UNIVERSIDAD SAN FRANCISCO DE QUITO

# Heat Transfer

Final Report

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## Abstract

The objective of this study was to create a tool to optimize the dimensions and costs of a shell & tube heat exchanger given a certain heat transfer rate. Using MATLAB, a program was created, along with a GUI, that finds optimal dimensions by minimizing the total cost while meeting design constraints. A case study is presented, in which the optimization algorithm used by our tool was found to outperform the gradient-based SQP method by 39% with the same input parameters. This study, though successful, could benefit from considering mechanical properties of heat exchanger.

**Keywords**: *Design Optimization, Genetic Algorithms, Heat Exchangers, Computer Aided Engineering.*

**Objectives:**

- Create a tool to aid the design of shell & tube heat exchangers, with built-in optimization functionality.
- Validate the tool by comparing its results with previous studies.

**Methodology:**

Given the properties of the two fluids that will be interacting in the shell-tube heat exchanger (see figure 1), as well as the flow rates, inlet and desired outlet temperatures, our tool finds the optimal values for: tube length, shell diameter, tube diameter, number of passes, number of tubes, and baffle spacing.

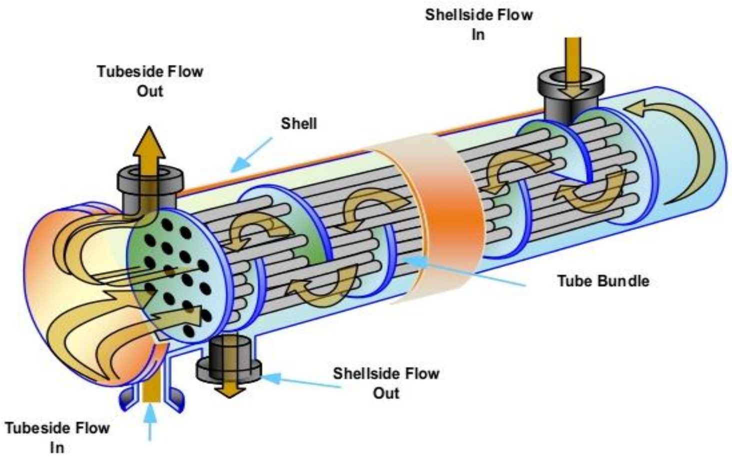


**Figure 1**: A Shell and Tube Heat Exchanger with one shell pass and one tube pass (cross counter flow)

Optimization is done with a genetic algorithm that finds the values of these heat exchanger design variables that will minimize the annual cost, while meeting the required heat transfer rate to achieve the imposed outlet temperatures. For this purpose, the cost function proposed by Kumar, Nagaraj & Halageri (2016) was used.

This function returns the annual cost (in dollars) of operation given the "effective heat transfer area and the pumping power to overcome the pressure drop" (Kumar et. al, 2016).

$$f = a_1 + a_2\, A^{a_3} + c_e HP$$

Where $a_1$ [\$] is a constant accounting for a fixed base cost, $a_2$ [$\$/m^2$] and $a_3$ are constants accounting for the cost of tube/shell material.

The power to overcome the pressure drop is:

$$P = \frac{1}{\eta}\left(\frac{m_t}{\rho_t}\Delta P_t + \frac{m_t}{\rho_t}\Delta P_s\right)$$

Where $\eta$ is the pump efficiency, $\rho$ is the fluid density, $m$ is the fluid mass flow rate and $\Delta P$ represents the pressure drop.

The heat transfer area is defined by:

$$A = \frac{Q}{U * LMTD}$$

Where:

Q = Heat transferred in kCal / h

U = Total heat transfer coefficient kCal / h*m$^2$ * ºC

LMTD = Logarithm of the average temperature difference in º C.

= (T1 – t2) – (T2 – t1) = (°C) (°F).

Where:

T1 = Inlet tube side fluid temperature;

t2 = Outlet shell side fluid temperature;

T2 = Outlet tube side fluid temperature;

t1 = Inlet shell side fluid temperature.

