Simulated Crossflow Heat Exchanger System Using Simulink Modeling

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Abstract

Applied engineering coursework that incorporates direct hands-on learning processes has been shown to provide a superior educational experience over indirect course structures. Emphasis on observational and empirical learning elements is an integral component in the creation of well-rounded and competent engineers and is a skill that is fostered in the laboratory environment. Just like all aspects of engineering, the structure of these experiential courses must be dynamic and adaptable. For example, these courses should be able to adapt to modern challenges and industry trends. Incorporating the use of virtual simulators to provide practical engineering experiences, in addition to traditional face-to-face techniques, might help to accomplish this. The engineering Thermal-fluids Laboratory course at the University of Texas at Tyler (MENG 3211) is one such curriculum that has made substantial progress in the modernization of experiential teaching techniques by incorporating thermal system analysis in the form of virtually simulated heat exchangers. These virtual systems provide an innovative way for students to gain experience and knowledge with practical engineering applications through the use of an interactive user interface which provides a useful preview of what to expect when working with a physical heat exchanger. Given that physically constructing and maintaining a functioning heat exchanger is an expensive and laborious process, this use of computer software allows for a more accessible and convenient approach to test and analyze dynamic thermal-fluids systems. The system can be defined as a set of nonlinear transient energy balance equations for user-specified inputs such as fluid flow rates, and then thoroughly analyzed in real-time using MATLAB® and Simulink®. By using this model, the user is given the ability to control the heat exchanger system, as well as the disturbances which are occurring, and analyze how they affect the heat transfer process in real-time. Compared to data retrieved from a physical heat exchanger, the exiting fluid temperatures over any given timeframe simulated by the virtual software are shown to exhibit a similar profile and remain within 15% error. Furthermore, the simulated temperature response in reaction to a change in fluid flow rate is shown to properly depict the resulting output in accordance with established principles of thermodynamics and heat transfer. Overall, virtually simulated engineering systems such as this have the potential to provide a highly beneficial practical learning experience for undergraduate engineering students with the added benefit of being remotely accessible and not requiring physical upkeep and maintenance.

Introduction

Heat exchangers are thermal-fluids devices in which a transfer of energy by heat transfer is facilitated between two or more mediums. These mediums can generally be any kind of fluid though they are usually water or air. The most prevalent use of heat exchangers in engineering systems consists of large-scale industrial applications where hot working fluids, passing through chemical or mechanical processes, must be cooled. These fluids pass continuously through a heat changer, alongside a coolant, in order to regulate their temperature and prevent hazards from occurring. Heat exchangers are also useful in academic environments where they are commonly used to provide students with exposure to thermal-fluids concepts and practical engineering systems.

Several different types of heat exchanger configurations exist, with the most widely used being the double pipe configuration, shell and tube configuration, and crossflow configuration. As shown...
in Figure 1, the crossflow heat exchanger is of special importance due to the wide variety of applications in which it can be utilized, both academic and industrial, such as HVAC systems, thermal power plants, and automobiles. This configuration typically employs a hot working liquid flowing through one or more pipes which are cooled by a forced ambient airflow moving perpendicularly to the flow of the liquid.

Thermal-fluids systems such as these are especially useful in academic environments due to the direct interaction required to study them. Analysis of these systems usually requires a laboratory environment to capture the full scope of their utility in which empirical techniques must be utilized. This hands-on learning is highly beneficial in the creation of well-rounded and knowledgeable engineers and due to the dynamic and ever-changing nature of engineering systems in general, these learning techniques must be equally modifiable in order to adapt to and overcome modern challenges [1].

In general, education in engineering requires both theoretical and practical knowledge, and in most cases, students gain theoretical knowledge in the classroom, but laboratory experience is needed to obtain practical skills [2]. The engineering Thermal-Fluids Laboratory course at the University of Texas at Tyler (MENG 3211) is one such curriculum that has made substantial progress in the development and integration of thermal-system analysis in the form of virtually simulated heat exchangers. This virtual analysis provides an accurate preview of what to expect when working with a physical engineering system without the drawbacks which are usually associated with maintaining physical laboratory equipment such as expensive construction costs and laborious maintenance. Furthermore, if a university campus does not employ a high number of physical thermal-fluids systems which is a likely scenario given the aforementioned financial and maintenance constraints, it can lead to an inability of meeting the demand associated with their use.
Originally developed as a virtual shell and tube heat exchanger by a Senior Capstone group within the Department of Mechanical Engineering at the University of Texas at Tyler, this modernization of traditional face-to-face teaching methods provides an innovative way to employ hands-on learning through the use of an interactive user interface. As presented further, the project has been modified and improved by the undergraduate mechanical engineering student authors of this report, currently enrolled at the University of Texas at Tyler, and formed into a fully functional crossflow heat exchanger simulator to be used for future undergraduate studies.

