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Modeling Two Phase Flow Heat Exchangers for Next Generation Aircraft

Hayder Hasan Jaafar Al-sarraf

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MODELING TWO PHASE FLOW HEAT EXCHANGERS FOR NEXT GENERATION AIRCRAFT

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering

By

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B.Sc. Mechanical Engineering, Kufa University, 2005

2017

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ABSTRACT


Two-phase heat exchangers offer the potential of significant energy transfer by taking advantage of the latent heat of vaporization as the working fluid changes phase. Unfortunately, the flow physics of the phase change process is very complex and there are significant gaps in the fundamental knowledge of how several key parameters are affected by the phase change process. Therefore, an initial investigation modeling a two-phase flow heat exchanger has been accomplished. Many key assumptions have been defined which are critical to modeling two-phase flows. This research lays an initial foundation on which further investigations can build upon. Two-phase heat exchangers will be a critical enabling technology for several key aerospace advancements in the 21st century.

In this research, modeling two-phase flow heat exchangers to be used in modeling of NASA’s next generation aircraft (N3- X) is accomplished. The heat exchanger model, which could be a condenser or an evaporator, currently accommodates two working fluids; kerosene (jet fuel) and a refrigerant (R134a).

The primary goal is to obtain a dynamic, robust model by using numerical simulation tools (MATLAB/ SIMULINK) which can simulate the system efficiently and would be
used in the conceptual aircraft (N3-X) model. The final goal of this project is to investi-
gate the influence of pressure and enthalpy perturbations on the system. In other
words, how quickly this system responds to change to perturbations, therefore the model
will be transient.

Two examples are used for demonstration of the transient response of a two-phase
heat exchanger to a perturbation in pressure and enthalpy. Initially, pressure perturbation
variation effects on how the quality of R134a effects the magnitude of the two-phase
flow heat transfer coefficient, therefore the two-phase heat transfer rate calculated. This
changing pressure approach used to provide a rapid thermal response to a rapid thermal
load variation. Other conventional thermal methods (decreasing the temperature of the
cold fluid or increasing the mass flow rate) results in slower response times than
changing the pressure. For this analysis, a sample time of 0.000001 seconds was used.

In addition, an enthalpy perturbation was investigated. Since, changing pressure
suddenly from higher value (650 kPa) to the lower value (555 kPa) is not a real, physical
scenario in life, the pressure change with transfer function would be employed to
transform the system into first order system with two different time constants. Eventually,
the time constant of the system plays a significant role in obtaining a quicker response.
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<th>Description</th>
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<tbody>
<tr>
<td>BLI</td>
<td>Boundary Layer Ingestion</td>
</tr>
<tr>
<td>BWB</td>
<td>Blended Wing Body</td>
</tr>
<tr>
<td>HTS</td>
<td>High Temperature Superconductors</td>
</tr>
<tr>
<td>HWB</td>
<td>Hybrid Wing Body</td>
</tr>
<tr>
<td>N3-X</td>
<td>NASA Next Generation Aircraft</td>
</tr>
<tr>
<td>PHE</td>
<td>Plate Heat Exchanger</td>
</tr>
<tr>
<td>OSF</td>
<td>Offset Strip fin heat exchanger</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>s</td>
<td>Transverse spacing (free flow width), mm</td>
</tr>
<tr>
<td>h</td>
<td>Free flow height, mm</td>
</tr>
<tr>
<td>t</td>
<td>Fin thickness, mm</td>
</tr>
<tr>
<td>l</td>
<td>Fin length, mm</td>
</tr>
<tr>
<td>tf</td>
<td>Plate thickness, mm</td>
</tr>
<tr>
<td>L</td>
<td>Heat exchanger length, mm</td>
</tr>
<tr>
<td>α</td>
<td>s/h ratio</td>
</tr>
<tr>
<td>δ</td>
<td>t/l ratio</td>
</tr>
<tr>
<td>γ</td>
<td>t/s ratio</td>
</tr>
<tr>
<td>β</td>
<td>surface compactness factor, ((m^2/m^3))</td>
</tr>
<tr>
<td>f</td>
<td>Fanning friction factor, dimensionless</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number, dimensionless</td>
</tr>
<tr>
<td>Pr</td>
<td>Prandtl number, dimensionless</td>
</tr>
<tr>
<td>Nu</td>
<td>Nusselt number, dimensionless</td>
</tr>
<tr>
<td>μ</td>
<td>Dynamic viscosity, pa-sec</td>
</tr>
<tr>
<td>cp</td>
<td>Specific heat at constant pressure, j/kg-k</td>
</tr>
<tr>
<td>cv</td>
<td>Specific heat at constant volume, j/kg-k</td>
</tr>
</tbody>
</table>
Thermal conductivity, w/m-k
ΔP  Pressure drop, pa
ṁ  Mass flow rate, kg/sec
Dh  Hydraulic diameter, m
Ac  Cross sectional area, m²
As  Surface area, m²
hl  Convective heat transfer coefficient @ liquid phase, w/m²-k
hG  Convective heat transfer coefficient @ vapor phase, w/m²-k
hTP  Heat transfer coefficient @ two phase, w/m²-k
Co  Convective number, dimensionless
Bo  Boiling number, dimensionless
Ffl  Fluid dependent parameter, dimensionless
ρl  Liquid density, kg/m³
ρG  Gas density, kg/m³
x  Quality, dimensionless
q''  Heat transfer per unit area, w/m²
G  Mass flux, kg/m²-sec
hlg  Enthalpy of evaporation, j/kg
h  Specific enthalpy, j/kg
u  Internal energy, j/kg
p  Pressure, pa
v  Specific volume, m³/kg
To  Dead-state temperature, k
Tc  Cryogenic temperature, k
hin  Enthalpy in, j/kg
hout  Enthalpy out, j/kg
Q̇  Heat transfer rate, w/sec
nm  Nautical mile
Subscripts

m Average value for the two-phase mixture
wall Fluid near the wall
l Liquid phase
G Gas phase
TP Two-phase
HX Heat exchanger
c Cold side
h Hot side
in Inlet
out Outlet
irr Irreversible
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Primarily, I would like to give big thanks to my thesis directors; Dr. Mitch Wolff, and Dr. Rory Roberts. They have not treated me as a student, they have worked with me as a colleague. I have learned lots of knowledge from them regarding research skills, selecting appropriate courses, and becoming a good researcher. Both have already given me many and many of hours to help me out solve programming issues, and teach me even fundamentals. In the beginning of doing this research, they encouraged me to learn new software enabling me to accomplish my thesis smoothly such as MATLAB/ Simulink software, and Engineering Equations Solver, EES. They guided me wisely and considered my time sufficiently. The most wonderful thing, they have open – door policy so that I could stop by to ask them and then solve all problems I had.

Additionally, I would also like to thank my fellow students whom have been working on the electric aircraft project headed by Dr. Mitch Wolff and Dr. Rory Roberts for their support and advice. These indispensable students are: Jay Vora, Abada, Hashim Hameed, Al Agele, Saif Shamil Hamzah, and Foshee, Robert.

Also, my thanks go towards my sponsor, Higher Committee of Education Development in Iraq, HCED who granted me full funded scholarship. This amazing opportunity enables me to get advanced education from Wright state University.

Finally, unlimited thanks to my father, mother, brother, and sisters for their efforts to make this study successful and stress less.
In short, I am so grateful that I am a person who surrounded with this spectacular environment.
INTRODUCTION

Overview – NASA 2035 Commercial Aircraft Concept

There has been and continues noticeable increases in aviation demands over several decades [1-3], Figure 1. This increased number of flights results in the amount of hydrocarbon fuels burned increasing as well. The hydrocarbon-fossil fuels worldwide are a limited resource. Typically, fossil fuel becomes more expensive day by day [1]. Figure 2 illustrates the rising of price and consumption for different types of fuels. From another perspective, the global concerns are rising regarding the environment, less pollution (i.e., the greenhouse gases emissions). Therefore, NASA has proposed a new generation of aircraft (N3-X) to address these various issues. Figure 2 shows how much increases are in aviation demands.

Figure 1: The increase in aviation demands [2]
The main features of this aircraft are a significant departure from conventional aircraft. To address the various performance issues, the new aircraft model must have many improvements in comparison with current aircraft. The existing baseline aircraft used by NASA is the Boeing 777-200LR [1] [2]. NASA has proposed a commercial subsonic aircraft working completely by electric power to obtain the desired performance goals. There are no hydraulic and pneumatic subsystems on the board of aircraft. Consequently, minimizing weight, complexity, operating and maintenance cost. In addition, they propose a hybrid wing body (HWB) or blended wing body (BWB). An advantage of this type of aircraft design is by increasing the boundary layer ingestion (BLI) into the propulsion system overall aircraft drag is decreased [3]. These advancements are on the external shape level. Internally, they will make use of high temperature superconductor (HTS) technology to substantially improve the usage of the electric power generated [4]. The electric power comes from two wingtip turbo generators and passes through HTS transmission cables. Figure 3 shows the proposed N3-X aircraft concept. Figure 4 gives...
details of the wingtip turbo generators and transmission cables.

Figure 3: Proposed NASA N3-X aircraft.

Figure 4: N3-X wingtip turbo generator and transmission cables [2]

The various goals of this conceptual aircraft are to address noise, fuel consumption, pollution, and mission length [5] [4]. These goals are listed in Table 1.
Table 1: NASA conceptual design goals [4]

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise (cum below Stage 4)</td>
<td>- 32 dB</td>
<td>- 42 dB</td>
<td>- 71 dB</td>
</tr>
<tr>
<td>LTO NOx Emissions (below CAEP 6)</td>
<td>-60%</td>
<td>-75%</td>
<td>better than -75%</td>
</tr>
<tr>
<td>Performance: Aircraft Fuel Burn</td>
<td>-33%**</td>
<td>-50%**</td>
<td>better than -70%</td>
</tr>
<tr>
<td>Performance: Field Length</td>
<td>-33%</td>
<td>-50%</td>
<td>exploit metroplex* concepts</td>
</tr>
</tbody>
</table>

*** Technology Readiness Level for key technologies = 4-6
** Additional gains may be possible through operational improvements
* Concepts that enable optimal use of runways at multiple airports within the metropolitan areas

Technical Specifications

This electric aircraft is a significant departure from traditional aircraft. NASA has proposed several innovative technologies, which will be highlighted. The propulsion system will be changed to a distributed propulsion system consisting of 14 electric fans driven by HTS motors [6]. This array of fans is located in the rear of the fuselage maximizing the boundary layer ingestion. Consequently, the thrust is obtained with reduced drag. In addition, high temperature superconductor technology will be employed in this aircraft. Therefore, motors, rectifiers, inverters, and power lines will be made from superconductor components only [7] [8]. The beauty of using these types of conductors is that the resistance will be zero if the operating temperature is at the appropriate level (i.e. a cryogenic temperature) [9]. Figure 5 demonstrates the relationship between the resistance and temperature for normal and superconductor power transmission.
Figure 5: Resistance versus temperature [2]

There are three kinds of HTS lines, which can be used as shown in Table 2

<table>
<thead>
<tr>
<th>HTS</th>
<th>Definition</th>
<th>Operating temperature (°K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>BSCCO Bismuth Strontium Calcium Copper Oxide</td>
<td>below 59</td>
</tr>
<tr>
<td>2.</td>
<td>YBCO Yttrium Barium Copper Oxide</td>
<td>60 ~77</td>
</tr>
<tr>
<td>3.</td>
<td>MgB$_2$ Magnesium Diboride</td>
<td>30 ~ 39</td>
</tr>
</tbody>
</table>

From the operating temperatures, the need of a cryogenic system to maintain these low temperatures is evident [10]. The need of a cryogenic system to provide the thermal loads required for superconductor operation has led to the need for a two-phase heat exchanger. The ability to use a two-phase heat exchanger will substantially reduce the size of the required thermal management system. Unfortunately, there is not much known about how a two-phase heat exchanger performs – basically the phase change is a transient phenomenon therefore a transient heat exchanger.
Two Phase Flow Heat Exchangers

Selecting an appropriate heat exchanger that can manage these thermal loads and provide a suitable cooling rate will be addressed next. Plate fin heat exchangers, PHE will be used because of their compactness, lightweight, and high heat transfer rate which match aerospace industry needs [14] [15] [16] [17] [18]. The value of heat transfer coefficient of PHE heat exchangers is nine times the heat transfer coefficient in typical circular tubes heat exchangers for the same Reynolds number [15]. Enhancing heat exchange through the heat exchanger is essential. Namely, the input energy is conserved. [19] [20]. Figure 6 illustrates the basic components of a PHE.

![Figure 6: Basic components of a PHE](image)

There are several kinds of PHE heat exchangers as listed below [21]

1. Plain rectangular
2. Plain trapezoidal
3. Wavy
4. Serrated or offset strip fin
5. Louvered
6. Perforated
An offset strip-fin PHE will be used in this investigation. Figure 7 is given to illustrate the geometry parameters of an offset strip-fin PHE.

Figure 7: Offset strip-fin configuration [16]

Hence, the flow is 1D and counter flow. Figure 8 shows a typical offset strip-fin (OSF) configuration.

Figure 8: The regular configuration of OSF

Two different working fluids are used in this investigation, which are kerosene (jet fuel) and R134a. R134a is the hot fluid, while kerosene is cold fluid. Since R134a enters the heat exchanger as a superheated vapor, it will undergo a condensation process in the heat exchanger. This process occurs inside the R134a saturated liquid/vapor dome, the refrigerant will be two-phases (liquid + vapor). Figure 9 shows R134a phases and the saturated dome.
Figure 9: R134a phases and the saturated dome
BACKGROUND

A heat exchanger is one of most wide spread pieces of equipment used in industry. It is used in oil refineries, food processing, and cooling/ refrigeration applications [15] [16]. The geometry of heat exchangers varies depending on the use and types of fluids for the heat exchange. A high percentage of heat exchangers used in different industries work with a two-phase flow [22]. Therefore, providing an essential need to clearly understand phase change through heat exchangers [19].

The background of two-phase flow heat exchangers begins in very ancient eras when people first used cooking-vessels to prepare their food. In addition, Archimedes used two-phase flow heat exchangers in the steam-gun, which has been considered the first application of two phase flow heat exchangers in the military. Heron created a turning sphere, which was operated by steam. Figure 10 shows Heron’s turning sphere invention.

