Thermal Fluid System

Heat Exchanger Project

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The first step of this project was to achieve a base design by adjusting the input parameters to achieve a heat ratio relatively close to 1.00 (Qcalculated:Q desired),

While there are many inputs that can result in a base design with such ratio, it is important to change design variable without violating the heat exchanger constraints, such as:

Diesel engine exhaust gas is cooled by using engine coolant (50/50 Ethylene Glycol)

- Exhaust gas enters the shell & tube heat exchanger EGR (Exhaust Gas Recirculation) cooler at 720 C and exists at 125C
- Exhaust gas mass flow rate is 13.6kg/min
- Engine coolant at 85C is available at the inlet of the heat exchanger

We notice a significant required cooling rate; it must meet this requirement, so we need to compute the required coolant flow rate as a key design variable to minimize boiling.

We need to minimize the coolant & gas side pressure drop to ensure meeting the engine power. Since exceeding the maximum allowed pressure cap can result in breaking the lifter spring and cause system failure (Figure1).

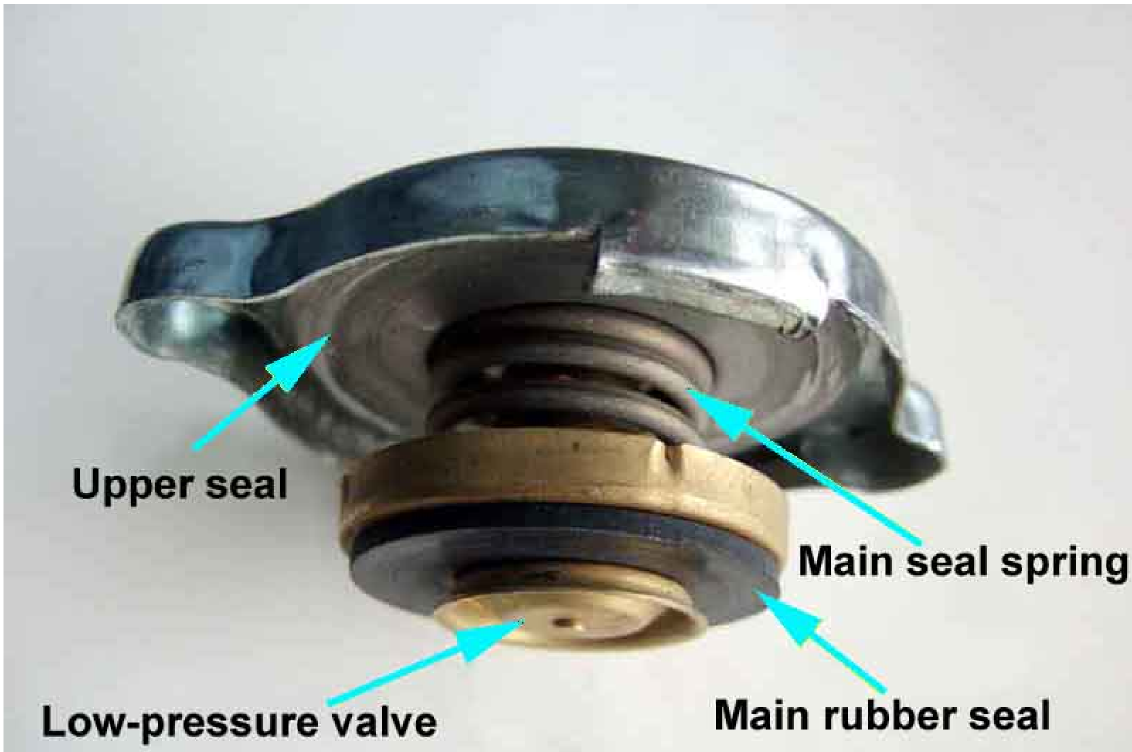


Figure 1 Cooling system pressure cap

There is also packaging design requirements to be met, such as the length of the heat exchanger, which can not exceed 0.75m (Header plates included), as well as the shell outer diameter that cannot exceed 0.145m

It is also important to consider structural constraints such as the tube and shell strength considering their materials properties, and the operation conditions given that the engine is operating at a range of 600-2100 rpm and uses a 15psi pressure cap in the cooling system.

It is important to maintain a maximum pressure of 15psi

As the base design is met, we will list the values of all heat exchanger design that result in a base design, then go over the significance of each variable based on several assumptions, one factor at a time runs (OFAT), and design of experiment (DOE).

Initial Input Variables

The key decision in this step is the coolant and exhaust gas placement. The fluid placement decision considers the thermal radiation that can be generated if the exhaust gas is placed in the shell side, and most importantly, the safety concerns of the high temperature (750 C) the gas can cause to the adjacent components or the physical harm it can cause to the individual(s) coming in contact with the heat exchanger.

- First decision is to place the **exhaust gas in the tube side** and the coolant (**50/50 Ethelyn Glycol) in the shell side**.
- Since the exhaust gas is extremely corrosive, the **tubes' material** must withstand such effect, therefore **stainless steel** was chosen.
- The baffles factor is assumed negligible and no baffles were used in this design.

