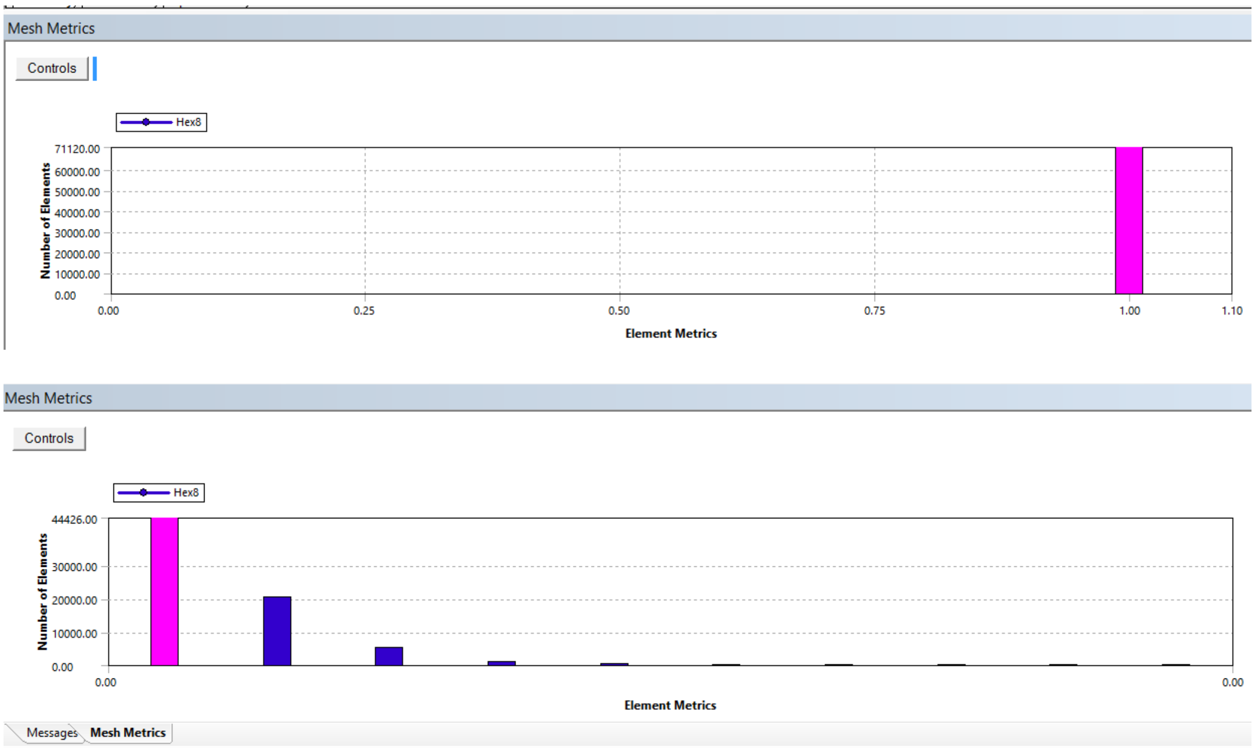
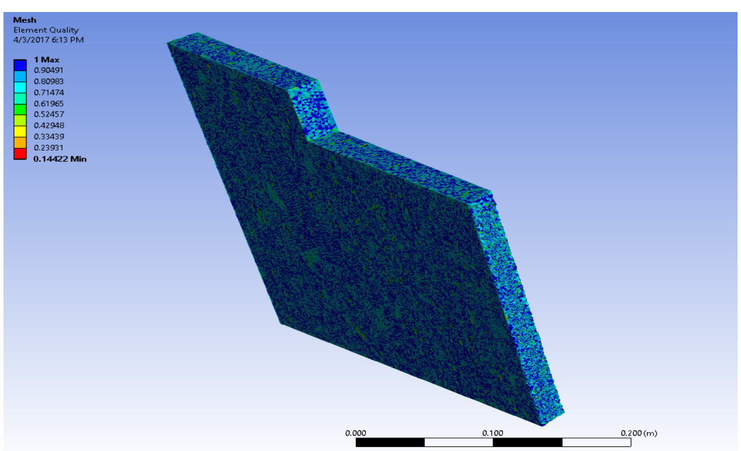


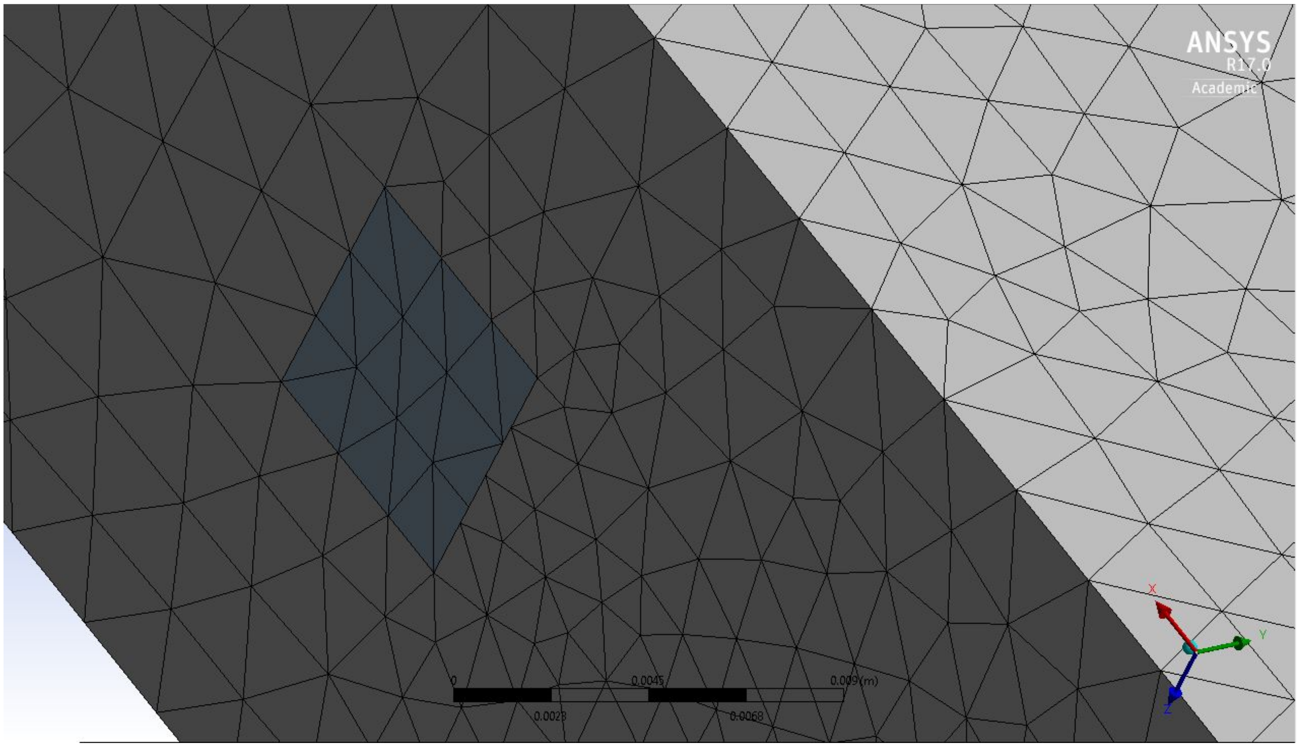
Figure 10: Element quality and skewness of the Duct mesh are in good range.

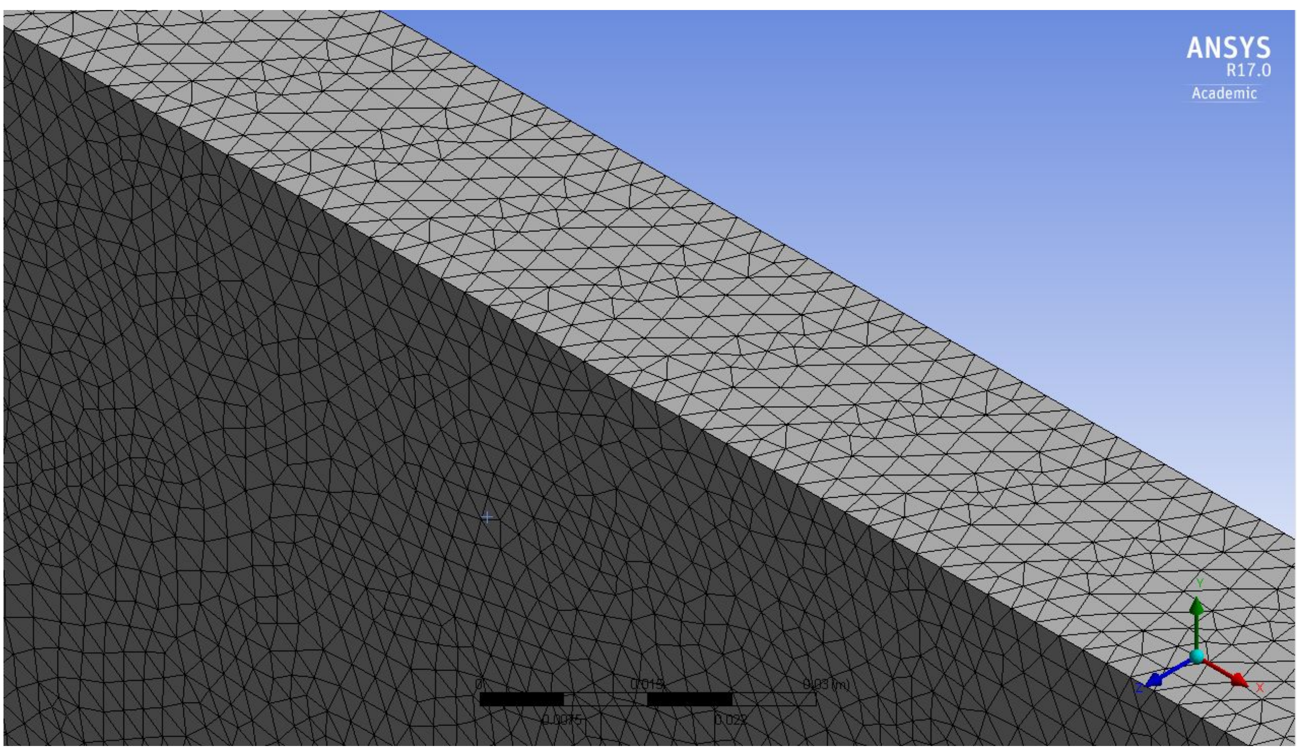
The average element quality is close to 1 and the skewness is close to 0 which is good indication of the quality of the mesh.