Figure 10: Heron's turning sphere invention [22]
Ancient Egyptians also used two-phase flow heat exchangers in wine production. In the nineteenth century—industrial revolution, James Watt discovered the steam engine which opened many applications to use two-phase flow in so many fields [22]. Heat exchangers can be classified according to following criteria shown in Figure 11.
Classification according to process function

Condensers  Liquid-to-vapor phase-change exchangers  Heaters  Coolers  Chillers

Classification according to design or type

Tubular  Plate-type  Extended surface  Regenerative

PHE  Spiral  Plate coil  Printed circuit

Gasketed  Welded  Brazed

Double-pipe  Shell-and-tube  Spiral tube  Pipe coils

Cross-flow to tubes  Parallel flow to tubes

Ordinary separating wall  Heat-pipe wall
Figure 11: Heat exchangers classifications [23]

As previously discussed, for the aircraft industry a PHE heat exchanger is typically utilized to address the various application requirements, therefore a PHE heat
exchanger with a typical offset strip-fin (OSF) configuration is used for this research. As shown in Figure 9, the OSF causes the boundary layer to be recreated after every couple of strips. In addition, the OSF design causes the flow to be unsteady. Unsteadiness in the flow will expedite the transition to turbulent flow which enhances heat transfer rate [23].

It is obvious the importance of understanding two phase mode and analyzing its characteristics [19]. The first step requires coming up with a suitable correlation of the heat transfer coefficient. The initial attempts to correlate heat transfer coefficient were for flow in tubes, but for single phase flow only. Dittus and Boelter, Incropera and Dewitt, and Gnielinski arrived at the following equations to find Nusselt number used to calculate heat transfer coefficient. Their three equations respectively are:

\begin{align*}
\text{Nu} &= 0.023 \, Re^{0.8} \, Pr^{0.4} \\
\text{Nu} &= 0.023 \, Re^{0.8} \, Pr^{0.4} \left( \frac{\mu_m}{\mu_{wall}} \right)^{0.14} \\
\text{Nu} &= \frac{\zeta/8 \, (Re - 1000) \, Pr}{12.7 \, \sqrt{\zeta/8 \, (Pr^{2/3} - 1) + 1.07}}
\end{align*}

\begin{align*}
\text{where } \zeta &= (0.79 \, \ln(Re) - 1.64)^{-2}
\end{align*}

Various studies have been made to obtain suitable correlation of two-phase flow heat transfer coefficient in plate heat exchangers with Kandlikar proposing the best correlation (17% error) [24]. A fluid dependent parameter (correction factor [25]) is included in this equation in addition to the convective and boiling number. Table 3 lists values of the fluid dependent parameter for various types of fluids in copper and brass tubes.
Table 3: Fluid dependent parameter for various types of fluids in copper and brass tubes [25]

<table>
<thead>
<tr>
<th>ref</th>
<th>Fluid</th>
<th>Fluid dependent parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Water</td>
<td>1</td>
</tr>
<tr>
<td>2.</td>
<td>R-11</td>
<td>1.30</td>
</tr>
<tr>
<td>3.</td>
<td>R-12</td>
<td>1.50</td>
</tr>
<tr>
<td>4.</td>
<td>R-13B1</td>
<td>1.31</td>
</tr>
<tr>
<td>5.</td>
<td>R-22</td>
<td>2.20</td>
</tr>
<tr>
<td>6.</td>
<td>R-113</td>
<td>1.30</td>
</tr>
<tr>
<td>7.</td>
<td>R-114</td>
<td>1.24</td>
</tr>
<tr>
<td>8.</td>
<td>R-124</td>
<td>1.9</td>
</tr>
<tr>
<td>9.</td>
<td>R-134a</td>
<td>1.63</td>
</tr>
<tr>
<td>10.</td>
<td>R-152a</td>
<td>1.10</td>
</tr>
</tbody>
</table>

It is interesting to note that for stainless-steel, the fluid dependent parameter is 1 for all fluids [26].
MATHEMATICAL MODELING

A physics based model of a two-phase flow heat exchanger has been developed. The model was developed in the MATLAB/Simulink software environment. Various assumptions have been made in this model. The main characteristics of this model are as follows:

- One dimensional flow
- Indirect contact type (not mixing)
- Two fluids used; kerosene/ jet fuel (cold side) and R134a (hot side)
- Compact surface ($\beta \geq 700 \, m^2/m^3$)
- Extended surface (plate fin) heat exchangers
- Single pass (counter flow)
- Single-phase convection for kerosene and two-phase convection for R134a
- Process function is as condensers

Figure 12 illustrates the geometry of the heat exchanger modeled.
Table 4 lists the mass flow rate and temperature of the two fluids used in this research.

Table 4: Mass flow rate and temperature for both sides

<table>
<thead>
<tr>
<th>ref</th>
<th>side</th>
<th>( \dot{m} ) (kg/sec)</th>
<th>Temperature (k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Cold</td>
<td>1</td>
<td>280</td>
</tr>
<tr>
<td>2.</td>
<td>Hot</td>
<td>1.5</td>
<td>360</td>
</tr>
</tbody>
</table>

The model is developed such that the heat exchanger could be made from one of the three materials; Stainless Steel 316, Copper, or Aluminum. Table 5 lists the material characteristics for each of these metals.

Table 5: \( C_P, \rho, \) and \( k \) for SS-316, Cu, and Al

<table>
<thead>
<tr>
<th>ref</th>
<th>Material</th>
<th>( C_P ) (J/kg-(k ))</th>
<th>( \rho ) (kg/(m^3 ))</th>
<th>( k ) (w/m-(k ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Stainless steel- 316</td>
<td>502</td>
<td>8027</td>
<td>16.26</td>
</tr>
<tr>
<td>2.</td>
<td>Aluminum</td>
<td>896</td>
<td>2707</td>
<td>220</td>
</tr>
<tr>
<td>3.</td>
<td>Copper</td>
<td>380</td>
<td>8954</td>
<td>386</td>
</tr>
</tbody>
</table>

A basic diagram of the heat exchanger model is shown in Figure 13. The model uses one node to model the flow from inlet to the exit of each fluid.

![Diagram of the heat exchanger model](image)

The assumptions made in this model are:
Adiabatic system (heat in and heat out are zero)
Kinetic and potential energy are negligible
Linear interpolation between pressure lines inside the dome

Primarily, this model consists of four subsystems. The subsystems are:

- Cold balance
- Hot balance
- Heat exchanger balance
- Exergy analysis

To investigate these subsystems, each subsystem will be studied discretely to understand the input and output parameters.

**Cold Subsystem Balance**

This subsystem simply takes care of the kerosene/jet fuel analysis. In general, it is made up of a subsystem to calculate the fanning friction factor, a subsystem to compute the pressure drop, and a subsystem to calculate the energy balance analysis. For this purpose, Manglik and Bergles correlations are used with the following equations [28].

\[
f = 9.6243 \times Re^{-0.7422} \times \alpha^{-0.1858} \times \delta^{0.3053} \times \gamma^{-0.2859} \times (1 + 7.669 \times 10^{-8} \times Re^{4.429} \times \alpha^{0.92} \times \delta^{3.787} \times \gamma^{0.238})^{0.1}
\]  
(5)

\[
D_h = \frac{4shl}{2(sl+hl+th)+ts}
\]  
(6)

\[
Re = \frac{\dot{m} \times D_h}{\mu \times A_c}
\]  
(7)

\[
\Delta P = \frac{f}{2} \times \frac{L}{D_h} \times \frac{1}{\rho} \times \left(\frac{\dot{m}}{A_c}\right)^2
\]  
(8)
Applying an energy balance for the kerosene will allow the outlet temperature to be calculated, utilizing the following equations:

$$\frac{dE}{dt} = \dot{Q} + m \times (h_{in} - h_{out})$$  \hspace{1cm} (9)

$$\frac{dE}{dt} = m \times c_v \times \frac{dT}{dt}$$  \hspace{1cm} (10)

The left-hand side of Equation 10 is the time rate of change of energy which equals the time rate of change in internal energy only because the kinetic and potential energy are negligible.

Recalling $c_p$ and $c_v$ for incompressible fluids are identical, so using either $c_p$ or $c_v$ in (10) wouldn’t affect the result. By integrating the $\frac{dT}{dt}$ term, the outlet kerosene temperature is determined. Equation (11) is used to calculate the rate of entropy change for kerosene.

$$\frac{dS}{dt} = \frac{m \times c_p}{T} \times \frac{dT}{dt}$$  \hspace{1cm} (11)

**Hot Subsystem Balance**

The hot fluid, R134a, model is now presented. The following parameters are calculated using the same equations as the cold subsystem: the fanning friction factor, the hydraulic diameter, the pressure drop, and the energy balance models use the same equations as the cold subsystem balance. However, the outcome of the energy balance is the internal energy not the temperature. Using the thermodynamic definition of enthalpy (Eqn. 12), the model formulated an enthalpy-based model.

$$h = u + pv$$  \hspace{1cm} (12)

Many different pressure lines have been selected to approximate the thermodynamic properties. Hence, 66.19, 132.8, 243.5, 414.9, and 665.8 kPa have been used to get specific volume, density, enthalpy, enthalpy of evaporation, internal energy,
temperature, quality, specific heat, dynamic viscosity, thermal conductivity, and entropy for R134a. Appendix A contains a list of the lookup tables used in the model. The lookup tables have been determined using EES. Various pressure lines have been taken to diminish errors. But, errors still exist because the assumption of a linear interpolation is not always valid. In addition, some thermodynamic properties cannot be determined directly inside the dome. Dynamic viscosity, specific heat, and thermal conductivity are examples of these properties. To address this problem, the following equations are used [29].

\[ \mu_{TP} = \mu_l + x (\mu_G - \mu_l) \]

\[ c_p_{TP} = c_p_l + x (c_p_G - c_p_l) \]  \hspace{1cm} (14)

\[ k_{TP} = k_l + x (k_G - k_l) \]  \hspace{1cm} (15)

Utilizing Equations (13) - (15), the respective properties are easily calculated.

**Heat Exchanger Subsystem**

From the previous subsystems, temperature distributions for kerosene and R134a are known to use in the heat exchanger calculations. This subsystem will be divided into two parts.

Part 1: Kerosene heat transfer coefficient

Part 2: R134a heat transfer coefficient or two-phase flow heat exchanger

Initially, the Prandtl and Nusselt number, heat transfer equations are used to implement these calculations.

\[ Pr = \frac{\mu c_p}{k} \]  \hspace{1cm} (16)

\[ h = \frac{Nu k}{D_h} \]  \hspace{1cm} (17)

For part 1, one would use (Eqn. 3) to compute Nusselt number using the Prandtl number. Then, utilizing (Eqn. 17) the heat transfer coefficient is calculated. Note, the dynamic
viscosity varies according to temperature. This variation is handled via a lookup table (Appendix A). Next, heat transfer rate is calculated by

$$Q_c = h_c A_s (T_{HX} - T_c)$$  \hspace{1cm} (18)

For part 2, since R134a enters the heat exchanger as superheated vapor, there are three regions R134a could reach because of condensation. In other words, the amount of heat transferred from R134a to kerosene will determine the phase of refrigerant at exit. Therefore, there are three states R134a could exit the heat exchanger.

- Vapor
- Saturated mixture
- Liquid

In such cases, three simulation models have been created to address this issue. If R134a comes out in one phase (vapor or liquid), then (Eqn. 3) is used in the model. However, for the saturated mixture (liquid + vapor), a two-phase heat transfer coefficient correlation proposed by Kandlikar is used. The basis for that comparison depends on quality, which specifies the state of the refrigerant. This is modeled using a Simulink “State flow logic”. The advantage of state flow use is making logic, much cleaner, simpler, and more maintainable. Hence, transition between states would be easier by state flow logic. Furthermore, ability to see the transition is available for any values of quality. Hence, the condition placed is that if \( x \geq 1 \), the Nusselt number at vapor phase would be implemented. While if \( 0 < x < 1 \), the two-phase heat transfer coefficient would be computed. Otherwise, \( x = 0 \), then, the Nusselt number at liquid phase would be calculated. The next equations would be used to execute the model.
\[ h_{TP} = [(1.183744 \, Co^{-0.3} + 225.5474 \, Bo^{2.8} \, F_{II})] \, (1 - x)^{0.003} \, h_t \]  \quad (19)

\[ Co = \left( \frac{r_{\text{hoG}}}{r_{\text{hoI}}} \right)^{0.5} \ast \left[ \frac{1-x}{x} \right]^{0.8} \]  \quad (20)

\[ Bo = \frac{q''}{G \cdot \rho_{G}} \]  \quad (21)

Once \( h \) has been calculated, finding the heat transfer rate is straightforward. Equation (22) is used.

\[ Q_h = h \, A_s \, (T_h - T_{HX}) \]  \quad (22)

Now, the magnitude of \( Q \) for both kerosene and R134a is known. By applying an energy balance on the heat exchanger material, the heat exchanger temperature, \( T_{HX} \), is calculated by integrating (Eqn. 24).

\[ Q_{HX} = Q_{\text{refrigerant}} + Q_{\text{kerosene}} \]  \quad (23)

\[ \frac{dT}{dt} = \frac{Q_{HX}}{m \cdot c_p} \]  \quad (24)

**Exergy Analysis Subsystem**

An exergy model of the two-phase heat exchanger is developed for future research where the heat exchanger model is incorporated with other component models to model a more complex system like an aircraft. An exergy analysis is consistent with the 2nd law of thermodynamics. The model is consistent with the previous heat exchanger model based on the 1st law of thermodynamics. The two-phase heat exchanger will be divided into three parts, the hot side, cold side, and heat exchanger materials.

The appropriate exergy equations as follows.

\[ m_c \, c_{cp} \, \frac{dT}{T_c} \, dt = -\frac{Q_c}{T_{HX}} + \dot{m} \, (S_{in,c} - S_{out,c}) + \dot{S}_{irr,c} \]  \quad (25)
\[
m_h \frac{cp_h}{T_h} \frac{dT}{dt} = -\dot{q}_h + \dot{m} (s_{in,h} - s_{out,h}) + \dot{S}_{irr,h} \tag{26}
\]

\[
m_{HX} \frac{cp_{HX}}{T_{HX}} \frac{dT}{dt} = \frac{\dot{q}_c + \dot{q}_h}{T_{HX}} + \dot{S}_{irr,HX} \tag{27}
\]

\[
\dot{X} = T_o \left[ \dot{S}_{irr,HX} + \dot{S}_{irr,h} + \dot{S}_{irr,c} \right] \tag{28}
\]

\[
\dot{X} = T_o \left[ m_{HX} \frac{cp_{HX}}{T_{HX}} \frac{dT}{dt} + m_h \frac{cp_h}{T_h} \frac{dT}{dt} - \dot{m} (s_{in,h} - s_{out,h}) + m_c \frac{cp_c}{T_c} \frac{dT}{dt} - \dot{m} \right.
\]

\[
\left. (s_{in,c} - s_{out,c}) \right] \tag{29}
\]

For the R134a analysis, a lookup table (appendix A) is used to find the entropy.

