AC 2007-823: COMPUTER SIMULATION OF LABORATORY EXPERIMENTS FOR ENHANCED LEARNING

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Computer Simulation of Laboratory Experiments  
for Enhanced Learning

Abstract

It is often difficult for chemical engineering students to obtain a clear understanding of the physical processes going on inside the complex industrial scale equipment they study in the laboratory. We are testing the hypothesis that computer simulations showing the solutions to the differential equations that govern the fluid flow, heat transfer, mass transfer, and chemical reactions within the equipment will solidify the link between experiment and theory and provide improved learning. In this paper we report on the development and implementation of a simulation of a double pipe heat exchanger in our unit operations laboratory using COMSOL Multiphysics™, a commercial finite element modeling software package. We also describe our evaluation plan and present preliminary results on comparison of performance and attitudes of students who used the simulation to those who did not.

Problems in the Laboratory

One educational goal of a typical engineering laboratory is to help students understand fundamental principles by connecting theory and equations in their text books to real world applications with real equipment and data. In addition to this goal, our senior level chemical engineering unit operations laboratory also tries to promote higher order thinking skills while meeting some of the ABET 2000 criteria regarding professional practice such as “an ability to communicate effectively”, “an ability to function on a multi-disciplinary team”, “an ability to design and conduct experiments as well as to analyze and interpret data”, and “an ability to identify, formulate, and solve engineering problems”\(^1\). Therefore, we do not provide specific instructions for the laboratory experiments to our three-person student teams. Instead, we give only brief one- or two-page general guidelines with hints about what should be learned along with safety information and suggested readings from textbooks that should already be familiar to the students. The teams are required to write a pre-lab report to ensure that they review the fundamental principles, “design” their own experiments, and communicate effectively by preparing written instructions that a lab technician could follow. This pre-lab exercise is also designed to help promote higher order thinking in the final report writing stage. Ideally, after the pre-lab stage, students will have a very good understanding of the fundamental principles and the expected results and will be able to collect all the necessary data as well as do most of the calculations and routine analysis of results while they are in the laboratory. That way, they have time for high level interpretation and critical analysis of the results at the final report writing stage. When we grade the final reports, we look for evidence of higher order analysis, synthesis, and evaluation as well as demonstration of a clear understanding of the fundamental principles and phenomena occurring. If something is missing, we try to provide feedback that encourages students to think more deeply about the subject when they prepare oral reports that are required for some of the experiments each team conducts.

Unfortunately, we have found that despite our good intentions, some students still end up at the oral report stage not only having failed to demonstrate higher order thinking skills but sometimes still lacking a clear understanding of “what is happening inside the pipes”. Part of the problem
may be that we require too much report writing and not enough thinking. Another suspicion we have is that old reports, not only from our former students but from other unit operations students from around the world, are so readily available that our expectation of a student starting from scratch to write a pre-lab report based on deep thought about a subject is not realistic. Often our review of the graded pre-lab report with the students reveals gaps in their understanding that are not readily apparent in the written report.

The biggest impediment to understanding the phenomena going on within the complex process equipment in the lab is that the processes are described by differential equations for chemical reactions and momentum, heat and mass transfer for which analytical solutions are scarce. The theoretical development behind the labs (and throughout the undergraduate curriculum) is, therefore, normally comprised of approximate methods involving empirical descriptions of lumped parameter models that describe the results but not the details of the physical process. To illustrate this point as well as the other points to be made in this paper we will use as an example the double pipe heat exchanger experiment in our lab.

Figure 1. Schematic diagram of double pipe heat exchanger with steam outside and water inside.