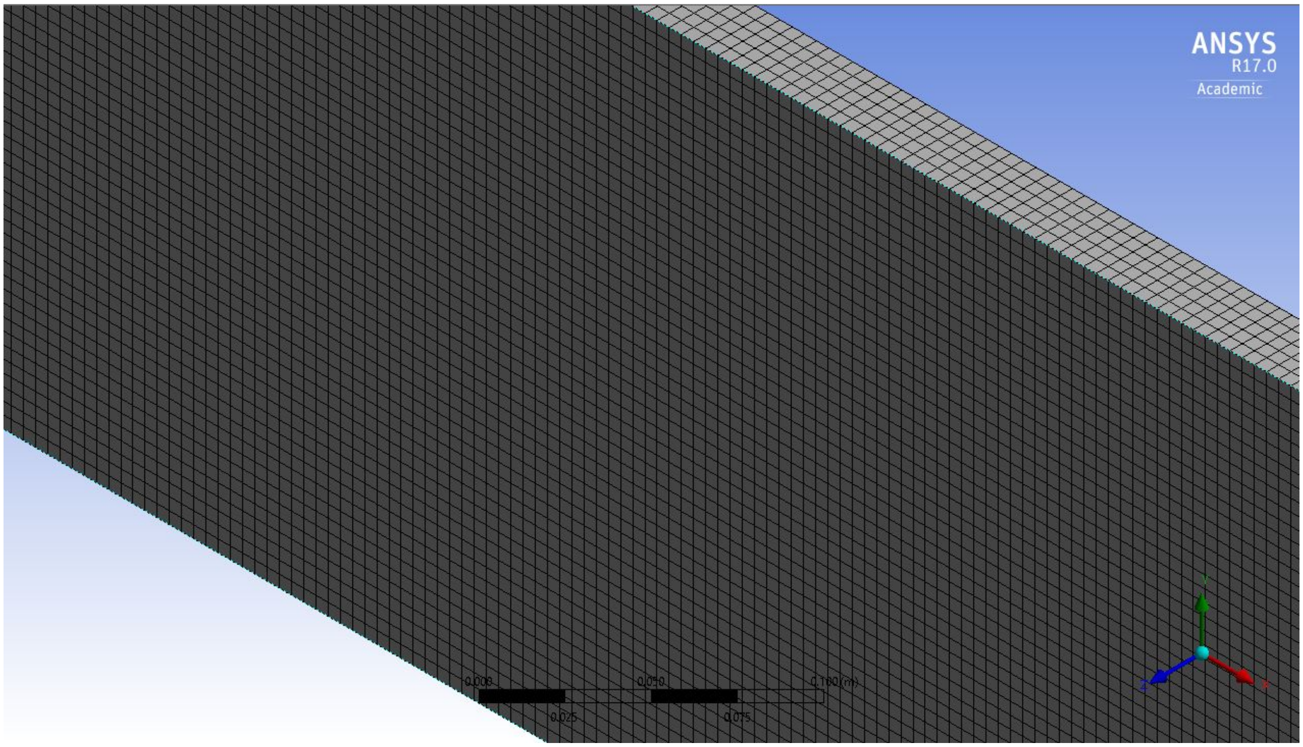
<u>**Heat Exchanger Units**</u>



Closer look at the mesh:







Details of "Mesh"

Defaults	
Physics Preference	CFD
Solver Preference	Fluent
Relevance	0
Export Format	Standard
Shape Checking	CFD
Element Midside Nodes	Dropped
Sizing	
Inflation	
Assembly Meshing	
Advanced	
Statistics	
Nodes	2824162
Elements	14616332
Mesh Metric	Element Quality
Min	0.14422
Max	1.
Average	0.83866
Standard Deviation	9.6394e-002

Details of "Mesh"

Defaults	
Physics Preference	CFD
Solver Preference	Fluent
Relevance	0
Export Format	Standard
Shape Checking	CFD
Element Midside Nodes	Dropped
Sizing	
Inflation	
Assembly Meshing	
Advanced	
Statistics	
Nodes	2824162
Elements	14616332
Mesh Metric	Skewness
Min	4.8827e-007
Max	0.89554
Average	0.2259
Standard Deviation	0.12094

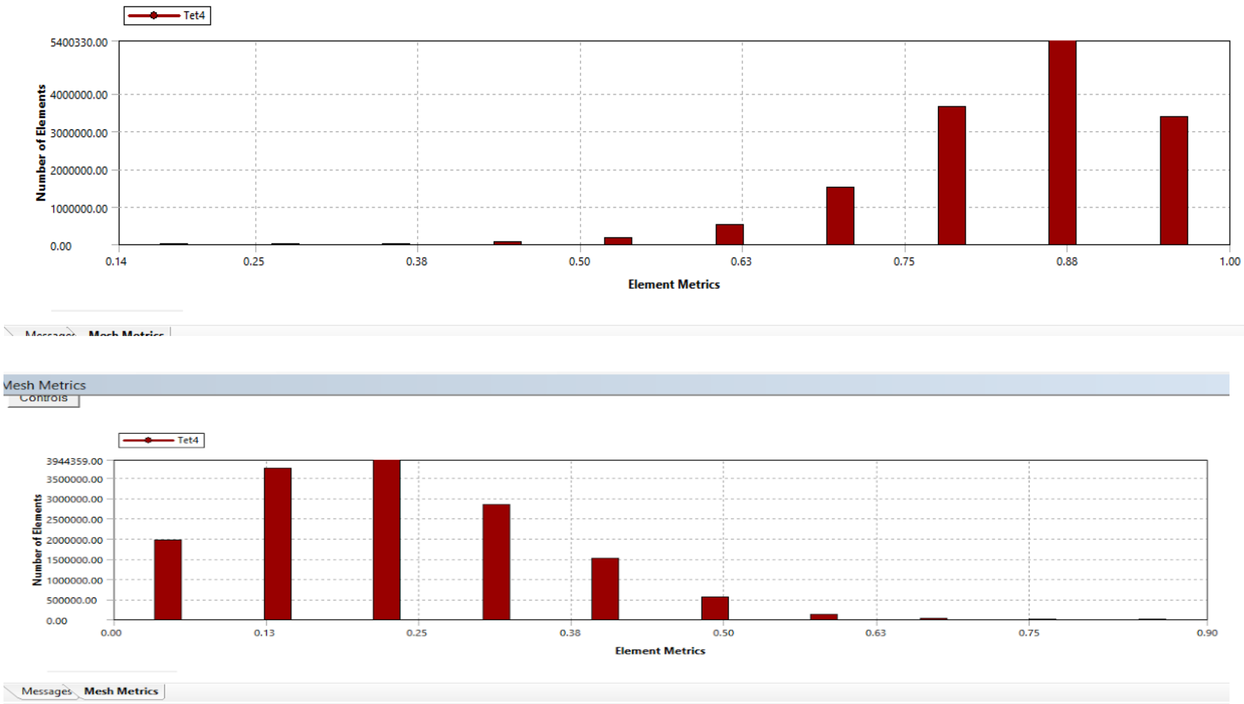
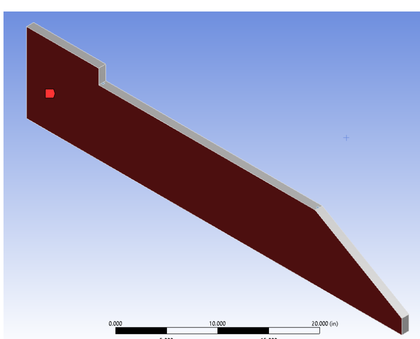
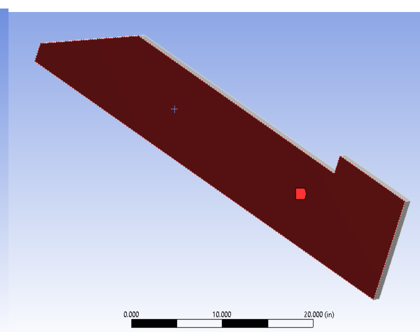


Figure 11: Element quality and skewness of each Heat exchanger unit mesh are in good range

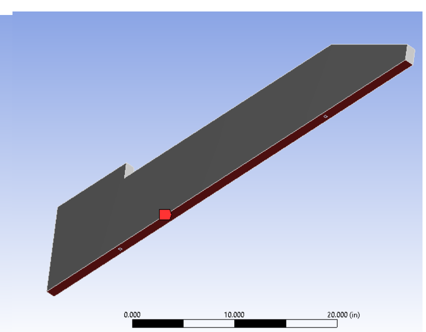
The average element quality is 0.83 and the minimum is 0.144. The skewness never go above 0.9. This mesh is acceptable.