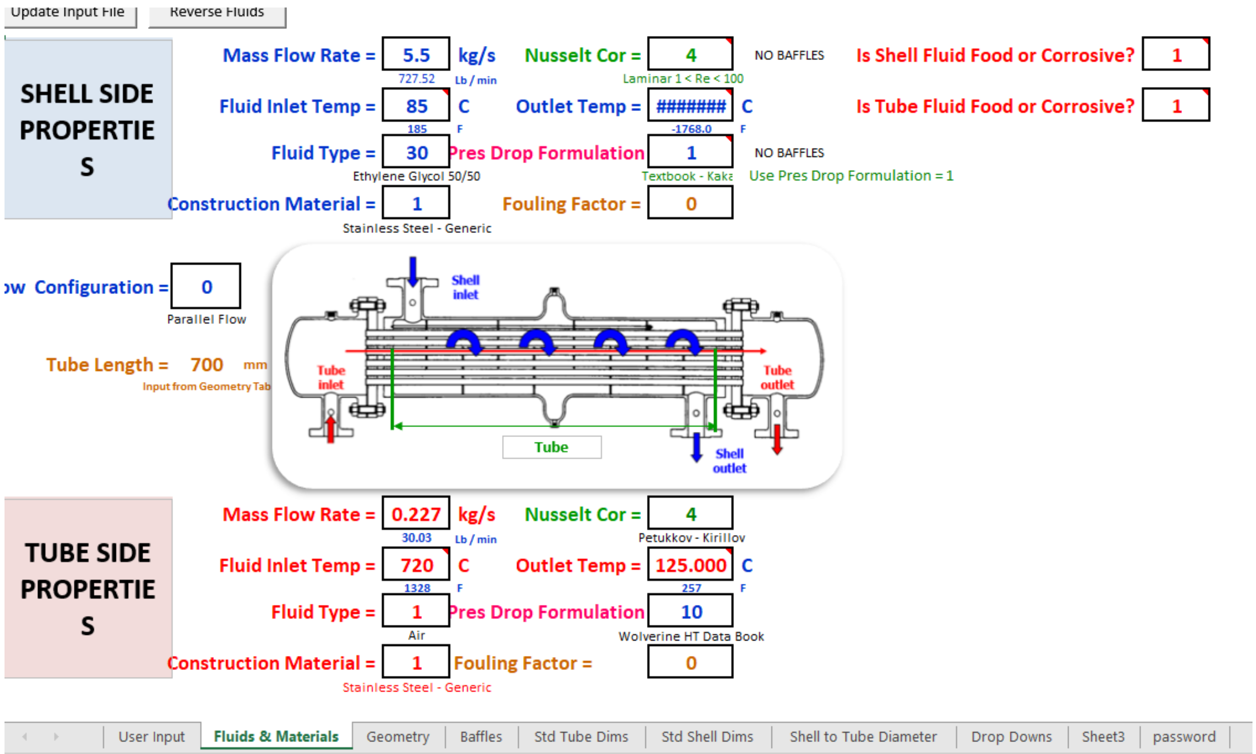


Figure 1a: Initial design variables

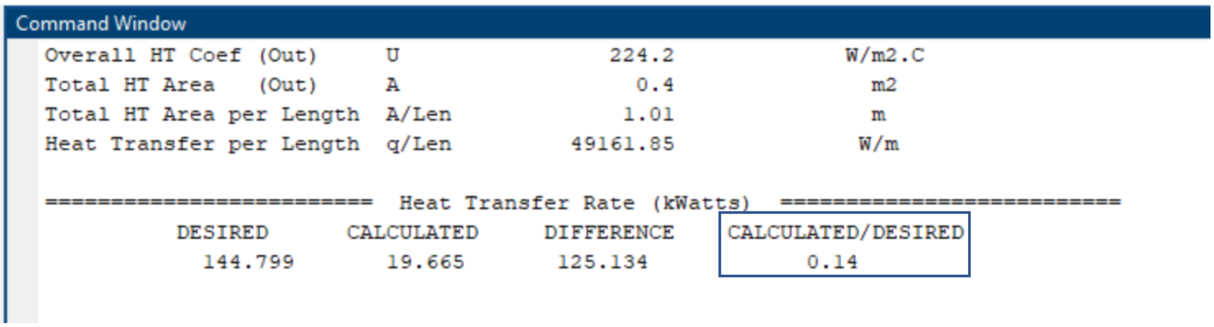
By setting Qdesired=Qcalculate, and eliminating the material variable and baffles and DT(LMTD) it appears that the variable that influences the heat transfer rate in this design is the surface area.

In order to increase the surface area, the tube length was also increased closer to the maximum length of 700mm.

It has also been noticed that decreasing the tube outer diameter greatly contributes to raising the heat transfer rate. This outcome is anticipated as the tube OD as we are increasing the number of tubes that can be fit in the shell, which is another factor that affects the heat transfer surface area. As a result, the tube flow area also increases.

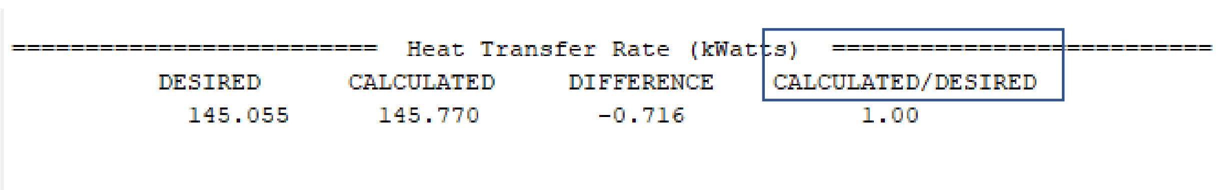
These geometry variables are known to reduce the Reynolds number as the flow velocity is reduced, and ultimately affect the overall heat transfer coefficient.

The initial heat ratio before adjusting the tube diameter was 14% (Figure 2a), after multiple runs and adjustments to the tube diameter, this rate was optimized to 100% (Figure 2 b).



```
Command Window
Overall HT Coef (Out)      U              224.2          W/m2.C
Total HT Area   (Out)      A                0.4            m2
Total HT Area per Length   A/Len            1.01           m
Heat Transfer per Length   q/Len        49161.85          W/m

=========================  Heat Transfer Rate (kWatts)  ==========================
          DESIRED      CALCULATED     DIFFERENCE    CALCULATED/DESIRED
           144.799       19.665        125.134             0.14
```

Figure 2-a: Original design heat transfer rate output ratio



```
=========================  Heat Transfer Rate (kWatts)  ==========================
          DESIRED      CALCULATED     DIFFERENCE    CALCULATED/DESIRED
           145.055      145.770        -0.716              1.00
```

Figure 3-b: Resulting heat transfer ratio

While the shell’s side fluid (Glycol coolant) mass flow rate has a great impact on the ratio output, it is important however to consider the output temperature of this type of fluid.

In order to maintain the Glycol coolant below its boiling point (129C), its mass flow rate was calculated to be higher than 1.5 kg/s, initially changing this rate to 5.5kg/s reflected a reasonable coolant output temperature of 92C as shown in figure 4-b below.

• Hand calculations:

Goal ⇒ $q_{desired} = \dot{m}_{exh} C_{p_{exh}} \Delta T_{exh} = 144.8\ kW$ $= q_{actual}$

$\dot{m}_{exh} = 13.6\ kg/min = 0.226\ kg/sec$

$\Delta T_{exh} = 720°C - 125°C = 595°C$

$C_{p\ air} @ T_{avg} = 422.5°C =$

$q_{actual} = q_{desired} = 144.8\ kW$

$q_{actual} = U A_s \Delta T_{LMTD}$

U: overall HTC

• ΔT_{LMTD} can ~~not~~ be adjusted by increasing the mass flow rate but that can cause significant pressure drop, so that is out of control variable.

• A_s can be increased ⇒ $A_s = \pi D_o L N_t$

shell ID Tube layout OD/D$_o$

• $U \propto h_{exh}, h_{coolant}$, ~~Tube conductivity~~

↳ Coolant mass flow rate

↳ ruled out since material was already made. (Steel)

Figure 4-a : Hand calculations of the minimum mass flow rate value required

================== Heat Exchanger Temperature Table (Celcius) ===================

	In	Out	Delta	Bulk	Wall	LMTD	CF	dT_in	dT_out
Tube	720	125	-595	422	256	203	1.00	635	33
Shell	85	92	7	89				Parallel Flow	

Figure 4-b: Coolant (shell side) output temperature

<u>OFAT (One Factor At a Time) Analysis</u>

In this step a DOE was performed using MATLAB by analyzing one factor at a time (OFAT). The goal is to select a range of each design input variable that is within the range of +/-25% of the desired heat transfer rate.

To select the appropriate range, a Matlab run was performed to analyze 4 variables (Shell fluid's mass flow, tube length, tube OD, shell ID) at 2 levels for each (Figure 5a-b)

```
I_Make_DOE_Study    = 1;

I_Reverse_Factors   = 1;

Number_of_Design_Variables               = 4;
Number_of_Levels_for_each_Design_Variable  = 2;
```

```
   mdot_shell        = Var_mdot_shell        (DOE_Matrix(DOE_run,1));
%    mdot_tube         = Var_mdot_tube         (DOE_Matrix(DOE_run,1))

    Tube_Len          = Var_Tube_Len          (DOE_Matrix(DOE_run,2));
%    Tube_th           = Var_Tube_th           (DOE_Matrix(DOE_run,5))
    Tube_OD           = Var_Tube_OD           (DOE_Matrix(DOE_run,3));
%    Tube_Layout_Angle = Var_Tube_Layout_Angle(DOE_Matrix(DOE_run,7))

   Shell_ID          = Var_Shell_ID          (DOE_Matrix(DOE_run,4));
```