Figure 1 shows a schematic of our double pipe heat exchanger experiment with steam on the outside and water on the inside. The heat transfer to the water in this process consists of conduction and convection and is described by the differential equations\(^2:\)

\[
q = -\nabla \cdot (k \nabla T) + \rho C_p \cdot \nabla T \\
\rho \cdot \nabla = \nabla p + \mu \nabla \nabla
\]

where \(q\), \(k\), \(T\), \(\rho\), \(C_p\), \(\mathbf{u}\), \(p\), and \(\mu\) represent heat flow, thermal conductivity, density, heat capacity, velocity vector, pressure, and viscosity, respectively. Unfortunately, an analytical solution to these equations is not available except for the simplest geometries and flow patterns. Therefore,
a practical engineering approach based on Newton’s law of cooling is presented to undergraduate engineering students for describing the convective heat transfer from a surface at $T_s$ to a fluid with bulk temperature $T_f$ using

$$q = h \cdot A \cdot (T_s - T_f) \quad (3)$$

where $q$ is the heat flow by convection, $A$ is the surface area for heat transfer, and $h$ is a heat transfer coefficient that depends on the geometry and the fluid properties and flow profile. Heat transfer coefficients can be estimated from generalized correlations or determined experimentally by measuring $q$, $A$, $T_s$, and $T_f$ and solving for $h$ in Equation 3. Our process with water flowing inside a pipe while steam is condensing outside requires two heat transfer coefficients; an inside heat transfer coefficient, $h_i$, describing the heat transfer from the pipe to the flowing water and an outside heat transfer coefficient, $h_o$, describing heat transfer to the pipe from the condensing steam. In our unit operations laboratory, students are required to use the so-called “Wilson plot method” to estimate $h_i$ and $h_o$ and determine the dependence of $h_i$ on the water flow rate. The Wilson plot method was developed in 1915 long before the existence of any computer but is still widely used. It is based on the assumption that the overall resistance to heat transfer is equal to the sum of the individual resistances

$$R_T = R_i + R_w + R_o = 1/(U_o A_o) \quad (4)$$

where $R_T$ is the overall resistance to heat transfer, $U_o$ is an overall heat transfer coefficient, $A_o$ is the surface area based on the outside pipe diameter, and

$$R_i = 1/(h_i A_i) = \text{inside resistance} \quad (5)$$

$$R_w = W_t / (k A L) = \text{pipe wall resistance} \quad (6)$$

$$R_o = 1/(h_o A_o) = \text{outside resistance} \quad (7)$$

where $W_t$, $k$, and $L$ are the pipe wall thickness, thermal conductivity, and length, respectively. In the lab, the students fix the steam pressure and vary the water flow rate. At each water rate they measure inlet and outlet water temperature, steam condensation rate, and inlet steam enthalpy as well as water flow rate. To generate a Wilson plot of $1/U_o A_o$ against water velocity to the -0.8 power like that shown in Figure 2, the students determine the heat transferred to the water at each water flow rate from an energy balance:

$$q = \dot{n} \cdot \dot{C}_p \cdot (T_{out} - T_{in}) \quad (8)$$

where $\dot{n}$ is the mass flow rate of the water. Next, they determine $U_o A_o$ from

$$q = U_o A_o \cdot \Delta T_{LM} \quad (9)$$

where $\Delta T_{LM}$ is the log mean temperature across the heat exchanger. The x axis of the Wilson plot is average water velocity raised to the -0.8 power because it is implicitly assumed that the
inside heat transfer coefficient is the only factor that depends on water velocity and that its dependence is given by the empirical Dittus-Boelter equation for fluids in turbulent flow as

\[
\frac{h_i D}{k} = 0.023 \text{Re}^{0.8} \text{Pr}^n
\]

with \( n = 0.4 \) for heating the fluid in the pipe and \( n = 0.3 \) for cooling the fluid. \( \text{Re} \) is, of course, the Reynolds number equal to \( \rho \cdot V \cdot D / \mu \) and \( \text{Pr} \) is the Prandtl number equal to \( Cp \mu / k \). Combining Equations 5, 6, and 7 with Equation 4 and knowing the pipe wall thickness and thermal conductivity allows the students to determine \( h_i \) and \( h_o \) from the slope and intercept of the Wilson plot. Equation 2, the Navier Stokes equation, describing the fluid flow does not come into play in the Wilson plot method because the water is assumed to flow in plug flow with a constant velocity profile at the average water velocity.