The heat rate ($Q$) achieve the desired outlet temperatures is:

$$Q = m_h * cp_h \, (T_{h,i} - T_{h,o})$$

The total heat transfer coefficient U is defined by the equation:

$$U = \frac{1}{\left(\frac{1}{h_s}\right) + R_{fs} + (d_o/d_i) * \left[R_{ft} + \left(\frac{1}{h_t}\right)\right]}$$

The tube length is calculated with:

$$L = \frac{A}{\pi d_o N_t}$$

To validate the optimization capabilities of our tool, the case study presented in Kumar et. al (2016) was reproduced. In that study, they used a Sequential Quadratic Programming algorithm (built into MATLAB) to perform the optimization of the cost function. Gradient-based method such as SQP are prone to premature convergence (in local maxima/minima) and the quality of its solutions depend heavily on the initial guess provided (De Santos, 2015). A genetic algorithm, on the other hand, is more suited for large multi-dimensional search spaces without the need for an initial guess because it searches for the optimum by constantly evolving 'population' of points, rather than from an individual point (Haupt, 2004) (see figure 2).

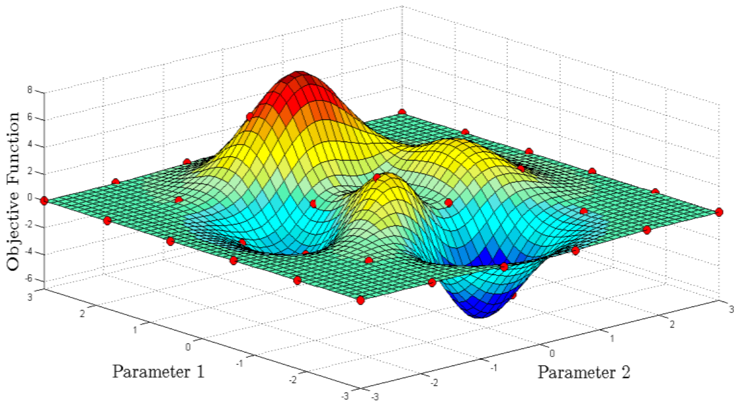


**Figure 2:** Genetic algorithm population sampling a hypothetical cost function with multiple local maxima and minima.

To plot the temperature distributions along the heat exchanger, the log-mean temperature difference method does not suffice. It is instead necessary to solve the following partial differential equations found in (Newman, 2001) (note that these are not coupled):

$$\frac{\partial T_{tube}}{\partial t} = -v_{tube}\frac{\partial T_{tube}}{\partial x} - \frac{2\pi U(T_{in} - T_{out})}{\rho\widehat{C_p}r} + D\frac{\partial^2 T}{dx^2}$$

$$\frac{\partial T_{shell}}{\partial t} = -v_{shell}\frac{\partial T_{shell}}{\partial x} - \frac{2\pi U r_{tube}(T_{in} - T_{out})}{\rho\widehat{C_p}(r_{shell}^2 - r_{tube}^2)} + D\frac{\partial^2 T}{dx^2}$$

The term proportional to the second derivative of the temperature with respect to $x$ is added for numerical stability and can be justified as accounting for the thermal diffusion that would inevitably occur in a real system. $D$ is a coefficient in the order of $1E-4$.

This calculation procedure was implemented as well; the Matlab function *pdepe* was used to solve the PDEs and obtain plots of the temperature distribution of the two fluids along the exchanger for multiple intermediate time steps.

A graphical user interface was created to showcase the functionality of the tool:

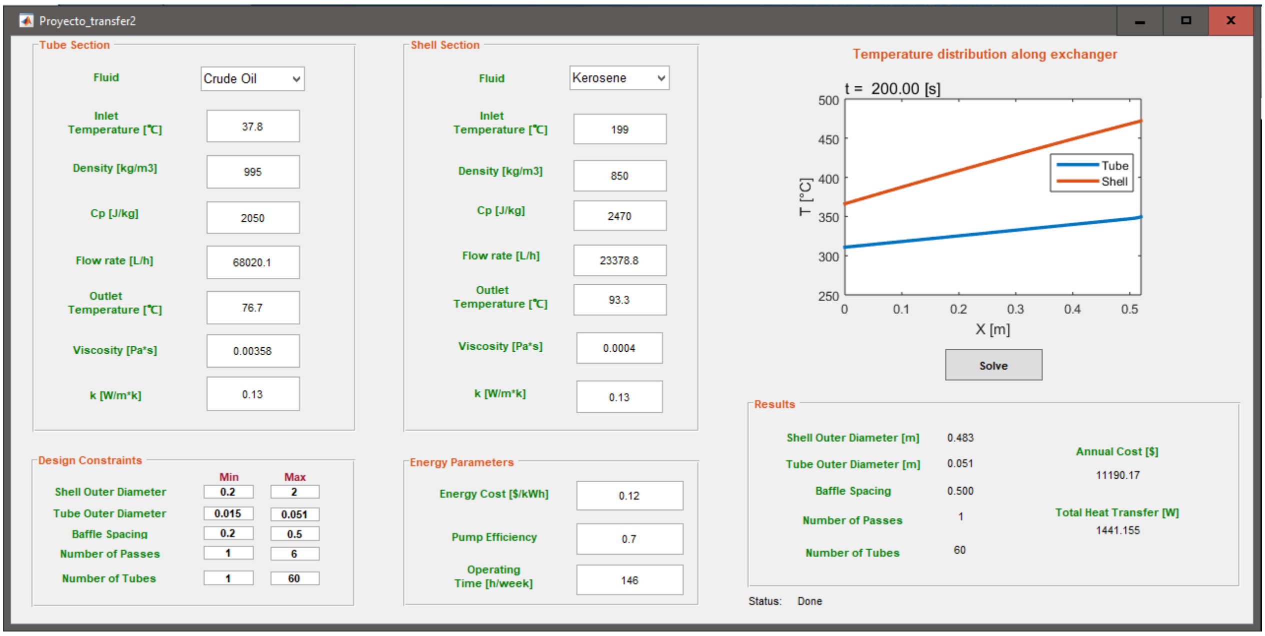


**Figure 3:** Heat exchanger design GUI

A git repository with the source code in its entirety can be found at: https://github.com/linomp/shell_and_tube_hx_design

**Results:**

The same case study presented in Kumar et. al (2016) was carried out, with the same operating conditions but with our tool that uses a GA for the optimization procedure. The following table summarizes the input parameters.

| | Fluid | Mass Flow (kg/s) | $T_i$ (°C) | $T_o$ (°C) | ρ (kg/m$^3$) | $c_p$ (kJ/kg-K) | μ (Pa-s) | k (W/m-K) |
|---|---|---|---|---|---|---|---|---|
| Shell Side | Kerosene | 5.52 | 199.00 | 93.30 | 850.00 | 2.47 | 0.0004 | 0.13 |
| Tube Side | Crude Oil | 18.80 | 37.80 | 76.70 | 995.00 | 2.05 | 0.00358 | 0.13 |

**Table 1**. Input parameters for the Crude-Kerosene case study (Kumar et. al, 2016).

We can see in the next figure how fast the iterations stabilize to find the best solution in terms of cost.

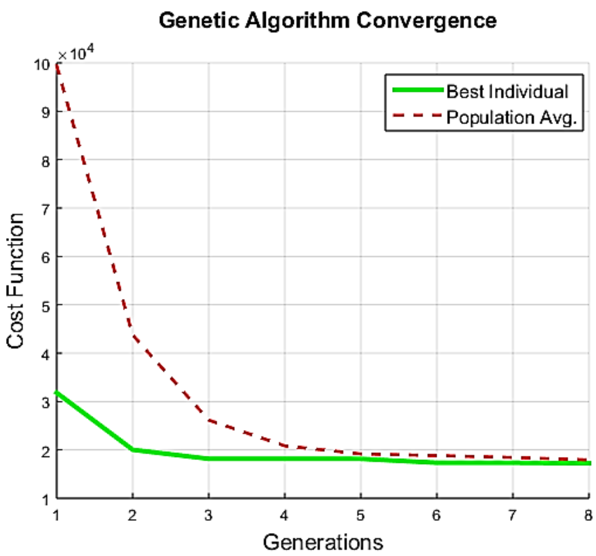


**Figure 4**: Evolution of the cost function value through the GA iterations.

The next figure shows the inlet and outlet temperature from the tube and the shell as a function of length. The fluid that enters the shell is the one that will be cooled down, so the temperature from the tube increases up to 50 [°C] more and the shell temperature decreases to about 100 [°C].