Figure 5a: DOE setup on MATLAB

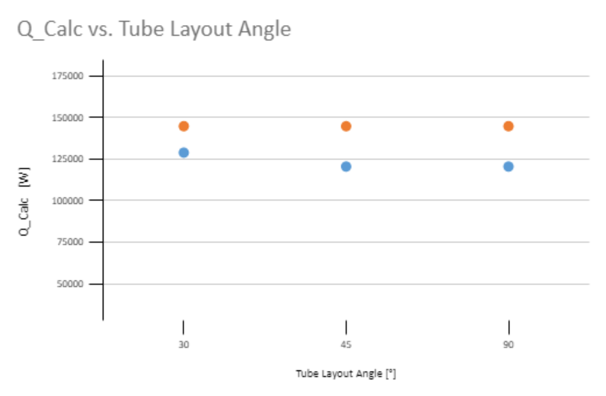
Figure 5b: DOE variables

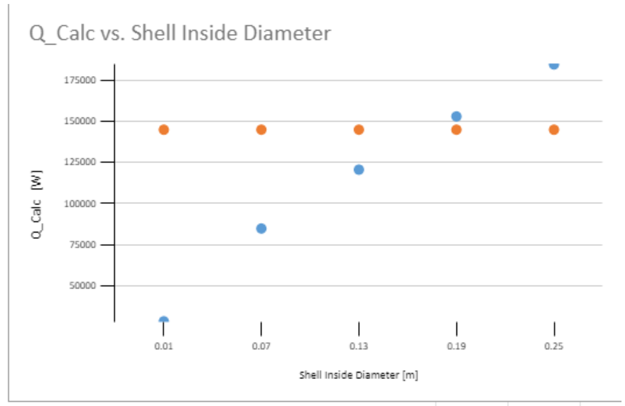
After each range was analyzed with respect to the dependent variables (Weight, tube and shell pressure drop, design heat transfer rate), the data was collected and tabulated accordingly to be graphed.

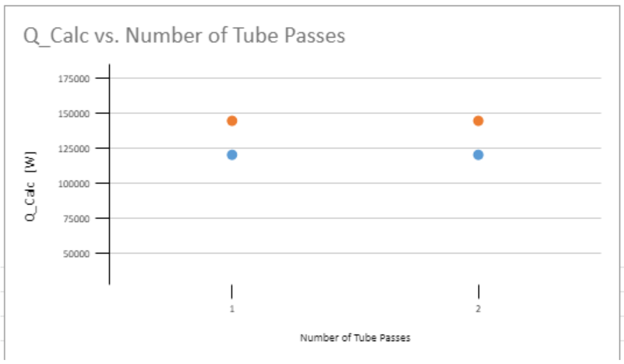
OFAT Using Matlab requires manually entering 5 increments of the each value's range

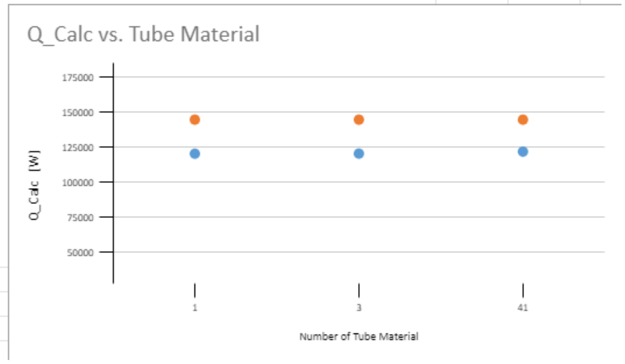
```
Var_mdot_shell                  = [2 3 5 7 10];
Var_mdot_tube                   = [1.5       3.5];

Var_Tube_Len                    = [0.450  0.600 .650 .700 .750];
Var_Tube_th                     = [0.4E-3 0.5E-3 0.6E-3];
Var_Tube_OD                     = [.0045 0.006 0.0075 .009];
Var_Tube_Layout_Angle           = [30       45      90];
Var_N_tube_pass                 = [1    1   2];
Var_I_tube_mat                  = [3   11   41];

Var_Shell_ID                    = [0.09 0.118 0.127 0.136  0.145];
```

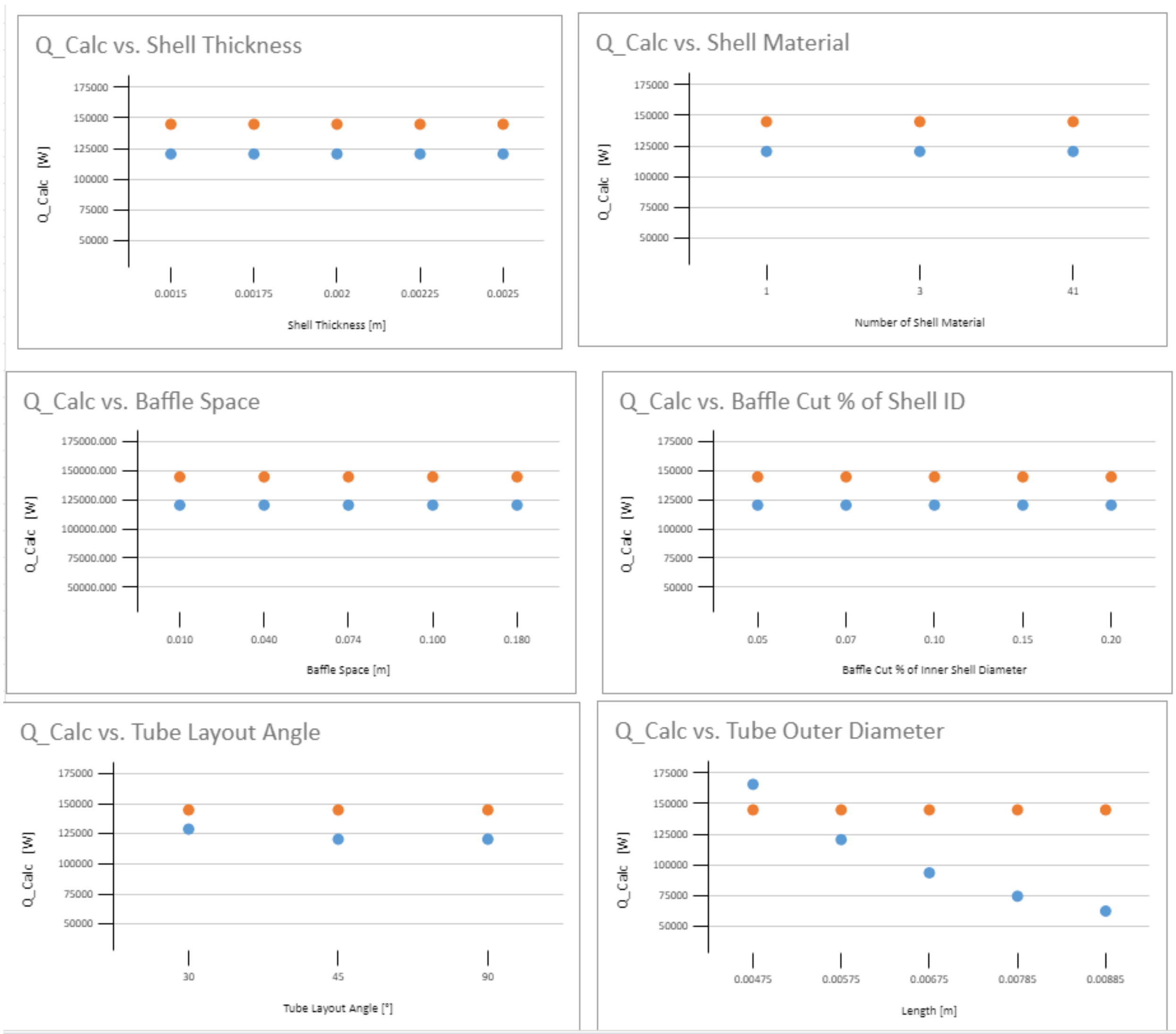
and run each value separately, after each run, the computed data was graphed using Excel and generated the interactions below, note that the Q-Calculated data points are indicated by the blue dots, while the Q-Desired values are in orange