Combining all of the various subsystem models together results in the complete two-phase heat exchanger model shown in Figure 14.
Figure 14: The whole heat exchanger simulation model
RESULTS

Transient analysis of a two-phase heat exchanger is critical to managing the thermal loads on next generation aircraft especially the NASA N3-X concept vehicle. A step change is typically a limiting transient input. Therefore, a step change in both pressure and enthalpy will be initially investigated to define the limits of the model. The overall duration of the simulation will be 6 seconds with a time step of $10^{-6}$ seconds. A simulation time step of $10^{-4}$ seconds is stable but to ensure model stability a time step two orders of magnitude lower was used for all of the results presented. The pressure step change is from 650 to 555 kPa and the enthalpy step change is from 350 to 300 kJ/kg.

Pressure Perturbation

A step change in the heat exchanger pressure for the cold side is presented. Figure 15 shows the pressure step change for R134a from 650 to 555 kPa. The enthalpy of the R134a is shown in Figure 16. The enthalpy of the R134a is constant as the pressure is changed.

![Figure 15: Hot side (R134a) pressure step change](image-url)
The kerosene temperature out of the heat exchanger is 282.3 K before the step change in R134a pressure, while $T_{c, out}$ is 281.8 K after the pressure step changes. Therefore, dropping the refrigerant pressure results in a decrease in kerosene temperature out of the heat exchanger of 0.5 °K. The reduction in operating pressure of the condensing heat exchanger reduces the saturation temperature of the refrigerant, which in turn reduces the amount of heat rejected from the refrigerant to kerosene through the heat exchanger.
The effect of the step change in pressure of the R134a on the R134a temperature is shown in Figure 18. The temperature out decreases due to the change in saturation temperature caused by the drop in pressure. As expected, a step decrease in the pressure of the R134a will affect the R134a temperature ($T_{h,\text{out}}$) directly. In the steady-state regions, when the pressure is 650 kPa, $T_{h,\text{out}}$ is 297 K, while at 555 kPa, $T_{h,\text{out}}$ is 292 K, which is due to the change in saturation pressure and temperature. The transient response predicted by the model between the two steady state values is of significant interest. Note: the temperature is calculated using pressure and internal energy through a lookup table. The model predicts the transient change to occur over 0.000001 seconds as result of the sudden change in pressure. This is due to the temperature being a non-dynamic state in the model. With respect to the conservation of energy, the internal energy is in a dynamic state in the model. Therefore, the transient response is calculated for temperature is a result of the step change in pressure. The model is capturing some trends in the transient region of the two-phase fluid. The initial response of over 0.1 seconds is driven by the internal energy of the mass in the control volume. The slower response is due the thermal equilibrium of the heat exchanger temperatures. Will the refrigerant temperature actually change to 292 K this quickly as shown? If not, how much? Experimentation and further analysis at the molecular level is needed to determine non-equilibrium physics of the fluid. Figure 19 presents the response of the heat exchanger material temperature to the step change. The temperature of the heat exchanger material is a dynamic state and the step change results in an appropriate first order response.
Figure 18: Hot flow (R 134a) temperature out with pressure step change

Figure 19: Heat exchanger material temperature with a pressure change

Figure 20 shows the heat transfer coefficient of kerosene, which only changes slightly due to the fluid properties changing with temperature.
Figure 20: Cold flow (kerosene) heat transfer coefficient, $h_c$, with pressure step change

On the contrary, the heat transfer coefficient of the two-phase refrigerant, $h_{TP}$ changes significantly with the pressure drop, Figure 21. Table 6 provides the steady-state values, which are nearly twice. This reinforces the idea of rapid pressure change approach for achieving a rapid thermal response to a transient heat load.

<table>
<thead>
<tr>
<th>Ref</th>
<th>Pressure (kPa)</th>
<th>$h_{TP}$ (w/m² - k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>650</td>
<td>3140</td>
</tr>
<tr>
<td>2.</td>
<td>555</td>
<td>4360</td>
</tr>
</tbody>
</table>

Figure 22 highlights the dependency of the quality on the pressure (as the pressure is decreased because the step change; the quality quickly increases). Hence, the quality is 0.6241 at a pressure of 650 kPa, while at a pressure of 555 kPa, the quality is 0.8023. As the pressure drops, R134a quality increases for the same value of internal energy. The quality does not change instantly with the pressure, but starts to increase as the internal energy of the fluid increases. The initial response takes approximately 0.01 seconds.

The two-phase flow heat transfer coefficient is influenced significantly by the value of the quality, therefore, the heat transfer coefficient ($h_{TP}$) will increase even if temperature
decreases. Basically, $h_{TP}$ is a function of temperature and quality. The quality has a slight overshoot. The internal energy is not in equilibrium and it increases as the refrigerant is evaporating instead of condensing during the transient region. The quality reaches a steady-state value as the temperature of the heat exchanger settles to 285.6 K. This takes approximately 0.2 seconds.

Figure 23 shows how much heat is transferred from the hot side (R134a) through the heat exchanger material into the cold side (Kerosene). The cold side heat transfer, $Q_c$, decreases because $h_c$ decreases and the temperature difference between the two flows decreases.

![Two phase flow heat transfer coefficient vs. time](image)

Figure 21: Hot side (R134a) heat transfer coefficient ($h_{TP}$) with pressure step change

![X vs. time](image)

Figure 22: Hot side (R134a) quality with pressure step change
Figure 23: Heat transferred to the cold fluid (Kerosene) with pressure step change

Figure 24: Heat transferred from hot side (R134a) with pressure step change

The heat transfer on the hot side (R134a) increases initially as the quality increases resulting in evaporation instead of condensation, but decreases with the reduction of quality as the heat exchanger becomes in thermal equilibrium. Once equilibrium in the
quality is reached, heat leaves the refrigerant resulting in condensing of the refrigerant once again. The steady state values of \( Q_h \) for the respective pressures of 650 and 555 kPa are presented in Table 7. Even though the heat transfer coefficient increases for the refrigerant the overall heat transfer decreases. This is because the temperature difference between the heat exchanger and refrigerant decreases from 10.2 K to 6.6 K. Table 7 demonstrates \( Q_h \) with respect to pressure 650 kPa and 555 kPa.

<table>
<thead>
<tr>
<th>Ref</th>
<th>Pressure (kPa)</th>
<th>( Q_h ) (w)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>650</td>
<td>116000</td>
</tr>
<tr>
<td>2.</td>
<td>250</td>
<td>91700</td>
</tr>
</tbody>
</table>

Figure 25: Total entropy generated with pressure step change

The steady state regions in Figure 25 show that entropy generated equals to 798 (w/k) at pressure 650 kPa, but at pressure of 555 kPa, \( \dot{S}_{gen} = 632 \) (w/k). Figure 26 presents the enthalpy out for R134a. R134a enthalpy out at 650 kPa is 184 kJ/kg, while at 555 kPa it is 208 kJ/kg.
The step change in pressure results in a sudden change in enthalpy of the fluid. The sudden step in enthalpy follows the 0.01 second response in quality. Therefore, there are two time scales in the quality and enthalpy results. The time constants are from the equilibrium in the fluid and the heat exchanger temperatures.

**Enthalpy Perturbation**

The two-phase heat exchanger model will be used to analyze a step change in enthalpy. The hot side enthalpy for the R134a is reduced from 350 kJ/kg to 300 kJ/kg by a step change, Figure 27. This change in enthalpy does not result in any change of the hot side pressure, Figure 28. The effect of the enthalpy step change on the cold side (Kerosene) temperature out is shown in Figure 29. It is clear from this figure that the impact of an enthalpy step change is similar to the pressure step change effect. Hence, both cause a decrease in the cold side (Kerosene) temperature out. The steady state cold side temperatures are given in Table 8.

![R134a Enthalpy vs.time](image)...
Figure 27: Hot side (R134a) enthalpy step change

Figure 28: Hot side (R134a) pressure with enthalpy step change

Figure 29: Cold flow (Kerosene) temperature out with enthalpy step change
**Table 8: Steady state $T_{c,\text{out}}$**

<table>
<thead>
<tr>
<th>ref</th>
<th>Enthalpy (kJ/kg)</th>
<th>$T_{c,\text{out}}$ (k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>350</td>
<td>282.5</td>
</tr>
<tr>
<td>2.</td>
<td>300</td>
<td>282.2</td>
</tr>
</tbody>
</table>

Since the pressure has not changed, the hot side (R134a) temperature out will remain at the saturated temperature as shown in Figure 30 as long as the quality is less than 1.0. This means there will be no opportunity for any error in the hot side (R134a) temperature out calculations because pressure is constant and the internal energy is dynamically calculated with a step change in enthalpy.

**Figure 30: Hot side (R134a) temperature out with enthalpy step change**
Figure 31: Heat exchanger material temperature with enthalpy step change

The enthalpy step change results in a slight change in the heat exchanger material temperature as shown in Figure 31. The heat exchanger material temperature shows a first order response for the enthalpy perturbation, which is similar to the pressure perturbation response in the previous section.

Figure 32: Hot side (R134a) heat transfer coefficient, $h_{TP}$, with enthalpy step change
Figures 32 and 33 illustrate the convection coefficient and quality response of the hot side refrigerant (R134a). As enthalpy decreases, the quality will decrease. Since $h_{TP}$ is related to the quality, therefore $h_{TP}$ will also decrease. Figure 34 shows the heat transferred to the cold side (Kerosene) $Q_c$, which is reduced due to the decrease in temperature difference between the heat exchanger and Kerosene. Figure 35 presents the heat transferred from the hot side (R134a) to the heat exchanger during the perturbation. There are two different responses to the enthalpy step change. The step change in enthalpy results in a near step change in the quality, which drives the heat transfer. The heat exchanger thermal mass drives a slower response time. The temperature difference between the R134a and heat exchanger material is increasing because $T_h$ is constant at saturated pressure and $T_{HX}$ decreases. So, the difference is larger which explains $Q_h$ gets larger slowly over time.
Figure 34: Heat transferred to the cold fluid (Kerosene) with enthalpy step change

Figure 35: Heat transferred from hot side (R134a) with enthalpy step change

Now, the entropy variation is analyzed. The change in entropy is based on the enthalpy step change. A non-physical instantaneous change in entropy is predicted as shown in Figure 36 at the instant the enthalpy is changed. This happens because of the instantaneous change of a non-dynamic parameter. Table 9 presents the steady-state entropy values.
Figure 36: Total entropy generated with enthalpy step change

Table 9: Steady state total entropy generated

<table>
<thead>
<tr>
<th>ref</th>
<th>Enthalpy (kJ/kg)</th>
<th>Entropy generated (w/k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>350</td>
<td>846</td>
</tr>
<tr>
<td>2.</td>
<td>300</td>
<td>771</td>
</tr>
</tbody>
</table>

Realistic Pressure Response

Previously, an ideal step change in pressure was investigated. In this section, a transfer function is employed to emulate the response time of a plenum volume and a valve for perturbing the pressure of the system. The ideal input pressure would be a step change but a first order response is more realistic. The initial pressure is 650 kPa, while the final pressure is 555 kPa. This investigation will provide a more realistic test of the two-phase flow heat exchanger model using different time constants. Finally, a comparison between the transfer function results and the previous pressure step change results can be made. The sample time has been taken as 0.00001sec. To approximate the volume for a given
time constant, the ideal gas equation of state is used for simplicity even though R134a does not behave as an ideal gas.

\[ PV = mRT \]  \hspace{1cm} (30)

is transformed to the following form

\[ P = \frac{mRT}{V} \]  \hspace{1cm} (31)

Taking the derivative of Eqn. (31) with respect to time results in

\[ \frac{dP}{dt} = \frac{RT}{V} \frac{dm}{dt} \]  \hspace{1cm} (32)

where the term \( \frac{V}{RT} \) represents the time constant. To calculate the time constant, the temperature (T) is taken as 298 k and R for R134a is 81.5 \( \frac{J}{kg \cdot K} \). Note, that Eqn. (32) assumes temperature is not changing with time. This does introduce some additional error in the approximation of the time constant for a given volume and temperature. Two different time constants were analyzed to evaluate a range of approximate volumes. From Figure 19 in pressure step change section the heat exchanger mass time constant is 0.3 seconds which will be constant for both time constants 0.1 and 0.01 seconds.

**Time constant = 0.1 sec.**

Figure 37 shows the hot side (R134a) pressure change from 650 kPa to 555 kPa as a first order response with a time constant of 0.1 seconds. In this case, the plenum volume is approximately 2.4 \( m^3 \).
Figure 37: Hot side (R134a) pressure response for a time constant of 0.1sec

Figure 38 plots the hot side (R134a) temperature out during the pressure response for a 0.1 time constant. The hot side (R134a) temperature changes simultaneously with respect to the pressure changes if the hot side (R134a) quality is less than 1. Therefore, $T_{h,out}$ decreases as the pressure decreases from 650 kPa to 555 kPa.

Figure 39: Hot side (R134a) temperature out for a time constant of 0.1sec

Figure 39 shows the hot side (R134a) quality during the pressure response for a 0.1 time constant. Since the pressure decreases, the quality increases as stated earlier. In the time range (1~1.3) seconds, the hot side (R134a) quality increases due to the decrease in the refrigerant pressure. Next, the quality decreases after 1.3 seconds because the hot side
(R134a) heat transferred increases. The change in equilibrium of the fluid is more evident in Figure 41.

Figure 39: Hot side (R134a) quality for a time constant of 0.1sec

Figure 40 shows the heat transferred from the hot side refrigerant during the pressure response for a transfer function with a 0.1 sec time constant. The heat transfer rate does not have the sudden step change as in the previous section, but still has the undershoot due to the changing quality of the fluid as it reaches a new equilibrium.