Methodology

The virtual thermal-fluids system presented in this report can be described as a set of nonlinear transient energy balance equations that define the heat transfer process occurring in a crossflow heat exchanger. With the use of an interactive and user-friendly virtual interface, the governing equations are configured to accept user-defined inputs such as fluid flow rates and determine the output of the system in the form of a transient temperature response for the two fluids which are involved in the process. Moreover, the response of the system is analyzed in real-time with the use of MATLAB® and Simulink® software, including the Simulink S-Function block. This block is used to generate real-time solutions for nonlinear systems which can be modified and updated by the user as the simulation is being conducted, similar to a physical system.

The virtual crossflow heat exchanger simulation software incorporates three MATLAB® scripts including an initialization script, a calculation script, and an S-Function script, in addition to a Simulink® data file containing the user interface and the block diagram of the system. As shown in Figure 2, the simulation sequence is performed beginning with the initialization script which defines the initial conditions of the system, followed by the calling of the calculation script which contains the governing equations of heat transfer and the defined properties of the heat exchanger geometry and thermodynamic fluid data [3], followed by the calling of the S-Function script which evaluates and executes the nonlinear governing equations. Technical sources referenced for the derivation of the equations used to define the system are provided for the reader in the bibliography section [3, 4]. A preview of the MATLAB® scripts used for this simulator can be viewed in Appendix A.

![Figure 2. Simulation implementation flowchart.](image-url)
Initially, several technical assumptions must be made about the heat exchanger system. A full list of the assumptions used for this model can be viewed in Figure A.1 which includes important ones such as:

- steady-state flow in terms of mass balance
- incompressible and inviscid fluid with uniform thermal fluid properties
- no external work
- negligible potential energy and kinetic energy
- no phase changes
- no fouling, which means a clean heat exchanger with no debris or contaminants to act as insulation
- uniform fluid properties evaluated at the average of the inlet and outlet temperatures

The system can then begin to be defined with the fundamental energy balance equation as shown in Equation (1)

\[
\frac{dE}{dt} = \dot{Q} - \dot{W} + \left[ \dot{m}h + \rho g y + \frac{\rho v^2}{2} \right]_{in} - \left[ \dot{m}h + \rho g y + \frac{\rho v^2}{2} \right]_{out} \tag{1}
\]

where \( E \) is the total energy in the control volume, \( \dot{m} \) is the mass flow rates in and out of the system, \( h \) is the enthalpy in and out of the system, \( \rho g y \) is the potential energy of the fluid, \( \frac{\rho v^2}{2} \) is the kinetic energy of the fluid, \( \dot{Q} \) is the heat transfer rate and \( \dot{W} \) is the work rate or power term.

The overall heat transfer rate occurring between two fluids in a crossflow heat exchanger configuration can be further defined by Equation (2)

\[
\dot{Q} = UAF\Delta T_{LM} \tag{2}
\]

in which \( U \) is the overall heat transfer coefficient accounting for conductional and convectional effects, \( A \) is the surface area across which heat transfer occurs, \( F \) is the correction factor accounting for the crossflow effect, and \( \Delta T_{LM} \) is the logarithmic mean temperature difference between the two fluids. Moreover, the heat transfer rates associated specifically with the hot and cold fluids which are derived from Equation (2) and define the nonlinear governing equations which drive the heat transfer between the two fluids are defined by Equations (3) and (4), respectively

\[
\frac{dT_h}{dt} = \left( \frac{w_h\rho}{m_h} \right) (T_{hi} - T_h) - \left( \frac{UAF}{m_h c} \right) \frac{(T_h - T_c) - (T_{hi} - T_{ci})}{\ln \left( \frac{T_h - T_c}{T_{hi} - T_{ci}} \right)} \tag{3}
\]