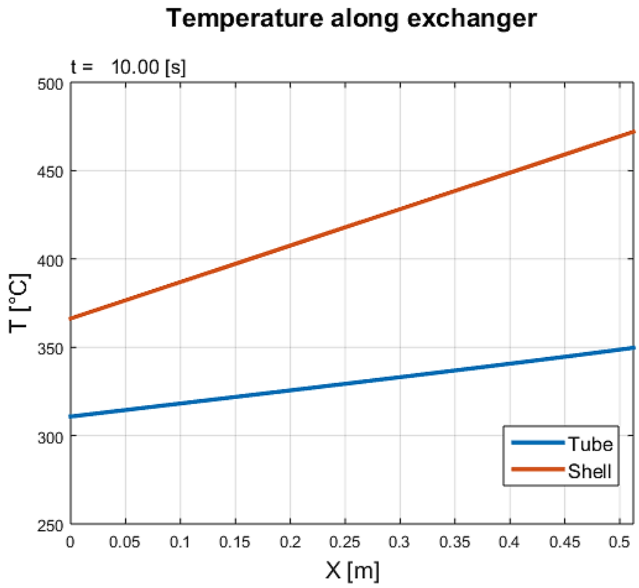


**Figure 5**: Temperature distribution of the two fluids along the exchanger (Steady State).

In the following figure, we demonstrate its value. We have reduced its price in comparison to the Kumar study, while using the same initial conditions and earning a profit of $7190 from that case.

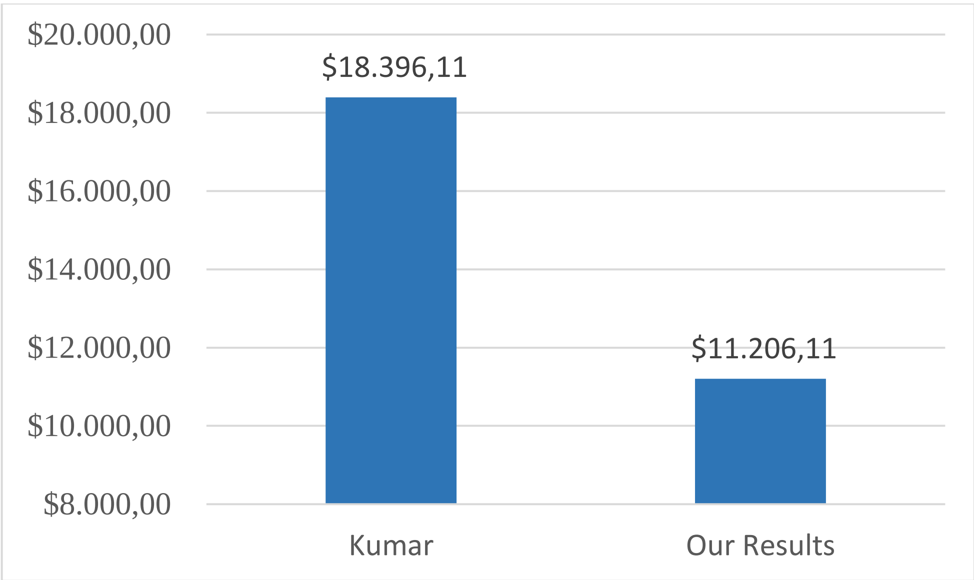


**Figure 6**: Minimum cost function value. SQP (right) vs. GA (left)

**Conclusions and Remarks:**

- The case study results showed a 39% decrease in costs with respect to the SQP method used by Kumar et. al (2016).
- The tool developed allows to find dimensions that satisfy heat exchanger design goals while keeping the costs at a minimum. However, mechanical properties of the heat exchanger should be assessed for safety.

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