Figure 40: Heat transferred from hot side (R134a) for a time constant of 0.1sec
The temperature difference between the hot side (R134a) temperature and the heat exchanger material temperature decreases by time during the transient region as shown in Figure 41 because $T_{h, out}$ decreases as a result of pressure decreases.

![Temperature Difference Graph](image1.png)

Figure 41: Temperature difference between Hot side (R134a) and the heat exchanger material for a time constant of 0.1sec

Figure 42 shows the total entropy generated during the pressure response for a transfer function with 0.1 sec time constant. Since the total entropy generated is a function of the temperatures and the latter decrease due to the pressure drop, the total entropy generated decreases.

![Total Entropy Generated Graph](image2.png)

Figure 42: Total entropy generated for a transfer function with a time constant of 0.1sec
After running the model with a specified time constant (0.1 sec), a comparison to the step change results is done. All figures of the results are identical except for pressure, $T_{\text{h, out}}$, $Q_h$, and total entropy generated results. Therefore, a 0.1 second time constant with a first order response does not introduce any issues with the model. The approximate time constant of the heat exchanger temperature is 0.3 seconds. With the plenum volume time constant of 0.1 seconds the heat exchanger-to-plenum volume ratio of time constants is approximately 3-to-1. This ratio of time constants results in normal operation of the heat exchanger, but larger ratios of time constants result in different behavior in heat transfer as is presented in the next section.

**Time constant = 0.01 sec.**

Figure 43 shows the hot side (R134a) pressure change from 650 kPa to 555 kPa as a first order response with a time constant of 0.01 seconds. The plenum volume for this time constant is approximately $0.24 \, m^3$. The pressure response is relatively faster and equates to a 30- to- 1 ratio for heat exchanger temperature to plenum volume time constant.

![Pressure vs. time](image)

Figure 43: Hot side (R134a) pressure response for a time constant of 0.01sec
Figure 44 shows the hot side (R134a) temperature out during the pressure change for a 0.01 second transfer function. As expected, the hot side (R134a) temperature direction is similar to the hot side (R134a) pressure as long as the refrigerant quality is less than one. The results of the $T_{h,\text{out}}$ for 0.1 time constant are identical to the results of the $T_{h,\text{out}}$ for 0.01 time constant. Therefore, selecting different time constants will not affect the results.

![RefTempOut vs. time](image)

Figure 44: Hot side (R134a) temperature out for a time constant of 0.01sec

Figure 45 shows the temperature difference between the hot side (R134a) and the heat exchanger materials. In the time range (1~ 1.04) seconds, the temperature difference decreases due to the hot side (R134a) temperature decreases because the pressure decreases. After 1.04 seconds, the temperature difference increases due to the decrease in the heat exchanger material temperature.
Figure 45: Temperature difference between Hot side (R134a) and the heat exchanger material for a time constant of 0.01sec

Figure 46 shows the hot side (R134a) quality during the pressure response for a 0.01 time constant. Again, once the pressure decreases, the quality increases and vice versa. The response of the hot side (R134a) quality is quicker for this time constant than for 0.1 time constant. Hence, in one second, the refrigerant quality approximately reaches the equilibrium state.

Figure 46: Hot side (R134a) quality for a time constant of 0.01sec
Figure 47 shows the heat transferred from the refrigerant during a 0.01 second time constant transfer function- pressure change. The hot side (R134a) heat transferred in this Figure is similar to hot side (R134a) heat transferred in the pressure step change. Hence, there is a region in which the evaporation is occurring instead of condensation. In the time range (1~ 1.04) seconds, the hot side (R134a) heat transferred decreases as the $T_{h,\text{out}}$ decreases due to the pressure decreases. Next, after 1.04 seconds, the refrigerant heat transferred increases according to the temperature difference increase in that range of time.

Figure 47: Heat transferred from hot side (R134a) for a time constant of 0.01sec

Figure 48 represents the total entropy generated during time constant of 0.01 seconds first order pressure change.
Figure 48: Total entropy generated for a time constant of 0.01 sec
CONCLUSION

A stainless-steel two-phase heat exchanger has been modeled transiently. The numerical simulation tool (MATLAB/SIMULINK) was used to study and understand the influence of input perturbations on the operation of the heat exchanger. Two working fluids were selected; Kerosene and R134a.

The heat exchanger model demonstrates its ability to respond quickly to two different perturbations; pressure and enthalpy in very short period of time. Therefore, the results prove manipulation of pressure will dramatically change the heat transfer of R134a. The pressure drop results in a decrease in; kerosene temperature out, R134a temperature out, heat exchanger temperature, kerosene heat transfer coefficient, heat transferred to kerosene, heat transferred from R134a, and the total entropy generated. In turn, two-phase heat transfer coefficient, quality, and R134a enthalpy out increase as a result of the pressure drop. In particular, \( h_{TP} \) will be increased approximately twice.

There are two time constants of interest. The smaller time constant of the refrigerant fluid effected the fluid quality, enthalpy and heat transfer. Pressure manipulation of a refrigerant provides the opportunity to quickly change the fluid properties and overall heat transfer rate much faster than manipulating the inlet enthalpy or temperature. As shown in the enthalpy perturbation, the fluid temperature does not change. Pressure manipulation provides a rapid capability of manipulating both the heat transfer rate and the temperature of the refrigerant fluid. If a thermal system is designed with the ability to manipulate pressure, then the heat transfer rate may be actively rapidly controlled.
APPENDICES

APPENDIX A

In the Simulink model, it is very necessary to set up many lookup tables. These tables facilitate computing outcomes corresponding to incomes by linear interpolation procedure. There are basically various software/ programs could be used to do this task. However, EES program has been chosen to create these tables.
Table 10: Dynamic viscosity for kerosene versus temperature

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Table 11: Dynamic viscosity for R-134a @ different pressure lines versus enthalpy

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<th>$\mu @ P_3 = 243.5$ [pa - s]</th>
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Table 12: Density for R-134a @ different pressure lines versus enthalpy versus enthalpy

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Table 13: Specific heat for R134a @ different pressure lines versus enthalpy

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Table 14: Thermal conductivity for R134a @ different pressure lines versus enthalpy

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Table 15: Temperature for R134a @ different pressure lines versus enthalpy

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Table 16: Specific volume for R134a vs. internal energy @ different pressure lines

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<th>( V @ P_3 = 243.5 ) [m³/kg]</th>
<th>( V @ P_4 = 414.9 ) [m³/kg]</th>
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Table 17: Specific heat for R-134a @ liquid phase versus sat. temperature

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Table 18: Dynamic viscosity for R-134a @ liquid phase versus sat. temperature

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Table 19: Thermal conductivity for R-134a @ liquid phase versus sat. temperature

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Table 20: Density for R-134a @ liquid phase versus sat. temperature

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Table 21: Specific heat for R-134a @ vapor sat. phase versus sat. temperature

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Table 22: Dynamic viscosity for R-134a @ vapor sat. phase versus temperature

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<tr>
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<tr>
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<td>Row 7</td>
<td>298</td>
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<tr>
<td>Row 14</td>
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</tr>
<tr>
<td>Row 15</td>
<td>337.5</td>
</tr>
<tr>
<td>Row 16</td>
<td>344.6</td>
</tr>
<tr>
<td>Row 17</td>
<td>351.7</td>
</tr>
<tr>
<td>Row 18</td>
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</tr>
<tr>
<td>Row 19</td>
<td>365.9</td>
</tr>
<tr>
<td>Row 20</td>
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Table 23: Thermal conductivity for R-134a @ vapor sat. phase versus sat. temperature

<table>
<thead>
<tr>
<th>Row</th>
<th>Temperature [k]</th>
<th>Thermal conductivity [w/m-k]</th>
</tr>
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<tbody>
<tr>
<td>1</td>
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<td>0.008609</td>
</tr>
<tr>
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<td>0.009328</td>
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<td>4</td>
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<td>0.01074</td>
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<td>5</td>
<td>278</td>
<td>0.01144</td>
</tr>
<tr>
<td>6</td>
<td>288</td>
<td>0.01214</td>
</tr>
<tr>
<td>7</td>
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<td>0.01283</td>
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<td>8</td>
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<tr>
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### Table 24: Density for R-134a @ vapor sat. line versus sat. temperature

<table>
<thead>
<tr>
<th>Row</th>
<th>Temperature [k]</th>
<th>Density [kg/m³]</th>
</tr>
</thead>
<tbody>
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<td>238</td>
<td>3.499</td>
</tr>
<tr>
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<td>248</td>
<td>5.474</td>
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<tr>
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<td>258</td>
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</table>
Table 25: Enthalpy of evaporation for R-134a. versus sat. temperature

<table>
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<tr>
<th>Temperature [k]</th>
<th>Enthalpy of evaporation [J/kg]</th>
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</tr>
<tr>
<td>Row 20</td>
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Table 26: Entropy for R134a @ different pressure lines versus enthalpy

<table>
<thead>
<tr>
<th>Row</th>
<th>Enthalpy [J/kg]</th>
<th>S @ P_1 = 66.16 [J/kg-k]</th>
<th>S @ P_2 = 132.8 [J/kg-k]</th>
<th>S @ P_3 = 243.5 [J/kg-k]</th>
<th>S @ P_4 = 414.9 [J/kg-k]</th>
<th>S @ P_5 = 695.8 [J/kg-k]</th>
</tr>
</thead>
<tbody>
<tr>
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</tbody>
</table>
APPENDIX B

In this appendix, MATLAB files will be presented to set the foundation of creating the Simulink model. These files are doing four major tasks. First, setting the thermodynamic properties (specific heat, density, thermal conductivity, and dynamic viscosity) for fluids used in the heat exchanger model which are kerosene and R-134a. Second, initializing dimensions and size of the heat exchanger. Third, exporting all properties into the Simulink model mask. Therefore, the model will be ready to process all these data and find the results. Finally, plot outcomes with respect to time.

The code below is written to set the thermodynamic properties.

```matlab
function [cp, rho, k, mu, muT] = fluidproperties(val)
%val = input ('give me the name of fluid   ')

%%% Fluid properties,
% Specific heat, kJ/kg/K            [in polyval() form]
% Density, kg/m^3                   [in polyval() form]
% Thermal conductivity, W/m/K       [in polyval() form]
% Dynamic viscosity, kg/m/s         [in interp1() form]
% Temperatures for mu, K            [in interp1() form]

switch val
    case {'PAO'}
        cp = [3.7749e-3 1.02255];
        rho = [1.5859e-8 -2.6056e-5 1.4797e-2 -4.37867 1346.36];
        k = [5.8823e-5 1.5411e-1];
        mu = [0.90889, 0.11814, 0.030046, 0.011483, 0.0056626,
              0.003295, 0.0021441, 0.0015094, 0.0011254, 0.0008761, 0.0008275];
        muT = [220, 240, 260, 280, 300, 320, 340, 360, 380, 400, 405];
```

67
case {'JP8'}
    cp = [4.43359e-3 6.48908e-1];
    rho = [-7.23225e-1 1.02036e3];
    k = [-1.799e-4 1.67663e-1];
    mu = [0.0137298, 0.00807381, 0.00515649, 0.00360287, 0.00265331, 0.00205681, 0.00162952, 0.00131464, 0.00109445, 0.000937041, 0.000804244, 0.000701833, 0.000617844, 0.000543122, 0.000485191, 0.000435239, 0.000388231, 0.000353682, 0.000321021, 0.000295718];

case {'AIR'}
    cp = [2.80023e-13 -1.0498e-9 1.38033e-6 -0.000535927 1.06747];
    rho = [2.09244e-16 -7.65474e-13 1.12524e-9 -8.51881e-7 0.000353846 -0.0793459 8.72074];
    k = [-3.6206e-14 9.9793e-11 -1.13283e-7 0.000118727 -0.00171684];
    mu = [7.06e-6, 0.00001038, 0.00001336, 0.00001606, 0.0000172, 0.00001769, 0.00001853, 0.00001911, 0.00002002, 0.00002081, 0.00002177, 0.00002294, 0.00002682, 0.0000303, 0.00003349, 0.00003643, 0.00003918, 0.00004177];
    muT = [100, 150, 200, 250, 273, 283, 300, 313, 333, 350, 373, 400, 500, 600, 700, 800, 900, 1000];