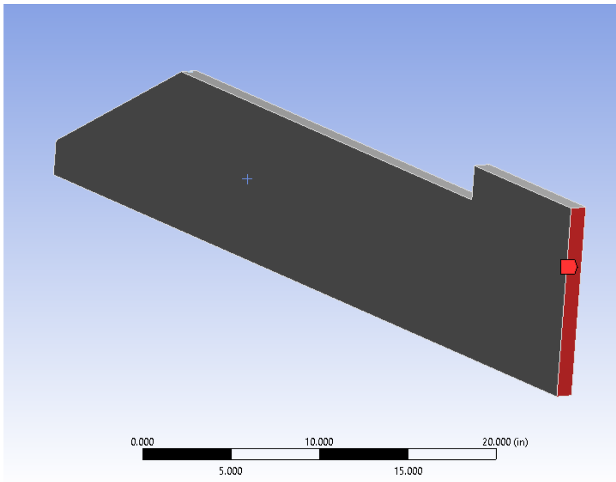
1 Symmetry Right



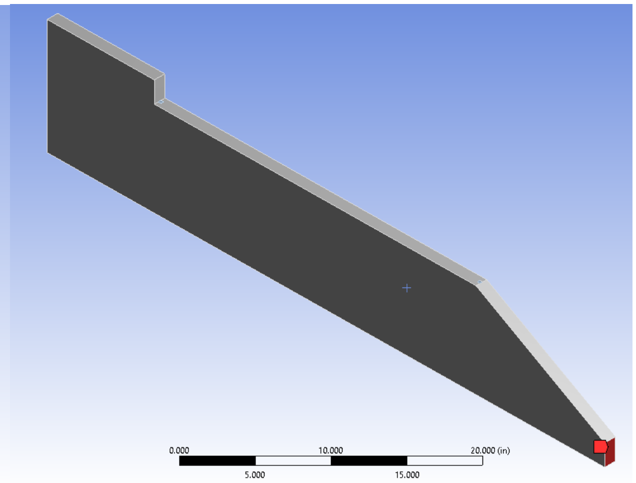
2 Symmetry Left



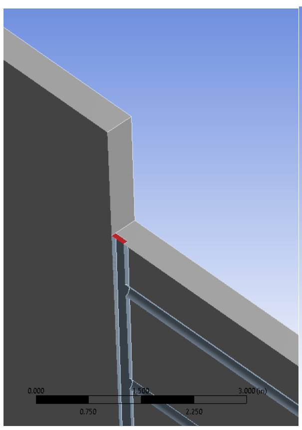
3 Symmetry Bottom



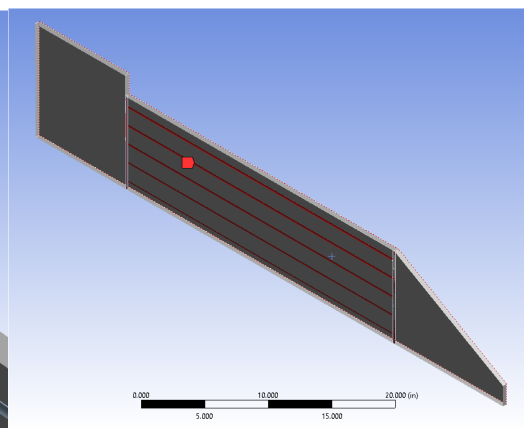
4 Velocity Inlet Air



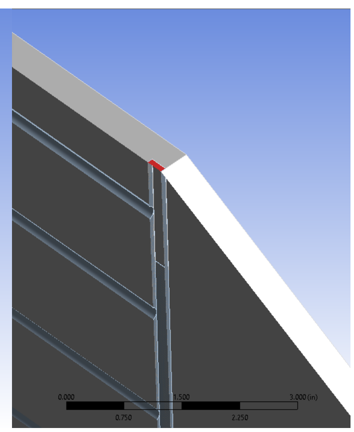
5 Pressure Outlet Air



3 Pressure Outlet Oil



5 Pipe Wall



6 Velocity Inlet Oil

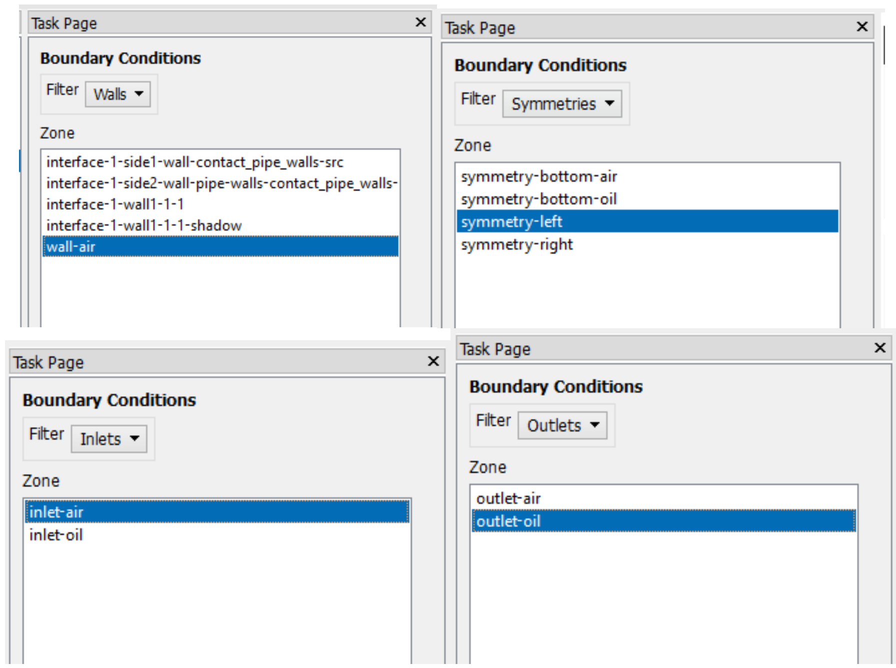
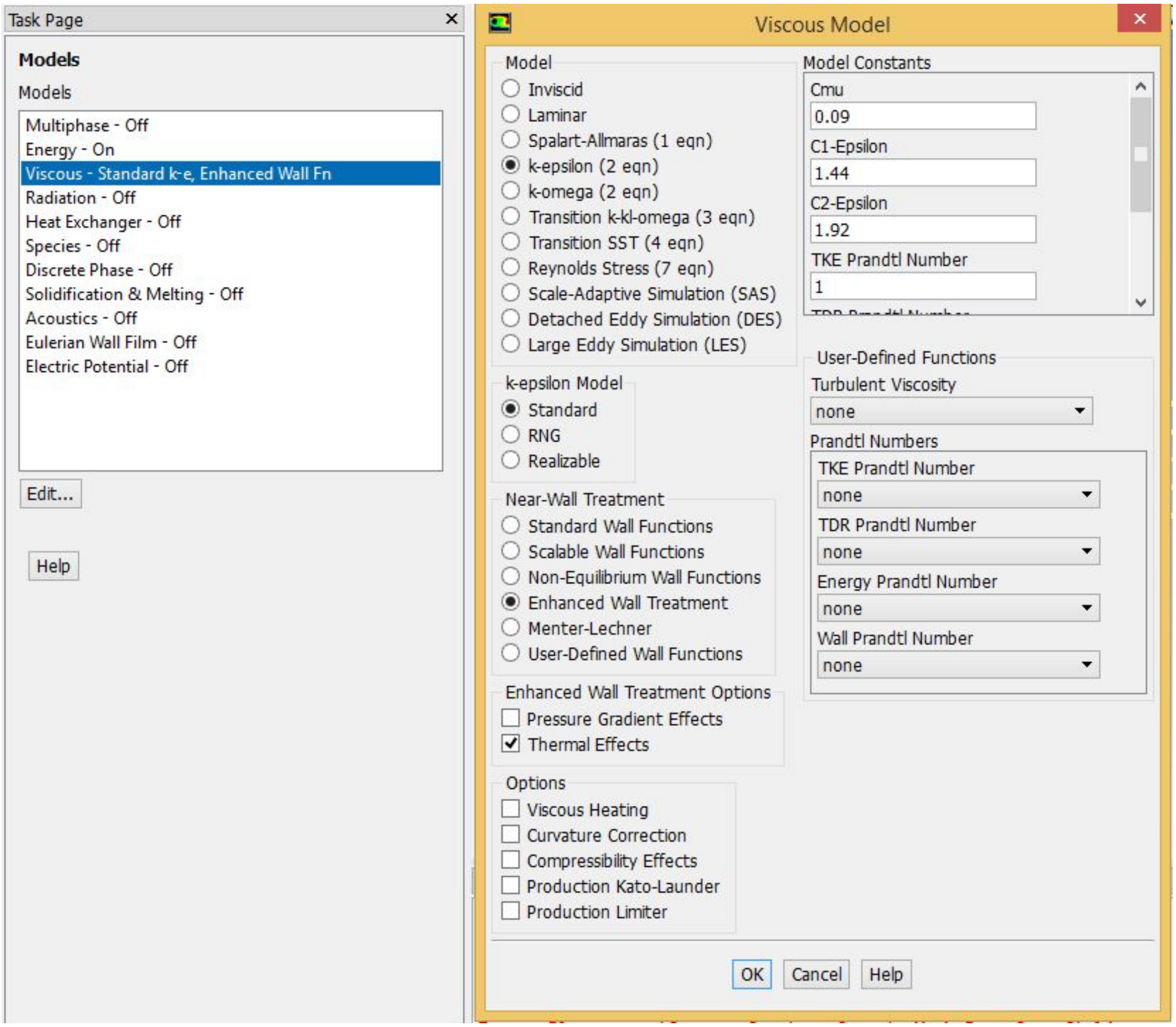