Through experimentation and application of the Wilson plot method our students should learn that the outside heat transfer coefficient, \( h_o \), is essentially constant but the inside heat transfer coefficient, \( h_i \), and therefore the overall heat transfer coefficient \( U_o \), depend on the average fluid velocity to the power 0.8. Although some of our students have experimental and calculation difficulties that prevent these observations, many of them do obtain these well known results. On the other hand, more students than we would like have difficulty explaining what is going on inside the pipe that accounts for the observed behavior. The fact that most of the resistance to heat transfer in the process is given by a non-turbulent boundary layer of water near the wall on the inside of the pipe and that the thickness of this boundary layer is smaller at higher flow rates, although well known, is not obvious from the Wilson plot method. Some students note that the outlet water temperature decreases with increasing flow rate and assume, incorrectly, that the heat transfer coefficient has decreased as well. Indeed, in oral reports we have discovered that many students can not explain clearly what the heat transfer coefficient represents and what factors it depends on.

![Figure 2. Wilson plot for heat exchanger using data from reference 4.](image-url)
Simulation to the Rescue?

One route to improved learning could be to provide an additional connection between experiment and theory through computer simulation of the processes. Recent advances in computer technology and the development of robust finite element equation solvers coupled with user friendly graphical user interfaces has eliminated the need for specialized expertise to solve many problems involving differential equations. Commercial software packages like COMSOL Multiphysics™ allow students to set up and solve the partial differential equations that describe momentum, energy, and mass balances and also to visualize the velocity, pressure, temperature, and concentration profiles within the equipment. Visualization of the processes could provide students with a better understanding of what is happening inside the pipes. This visualization of differential equations may also enhance the learning of engineering mathematics for some students. For example, in discussing the use of a slope field graph to help students better understand the solution of differential equations, the College Entrance Exam Board recently stated “Writing the equation is one thing, but ‘seeing’ the solutions by plotting slope fields removes abstractness from the symbolic representation”6. It has been argued that the use of visualization to enhance learning may provide a welcoming environment to some students who would not ordinarily consider science careers7. Simulation may not only help reinforce concepts but it may also help “bring to life” the experiments and also the mathematics.

Simulations have been used in undergraduate teaching for many years. Dahm et al.8 conducted a survey of US chemical engineering departments and learned that process simulators like ASPEN and HYSYS are used extensively in process design courses and somewhat in stage-wise separations and thermodynamics courses. They discussed the potential pedagogical drawback that students can “…construct and use models without really understanding the physical phenomena …” and challenged educators to ensure that simulation enhances student understanding and not simply provides a crutch, but concluded that these simulators may have been underutilized in undergraduate education to date. An important difference between these process simulators and the finite element simulations described in this proposal is that the process simulator appears to the student as essentially a “black box” that yields process material and energy balance results for complex processes with little or no insight into what is going on within each unit. The goal of our simulations is precisely to show what is happening inside the units.

Simulations of laboratory experiments and of complex commercial chemical processes have also been used in teaching9-15. Advantages of simulated experiments include: cost effectiveness; convenience for study anytime anyplace; ability to include complex, hazardous, real world processes, and ability to direct student efforts toward experimental design and data analysis rather than operating equipment. Some studies have determined that simulated experiments can serve as effective preparation for conducting actual lab experiments10,11. Others have advocated using simulations instead of actual lab experience, especially for distance learning applications10,12,13. Most of these simulated experiments appear as “control panels” or as two dimensional, static pictures of process equipment that mysteriously yield the output expected from real 3D equipment with transient or steady state processes going on inside. The internal calculations of these simulators may actually be solutions of differential equations or they may be approximate graphical or empirical solutions, but they are not necessarily revealed to the
students. As noted above, an advantage of our approach is the simulations should reveal and stimulate interest in what is going on inside.

To avoid giving students simulated results that they could use instead of experimental results from the lab, we have modeled a heat exchange experiment that was recently described by Fernandez-Seara et al.\textsuperscript{4}. The process consists of cold water running through a 38 cm length of 4.88 mm ID / 6.40 mm OD copper pipe while it absorbs heat from steam condensing on the outside of the pipe. Our own heat exchanger experiment is very similar to theirs but with the added complications that it is on an industrial scale, uses pressurized steam in a double pipe arrangement, and precludes visualization of the steam condensing on the pipe.