case {'H2O'}
    cp = [4.0871e-10 -5.9806e-7 3.37478e-4 -8.56835e-2 1.23546e1];
\[
\rho = [-2.9681e-8 \ 4.91535e-5 \ -3.25219e-2 \ 9.18133 \\
8.21792e1];
\]
\[
k = [-2.98213e-11 \ 5.47109e-8 \ -4.25128e-5 \ 1.54729e-2 \ 1.44067];
\]
\[
\mu = [0.001791, 0.001308, 0.001003, 0.0007977, 0.0006531, 0.0005471, 0.0004668, 0.0004044, 0.0003549, 0.000315, 0.0002822, 0.0001961, 0.0001494, 0.000121, 0.0001015];
\]
\[
\muT = [273.16, 283.15, 293.15, 303.15, 313.15, 323.15, 333.15, 343.15, 353.15, 363.15, 373.15, 413.15, 453.15, 493.15, 533.15];
\]

```matlab
case 'Kerosene'
    cp = [0 2.01];
    rho = [0 820 ];
    k = [0 0.15];
    mu = [0.004077 0.003377 0.002797 0.002317 0.001919 0.001589 0.001316 0.00109 0.0009025 0.0009025 0.0009025 0.0009025 0.0009025 0.0009025 0.0009025 0.0009025 ];
    muT = [293 303 313 323 333 343 353 363 373 383 393 403 413 423 433 443 453 463 473 483];
```

```matlab
case 'R134a' % these values are exact numbers because we need to specify the exact number @ each internal energy value NOT in polynomials format
    cp = [1264 1293 1263 1262 1262; 1217 1290 1295 1294 1293;1171 1243 1322 1332 1331;1124 1197 1276 1364 1376;1078 1150 1229 1317 1418;1031 1104 1183 1271 1373;985.1 1057 1137 1225 1327;938.6 1011 1090 1179 1281;892.2 964.5 1044 1133 1235;845.8 918.1 997.7 1087 1190;799.4 871.6 951.3 1041 1144;769 825.2 905 994.5 1098;802.9 826 869 948.3 1052;842.3 857 882.4 925 995.9;881.1 891.6 909.3 937.9
```
\[ \rho = [1403 \ 1403 \ 1404 \ 1404 \ 1405; 36.99 \ 560 \ 1355 \ 1356 \ 1357; 18.73 \ 62.3 \ 555.2 \ 1306 \ 1307; 12.54 \ 32.99 \ 98.07 \ 639.8 \ 1254; 9.429 \ 22.43 \ 53.79 \ 146.1 \ 770.6; 7.553 \ 16.99 \ 37.05 \ 82.47 \ 208.3; 6.3 \ 13.68 \ 28.26 \ 75.45 \ 120.4; 5.403 \ 11.44 \ 22.84 \ 44.08 \ 84.68; 4.73 \ 9.838 \ 19.17 \ 35.76 \ 65.31; 4.206 \ 8.627 \ 16.51 \ 30.08 \ 53.14; 3.787 \ 7.682 \ 14.5 \ 25.95 \ 44.8; 3.413 \ 6.923 \ 12.93 \ 22.83 \ 38.72; 3.051 \ 6.196 \ 11.59 \ 20.37 \ 34.1; 2.777 \ 5.621 \ 10.46 \ 18.25 \ 30.33; 2.56 \ 5.171 \ 9.591 \ 16.64 \ 27.42; 2.383 \ 4.806 \ 8.893 \ 15.37 \ 25.18; 2.235 \ 4.504 \ 8.318 \ 14.34 \ 23.39; 2.109 \ 4.247 \ 7.834 \ 13.47 \ 21.92; 2.001 \ 4.026 \ 7.419 \ 12.74 \ 20.68; 1.906 \ 3.833 \ 7.058 \ 12.1 \ 19.61 ]; \\
\[ k = [0.1083 \ 0.1084 \ 0.1085 \ 0.1086; 0.09905 \ 0.1021 \ 0.1024 \ 0.1025 \ 0.1027; 0.08978 \ 0.0931 \ 0.09566 \ 0.09606 \ 0.09626; 0.0805 \ 0.08408 \ 0.08694 \ 0.089 \ 0.09444; 0.07123 \ 0.07506 \ 0.07822 \ 0.08062 \ 0.08216; 0.06195 \ 0.06605 \ 0.06951 \ 0.07224 \ 0.07416; 0.05268 \ 0.05703 \ 0.06079 \ 0.06386 \ 0.06615; 0.0434 \ 0.04801 \ 0.05207 \ 0.05548 \ 0.05815; 0.03412 \ 0.039 \ 0.04335 \ 0.0471 \ 0.05014; 0.02485 \ 0.02998 \ 0.03463 \ 0.03872 \ 0.04214; 0.01557 \ 0.02096 \ 0.02591 \ 0.03033 \ 0.03413; 0.009281 \ 0.01195 \ 0.01719 \ 0.02195 \ 0.02613; 0.01169 \ 0.01194 \ 0.01234 \ 0.01357 \ 0.01813; 0.01378 \ 0.01396 \ 0.01425 \ 0.01471 \ 0.01539; 0.01558 \ 0.01572 \ 0.01594 \ 0.0163 \ 0.01682; 0.01712 \ 0.01723 \ 0.01742 \ 0.0177 \ 0.01812; 0.01845 \ 0.01854 \ 0.01869 \ 0.01892 \ 0.01927; 0.01957 \ 0.01964 \ 0.01977 \ 0.01997 \ 0.02026; 0.02051 \ 0.02057 \ 0.02068 \ 0.02086 \ 0.02111; 0.02129 \ 0.02135 \ 0.02144 \ 0.02159 \ 0.02182 ]; \\
\[ \mu = [0.0004305 \ 0.0003462 \ 0.0004317 \ 0.0004328 \ 0.0004345; 0.0003913 \ 0.0003438 \ 0.0003411 \ 0.000342 \ 0.0003433; 0.0003522 \ 0.0003111 \ 0.0002797 \ 0.0002769 \ 0.000278; 0.000313 \ 0.0002784 \ 0.0002518 \ 0.0002305 \ 0.0002286; 0.0002738 \ 0.0002457 \ 0.0002239 \ 0.0002063 \ 0.0001915 ]; 

The following code is written to initialize the dimensions and size of the heat exchanger.

```matlab
function [parameter] = HXsize_v12(params, fluids, params2, material)
    params = [1, 1, 6.35, 0.1, 0.9, 0.83, 10, 6.35, 0.1, 0.9, 0.07]; % numbers from simulink model
    % disp (cp)
    % disp (rho)
    % disp(k)
    % disp(mu)
    % disp(muT)
end
```

The following code is written to initialize the dimensions and size of the heat exchanger.
params2 = [1, 1.5, 293, 360.3, 32, 1]; % numbers from simulink model
%HXsize(s1, h1, tf1, l1, t1, L, s2, h2, tf2, l2, t2) % %For Matlabs optimization toolbox.
%This function written by Peter Weise determines the weight and pressure
%drop of a compact heat exchanger based on its physical parameters and
%heat transfer characteristics. The methodology used is laid out in the
%book "Compact Heat Exchangers: Selection, Design, and Operation" by
J.E.
%Hesselgreaves. Also see "Compact Heat Exchangers" by Kays and London.
%%% Heat exchanger fixed parameters: The following parameters need to be
%%% fixed for a given optimization trial. However, they can be varied.
%%% For example, the heat load varies from one heat exchanger to another.
%%% Additionally, the fluids vary from one exchanger to another.
s1 = params(1)/1000; %
h1 = params(2)/1000; %
l1 = params(3)/1000; %
tf1 = params(4)/1000; %
t1 = params(5)/1000; %
s2 = params(6)/1000; % Only used for MATLAB optimization toolbox.
h2 = params(7)/1000; %
l2 = params(8)/1000; %
tf2 = params(9)/1000; %
t2 = params(10)/1000; %
L = params(11); %
fluids.ctype = get_param(gcb, 'ctype')
fluids.htype = get_param(gcb, 'htype')
fluid1 = fluids.ctype
fluid2 = fluids.htype
m_dot1 = params2(1);  %(kg/s) cold flow rate
m_dot2 = params2(2);  %(kg/s) hot flow rate
T_in1 = params2(3);  %(K) inlet temperature. In the actual T2T model, the inlet temperature will be based on downstream conditions and accepted as an input.
T_in2 = params2(4);  %(K) inlet temperature. See note above
Q_dot = params2(5);  %(kW) heat load
% set_param(gcb, 'mdot1', m_dot1);
% set_param(gcb, 'mdot2', m_dot2);
% set_param(gcb, 'Tin1', T_in1);
% set_param(gcb, 'Tin2', T_in2);
% set_param(gcb, 'load', Q_dot);
eta = 0.7;  %(N) fin efficiency
b1 = h1 + tf1;
b2 = h2 + tf2;
switch material
  case {'Stainless steel - 316'}
    rho_m = 8027;
  case {'Aluminum'}
    rho_m = 2707;
  case {'Copper'}
rho_m = 8954;

end

%% Solves for the properties of each fluid based on inlet temperatures, steady state outlet temperatures and fluid property correlations.

[f1.cp, f1.rho, f1.k, f1.mu, f1.muT] = fluidproperties(fluid1);
[f2.cp, f2.rho, f2.k, f2.mu, f2.muT] = fluidproperties(fluid2);
b = 500;  % pressure line
a = 300000;  % enthalpy

%%% Specific heat

\[
\text{cp1} = \text{polyval}(f1.cp,T\_in1);
\]

% \text{cp2} = \text{polyval}(f2.cp,T\_in2);

\[
\begin{align*}
X &= [66.19, 132.8, 243.5, 414.9, 665.8] \\
Y &= [6290, 27012, 47733, 89176, 109898, 130619, 151341, 172063, \\
& 192784, 213506, 234227, 254949, 275671, 296392, 317114, 337835, 358557, 379278, \\
& 400000] \\
Z\_cp &= [1264, 1293, 1263, 1262, 1262; 1217, 1290, 1295, 1294, 1293; 1171, 1243, 1322, 1332, 1331; 1124, 1197, 1276, 1364, 1376; 1078, 1150, 1229, 1317, 1418; 1031, 1104, 1183, 1271, 1373; 985.1, 1057, 1137, 1225, 1327; 938.6, 1011, 1090, 1179, 1281; 892.2, 964.5, 1044, 1133, 1235; 845.8, 918.1, 997.7, 1087, 1190; 799.4, 871.6, 951.3, 1041, 1144; 769, 825.2, 905, 994.5, 1098; 802.9, 826, 869, 948.3, 1052; 842.3, 857, 882.4, 925, 995.9; 881.1, 891.6, 909.3, 937.9, 982.8, 918.4, 926.2, 939.5, 960.5, 992.7; 954, 960.1, 970.3, 986.5, 1011, 987.8, 992.7, 1001, 1014, 1033, 1020, 1024, 1031, 1041, 1057, 1051, 1054, 1060, 1069, 1082].*1e\-03; \\
\text{cp2} &= \text{interp2}(X,Y,Z\_cp,b,a);
\]

%%% Density

\[
\text{rho1} = \text{polyval}(f1.rho,T\_in1);
\]

% \text{rho2} = \text{polyval}(f2.rho,T\_in2);
\[
Z_{\rho} = \begin{bmatrix}
1403 & 1403 & 1404 & 1404 & 1405 \\
36.99 & 560 & 1355 & 1356 & 1357 \\
18.73 & 62.3 & 555.2 & 1306 & 1307 \\
12.54 & 32.99 & 98.07 & 639.8 & 1254 \\
9.429 & 22.43 & 53.7 & 146.1 & 770.6 \\
7.553 & 16.99 & 37.05 & 82.47 & 208.3 \\
6.3 & 13.68 & 28.26 & 57.45 & 120.4 \\
5.403 & 11.44 & 22.84 & 44.08 & 84.68 \\
4.73 & 9.838 & 19.17 & 35.76 & 65.31 \\
4.206 & 8.627 & 16.51 & 30.08 & 53.14 \\
3.787 & 7.682 & 14.5 & 25.95 & 44.8 \\
3.413 & 6.923 & 12.93 & 22.83 & 38.72 \\
2.383 & 4.806 & 8.893 & 15.37 & 25.18 \\
2.001 & 4.026 & 7.419 & 12.74 & 20.68 \\
1.906 & 3.833 & 7.058 & 12.1 & 19.61 \\
\end{bmatrix}
\]

\[
\rho_2 = \text{interp2}(X,Y,Z_{\rho},b,a);
\]

%%% Thermal Conductivity

\[
k_1 = \text{polyval}(f1.k,T_{in1});
\]

% k2 = polyval(f2.k,T_{in2});

\[
Z_{k} = \begin{bmatrix}
0.1083 & 0.1084 & 0.1085 & 0.1087 & 0.09905 & 0.1021 & 0.1024 \\
0.1025 & 0.1027 & 0.08978 & 0.0931 & 0.09566 & 0.09606 & 0.09626 & 0.0805 & 0.08408 \\
0.08694 & 0.089 & 0.08944 & 0.07123 & 0.07506 & 0.07822 & 0.08062 & 0.08216 & 0.06195 \\
0.06605 & 0.06951 & 0.07224 & 0.07416 & 0.05268 & 0.05703 & 0.06079 & 0.06386 \\
0.06615 & 0.0434 & 0.04801 & 0.05207 & 0.05548 & 0.05815 & 0.03412 & 0.039 & 0.04335 \\
0.0471 & 0.05014 & 0.02485 & 0.02998 & 0.03463 & 0.03872 & 0.04214 & 0.01557 \\
0.02096 & 0.02591 & 0.03033 & 0.03413 & 0.009281 & 0.01195 & 0.01719 & 0.02195 \\
0.02613 & 0.01169 & 0.01194 & 0.01234 & 0.01357 & 0.01813 & 0.01378 & 0.01396 \\
0.01425 & 0.01471 & 0.01539 & 0.01558 & 0.01572 & 0.01594 & 0.0163 & 0.01682 \\
0.01712 & 0.01723 & 0.01742 & 0.0177 & 0.01812 & 0.01845 & 0.01854 & 0.01869 & 0.01892 \\
0.01927 & 0.01957 & 0.01964 & 0.01977 & 0.01997 & 0.02026 & 0.02051 & 0.02057 \\
0.02068 & 0.02086 & 0.02111 & 0.02129 & 0.02135 & 0.02144 & 0.02159 & 0.02182 \\
\end{bmatrix}
\]

\[
k_2 = \text{interp2}(X,Y,Z_k,b,a);
\]

%%% Approximate outlet temperature

\[
T_{out1} = T_{in1} + Q_{dot}/(m_{dot1}\cdot cp1);
\]

\[
T_{out2} = T_{in2} - Q_{dot}/(m_{dot2}\cdot cp2);
\]
%%% Dynamic Viscosity

\[
\begin{align*}
\mu_1 &= \text{interp1}(f1.muT, f1.mu, (T_{in1}+T_{out1})/2); \\
\mu_2 &= \text{interp1}(f2.muT, f2.mu, (T_{in2}+T_{out2})/2); \\
Z_{\mu} &= \begin{bmatrix}
0.0004305 & 0.0003462 & 0.0004317 & 0.0004328 \\
0.0004345 & 0.0003913 & 0.0003411 & 0.000342 & 0.0003432 & 0.0003433 & 0.0003522 \\
0.0003111 & 0.0002797 & 0.0002769 & 0.000278 & 0.0002784 & 0.0002518 \\
0.0002305 & 0.0002286 & 0.0002257 & 0.0002239 & 0.0002318 & 0.0001915 \\
0.0002347 & 0.0002129 & 0.000196 & 0.0001821 & 0.0001703 & 0.0001955 & 0.0001802 \\
0.0001681 & 0.0001579 & 0.000149 & 0.0001564 & 0.0001475 & 0.0001402 & 0.0001337 \\
0.0001277 & 0.0001172 & 0.0001148 & 0.0001123 & 0.0001095 & 0.0001065 & 0.00007803 \\
0.00008212 & 0.00008439 & 0.00008534 & 0.00008522 & 0.00003887 & 0.00004941 \\
0.00005649 & 0.00006114 & 0.00006396 & 0.000009796 & 0.00001671 & 0.00002859 \\
0.00003695 & 0.00004269 & 0.00001082 & 0.0000109 & 0.00001104 & 0.00001275 \\
0.00002143 & 0.00001179 & 0.00001185 & 0.00001196 & 0.00001212 \\
0.00001239 & 0.00001271 & 0.00001276 & 0.00001284 & 0.00001297 \\
0.00001318 & 0.00001359 & 0.00001363 & 0.00001369 & 0.0000138 \\
0.00001398 & 0.00001442 & 0.00001446 & 0.00001451 & 0.00001461 \\
0.00001476 & 0.00001522 & 0.00001525 & 0.0000153 & 0.00001539 \\
0.00001552 & 0.00001599 & 0.00001602 & 0.00001607 & 0.00001614 \\
0.00001626 & 0.00001674 & 0.00001676 & 0.0000168 & 0.00001687 & 0.00001698 \\
\end{bmatrix}; \\
\mu_2 &= \text{interp2}(X, Y, Z_{\mu}, b, a); \\
\end{align*}
\]