Q_Calc vs. Tube Layout Angle
175000
150000
125000
100000
75000
50000
Q_Calc [W]
30
45
90
Tube Layout Angle [°]


Q_Calc vs. Shell Inside Diameter
175000
150000
125000
100000
75000
50000
Q_Calc [W]
0.01
0.07
0.13
0.19
0.25
Shell Inside Diameter [m]


Q_Calc vs. Number of Tube Passes
175000
150000
125000
100000
75000
50000
Q_Calc [W]
1
2
Number of Tube Passes


Q_Calc vs. Tube Material
175000
150000
125000
100000
75000
50000
Q_Calc [W]
1
3
41
Number of Tube Material



These graphs were then analyzed in order to rank each variable's impact on the calculated output of each value.

Table 1: Variables impact in tube ranking

Coolant in Shell				
Variable	**Impact on Outputs**			
Length	Weight	ΔPShell	ΔPTube	Qcalc

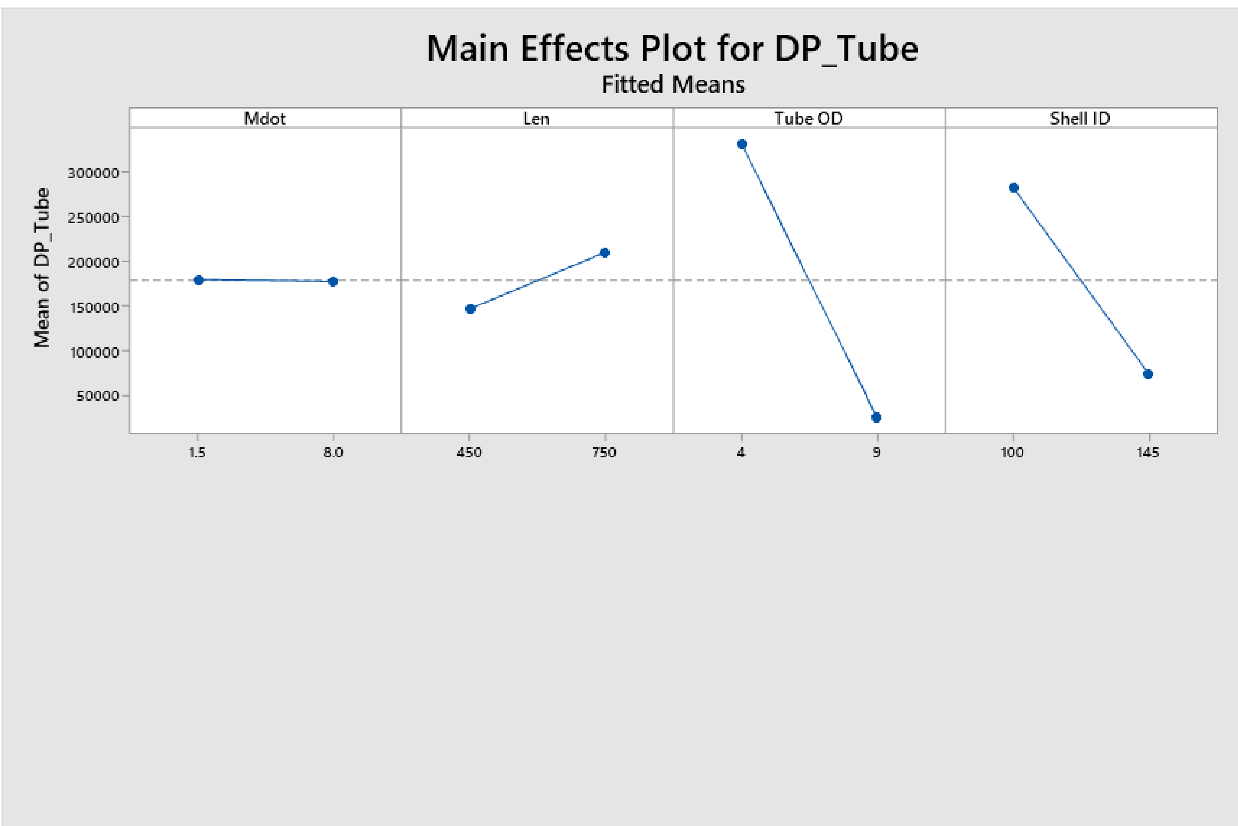
Flow Configuration	Weight	ΔPShell	ΔPTube	Qcalc
ṁ_shell	Weight	ΔPShell	ΔPTube	Qcalc
Tube Thickness	Weight	ΔPShell	ΔPTube	Qcalc
Tube Outer Diameter	Weight	ΔPShell	ΔPTube	Qcalc
Tube Layout Angle	Weight	ΔPShell	ΔPTube	Qcalc
Shell Inside Diameter	Weight	ΔPShell	ΔPTube	Qcalc
Number of Tube Passes	Weight	ΔPShell	ΔPTube	Qcalc
Tube Material	Weight	ΔPShell	ΔPTube	Qcalc
Shell Thickness	Weight	ΔPShell	ΔPTube	Qcalc
Shell Material	Weight	ΔPShell	ΔPTube	Qcalc
Baffle Space	Weight	ΔPShell	ΔPTube	Qcalc
Baffle Cut % of Shell ID	Weight	ΔPShell	ΔPTube	Qcalc
	Legend			
	High	Medium	Low	None