Figure 12 : Boundary conditions on Heat exchanger Units

These boundary conditions were applied to simulate a unit. Left symmetry was changed to wall to simulate one of the 4 units on the side. The results were very close.

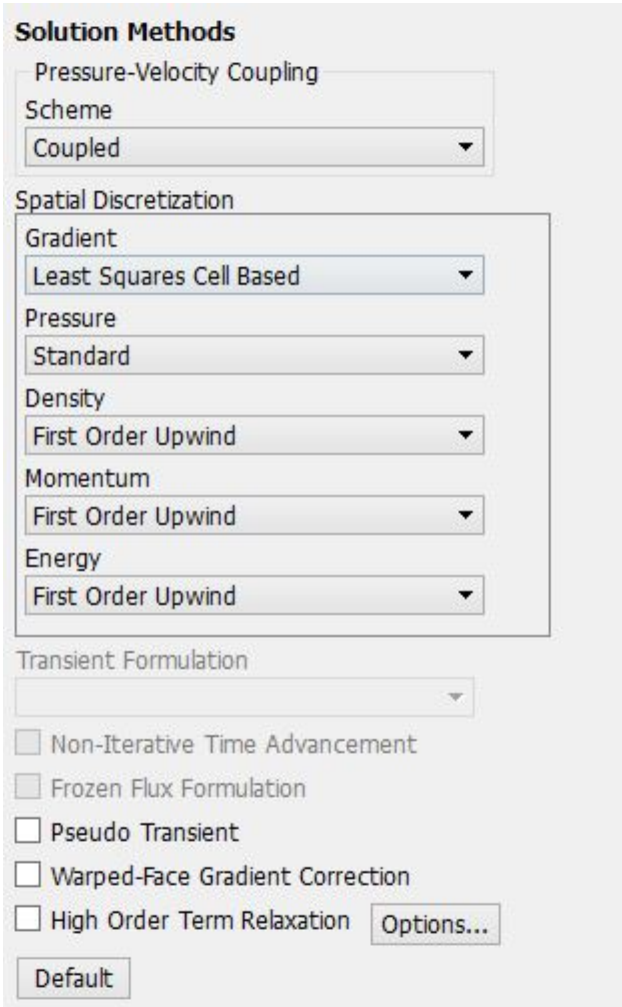
SIMULATION SETUP

Models



Energy model was turned on for temperature simulation. Standard k-e model with enhanced wall treatment was used to model turbulence.

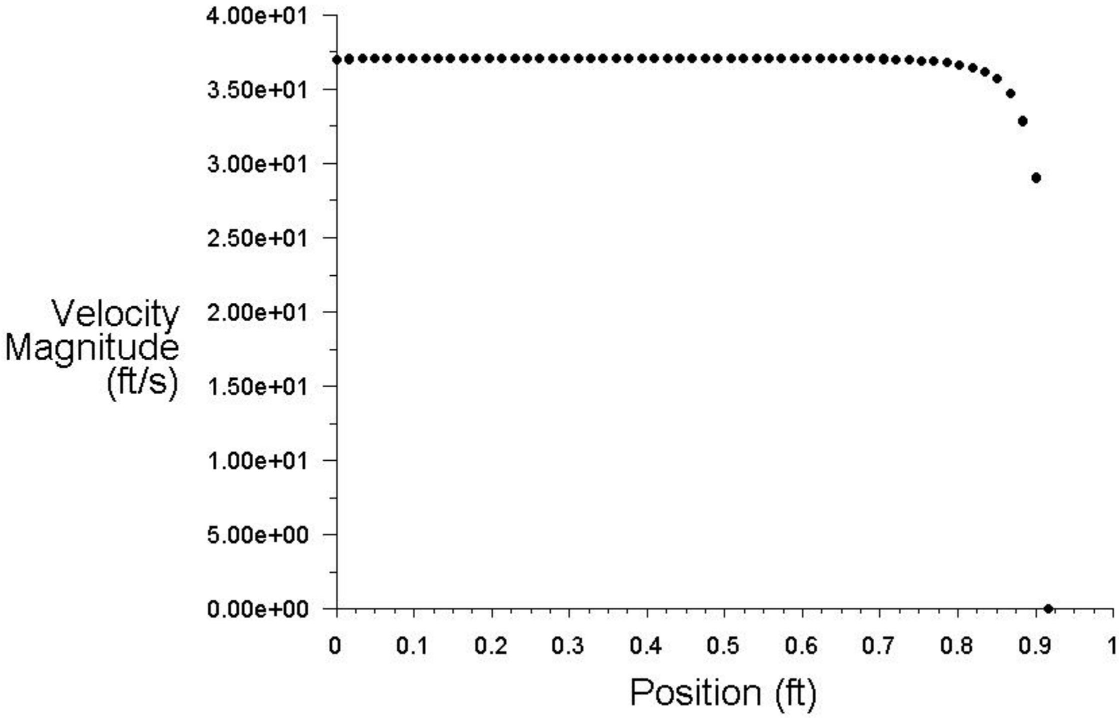
Solution Methods



Coupled method was chosen for pressure-velocity coupling, and discretization methods were all chosen to by first order upwind to improve convergence performance.

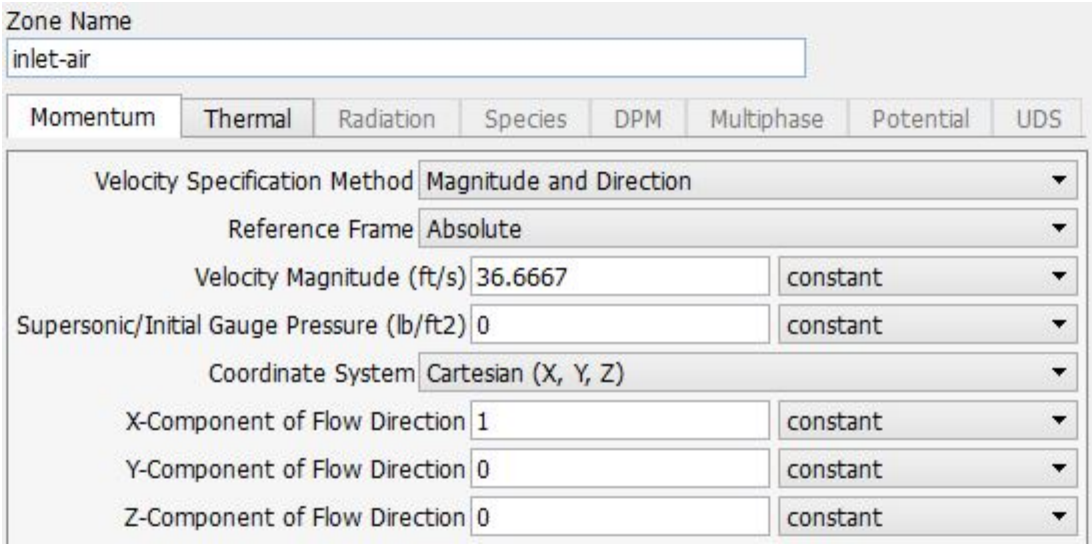
Boundary Conditions Used

Air velocity for heat exchanger model is set to uniform inlet velocity because of the outlet result of air duct simulation. In the air duct simulation, the velocity reached fully-developed laminar flow after less than 6 in of distance. Here is x-y plot of duct simulation at 6 inch into the duct.