%%% Calculate important heat exchanger physical parameters

\[
\begin{align*}
\text{parameter.dh1} &= (4*s1*h1*l1)/(2*(s1*l1+h1*l1+tf1*h1)+tf1*s1); \\
\text{parameter.dh2} &= (4*s2*h2*l2)/(2*(s2*l2+h2*l2+tf2*h2)+tf2*s2); \\
\sigma_1 &= s1*(b1-tf1)/(s1+tf1)/(b1+t1); \quad \text{%porosity of side 1} \\
\sigma_2 &= s2*(b2-tf2)/(s2+tf2)/(b2+t2); \quad \text{%porosity of side 2} \\
\alpha_1 &= s1/h1; \quad \text{%various aspect ratios used in calculating j and f} \\
\delta_1 &= tf1/l1; \\
\gamma_1 &= tf1/s1; \\
\end{align*}
\]
alpha2=s2/h2;
delta2=tf2/l2;
gamma2=tf2/s2;

%%% Initialize Ac1 and Ac2. Correct values will be solved for in an
%%% iterative process.
parameter.Ac1_opt = 0.01;
parameter.Ac2_opt = 0.01;
difference1 = inf;
difference2= inf;
count = 0;

%%% This iterative while loop solves for Ac1 and Ac2.
if params2(6)>0.5

    while count<=100 && abs(difference1)>=1e-5 &&
abs(difference2)>=1e-5

        %%% parameter. Reynolds' number
        Re1=m_dot1*parameter.dh1/mu1/parameter.Ac1_opt;
        Re2=m_dot2*parameter.dh2/mu2/parameter.Ac2_opt;

        %%% Fanning friction factor
        parameter.f1=9.6243*(Re1^(-0.7422))*(alpha1^-
0.1856)*(delta1^0.3053)*(gamma1^0.2659)*((1+7.669E-
8*(Re1^4.429)*(alpha1^0.92)*(delta1^3.767)*(gamma1^0.236))^0.1);
        parameter.f2=9.6243*(Re2^(-0.7422))*(alpha2^-
0.1856)*(delta2^0.3053)*(gamma2^0.2659)*((1+7.669E-
8*(Re2^4.429)*(alpha2^0.92)*(delta2^3.767)*(gamma2^0.236))^0.1);

        %%% Colburn coefficient
        j1=0.6522*(Re1^-0.5403)*(alpha1^-0.1541)*(delta1^-
0.1409)*(gamma1^-0.0678)*((1+5.269E-
5*(Re1^1.34)*(alpha1^0.504)*(delta1^0.456)*(gamma1^-1.055))^0.1);
\[
\begin{align*}
    j_2 &= 0.6522 \times (Re_2^{-0.5403} \times (\alpha_2^{0.1541} \times (\delta_2^{0.1409} \times (\gamma_2^{0.0678} \times ((1 + 5.269E^{-5} \times (Re_2^{1.34} \times (\alpha_2^{0.504} \times (\delta_2^{0.456} \times (\gamma_2^{1.055}))^{0.1})
    
\text{%%% Effectiveness-Ntu method}

    T_{h1} &= \max(T_{in1}, T_{in2}); \\
    T_{c1} &= \min(T_{in1}, T_{in2}); \\
    C_{max} &= \max(m_{dot1} \times cp1, m_{dot2} \times cp2); \\
    C_{min} &= \min(m_{dot1} \times cp1, m_{dot2} \times cp2); \\
    C_{star} &= C_{min}/C_{max}; \\
    \epsilon &= \frac{Q_{dot}}{C_{min} \times (T_{h1} - T_{c1})}; \\
    \text{if } 0 \geq \epsilon || \epsilon > 1 \\
    \text{disp('epsilon must be between 0 and 1. Heat load (Q_{dot}) is too large or T_{h1}-T_{c1} is too small')} \\
    \text{break}
\end{align*}
\]

\[
\text{if } 0.99 \leq C_{star} \leq 1.01 \\
    N_{tu} &= \frac{\epsilon}{1 - \epsilon}; \\
\text{else} \\
    N_{tu} &= \frac{\log((\epsilon - 1)/(C_{star} \times \epsilon - 1))}{(C_{star} - 1)};
\end{align*}
\]

\[
N &= 2 \times N_{tu}/\eta;
\]

\text{%%% Pressure drop}

\[
\begin{align*}
    \text{parameter.del}_P_1 &= \left(\frac{(m_{dot1}/\text{parameter.Ac1_opt})^{2} \times 4 \times L \times \text{parameter.f1}}{2 \times \rho_{1}}\right) / \text{parameter.dh1}; \\
    \text{parameter.del}_P_2 &= \left(\frac{(m_{dot2}/\text{parameter.Ac2_opt})^{2} \times 4 \times L \times \text{parameter.f2}}{2 \times \rho_{2}}\right) / \text{parameter.dh2};
\end{align*}
\]

\text{%%% Prandtl number}

\[
\begin{align*}
    Pr_1 &= \frac{cp_1 \times \mu_1}{k_1} \times 1000; \\
    Pr_2 &= \frac{cp_2 \times \mu_2}{k_2} \times 1000;
\end{align*}
\]
%%% Flow velocity
G1 = sqrt(2*rho1*parameter.del_P1*j1/parameter.f1/(Pr1^(2/3))/N);
G2 = sqrt(2*rho2*parameter.del_P2*j2/parameter.f2/(Pr2^(2/3))/N);

%%% Flow area
Ac1_0 = m_dot1/G1;
Ac2_0 = m_dot2/G2;
difference1 = parameter.Ac1_opt - Ac1_0;
difference2 = parameter.Ac2_opt - Ac2_0;
parameter.Ac1_opt = Ac1_0;
parameter.Ac2_opt = Ac2_0;
count = count + 1;

end

%parameter.Ac1_opt=parameter.Ac1;
%parameter.Ac2_opt=parameter.Ac2;
else
parameter.Ac1_opt = str2num(get_param(gcb,'Ac1_opt'));
parameter.Ac2_opt = str2num(get_param(gcb,'Ac2_opt'));
end

parameter.Ac1 = parameter.Ac1_opt;
parameter.Ac2 = parameter.Ac2_opt;
parameter.Ac1;
parameter.Ac2;

%disp('iterations =')
%disp(count)

%%% Calculate volume and Weight
parameter.weight_kg = rho_m*L*(parameter.Ac1/sigma1*(1-sigma1)+parameter.Ac2/sigma2*(1-sigma2));

parameter.weight_f1 = (parameter.Ac1*rhol*L);
parameter.weight_f2 = parameter.Ac2*rho2*L;
parameter.vol_HX = L*(parameter.Ac1/sigma1*(1-sigma1)+parameter.Ac2/sigma2*(1-sigma2));

parameter.vol_f = (parameter.Ac1+parameter.Ac2)*L;

Beta = [4*sigma1/parameter.dh1 4*sigma2/parameter.dh2];

parameter.vol1 = L*parameter.Ac1;

parameter.vol2 = L*parameter.Ac2;

parameter.Asl = Beta(1) * (L*(parameter.Ac1/sigma1*(1-sigma1)) + parameter.Ac1);

parameter.As2 = Beta(2) * (L*(parameter.Ac2/sigma2*(1-sigma2)) + parameter.Ac2);

parameter.L = L;

%%% Additional outputs,

parameter.ratios1 = [alpha1 delta1 gamma1];

parameter.ratios2 = [alpha2 delta2 gamma2];

parameter.Achx = (sqrt(parameter.Ac1) + sqrt(parameter.Ac2))/2*parameter.L;

parameter.Aht1 = parameter.Ac1*(s1 + tf1)/(s1*h1)*L;

parameter.Aht2 = parameter.Ac2*(s2 + tf2)/(s2*h2)*L;

% Feb 7, 2017

Third, the next code is written to export and feed the Simulink model.

number = str2num(get_param(gcb,'number'));

cctype = get_param(gcb,'cctype');

%%%%%%%%%%%%%%%% START COLD FLUID PROPERTIES

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%% Get parameters,

%ctype = input (' get the cold flow  ')

%ctype = get_param(gcb,'ctype');

R_c = '0';
check_c = '0'; % 1=incompressible, 2= ideal Gas, 3= real Gas, 4= 2-phase

%%% Fluid properties,

% Specific heat, J/kg/K [in polyval() form]
% Density, kg/m^3 [in polyval() form]
% Thermal conductivity, W/m/K [in polyval() form]
% Dynamic viscosity, kg/m/s [in interp1() form]
% Temperatures for mu, K [in interp1() form]

switch ctype
    case {'PAO'}
        cp = '^[3.7749e-3 1.02255]*1000';
        rho = '^[1.5859e-8 -2.6056e-5 1.4797e-2 -4.37867 1346.36]';
        k = '^[1.9058e-21, -5.882e-05, 0.1541]';
        mu = '^[0.90889, 0.11814, 0.030046, 0.011483, 0.0056626,
            0.003295, 0.0021441, 0.0015094, 0.0011254, 0.0008761, 0.0008275,
            0.00001]';
        muT = '^[220, 240, 260, 280, 300, 320, 340, 360, 380, 400,
            405, 1000]';
    case {'JP8'}
        cp = '^[4.43359e-3 6.48908e-1]*1000';
        rho = '^[7.23225e-1 1.02036]';
        k = '^[1.799e-4 1.67663e-1]';
        mu = '^[0.0137298, 0.00807381, 0.00515649, 0.00360287,
            0.00265331, 0.00205681, 0.00162952, 0.00131464, 0.00109445,
            0.000937041, 0.000804244, 0.000701833, 0.000617844, 0.000543122,
            0.000485191, 0.000435239, 0.000388231, 0.000353682, 0.000321021,
            0.000295718, .00001]';
end

case {'AIR'}
    cp = '[2.80023e-13 -1.0498e-9 1.38033e-6 -0.000535927 1.06747].*1000';
    rho = '[2.09244e-16 -7.65474e-13 1.12524e-9 -8.51881e-7 0.000353846 -0.0793459 8.72074]';
    k = '[-3.6206e-14 9.9793e-11 1.3283e-7 -0.000118727 -0.00171684]';
    mu = '[7.06e-6, 0.00001038, 0.00001336, 0.00001606, 0.0000172, 0.00001769, 0.00001853, 0.00001911, 0.0000172, 0.00002177, 0.00002294, 0.0000303, 0.00003349, 0.00003643, 0.00003918, 0.00004177]';
    muT = '[100, 150, 200, 250, 273, 283, 300, 313, 333, 350, 373, 400, 500, 600, 700, 800, 900, 1000]';
    R_c = '287';
    check_c = '1';
end

case {'H2O'}
    cp = '[4.0871e-10 -5.9806e-7 3.37478e-4 -8.56835e-2 1.23546e1].*1000';
    rho = '[-2.9681e-8 4.91535e-5 -3.25219e-2 9.18133 8.21792e1]';
    k = '[-2.98213e-11 5.47109e-8 4-2.5128e-5 1.54729e-2 -1.44067]';
    mu = '[0.001791, 0.001308, 0.001003, 0.0007977, 0.0006531, 0.0005471, 0.0004668, 0.0004044, 0.0003549, 0.000315, 0.0002822, 0.0001961, 0.0001494, 0.000121, 0.0001015, .0001]';
muT = '[273.16, 283.15, 293.15, 303.15, 313.15, 323.15,'\n       333.15, 343.15, 353.15, 363.15, 373.15, 413.15, 453.15, 493.15, 533.15,'\n       1000]';

    case {'Kerosene'}
        cp = '[0 2010]';
        rho = '[0 820 ]';
        k = '[0 0.15]';
        mu = '[0.004077 0.003377 0.002797 0.002317 0.001919 0.001589 0.001316 0.00109 0.0009025 0.0009025 0.0009025 0.0009025 0.0009025 0.0009025 0.0009025 0.0009025 0.0009025 0.0009025 0.0009025 0.0009025 0.0009025 0.0009025 0.0009025 0.0009025 0.0009025 0.0009025]';
        muT = '[293 303 313 323 333 343 353 363 373 383 393 403 413 423 433 443 453 463 473 483]';
    end

%%%% Calculate enthalpy, J/kg
    icp = [str2num(cp)./(length(str2num(cp)):-1:1), 0];
%%%% For polyval,
    hin = strcat('[' ,num2str(icp), ']');

%%%% Calculate entropy J/kg-K
    cp1 = str2num(cp);
    n=length(cp1);
    if n==1
        coef_s = [0 cp1];
    else
        kk = (n-1):-1:1;
        coef_s = [cp1(1:(n-1))./kk 0 cp1(n)];
    end
    s_a = ['[', num2str(coef_s(1:(end-1))), ',']];
    s_end  = num2str(coef_s(end));
%% Make coefficients available to masked subsystem

set_param(gcb, 'rho_c', rho);
set_param(gcb, 'enthalpy_c', hin);
set_param(gcb, 'cp_c', cp);
set_param(gcb, 'mu_Input_c', muT);
set_param(gcb, 'mu_Output_c', mu);
set_param(gcb, 'k_c', k);
set_param(gcb, 'entropy_c', s_a);
set_param(gcb, 'entropy_end_c', s_end);
set_param(gcb, 'R_c', R_c);
set_param(gcb, 'fluid_check_c', check_c);

END COLD FLUID PROPERTIES

% Get parameters,
htype = get_param(gcb, 'htype');
R_h = '0';
check_h = '0';