COMSOL Multiphysics makes it relatively easy to obtain numerical solutions to Equations 1 and 2, the differential equations that underlie the momentum and energy balances for our process. One complication not yet noted is that the water is in the turbulent flow regime. Fortunately, COMSOL Multiphysics has a built-in $k\text{-}\varepsilon$ turbulent flow model that provides the appropriate modifications to Equation 2 to account for fluctuating turbulent eddies\textsuperscript{16}. Since our students are not familiar with COMSOL Multiphysics or the $k\text{-}\varepsilon$ model we have prepared a tutorial that begins with a simple laminar flow heat exchange process and explains the basics of turbulence modeling before discussing the more complex turbulent flow heat exchanger described here.

Our heat exchanger model uses the $k\text{-}\varepsilon$ model for the momentum balance together a conduction and convection energy balance model in COMSOL’s Chemical Engineering Module to predict outlet water temperature given inlet water flow rate, inlet water temperature, and steam temperature. We solved the two models separately by solving the $k\text{-}\varepsilon$ model first using fluid properties at an estimated average temperature. Then we solved the convection and conduction model using the results from the $k\text{-}\varepsilon$ model for flow behavior. The post processing features allow observation of velocity and temperature profiles as well as calculation of heat flux, average heat transfer coefficients, and an estimate of the thermal boundary layer thickness, $\delta_t$.

As shown in Figure 3 we have placed the copper water pipe vertically and have taken advantage of axial symmetry to simplify the calculation effort. The four subdomains shown in the diagram represent, from left to right, the water flowing inside the copper pipe in turbulent flow, a psuedo boundary layer, the copper pipe, and a thin layer of condensed steam on the outside of the pipe. The energy balance in subdomains II, III, and IV is given simply by

$$ q = -\nabla \cdot (k \nabla T) $$

(11)

The $k\text{-}\varepsilon$ turbulence model provides a reasonable estimate of the velocity flow profile as well as the “turbulent viscosity” that has been correlated with the eddy diffusivity. The eddy diffusivity is a way of accounting for the turbulent nature (characterized by eddy mixing) of the flow everywhere within the pipe, except for a small boundary layer region near the pipe wall, at high flow rates.\textsuperscript{2} The eddy diffusivity for heat transfer has been added to the thermal conductivity term in the energy balance for subdomain I to describe the dramatically increased heat transfer that results from eddy mixing

$$ q = -\nabla \cdot ((k + \varepsilon_n) \nabla T) + \rho C_p u \cdot \nabla T $$

(12)
where \( k \) = thermal conductivity, \( \varepsilon_H \) = eddy diffusivity for heat transfer = \( \rho C_p \nu T \), \( \rho \) = density, \( C_p \) = heat capacity, \( \nu T \) = turbulent viscosity obtained from the k-\( \varepsilon \) turbulence model, \( u \) = velocity vector from k-\( \varepsilon \) model.

Figure 3. COMSOL Multiphysics simulation of heat exchanger.

The momentum boundary layer is accounted for by a law of the wall boundary condition in the k-\( \varepsilon \) model. In theory, the resistance to heat transfer due to the laminar boundary layer could be accounted for by a law of the wall for heat transfer or by using a heat transfer coefficient to represent a discontinuity in temperature between the wall and the turbulent core. Instead, the thermal boundary layer is accounted for by a pseudo-boundary layer, subdomain II, that is considered to contain stagnant water with thermal conductivity \( k' = k' C_1 \Re^{0.8} \), where \( C_1 \) is a constant that was determined by trial to provide a good fit to experimental results and \( \Re \) is the Reynolds number of the water calculated at average flow and temperature conditions. This has been done because we wanted to use something close to the actual physical process to approximate and illustrate our process rather than resort to a heat transfer coefficient here. This definition of \( k' \) allows the pseudo-boundary layer to remain as a fixed arbitrary thickness on the screen but have a much smaller effective thickness that decreases with increasing water flow rate. The condensing steam on the outside of the pipe is modeled as a stagnant layer of liquid water at \( T_s = 100 \, ^\circ \text{C} \) with thermal conductivity \( k' = k' C_2 \), where \( C_2 \) is a constant obtained by trial to fit experimental data and allow the effective thickness of the condensed layer to be less than that which can be easily observed on the screen.