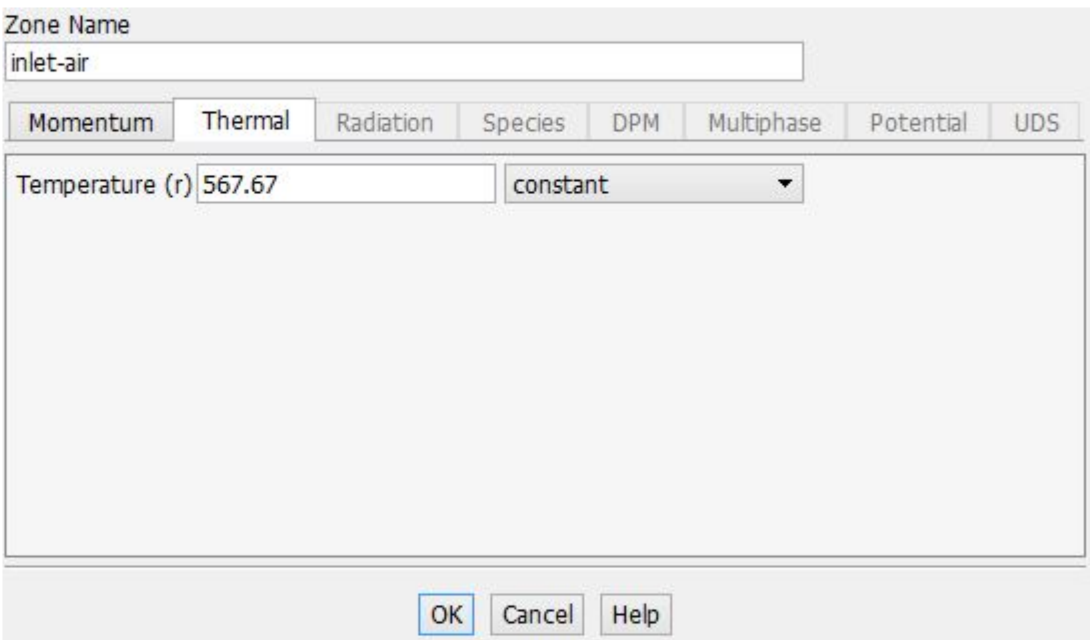


Therefore, in the heat exchanger model, the short duct is sufficient for flow to develop.

Air inlet velocity

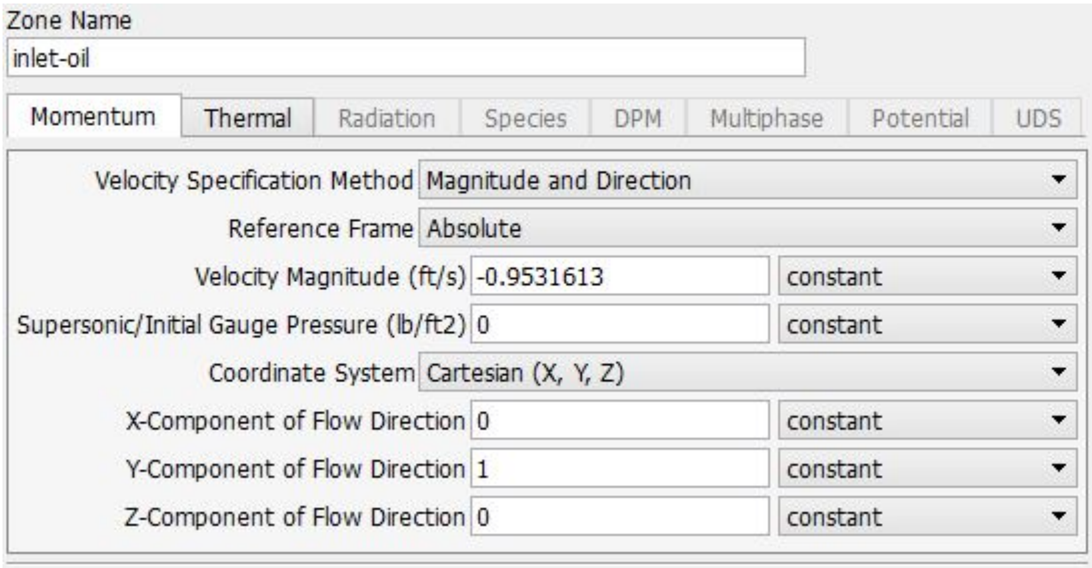


Air inlet temperature



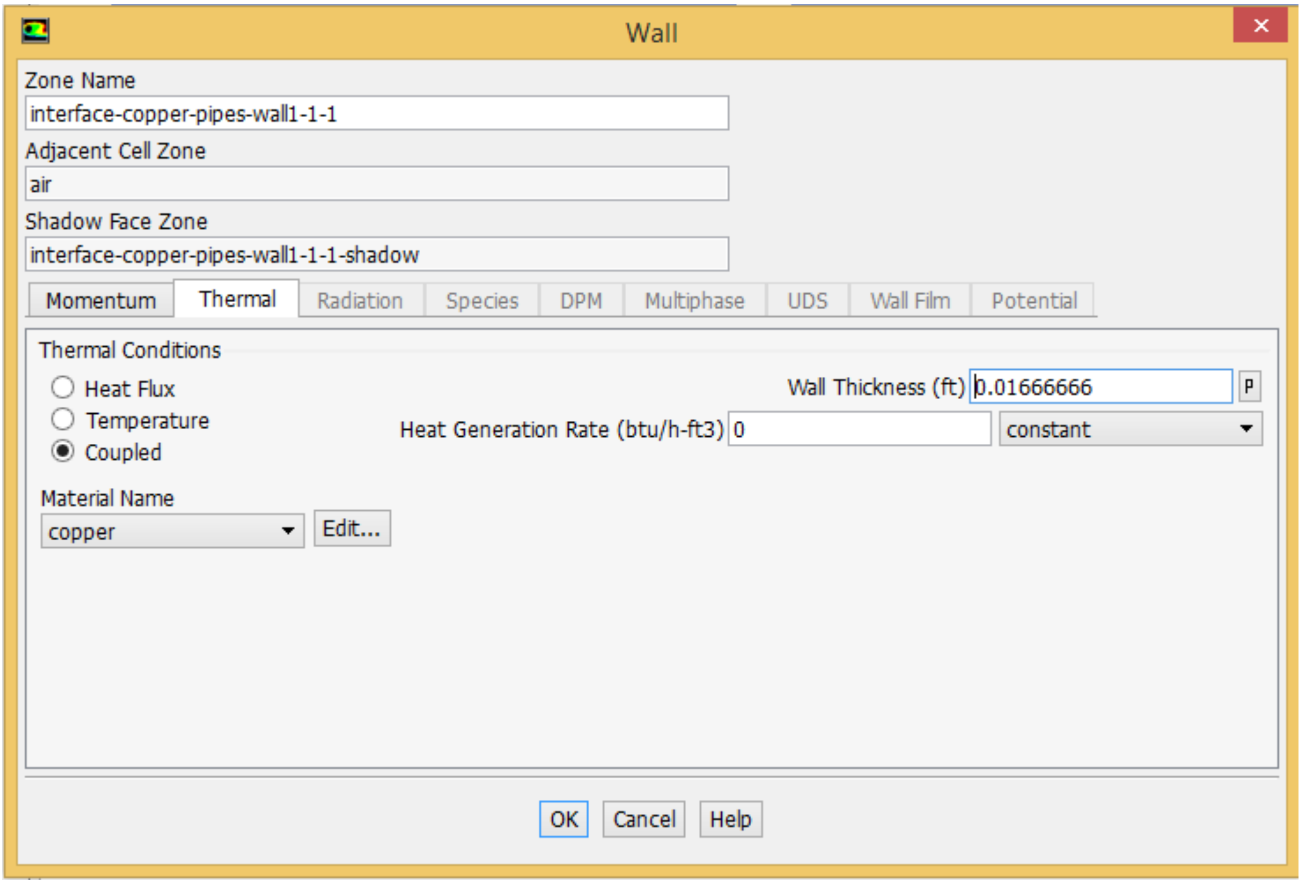
Both air velocity and air temperature were set as the problem statement.

Oil inlet velocity



Oil inlet temperature

Oil inlet temperature was set according to problem setup and oil inlet velocity was calculated by choosing inlet oil flow rate to be 3.5 gallons per minute.