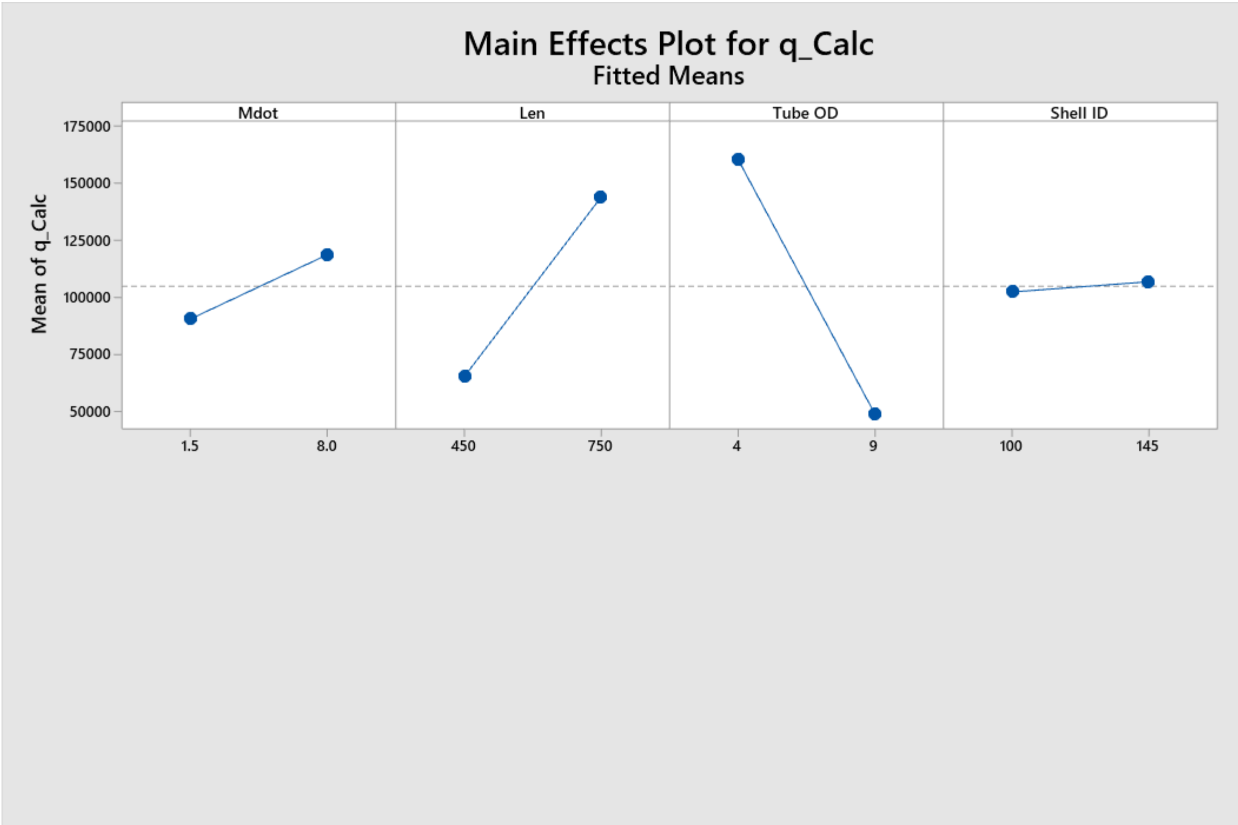
A similar factorial design analysis was performed using Minitab using the data from Matlab in the same order and ranges and the computed date accordingly. However, this analysis requires the range to be identified by min and max values

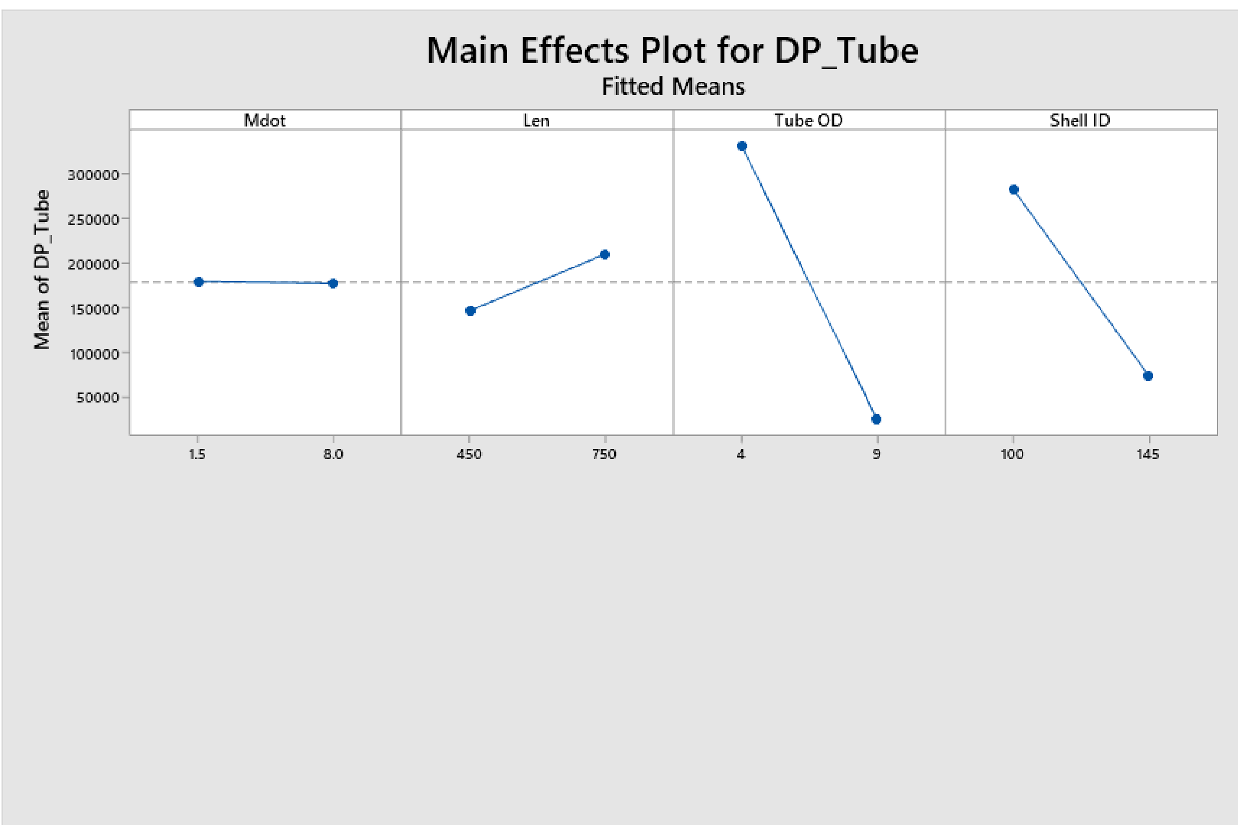
```
    Var_mdot_shell                        = [5.0 6.0 ];
    Var_mdot_tube                         = [1.5       3.5];

    Var_Tube_Len                          = [0.625  0.675];
    Var_Tube_th                           = [0.4E-3 0.5E-3 0.6E-3];
    Var_Tube_OD                           = [0.005 0.006];
    Var_Tube_Layout_Angle                 = [30       45      90];
    Var_N_tube_pass                       = [1    1   2];
    Var_I_tube_mat                        = [3   11   41];

    Var_Shell_ID                          = [0.135 0.145];




I_Make_DOE_Study    = 1;

I_Reverse_Factors   = 1;

Number_of_Design_Variables                = 4;
Number_of_Levels_for_each_Design_Variable = 2;
```

```
  I_counter_flow     = Var_I_counter_flow    (DOE_Matrix(DOE_run,1));
mdot_shell         = Var_mdot_shell        (DOE_Matrix(DOE_run,1));
  mdot_tube          = Var_mdot_tube         (DOE_Matrix(DOE_run,1));

 Tube_Len           = Var_Tube_Len          (DOE_Matrix(DOE_run,2));
  Tube_th            = Var_Tube_th           (DOE_Matrix(DOE_run,5));
 Tube_OD            = Var_Tube_OD           (DOE_Matrix(DOE_run,3));
  Tube_Layout_Angle = Var_Tube_Layout_Angle(DOE_Matrix(DOE_run,7));

Shell_ID           = Var_Shell_ID          (DOE_Matrix(DOE_run,4));
```

Then a main effects plot was generated for each range with respect to the design Q calculate value.The purpose of this plot is to distinguish each variable's impact level on the design heat transfer rate.




Main Effects Plot for q_Calc
Fitted Means
Mdot
Len
Tube OD
Shell ID
Mean of q_Calc
175000
150000
125000
100000
75000
50000
1.5
8.0
450
750
4
9
100
145


Main Effects Plot for DP_Tube
Fitted Means
Mdot
Len
Tube OD
Shell ID
Mean of DP_Tube
300000
250000
200000
150000
100000
50000
1.5
8.0
450
750
4
9
100
145

The slope in the main effect plot validates the design variables relationship to the Q value, as well as provides a relatively general idea on the variable level of impact through the slope steepness as they are all graphed using the same scale; for instance, both the length and shell ID increase with Q while the tube OD decreases. The shell ID however, does not tend to have a influence the Q value. Therefore, a shell thickness of approximately 1mm was the input, which is a lot thicker than the minimum calculated thickness calculated below (Figure 6) the purpose of making it thicker is to prevent manufacturing failures as the tubes need to be welded into the plate.