% Fluid properties,

% Specific heat, J/kg/K     [in polyval() form]
% Density, kg/m^3          [in polyval() form]
% Thermal conductivity, W/m/K [in polyval() form]
% Dynamic viscosity, kg/m/s [in interp1() form]
% Temperatures for mu, K   [in interp1() form]

switch htype
    case {'PAO'}
        cp = '[3.7749e-3 1.02255].*1000';
        rho = '[1.5859e-8 -2.6056e-5 1.4797e-2 -4.37867 1346.36]';
k = '[1.9058e-21, -5.882e-05, 0.1541]';
mu = '[0.90889, 0.11814, 0.030046, 0.011483, 0.0056626, 0.003295, 0.0021441, 0.0015094, 0.0011254, 0.0008761, 0.0008275, 0.00001]';
muT = '[220, 240, 260, 280, 300, 320, 340, 360, 380, 400, 405, 1000]';
case {'JP8'}
  cp = '[-4.43359e-3 6.48908e-1].*1000';
  rho = '[-7.23225e-1 1.02036e3]';
  k = '[-1.799e-4 1.67663e-1]';
  mu = '[0.0137298, 0.00807381, 0.00515649, 0.00360287, 0.00265331, 0.00205681, 0.00162952, 0.00131464, 0.00109445, 0.000937041, 0.000485191, 0.000435239, 0.000388231, 0.000353682, 0.000321021, 0.000295718, .00001]';
case {'AIR'}
  cp = '[-2.80023e-13 -1.0498e-9 1.38033e-6 -0.000535927 1.06747].*1000';
  rho = '[-2.09244e-16 -7.65474e-13 1.12524e-9 -8.51881e-7 0.000353846 -0.0793459 8.72074]';
  k = '[-3.6206e-14 9.9793e-11 -1.13283e-7 0.000118727 -0.00171684]';
  mu = '[7.06e-6, 0.00001038, 0.00001336, 0.00001606, 0.0000172, 0.00001769, 0.00001853, 0.00001911, 0.00002002, 0.00002081, 0.00002177, 0.00002294, 0.00002682, 0.0000303, 0.00003349, 0.00003643, 0.00003918, 0.00004177]';
muT = '[100, 150, 200, 250, 273, 283, 300, 313, 333, 350, 373, 400, 500, 600, 700, 800, 900, 1000]';
R_h = '287';
check_h = '1';
case {'H2O'}
    cp = '[4.0871e-10 -5.9806e-7 3.37478e-4 -8.56835e-2 1.23546e1].*1000';
    rho = '[-2.9681e-8 4.91535e-5 -3.2519e-2 9.18133 8.21792e1]';
    k = '[-2.98213e-11 5.47109e-8 -4.25219e-5 1.54729e-2 1.44067]';
    mu = ' [0.001791, 0.001308, 0.001003, 0.0007977, 0.0006531, 0.0005471, 0.0004668, 0.0004044, 0.0003549, 0.000315, 0.0002822, 0.0001961, 0.0001494, 0.0001211, 0.0001015, 0.0000811]';
    muT = '[273.16, 283.15, 293.15, 303.15, 313.15, 323.15, 333.15, 343.15, 353.15, 363.15, 373.15, 413.15, 453.15, 493.15, 533.15, 1000]';
case {'R134a'}
    % These values are exact numbers because we need to specify the exact number @ each internal energy value NOT in polynomials format
    cp = '[1264 1293 1263 1262 1262; 1217 1290 1295 1294 1293; 1172 1243 1322 1332 1331; 1124 1197 1276 1364 1376; 1078 1150 1229 1317 1418; 1031 1104 1183 1271 1373; 985.1 1057 1137 1225 1327; 938.6 1011 1093 1176 1279; 892.2 964.5 1044 1133 1235; 845.8 918.1 997.7 1087 1169; 799.4 871.1 951.3 1014 1144; 769 825.2 905 958.3 1098; 802.9 826 869 948.1 952.2 842.3 857 882.4 925 995.9; 881.1 891.6 909.3 937.9 982.1 918.4 926.2 939.5 960.5 992.7; 954 960.1 970.3 986.5 1011; 987.8 992.7 1001 1014 1033; 1020 1024 1031 1041 1057; 1051 1054 1060 1069 1082]';

\[ k = \begin{bmatrix} 0.1083 & 0.1084 & 0.1084 & 0.1085 & 0.1087; 0.09905 & 0.1021 \\ 0.1024 & 0.1025 & 0.1027; 0.08978 & 0.0931 & 0.09566 & 0.09606 & 0.09626; 0.0805 \\ 0.08408 & 0.08694 & 0.089 & 0.08944; 0.07123 & 0.07506 & 0.07822 & 0.08062 & 0.08216; 0.06195 & 0.06605 & 0.06951 & 0.07224 & 0.07416; 0.05268 & 0.05703 & 0.06079 \\ 0.06386 & 0.06615; 0.0434 & 0.04801 & 0.05207 & 0.05548 & 0.05815; 0.03412 & 0.039 \\ 0.04335 & 0.0471 & 0.05014; 0.02485 & 0.02998 & 0.03463 & 0.03872 & 0.04214; 0.01557 & 0.02096 & 0.02591 & 0.03033 & 0.03413; 0.009281 & 0.01195 & 0.01719 \\ 0.02195 & 0.02613; 0.01169 & 0.01194 & 0.01234 & 0.01357 & 0.01813; 0.01378 \\ 0.01396 & 0.01425 & 0.01471 & 0.01539; 0.01558 & 0.01572 & 0.01594 & 0.0163 \\ 0.01682; 0.01712 & 0.01723 & 0.01742 & 0.0177 & 0.01812; 0.01845 & 0.01854 \\ 0.01869 & 0.01892 & 0.01927; 0.01957 & 0.01964 & 0.01977 & 0.01997 & 0.02026; 0.02051 & 0.02057 & 0.02068 & 0.02086 & 0.02111; 0.02129 & 0.02135 & 0.02144 \\ 0.02159 & 0.02182 \end{bmatrix}; \\

\mu = \begin{bmatrix} 0.0004305 & 0.0003462 & 0.0003417 & 0.0004328 \\ 0.0004345; 0.0003913 & 0.0003438 & 0.0003411 & 0.000342 & 0.0003433; 0.0003522 \\ 0.0003111 & 0.0002797 & 0.0002769 & 0.000278; 0.000313 & 0.0002784 & 0.0002518 \\ 0.0002305 & 0.0002286; 0.0002738 & 0.0002457 & 0.0002239 & 0.0002063 & 0.0001915; 0.0002347 & 0.0002129 & 0.000196 & 0.0001821; 0.0001703; 0.0001955 & 0.0001802 \\ 0.0001681 & 0.0001579 & 0.000149; 0.0001564 & 0.0001475 & 0.0001402 & 0.0001337 \\ 0.0001277; 0.0001172 & 0.0001148 & 0.0001123 & 0.0001095 & 0.0001065; 0.00007803 \\ 87
\[
\begin{align*}
&0.00008212 0.00008439 0.00008534 0.00008522;0.00003887 0.00004941 \\
&0.00005649 0.00006114 0.00006396;0.00009796 0.00001671 0.00002859 \\
&0.00003695 0.00004269;0.00001082 0.0000109 0.00001104 0.00001275 \\
&0.00002143;0.00001179 0.00001185 0.00001196 0.00001212 \\
&0.00001239;0.00001271 0.00001276 0.00001284 0.00001297 \\
&0.00001318;0.00001359 0.00001363 0.00001369 0.0000138 \\
&0.00001398;0.00001442 0.00001446 0.00001451 0.00001461 \\
&0.00001476;0.00001522 0.00001525 0.0000153 0.00001539 \\
&0.00001552;0.00001599 0.00001602 0.00001607 0.00001614 \\
&0.00001626;0.00001674 0.00001676 0.0000168 0.00001687 0.00001698]' \\
\mu_T = [6290 27012 47733 68455 89176 109898 130619 151341 \\
172063 192784 213506 234227 254949 275671 296392 317114 337835 358557 \\
379278 400000]' \\
\text{check}_h = '2';
\end{align*}
\]

end

%%% Calculate entropy J/kg-K
cp1 = str2num(cp);
n=length(cp1);
if n==1
 coef_s = [0 cp1];
else
 kk = (n-1):-1:1;
 coef_s = [cp1(1:(n-1))./kk 0 cp1(n)];
end
s_a = ['[', num2str(coef_s(1:(end-1))), ',']'];
s_end = num2str(coef_s(end));

%%% Calculate enthalpy, J/kg
if check_h == 0 || check_h == 1
 icp = [str2num(cp)./(length(str2num(cp)):-1:1), 0];
\]
% For polyval,
hin = strcat('[',num2str(icp),']');

%%% Fluid properties for hot_balance,
set_param(gcb, 'rho_h', rho);
set_param(gcb, 'enthalpy_h', hin);
set_param(gcb, 'cp_h', cp);
set_param(gcb, 'mu_Input_h', muT);
set_param(gcb, 'mu_Output_h', mu);
set_param(gcb, 'k_h', k);

% set_param(gcb, 'entropy_h', s_a);

% set_param(gcb, 'entropy_end_h', s_end);
set_param(gcb, 'R_h',R_h);
set_param(gcb, 'fluid_check_h', check_h);

else
    RG_cp = cp ;
    RG_rh = rho ;
    RG_k = k ;
    RG_mu = mu ;
    RG_muT = muT ;

    set_param(gcb, 'RG_rho_h', RG_rh);

    % set_param(gcb, 'enthalpy_h', hin);
    set_param(gcb, 'RG_cp_h',RG_cp);
    set_param(gcb, 'RG_mu_Input_h', RG_muT);
    set_param(gcb, 'RG_mu_Output_h', RG_mu);
    set_param(gcb, 'RG_k_h', RG_k);
    % set_param(gcb, 'entropy_h', s_a);
    % set_param(gcb, 'entropy_end_h', s_end);
    set_param(gcb, 'RG_R_h',R_h);
    set_param(gcb, 'RG_fluid_check_h', check_h);

end
end

%%%%%%%%%%%%%%%%%% END HOT FLUID PROPERTIES
%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%% START HX MATERIAL PROPERTIES
%%%%%%%%%%%%%%%%%%

%%% Get parameters,
material = get_param(gcb,'material');
%material = get_param(gcb,'material');

%%% Material properties,
% Specific heat, J/kg/K
% Density, kg/m^3
% Thermal conductivity, W/m/K
switch material
    case {'Stainless steel - 316'}
        cp = '502';
        rho = '8027';
        k = '16.26';
    case {'Aluminum'}
        cp = '896';
        rho = '2707';
        k = '220';
    case {'Copper'}
        cp = '380';
        rho = '8954';
        k = '386';
end

%%% HX parameters,
set_param(gcb, 'cp_m', cp);
set_param(gcb, 'rho_m', rho);
set_param(gcb, 'k_m', k);

%%%%%%%%%%%%%%%%%%%%%%%% END HX MATERIAL PROPERTIES
%%%%%%%%%%%%%%%%%%%%%%%%

%%% Import geometry,
cgeo = str2num(get_param(gcb, 'cgeo'));
hgeo = str2num(get_param(gcb, 'hgeo'));
length1 = str2num(get_param(gcb, 'length'));
vec = [cgeo hgeo length1];

cctype = get_param(gcb, 'ctype');
htype = get_param(gcb, 'htype');
fluids.ctype = ctype;
fluids.htype = htype;

mdot1 = evalin('base', get_param(gcb, 'mdot1'));
mdot2 = str2num(get_param(gcb, 'mdot2'));
Tin1  = str2num(get_param(gcb, 'Tin1'));
Tin2  = str2num(get_param(gcb, 'Tin2'));
Q_load  = str2num(get_param(gcb, 'load'));
optimize = strcmp(get_param(gcb, 'optimize'), 'on');
vec2 = [mdot1 mdot2 Tin1 Tin2 Q_load optimize];

hx = HXsize_v2(vec, fluids, vec2, material);
if optimize > 0.5
    Ac1_opt = num2str(hx.Ac1_opt);
    Ac2_opt = num2str(hx.Ac2_opt);
set_param(gcb, 'Ac1_opt', Ac1_opt);
set_param(gcb, 'Ac2_opt', Ac2_opt);
end

%%% Volume of fluid, m^3
volume_c = num2str(hx.vol1);
volume_h = num2str(hx.vol2);
volume_tot = num2str(hx.vol_HX);
set_param(gcb, 'volume_c', volume_c);
set_param(gcb, 'volume_h', volume_h);
set_param(gcb, 'hx_total_volume', volume_tot);

%%% Surface area, m^2
surf_area_c = hx.As1;
surf_area_h = hx.As2;
nooverall = 0.9;
dummy1 = num2str(surf_area_c*nooverall/number);
dummy2 = num2str(surf_area_h*nooverall/number);
set_param(gcb, 'noAs_c', dummy1);
set_param(gcb, 'noAs_h', dummy2);

%%% Channel length, m
length1 = linspace(0,length1,number+1);
length1 = length1(2:end);
set_param(gcb, 'spacing', mat2str(length1));

%%% Free flow area, m^2
freeflow_c = num2str(hx.Ac1);
freeflow_h = num2str(hx.Ac2);
set_param(gcb, 'freeflow_c', freeflow_c);
set_param(gcb, 'freeflow_h', freeflow_h);

%%% Hydraulic diameter, m
Dh_c = num2str(hx.dh1);
Dh_h = num2str(hx.dh2);
set_param(gcb, 'Dh_c', Dh_c);
set_param(gcb, 'Dh_h', Dh_h);

%%% Geometric channel dimension ratios,
ratio_c = hx.ratios1;
% set_param(gcb, 'alpha_c', num2str(ratio_c(1)));
% set_param(gcb, 'delta_c', num2str(ratio_c(2)));
% set_param(gcb, 'gamma_c', num2str(ratio_c(3)));
ratio_h = hx.ratios2;
% set_param(gcb, 'alpha_h', num2str(ratio_h(1)));
% set_param(gcb, 'delta_h', num2str(ratio_h(2)));
% set_param(gcb, 'gamma_h', num2str(ratio_h(3)));

%%% Heat exchanger mass, kg
mass = hx.weight_kg;

% set_param(gcb, 'hx_total_mass', num2str(mass));
% set_param(gcb, 'hx_CV_mass', num2str(mass/number));

%%% Heat exchanger area / thickness, m
Aht = (hx.Aht1 + hx.Aht2)/2;
t = (cgeo(5) + hgeo(5))/2/1000;
set_param(gcb, 'Aht_t', num2str(Aht/t));

%%% Clear workspace,
clear cytpe cp rho k mu muT icp hin cpl n s_a s_end htype material
clear cgeo hgeo length1 vec fluids mdot1 mdot2 Tin1 Tin2 Q_load
vec2
clear number hx volume_c volume_h surf_area_c surf_area_h noverall
clear dummy1 dummy2 freeflow_c freeflow_h Dh_c Dh_h ratio_c ratio_h
clear mass Aht t Ac1_opt Ac2_opt
% Feb 7, 2017
Finally, this code is specialized to plot results versus time.