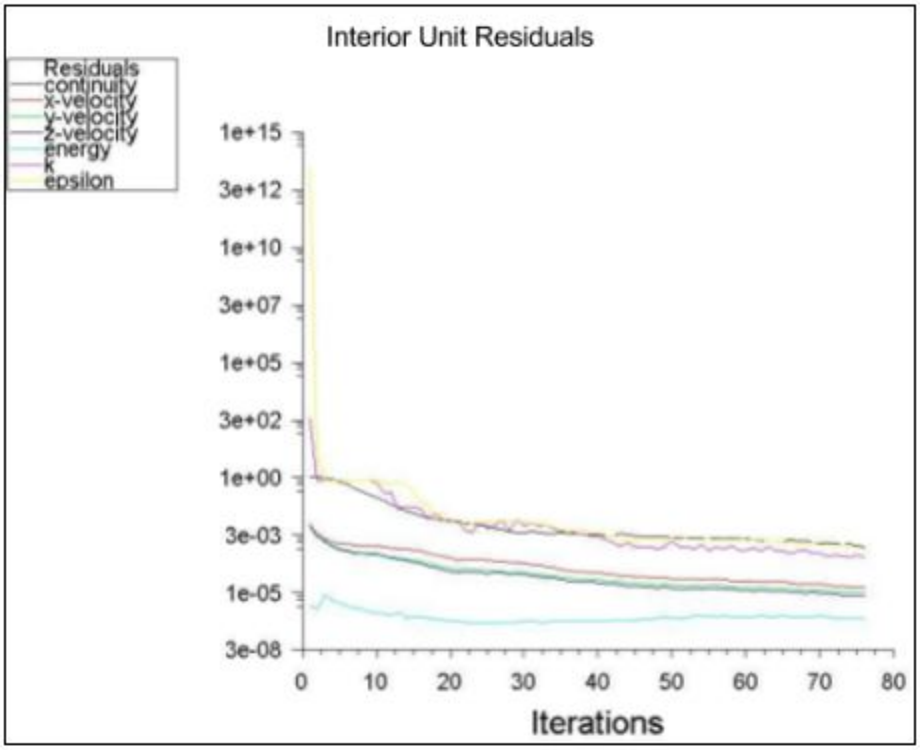


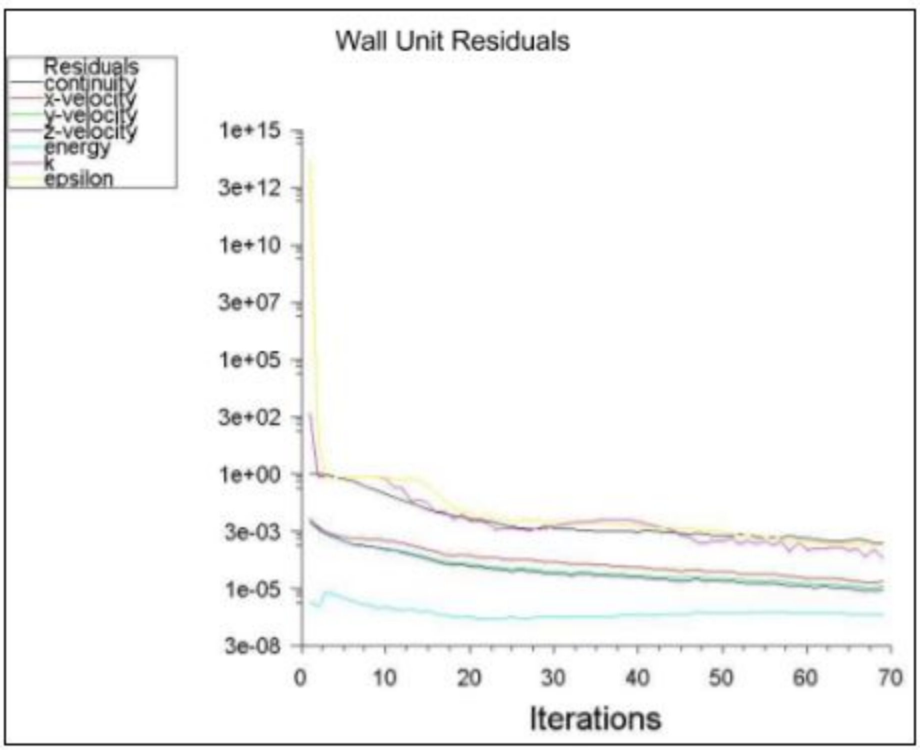
Interface between air and oil was set to a copper tube with thickness 0.2 inch.

Oil outlet and air outlet were both set to: pressure-outlet.

Wall and symmetry boundary conditions were set as explained in the previous section.

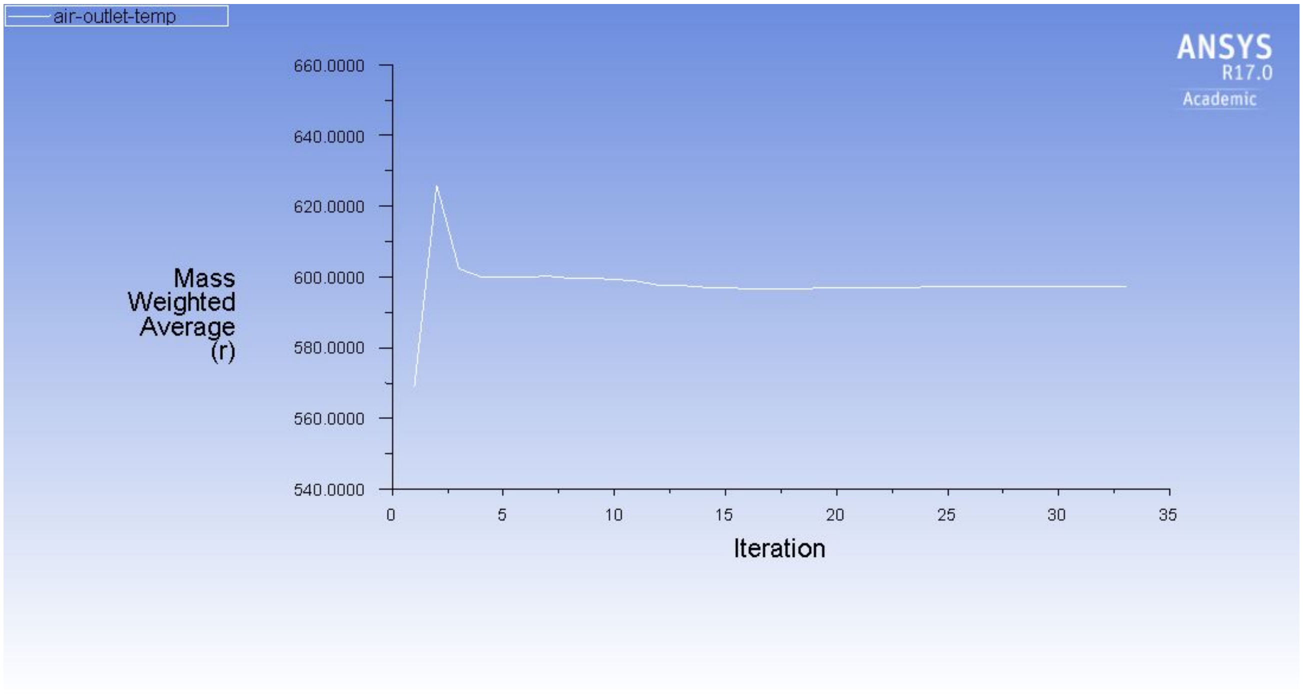
Residual Plots



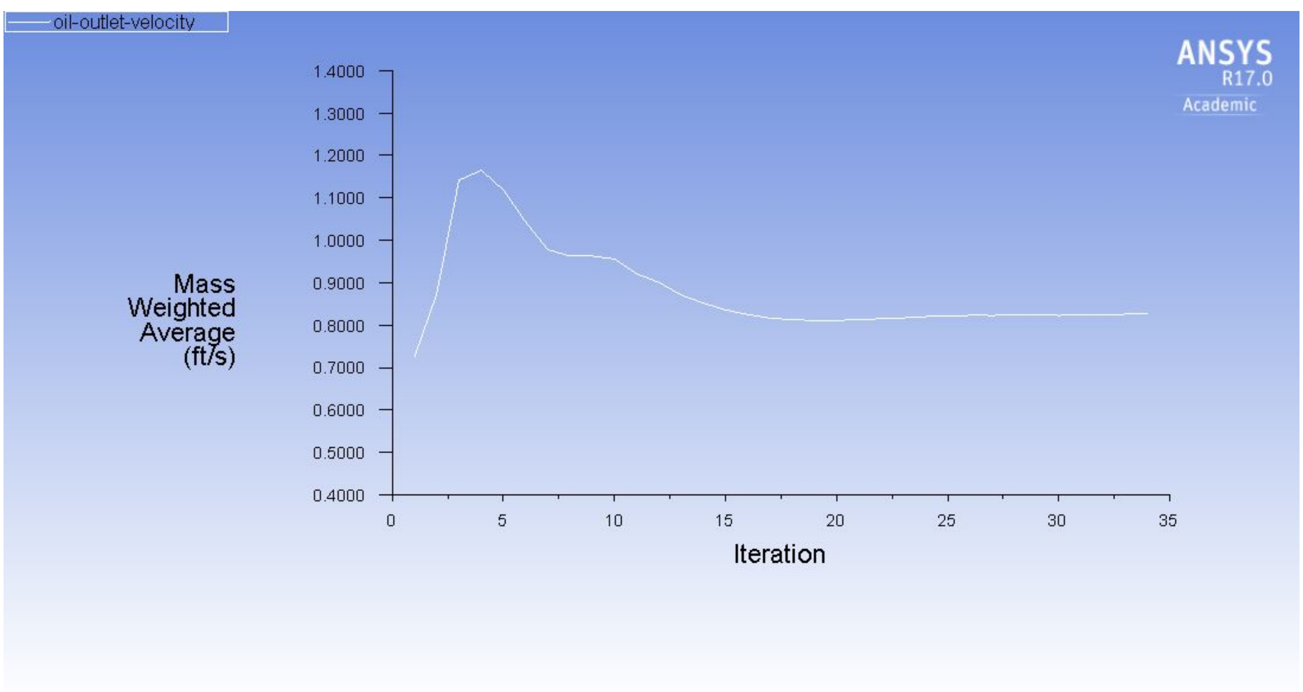


For both wall units and interior units, the residual convergence performances were good.