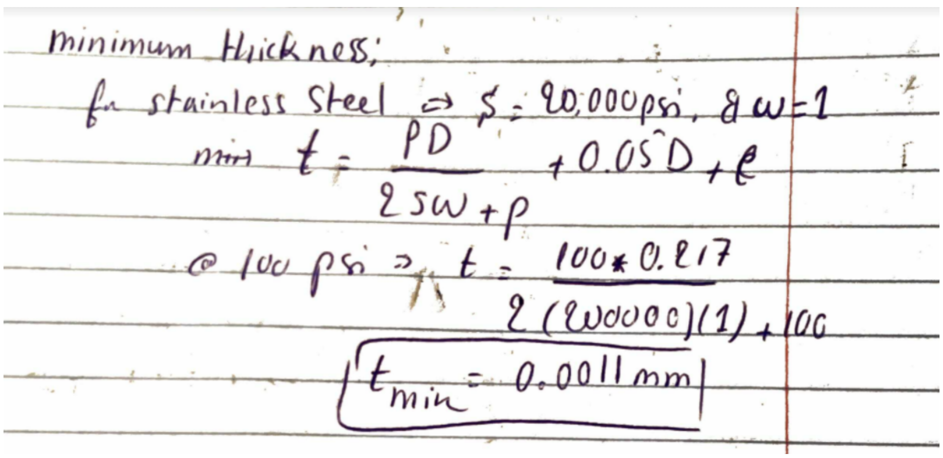
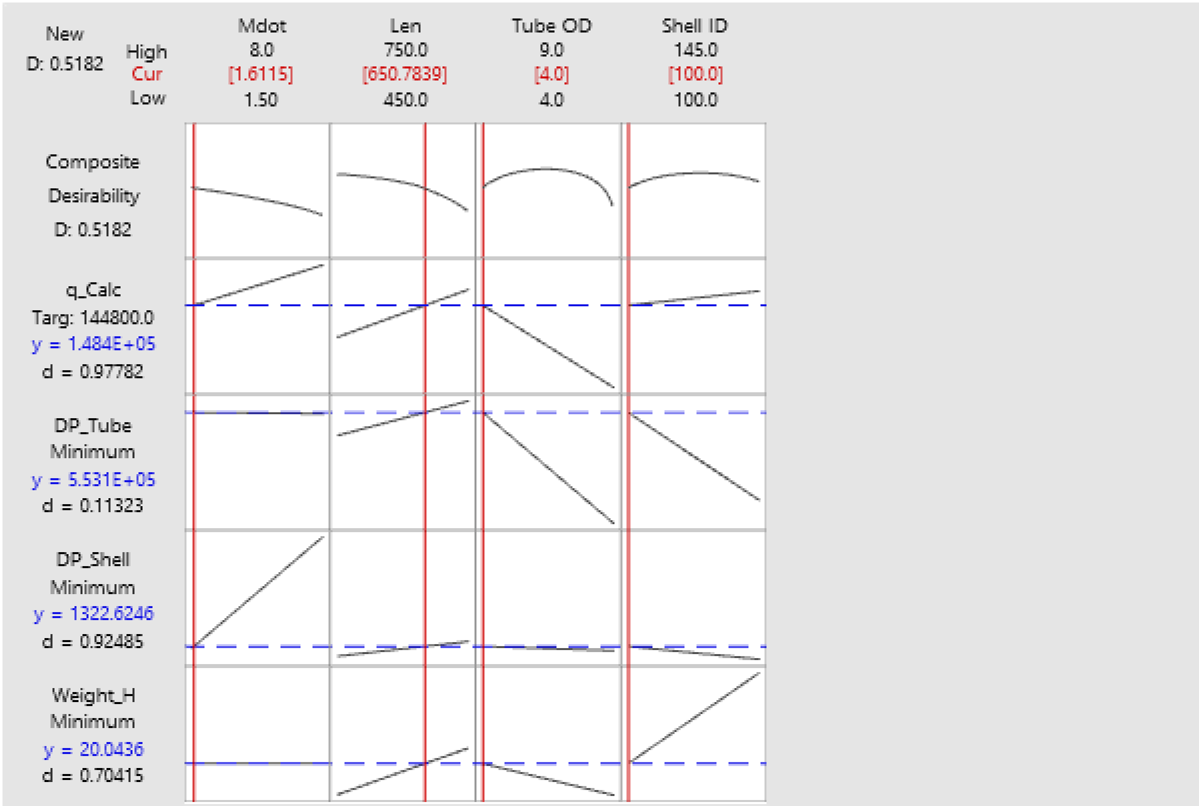


Figure 6: Minimum tube thickness hand calculations

Similarly, a DOE was also created using Minitab to analyze the results computed in MATLAB. Specifically, a factorial analysis was performed by selecting the interaction type for each variable, which was obtained from the 'Pareto Chart' to eliminate the least effective variable.

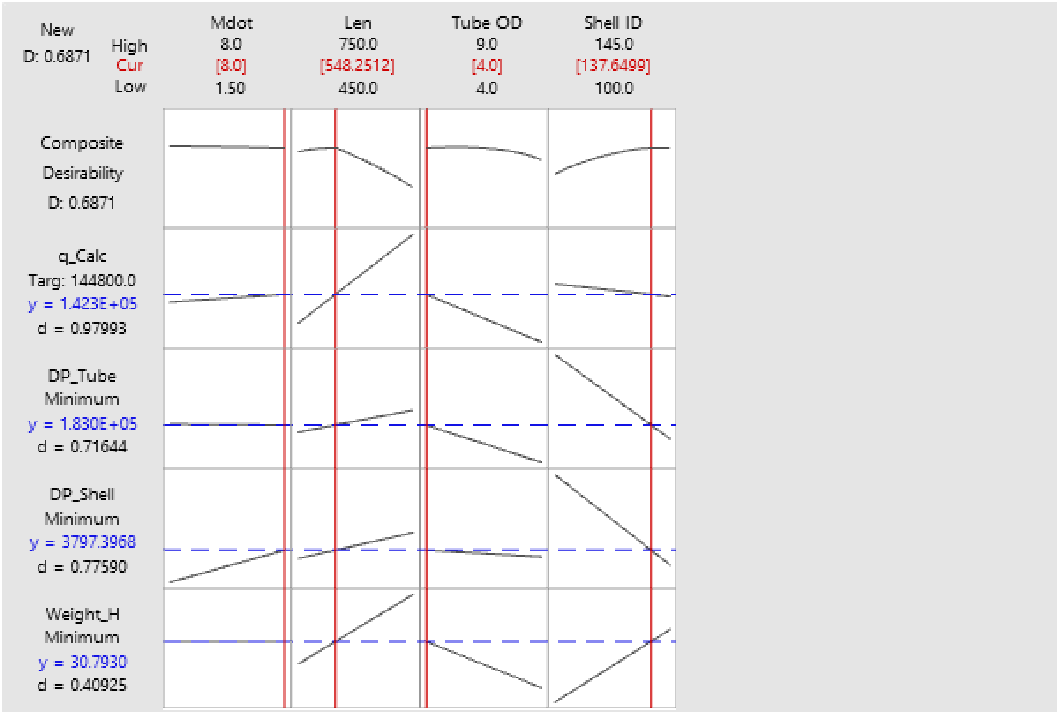
Once the eliminated interactions were eliminated, the remaining interaction were optimized on Minitab using the 'Response Optimizer' tool, which targets a certain variable while it allows manipulating the rest of the variables to the value that best serves the design goal and specifications :



Since each variable's range is relatively large, we notice that manipulating the sub-variables within a large range in order to optimize the Q output, did not automatically suggest values that benefit other design specifications, for instance, the pressure drop output is significantly out of spec, in the meantime we notice that the range of the variables that affect the pressure output is very large compared to that of the variables that serve Q.