% Fin plate Heat Exchanger plots

ti = 3; % Start time

whichElements = ti/SampleTime:1:length(time); % Which elements of the
arrays to plot

timeUnit = 'Sec'; % Unit for time axis

timeInterval = 1; % Divisor for time axis

theTime = (time(whichElements) - ti)/timeScale; % The scaled time array

xLimits = [0, theTime(end)]; % The limits for time axis

RShift = 459.67; % Difference of Rankin and Fahrenheit

K2R = 9/5; % Conversion fr

lbm2kg = 0.4536; % Conversion from lbm to kg

kPa2psi = 14.7/101.325; % Conversion from kPa to psi

% Set plotting defaults.

set(0,'DefaultFigureWindowStyle','docked'); % Undock all figures.

set(0,'DefaultFigureColor','w'); % Set default figure background color.

set(0,'DefaultLineWidth',4); % Set default line size.

set(0,'DefaultAxesFontSize',20); % Set default axes font size.

set(0,'DefaultTextFontSize',20); % Set default text font size.

set(0,'DefaultLineMarkerSize',12); % Set default marker size.

set(0,'DefaultAxesFontWeight','bold'); % Set the default axes font to
bold.

set(0,'DefaultTextFontWeight','bold'); % Set the default text font to
bold..

set(0,'DefaultAxesColorOrder',[0 0 0;0 0 0;0 0 1])

figure('Name','Pressure')

plot(theTime,Pressure(whichElements))
ylabel('Pressure [ kpa]');
xlabel(['Time [' timeUnit ']']);
xlim(xLimits);
title (' Pressure vs.time ')
grid on

figure('Name','Enthalpy')
plot(theTime,ENTHALPY(whichElements))
ylabel('Enthalpy [ kJ/kg]');
xlabel(['Time [' timeUnit ']']);
xlim(xLimits);
title (' Enthalpy vs.time ')
grid on

figure('Name','Kerosene Temperature')
plot(theTime,KerTempOut(whichElements))
ylabel('Temperature [\textcircled{K}]');
xlabel(['Time [' timeUnit ']']);
xlim(xLimits);
title (' KerTempOut vs.time ') grid on

figure('Name','R134a Temperature ')
plot(theTime,RefTempOut(whichElements))
ylabel('Temperature [\textcircled{K}]');
xlabel(['Time [' timeUnit ']']);
xlim(xLimits);
title (' RefTempOut vs.time ') grid on
```matlab
%%
figure('Name','Heat exchanger temperature')
plot(theTime,Thx(whichElements))
ylabel('Heat exchanger temperature [\circ K]');
xlabel(['Time [' timeUnit ']']);
xlim(xLimits);
title ('Heat exchanger temperature vs.time ')
grid on
%%
figure('Name','kerosene heat transfer coefficient')
plot(theTime,KerHeatCoef(whichElements))
ylabel('h_c [w/m^2-k]');
xlabel(['Time [' timeUnit ']']);
xlim(xLimits);
title ('kerosene heat transfer coefficient vs.time ')
grid on
%%
figure ('Name', 'Two phase flow heat transfer coefficient')
plot (theTime, h (whichElements))
ylabel('h_TP [w/m^2-k]');
xlabel(['Time [' timeUnit ']']);
xlim(xLimits);
title ('Two phase flow heat transfer coefficient vs. time ')
grid on
%%
figure('Name','X')
plot(theTime,x(whichElements))
ylabel('Quality');
xlabel(['Time [' timeUnit ']']);
```
xlabel(['Time [' timeUnit ']'])
xlim(xLimits);
title ('Heat transferred to kerosene vs.time ')
grid on

%%
figure('Name','Qh')
plot(theTime,Qh(whichElements))
ylabel('Qh [w]');
xlabel(['Time [' timeUnit ']'])
xlim(xLimits);
title ('Heat transferred from R134a vs.time ')
grid on

%%
figure('Name','Total Entropy generated')
plot(theTime,Sgen(whichElements))
ylabel('Total Entropy generated [w/k]');
xlabel(['Time [' timeUnit ']'])
xlim(xLimits);
title ('Total Entropy generated vs.time ')
grid on
```matlab

figure('Name','R134a Enthalpy')
plot(theTime,RefHOut(whichElements))
ylabel(' R134a Enthalpy [J/kg]');
xlabel(['Time [' timeUnit ']']);
xlim(xLimits);
title ('R134a Enthalpy vs.time ')
grid on

figure('Name','R134a Internal Energy')
plot(theTime,RefHOut1(whichElements))
ylabel(' R134a Internal Energy [J/kg]');
xlabel(['Time [' timeUnit ']']);
xlim(xLimits);
title ('R134a Internal Energy vs.time ')
grid on
```
APPENDIX C

To verify the results of the Simulink model, EES program has been used to check equations employed in the model. Below, EES script shows these equations.

$unitsystem SI K pa J Rad mass
$Tabstops 0.5 2 in

" verifications for the Simulink model "

" Cold balance - friction factor "
alpha = 1.20482
delta = 0.015748
gamma = 0.1
m_dot_c = 25 [ kg/s ]
D = 0.00098833 [m]
mu = 0.003567 [ pa - sec]
A_c = 0.001 [ m^2 ]
Re = m_dot_c * D / (mu * A_c)

f = 9.6243 * Re^(- 0.7422) * alpha ^(- 0.1856) * delta ^(- 0.3053) * gamma^(-0.2659) * ( 1+ 7.669 * 10^-8 * Re ^(-4.429) * alpha ^(0.92) * delta^(3.767) * gamma^(0.236))^(0.1)

" Cold balance - pressure drop "
L = 0.07 [m]
rho = 820 [kg/m^3]
press_drop = f * L / ( 2 * D * rho ) * (m_dot_c /A_c)^2

" Cold balance - energy equation "
Cp = 2010 [J/kg-k]
vol_c = 7.0001e-05 [m^3]

" mass flow rate "
" hydraulic diameter "
" dynamic viscosity "
" cross sectional area "
" Reynolds number "
" friction factor "

" length "
" density "
" pressure drop in (pa) "

" specific heat for kerosene "
" volume of kerosene "

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\[ Q_{\text{dot}} = 14607.48204086 \, [\text{w}] \]
\[ T_{\text{in}} = 300 \, [\text{k}] \]
\[ h_{\text{in}} = T_{\text{in}} \times Cp \]
\[ T_{\text{out}} = 300.3 \, [\text{k}] \]
\[ h_{\text{out}} = T_{\text{out}} \times Cp \]
\[ dE_{\text{dt}} = Q_{\text{dot}} + m_{\text{dot}} \times_c \times (h_{\text{in}} - h_{\text{out}}) \]
\[ dT_{\text{dt}} = dE_{\text{dt}} / (Cp \times \rho \times \text{vol}_c) \]

"heat transfer"
"temperature in"
"enthalpy in"
"temperature out"
"enthalpy out"
"energy balance"
"temperature change with respect to time"

"Cold balance - entropy equation"
\[ dS_{\text{dt}} = \rho \times \text{vol}_c \times Cp \times dT_{\text{dt}} / T_{\text{out}} \]

"entropy change with respect to time"

"Heat transfer coefficient - Cold"
\[ k = 0.15 \, [\text{w/m-k}] \]
\[ Pr = \mu \times Cp / k \]
\[ \zeta = (0.79 \times \ln (\text{Re}) - 1.64)^{-2} \]
\[ Z = \zeta / 8 \]
\[ \text{Nu} = \left( Z \times Pr \times (\text{Re} - 1000) \right) / \left( (12.7 \times \text{sqrt}(Z) \times (Pr \times (2/3) - 1)) + 1.07 \right) \]
\[ h = \text{Nu} \times k / D \]

"thermal conductivity"
"Prandtl number"
"zeta parameter in Gnielinski correlation"
"zeta divided by 8"
"nusselt number"
"convective heat transfer coefficient"

"Entropy generation - Cold"
\[ S_{\text{gen}} = dS_{\text{dt}} - m_{\text{dot}} \times Cp \times \ln (T_{\text{out}} / T_{\text{in}}) \]

"entropy generated"
alpha = 0.078302

delta = 0.015748

gamma = 0.12048

m_dot_h = 0.5 [ kg/sec]  " mass flow rate "

D = 0.0015099 [m]  " hydraulic diameter "

mu = 1.30327e-5 [ pa -sec]  " dynamic viscosity for R-134a"

A_c = 0.0018471 [m^2]  " cross sectional area "

Re = m_dot_h * D / (mu * A_c )  " Reynolds number "

f = 9.6243 * Re^(- 0.7422) * alpha ^(- 0.1856) * delta ^( 0.3053) * gamma^(0.2659) * ( 1 + 7.669 * 10^(-8) * Re ^ (4.429) * alpha ^(0.92) * delta^(3.767) * gamma^(0.236))^(0.1)  " friction factor "

L = 0.07 [m]  " length "

rho = 22.98 [ kg/m^3]  " density of R-134a "

press_drop = f * L / ( 2 * D * rho ) * (m_dot_h/A_c)^2  " pressure drop in pa "

Qdot = 14607.48 [w]  " heat transfer "

h_in = 300000 [ J/kg ]  " enthalpy in "

h_out = 270785.0359 [ J/kg ]  " enthalpy out "

p_out = 500 [kpa]  " pressure out "

v = 0.05184 [ m^3 / kg]  " specific volume "

dE_dt = -Qdot + ( m_dot_h * ( h_in - h_out))  " energy balance "

m = 0.002971 [kg]  " mass of R-134a "


\[ du_{dt} = \frac{dE_{dt}}{m} \]  
(internal energy change with respect to time)

\[ T_{out} = 331.5 \text{ [K]} \]  
(temperature out)

\[ u = 270759.118 \text{ [J/kg]} \]  
(internal energy)

\[ h_{\text{check}} = u + p_{out} \times v \]  
(\( h_{\text{check}} \) should equal to \( h_{out} \))

**Hot balance - entropy equation:**

\[ dS_{dt} = m \times \frac{du_{dt}}{T_{out}} \]  
(entropy change with respect to time)

\{ =============== \} \{ =============== \} \{ =============== \}

**Heat transfer coefficient - Hot**

**Liquid phase**

\[ \mu_l = 0.0001857 \text{ [pa} - \text{sec]} \]  
(dynamic viscosity @ liquid phase)

\[ C_p_l = 1440 \text{ [J/kg-k]} \]  
(specific heat @ liquid phase)

\[ k_l = 0.08144 \text{ [w/m-k]} \]  
(thermal conductivity @ liquid phase)

\[ Pr_l = \mu_l \times C_p_l / k_l \]  
(Prandtl number @ liquid phase)

\[ Re_l = m_{dot_h} \times D / (\mu_l \times A_c) \]  
(Reynolds number @ liquid phase)

\[ zeta_l = (0.79 \times \ln (Re_l) - 1.64)^{-2} \]  
(zeta parameter in Gnielinski correlation)

\[ Z_l = zeta_l / 8 \]  
(zeta divided by 8)
Nu_L = (Z_L * Pr_L * (Re_L - 1000)) / ((12.7 * sqrt(Z_L)) * (Pr_L ^ (2/3) - 1)) + 1.07  " Nusselt number @ liquid phase 

h_L = Nu_L * k_L / D  " heat transfer coefficient @ liquid phase 

| two phase |

mu_v = 1.21342e-05  " dynamic viscosity @ vapor phase 

Cp_v = 1056 [ J/kg-k]  " specific heat @ vapor phase 

k_v = 0.01493 [w/m-k]  " thermal conductivity @ vapor phase 

Pr_v = mu_v * Cp_v / k_v  " Prandtl number @ vapor phase 

Re_v = m_dot_h * D / (mu_v * A_c)  " Reynolds number @ vapor phase 

zeta_v = (0.79 * ln(Re_v) - 1.64)^(-2)  " zeta parameter in Gnielinski correlation 

Z_v = zeta_v / 8  " zeta divided by 8 

Nu_v = (Z_v * Pr_v * (Re_v - 1000)) / ((12.7 * sqrt(Z_v)) * (Pr_v ^ (2/3) - 1)) + 1.07  " Nusselt number @ vapor phase 

h_v = Nu_v * k_v / D  " heat transfer coefficient @ vapor phase 

| two phase |

F_fl = 1.63  " fluid dependant parameter 

x = 0.9949  " quality 

rho_g = 38.3 [ kg/m^3]  " vapor density 

\[ \rho_l = 1182 \text{ [kg/m}^3] \]  
\[ \text{"liquid density"} \]

\[ Co = (\rho_g / \rho_l)^{(0.5)} * ((1-x)/x)^{(0.8)} \]  
\[ \text{"convective number"} \]

\[ q = 4023 \text{ [W/m}^2] \]  
\[ \text{"heat transfer per unit area"} \]

\[ u_{lg} = 174349.4568 \text{ [J/kg]} \]  
\[ \text{"enthalpy for evaporation"} \]

\[ G = m_{dot\_h} / A_c \]  
\[ \text{"mass flux"} \]

\[ Bo = q / (G * u_{lg}) \]  
\[ \text{"boiling number"} \]

\[ h_r = (1.183744 * Co^{(-0.3)} + 225.5474 * BO^{(2.8)} * F_fl) * (1 - x)^{(0.003)} * h_l \]  
\[ \text{heat transfer coefficient for two phase"} \]

\[ \text{Entropy generation - Hot} \]

\[ s_{in} = 1057 \text{ [J/kg-k]} \]  
\[ \text{"entropy in"} \]

\[ s_{out} = 964.7 \text{ [J/kg-k]} \]  
\[ \text{"entropy out"} \]

\[ S_{gen} = dS_{dt} - m_{dot\_h} * (s_{in} - s_{out}) \]  
\[ \text{"entropy generated"} \]

---

**Figure 49: Results of hot flow (R-134a)**
Figure 50: Results of cold flow (kerosene)
REFERENCES


[22] F.Mayinger, “Classification nad Applications of Two - Phase flow Heat Exchangers.pdf.”