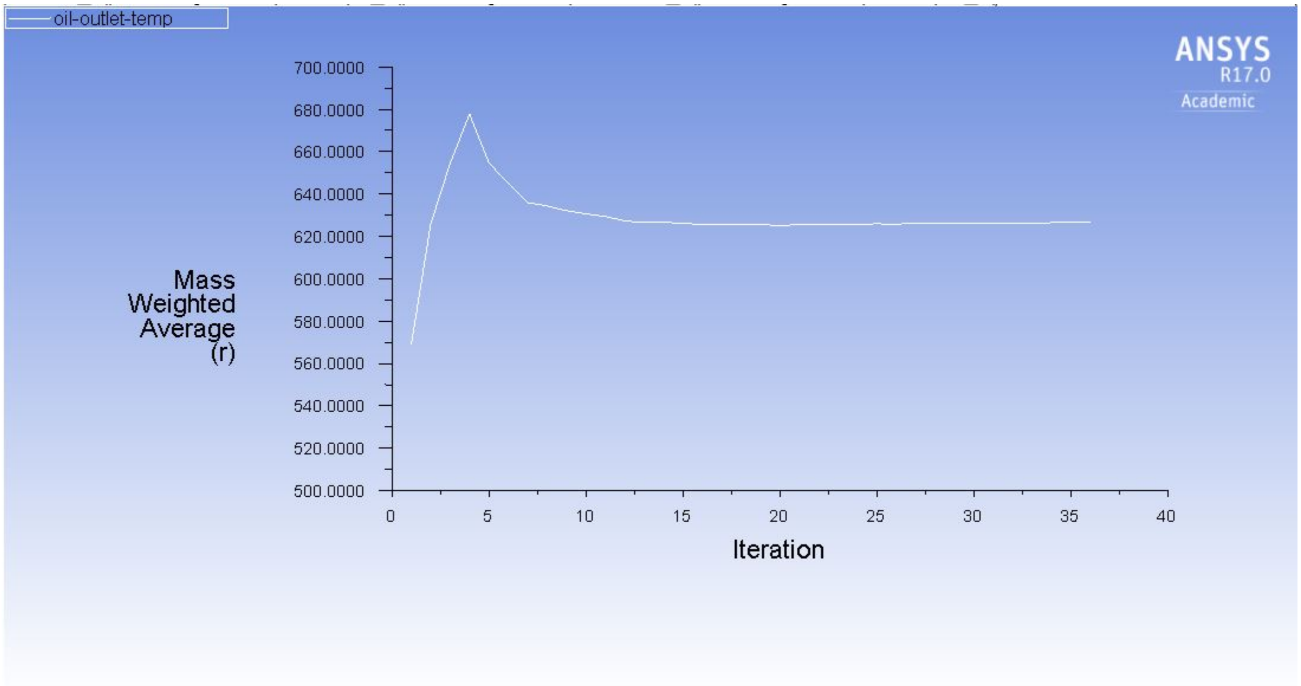
Monitor Convergence



Air outlet temperature surface monitor was set as a mass weighted average. The temperature of air outlet converged after 28 iterations.

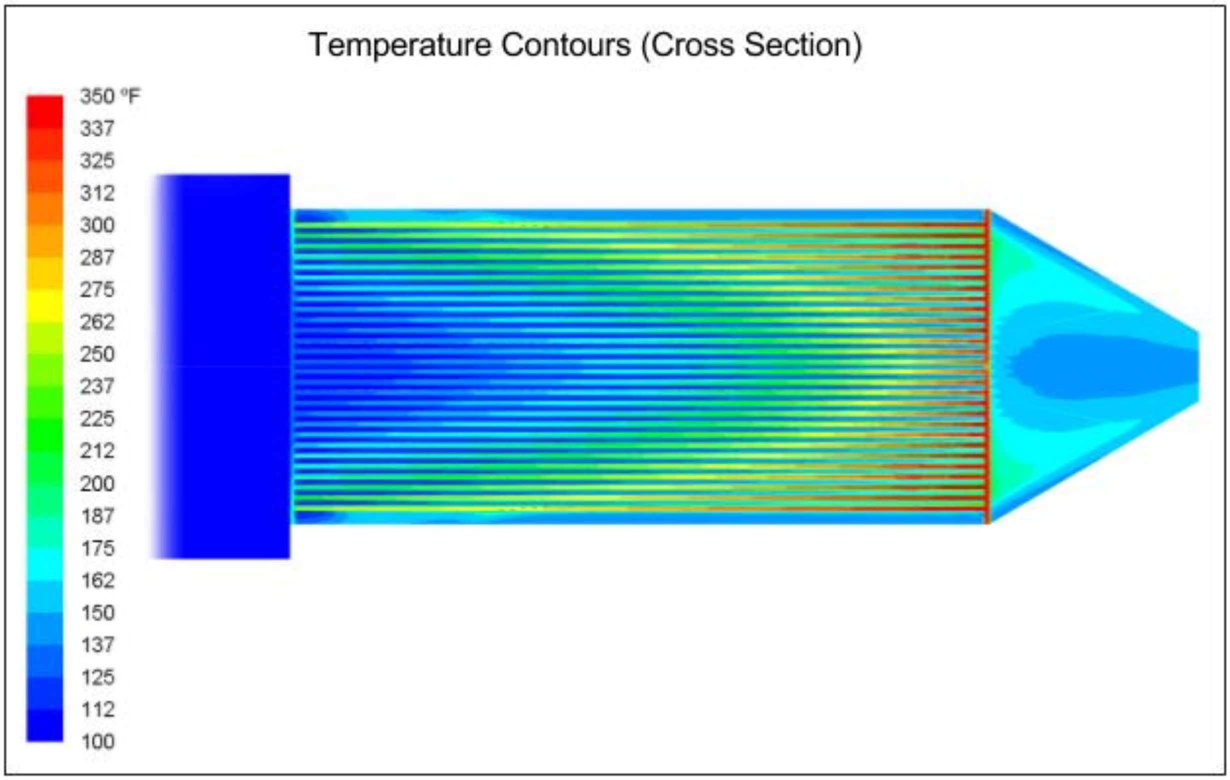


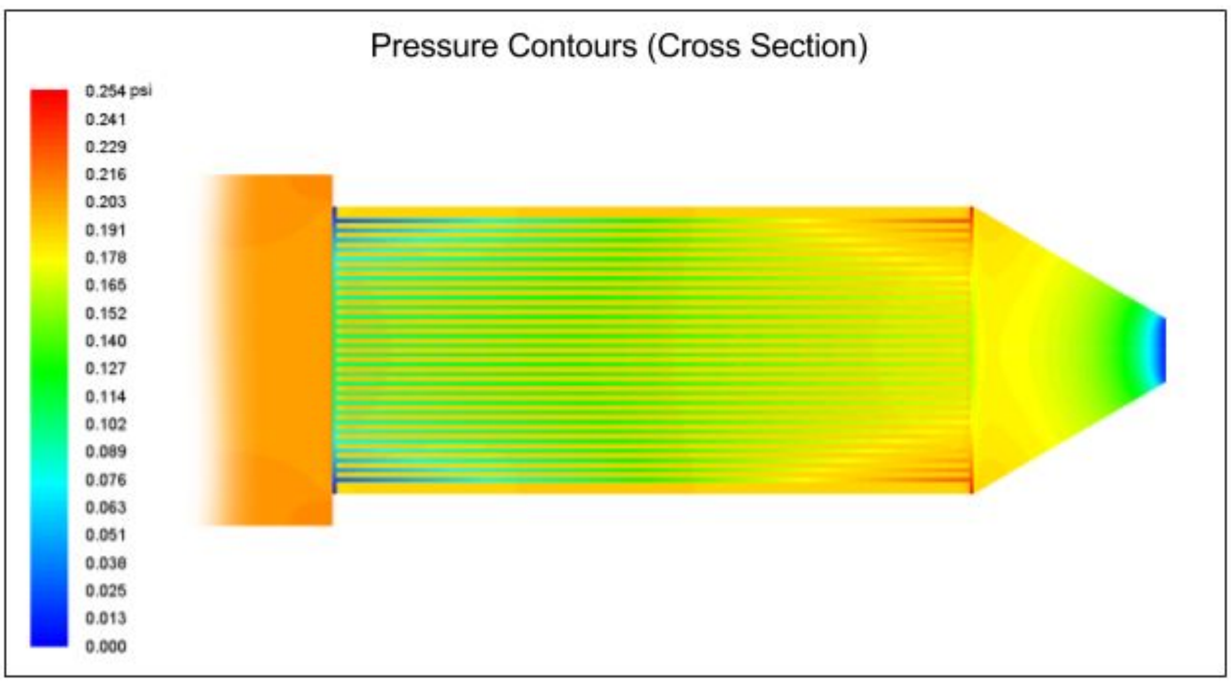
Oil outlet velocity surface monitor was set as a mass weighted average. The oil outlet velocity converged after 20 iterations.