In order to consider the rest of the variables with respect to the desired Q value, it is necessary to toggle the red bars to bring each variable as close as possible to the calculations while keeping in mind the design specifications and goal for each component as demonstrated below:

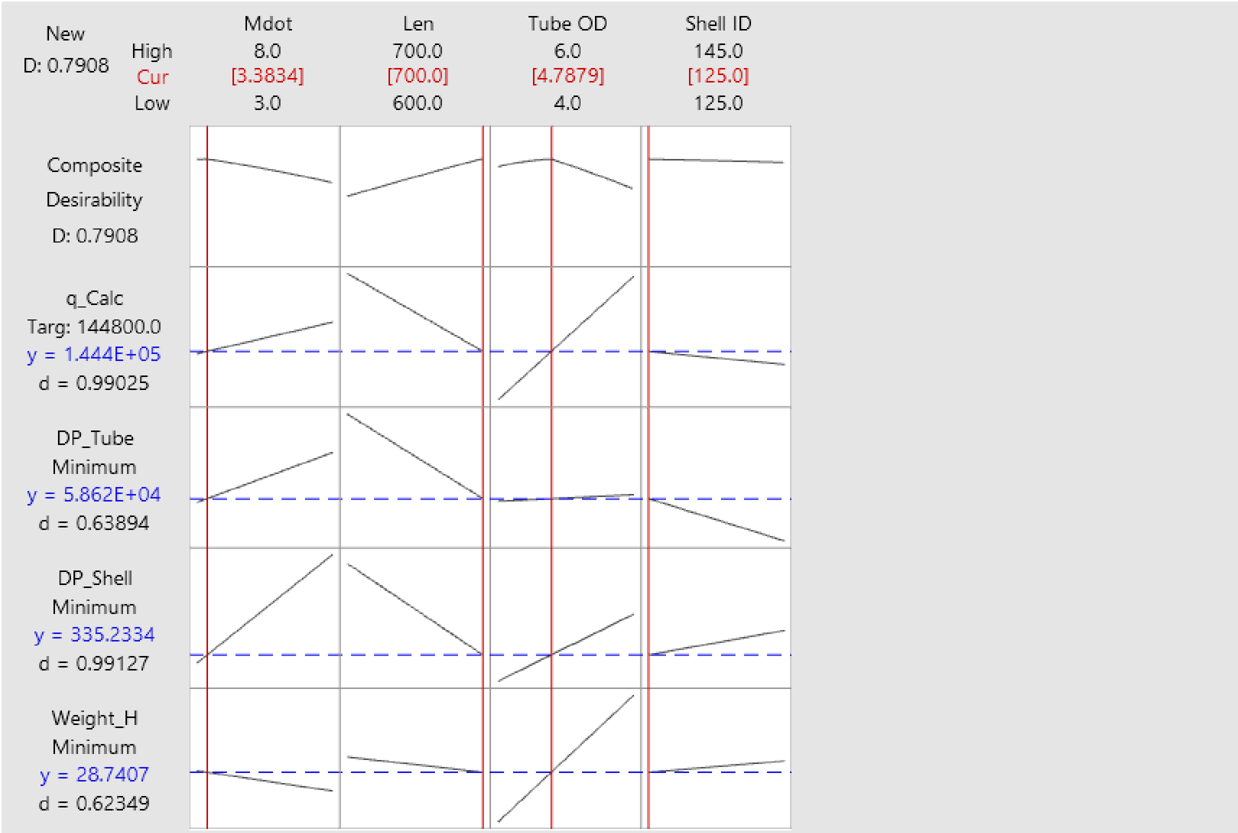
1. Read the values (in the red) that align with the design with the hand calculations.

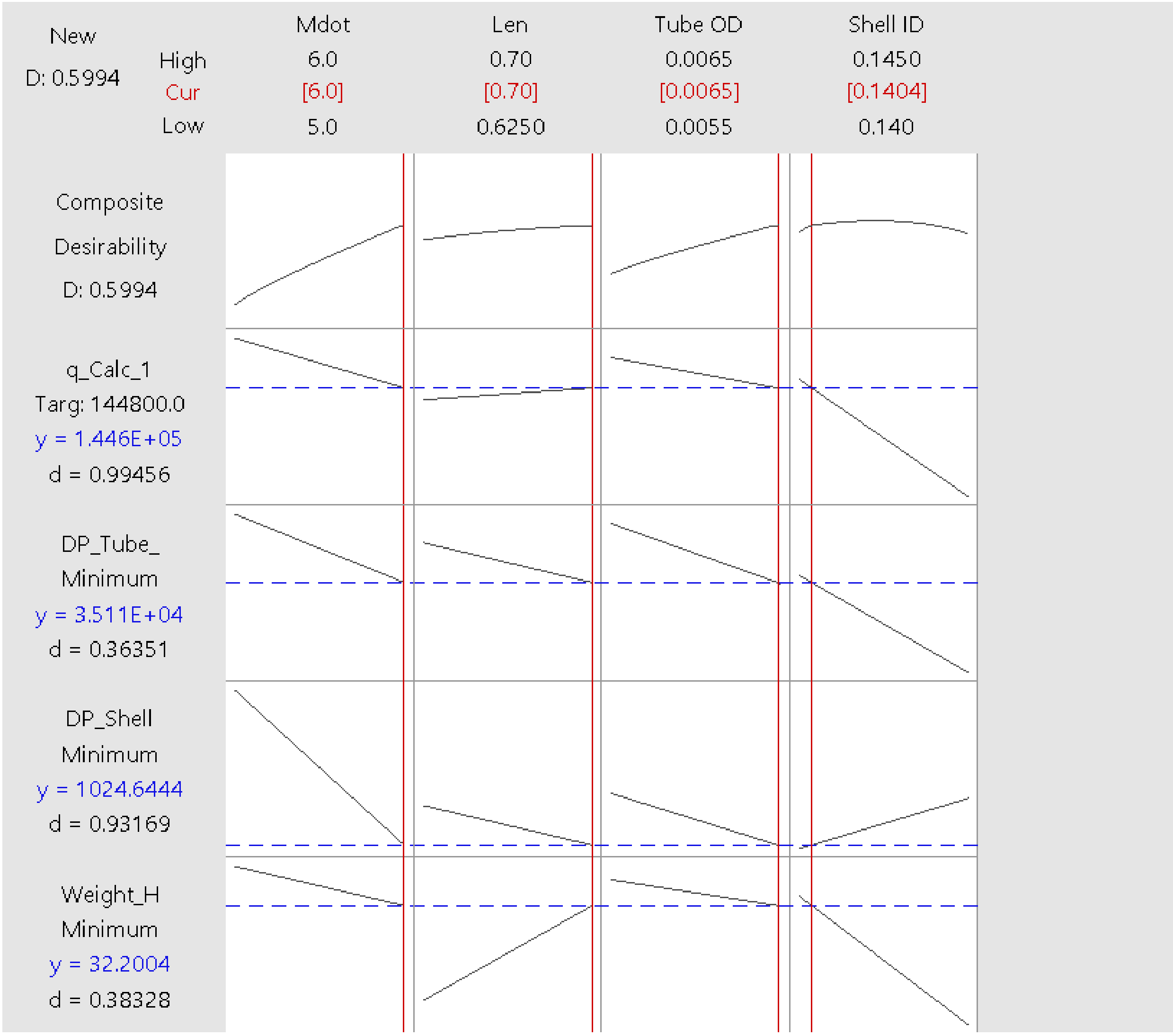


2. Adjust the range in MATLAB to bring it closer to the values in the Response Optimizer, run the script to generate new DOE data accordingly.