\[
\frac{dT_c}{dt} = \left( \frac{w_c\rho}{m_c} \right) (T_{ci} - T_c) + \left( \frac{UAF}{m_c c} \right) \frac{(T_h - T_c) - (T_{hi} - T_{ci})}{\ln \left( \frac{T_h - T_c}{T_{hi} - T_{ci}} \right)} - \frac{h_c A_c}{m_c c} (T_c - T_\infty) \tag{4}
\]

in which \( T_h \) and \( T_c \) are the temperature outputs of the hot fluid and cold fluid, respectively, and represent the state variables of the crossflow heat exchanger system. All additional variables included in Equations (3) and (4) are defined in Table 1.
Table 1. Governing equations variable description.

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>DESCRIPTION</th>
<th>MEASUREMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_h$</td>
<td>Hot fluid output temperature</td>
<td>°C</td>
</tr>
<tr>
<td>$T_{hi}$</td>
<td>Hot fluid inlet temperature</td>
<td>°C</td>
</tr>
<tr>
<td>$T_c$</td>
<td>Cold fluid output temperature</td>
<td>°C</td>
</tr>
<tr>
<td>$T_{ci}$</td>
<td>Cold fluid inlet temperature</td>
<td>°C</td>
</tr>
<tr>
<td>$w$</td>
<td>Fluid flow rate</td>
<td>m$^3$/s</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Fluid density</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>$m$</td>
<td>Fluid mass</td>
<td>kg</td>
</tr>
<tr>
<td>$c$</td>
<td>Fluid specific heat capacity</td>
<td>J/kg°C</td>
</tr>
<tr>
<td>$U$</td>
<td>Overall heat transfer coefficient (thermal transmittance)</td>
<td>W/m$^2$°C</td>
</tr>
<tr>
<td>$F$</td>
<td>Correction factor accounting for crossflow effect</td>
<td>unitless</td>
</tr>
</tbody>
</table>

Furthermore, a change in dynamic pressure is associated with the fluids in a heat exchanger system as a result of changes in their rate of flow. Regarding a crossflow heat exchanger configuration, the change in fluid pressure flowing through the tubes of the heat exchanger is defined by Equation (5)

$$\Delta P = \left( \frac{\rho v^2}{2} \right) \left( \frac{fl}{d} \right)$$

where $\Delta P$ is the change in pressure, $\rho$ is the fluid density, $v$ is the fluid velocity, $l$ is the length of the tubes, $d$ is the inside diameter of the tubes, and $f$ is the Darcy-Weisbach friction factor associated with the tubes. Based on extensive empirical data, scientists and researchers have developed methods to simplify calculations and determine approximate values for the Darcy-Weisbach friction factor. For the data presented in this report, the Swamee-Jain [5] equation is used as shown by Equation (6)

$$f = \frac{0.250}{\log \left[ \frac{\varepsilon}{3.7D} + \frac{5.74}{Re^{0.83}} \right]^2}$$

where $\varepsilon$ represents the roughness of the physical boundary through which the fluid is flowing through, $D$ is the characteristic length associated with the cross-sectional area which the fluid is flowing through, and $Re$ is the Reynolds number of the fluid. It is noteworthy to mention that since the cooling fluid in a crossflow heat exchanger is an ambient airflow, a net change in pressure does not exist for this fluid, or is at most a negligibly small value, since it is extracted and then expelled back into same source.

In addition to the MATLAB® scripts, the Simulink® block diagram is used to configure the flow of the variables in Equations (3) and (4) and is defined by signal connections between each variable which are represented by blocks. Sections of the crossflow heat exchanger block diagram are shown in Appendix B. Once initiated, the user can observe the transient output temperature responses of the two fluids numerically and graphically. The pressure changes across the inlet and outlet associated with the working fluid can also be observed. Furthermore, various thermal-fluids parameters of interest are calculated and displayed for both fluids, such as heat transfer coefficients,
Reynolds numbers, and mass velocities. Moreover, the system properties of the heat exchanger are also cataloged at the bottom of the interface which describe the geometric attributes of the virtual heat exchanger. The virtual user interface of the system is shown in Figure 3.
Results/Discussion

The output temperature response of the virtually simulated system was compared to the response of a physical crossflow heat exchanger system during an experiment performed at the University of Texas at Tyler [6]. Using initial conditions of 11.50 °C for the cold fluid, 25.00 °C for the hot fluid, 2.00 L/min flow rate for the cold fluid, and 3.80 L/min flow rate for the hot fluid, the response of the fluid temperatures corresponding to the data extracted from the physical heat exchanger and the virtually simulated heat exchanger are shown in Figures 4 and 5, respectively.