Oil outlet temperature surface monitor was set as a mass weighted average. The oil outlet temperature converged after 33 iterations.

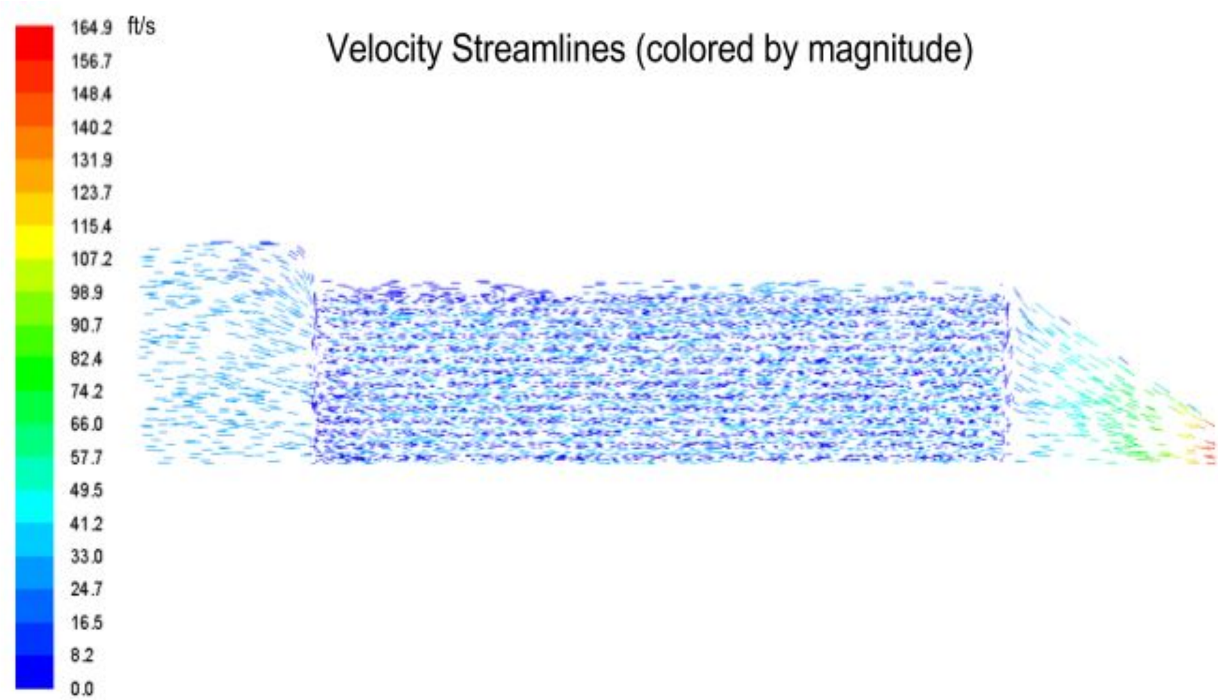
Contour Plots





Simulation was run both for the wall units and the interior units (as explained in previous sections), but contour plots are identical to naked eyes. For the purpose of conciseness, contour plots for the interior units are included in the report as shown in figure above.

Velocity Streamline



Velocity streamlines are displayed in the figure above. We observe that the air accelerated when it came from the duct to the heat exchanger, and when it came from heat exchanger to the exhaust port because of the change in cross-section area. Oil velocity, on the other hand, remains pretty consistent throughout.

No obvious eddies were observed.

Simulated Temperature

	Interior Unit Temp (ºF)	Wall Unit Temp (ºF)	Mean Temp (ºF)
OIL INLET	350.00	350.00	350.00
OIL OUTLET	179.81	187.65	181.11
AIR INLET	108.00	108.00	108.00
AIR OUTLET	149.79	159.88	151.47

Simulated Pressure Drop

	Interior Unit ΔP (psi)	Wall Unit ΔP (psi)	Mean ΔP (psi)
OIL	0.2545	0.2535	0.2543
AIR	0.2065	0.1377	0.1950

HAND CALCULATIONS

Entrance & Exit Temperatures (agrees with simulated values within order of magnitude)

For the hand calculation, we modeled it as a simple heat transfer problem with one resistance and capacitor.

For the approximated outlet temperature, we first look at how much time a unit of oil needs to pass the entire tube section (modeled as one single long tube). Then we calculated the U, total heat transfer cost, by calculate the equivalence resistance and capacitance. Then we calculated the tine constant for this steady state heat transfer model in order to get the approximate outlet temperature.

$$v = 0.017021\ \frac{ft}{sec} \quad (modeled\ as\ one\ pipe)$$

$$t = \frac{L}{v} = \frac{3.333\ ft}{0.017021\ \frac{ft}{s}} = 195.816\ sec$$

$$\tau = \frac{\rho c V}{UA} = \frac{\left(46.09\frac{lbm}{ft^3}\right)\left(0.5\frac{Btu}{lbm - ºR}\right)\ (336\pi(0.0104166)^2(3.333)\ \ ft^3)}{\left(0.0039135\frac{btu}{sec - ft^2 - ºR}\right)(0.2179\ ft^2)(336)} = 140.898\ sec$$

$$e^{\frac{-t}{\tau}} = e^{-1.389} = 0.249 = \frac{Toil_{out} - T_{inf}}{Toil_{in} - T_{inf}} = \frac{Toil_{out} - 108ºF}{350ºF - 10°\mathrm{F}}$$

$$Toil_{out} = 168.3\ ºF$$

For air outlet temperature. We assume that all the heat dissipates from oil transfer to air. So, by equating the heat in and out and using basic Q=cM(detT) equation we can approximate the air-outlet temperature.

$$(m_{dot-oil})(c_{oil})(T_{oil2}{-}T_{oil1})$$

$$= (0.00798\ ft^3/s)(53.688 lbm/ft^3)(0.5\frac{Btu}{lbm - \circ R})(168.3 - 350 \circ F)$$

=-38.92Btu/s

$$Q_{dot-air} = -Q_{dot-oil} = 38.92\ Btu$$

$$T_{air-out} = T_{air-in} + \frac{Q}{m_{dot-air} c m_{air}}$$

$$= 108°F$$

$$+ (38.92 Btu/s)/(36.6667\ ft/s)(1.5 ft)(1 ft)(0.0765 lb/ft^3)(0.24 Btu/lbmF)$$

=146.54°F

Comparison between simulated value and hand calculated value:

	Mean Unit Temp(°F)	Hand Calc Temp (°F)
Outlet-Oil	181.11	168.3
Outlet-Air	151.47	146.54

Values are similar, so simulation makes sense.

Oil Pressure Drop:

$$Re = \frac{pvD}{\mu} = 31.96$$

$$\Delta P = \frac{1}{2} f_d \frac{L}{D} \rho v^2$$
$$= \frac{1}{2}(1.772)\left(\frac{40''}{0.25''}\right)\left(762.8 \frac{kg}{m^3}\right)\left(0.22763 \frac{m}{s}\right)^2$$
$$= 5603\ Pa = 0.812\ psi$$

(Agrees within an order of magnitude, simulated = 0.254 psi)

SUMMARIZED OPERATING CONDITIONS

Oil flow rate ……………………….	3.5 gpm
Oil Temperature Difference …….	168.9 ºF
Oil Pressure Drop ………………..	0.254 psi
Air Temperature Difference …….	43.5 ºF
Air Pressure Drop ………………..	0.195 psi

HEAT EXCHANGER EFFICIENCY

The efficiency, η, can be calculated from $T_{Inlet-oil}$ and $T_{Outlet-oil}$, the inlet and outlet temperatures of the oil, respectively, and $T_{Inlet-air}$, the inlet air temperature as follows:

$$\eta = \frac{T_{Inlet-oil} - T_{Outlet-oil}}{T_{Inlet-oil-} - T_{Inlet\ air}} = \frac{350 - 151.47}{350 - 108} = 82.23\%$$

Although the calculated efficiency from above is about 82%, the actual efficiency should be lower than this value due to the assumption in the calculation that air temperature is constant throughout the device.

HEAT EXCHANGER SIZE & WEIGHT

Length ………………………. 52 in

Width ………………………... 22 in

Depth …………………....….. 12 in

Dry Weight Estimate …...…. 126 lbs

DESIGN TIME ESTIMATE

Initial Research & Design……... 5 hours

Preliminary Models……….......... 40 hours

Final Simulation…………..….... 100 hours

Results, Validation & Report.….. 25 hours

Total …………………………….. 170 hours

DESIGN BENEFITS

1. Rectangular aluminum shell is relatively lightweight and can easily be made from sheet metal
2. Copper pipes are arranged in 24 sheets, each disconnected from one another. If one unit needs repair, only that sheet must be removed.
3. Counterflow heat exchanger (generally more effective than parallel flow).