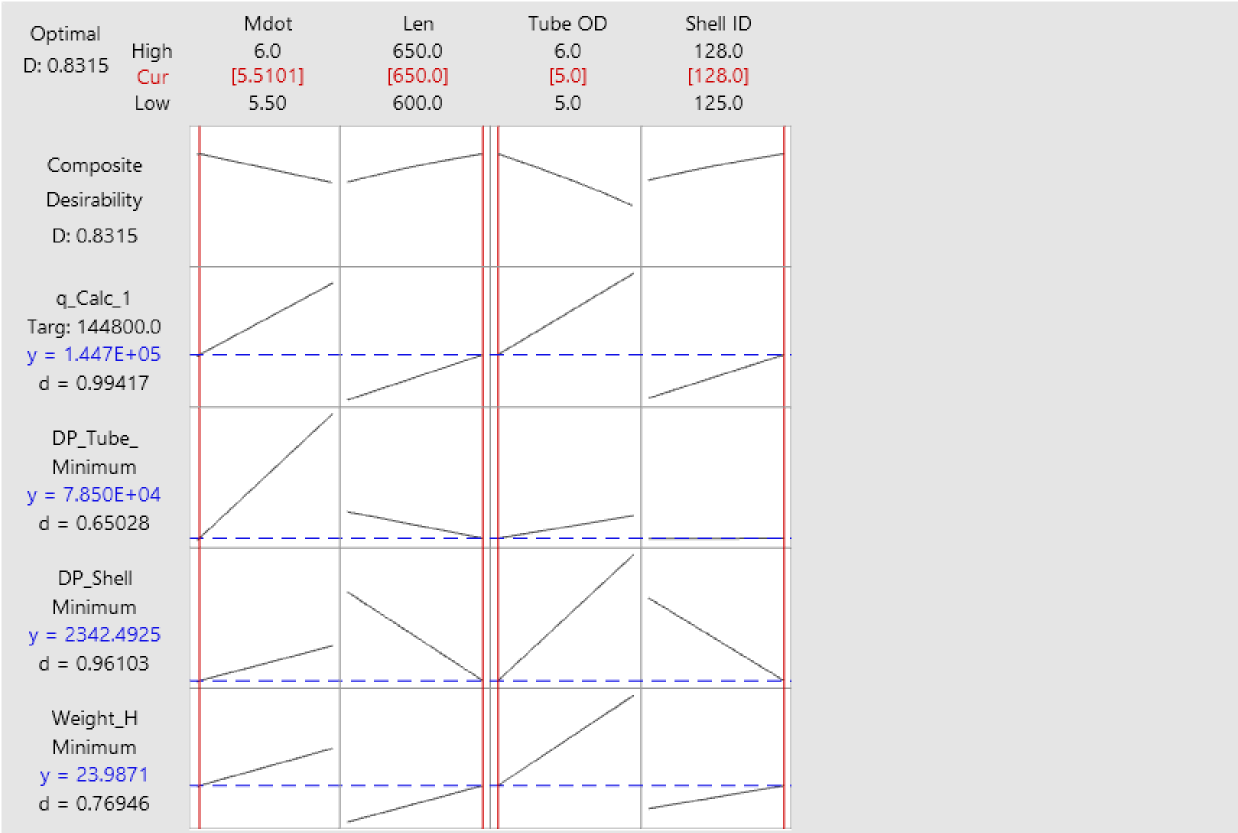
```
Var_mdot_shell                      = [3.0 8.0 ];
Var_mdot_tube                       = [1.5        3.5];

Var_Tube_Len                        = [0.600  0.750];
Var_Tube_th                         = [0.4E-3 0.5E-3 0.6E-3];
Var_Tube_OD                         = [0.004 0.006];
Var_Tube_Layout_Angle               = [30       45      90];
Var_N_tube_pass                     = [1    1    2];
Var_I_tube_mat                      = [3    11    41];
```

These steps were repeated multiple times until all the design variables were reduced to the range that satisfies the design requirements.


New
D: 0.7908
High
Cur
Low
Mdot
8.0
[3.3834]
3.0
Len
700.0
[700.0]
600.0
Tube OD
6.0
[4.7879]
4.0
Shell ID
145.0
[125.0]
125.0
Composite
Desirability
D: 0.7908
q_Calc
Targ: 144800.0
y = 1.444E+05
d = 0.99025
DP_Tube
Minimum
y = 5.862E+04
d = 0.63894
DP_Shell
Minimum
y = 335.2334
d = 0.99127
Weight_H
Minimum
y = 28.7407
d = 0.62349



While most of the variables are in spec, the pressure drop remains significantly high, so is the dry weight was still above its desired value (Shown below) therefore, more iterations were performed to lower the range with respect to the weight value. After few attempts, these two variables were improving as shown below:



While the results were improving with narrowing down the range of data, the optimizing tool provided a pretty clear idea on the possible combination of variables to generate the right design.

The final step was to verify the suggested data by running it on MATLAB, which did pass all the design requirements as shown below:

```
================== Heat Exchanger Temperature Table (Celcius) ===================
         In  Out Delta       Bulk  Wall        LMTD    CF          dT_in  dT_out
Tube    720 125 -595          422   256         203    1.00         635      33
Shell    85  92    7           89                                   Parallel Flow

 ==================== Tube Geometrical Parameters (meters) ======================
 Num of Tubes   Num of Passes       OD          ID          Length       Pitch
     329              1            5.0         4.2          670.0         6.3
   Shell Side Nusselt Correlation is Out of Validity Range
     Re is out of range
       Re should be within   1 < Re < 100

 ======================= Shell Geometrical Parameters (meters) ====================
 Shell ID    Baffle Cnt     Baffle Space    Baffle Cut     Baffle Th    Shell Th
 0.126          0              0.000          0.00%          0.000       0.002

 ====================  Shell & Tube Side Heat Transfer Parameters  ================
                               Shell Side       Tube  Side
Mass Flow Rate          mdot      5.500            0.227      kg/s


==========================  Heat Transfer Rate (kWatts)  ===========================
          DESIRED      CALCULATED      DIFFERENCE    CALCULATED/DESIRED
            144.799      142.988          1.811             0.99


=================== Heat Exchanger Pressure Drop (kPascal) ========================
                        SHELL SIDE                TUBE SIDE
                           3.360                    14.983

==========  Pump Power Consumption - (60% Efficiency) (kWatts & HP)  =============
                  Shell Side                           Tube Side
             0.030 kW     0.022 hp        8.595 kW      6.409 hp

============================  Heat Exchanger Weight (kg)  ==========================
    Dry       Wet              Shell  Tube  Baffle            Shell - Tube Fluid
    14.3      18.4               4.2   10.1    0.0                4.1        0.0
```