Figure 4. Transient data from physical crossflow heat exchanger.

Figure 5. Transient data from crossflow heat exchanger simulator.
From the data, it was observed that the final output temperature from the physical system was approximately 24.47 °C for the hot fluid and 13.91 °C for the cold fluid compared to the data from the simulator which was 24.13 °C for the hot fluid and 14.43 °C for the cold fluid. From Figure 4, it is also observed that the hot fluid initially gained temperature before steadily decreasing to its final temperature which was attributed to a fouling factor associated with the physical heat exchanger. The cold fluid temperature response also exhibited a similar phenomenon during the intermediate stage of the process in which the outlet temperature substantially reversed direction before continuing the original trend. With a sufficient duration of the experiment, however, it was observed that the hot fluid eventually cools to a final temperature substantially lower than the initial, and the cold fluid eventually warms to a final temperature substantially higher than the initial, as expected.

Furthermore, the temperature response of the simulator was observed to be much smoother comparatively which is associated with the virtual environment in which a fouling factor is not present and measurement calibration errors do not exist. The temperature response of the simulator can also be configured to represent realistic conditions more closely by allowing the user to control the flow rates and adjust the system as the simulation of being performed. The data from Figure 5 shows how step changes in the fluid flow rates during the simulation result in changes in the temperature response and causes it to deviate from idealized conditions. Overall, the final temperatures of the fluids associated with the simulator were observed to be within 15% error compared to the final fluid temperatures of the physical heat exchanger.

Thermodynamic fluid parameters of the simulated system are also cataloged on the user interface as shown in Figure 6. Similar to the temperature response of the system, these parameters are updated in real-time as changes occur to the fluid flow rates as the simulation is being conducted. The simulated changes in these parameters are configured to properly adjust in accordance with established principles of thermodynamics and heat transfer [3], i.e. when the fluid flow rates are increased, the convection coefficient increases, which causes the heat transfer rates to increase, etc.
When the simulation has been performed, Simulink® automatically compiles and exports the results into the MATLAB® workspace as a dataset consisting of numerical values for each fluid parameter at discrete time intervals over the duration of the simulation. Among other things, the user can save the dataset to access at a future time, use it to generate additional plots, or import it into a spreadsheet. Appendix C shows visuals of the MATLAB® workspace with the imported simulation data.

Conclusion

The modernization of experiential teaching techniques allows for virtually simulated crossflow heat exchanger systems to be an appropriate resource for undergraduate engineering curriculum. Interactive simulators of thermal-fluids systems help to facilitate hands-on learning experiences that provide students with a useful virtual view of what to expect when working with real engineering systems. The data presented in this report can be utilized to further develop and facilitate a gradual progression into a more widespread acceptance of virtual teaching techniques. Furthermore, the use of MATLAB® and Simulink® provides easily accessible and well-established platforms to perform these virtual simulations which are already commonly incorporated into engineering curriculums worldwide [7]. In conclusion, the work presented by this report has the ability to serve as a direct pipeline for engineering students to acquire firsthand knowledge of how practical engineering systems operate.

References

Appendix A - MATLAB® Scripts

Figure A.1. MATLAB® partial initialization script.
Figure A.2. MATLAB® partial calculation script.
Figure A.3. MATLAB® partial S-Function script.
Appendix B - Simulink® Crossflow Heat Exchanger Block Diagram

Figure B.1. Simulink® crossflow heat exchanger block diagram.
Figure B.2. Simulink® crossflow heat exchanger block diagram.
Figure B.3. Simulink® crossflow heat exchanger block diagram.
Figure B.4. Simulink® crossflow heat exchanger block diagram.
Appendix C - MATLAB® Workspace with Imported Simulation Data

![MATLAB Workspace with Imported Simulation Data](image)

**Figure C.1.** Imported dataset from Simulink® simulation.
Figure C.2. MATLAB® workspace with imported data from Simulink®.
Figure C.3. MATLAB® workspace with imported data from Simulink®.