It can readily be seen from Figure 3 that at steady state the water near the center of the pipe is always cooler than the water near the wall. It can also be seen that the average exit (top) water
temperature is several degrees higher than the entrance (bottom) temperature. The average (mixing cup) temperature of the exiting stream, which would be measured in the lab, can be obtained by post processing in COMSOL to calculate:

\[
\langle T \rangle = \frac{\int T \, v \, ds}{\int v \, ds}
\]  

(13)

where \( T \) is temperature, \( v \) is the velocity in the z direction, \( <> \) represents mixing cup average and \( ds \) represents the integral over the exiting pipe boundary. The total heat transferred to the water, \( q \), can also be easily obtained in post processing by integrating the heat flux across boundary number 4.

Table 1 shows good agreement between the experimental outlet water temperature and heat transfer results obtained in reference 4 and the simulated results we obtained with our COMSOL model. Our simulated heat exchanger could thus be used to generate data to be analyzed by the Wilson plot method to obtain heat transfer coefficients.

Figure 4 shows the temperature profile from a cross section halfway along the length of the heat exchanger. Moving from right to left, the relative resistance to heat transfer offered by the steam on the outside of the pipe, the pipe itself, the (pseudo) thermal boundary layer, and the turbulent water on the inside of the pipe can easily be seen. To reinforce the concepts and illustrate the meaning of the heat transfer coefficient, Equation 1 can be rearranged and solved for average heat transfer coefficients using data for \( \Delta T \) across different subdomains from Figure 4:

\[
h = \frac{q}{A \, \Delta T}
\]  

(14)

Table 1 shows that results for average heat transfer coefficients calculated at half the pipe length from temperature profiles like that shown in Figure 4 are in good agreement with heat transfer coefficients obtained from the Wilson plot method. As expected, \( h_o \) is nearly constant while \( h_i \) increases with increasing water velocity. Table 1 also shows that estimates obtained for the thermal boundary layer thickness by dividing the arbitrary thickness shown in Figure 4 by C1*Re^{0.8} are decreasing with increasing water flow rate as expected.

We anticipate that students who obtain and study simulated laboratory results like those shown here will obtain a better understanding of the effect of fluid velocity on heat transfer than students who simply plug experimental \( T \) and \( q \) results into empirical equations.
Table 1. Comparison of Experimental (E) and Simulated (S) Results for Heat Exchanger

V = average water velocity, Re = Reynolds number at average velocity, T_{in} = inlet water temperature, T_{out} = outlet water temperature, q = heat flow in Watts, h_o = steam side heat transfer coefficient, h_i = water side heat transfer coefficient, \( \delta t \) = pseudo boundary layer thickness. Experimental results from reference 4. Superscript W indicates Wilson plot method result.

<table>
<thead>
<tr>
<th>V (m/s)</th>
<th>0.31</th>
<th>0.45</th>
<th>1.06</th>
<th>1.49</th>
<th>1.76</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re</td>
<td>2840</td>
<td>4110</td>
<td>9420</td>
<td>13280</td>
<td>15600</td>
</tr>
<tr>
<td>T_{in} (°C)</td>
<td>45.7</td>
<td>46.8</td>
<td>48.1</td>
<td>49.3</td>
<td>49.9</td>
</tr>
<tr>
<td>q^E (W)</td>
<td>644.1</td>
<td>804.1</td>
<td>1406.8</td>
<td>1670.3</td>
<td>1724.9</td>
</tr>
<tr>
<td>q^S (W)</td>
<td>613</td>
<td>792</td>
<td>1360</td>
<td>1610</td>
<td>1734</td>
</tr>
<tr>
<td>T_{out}^E (°C)</td>
<td>73.0</td>
<td>70.0</td>
<td>65.5</td>
<td>63.9</td>
<td>62.7</td>
</tr>
<tr>
<td>T_{out}^S (°C)</td>
<td>72.6</td>
<td>70.8</td>
<td>65.5</td>
<td>64.0</td>
<td>63.3</td>
</tr>
<tr>
<td>h_o^W (W/m^2K)</td>
<td>11890</td>
<td>11890</td>
<td>11890</td>
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<td>11890</td>
</tr>
<tr>
<td>h_o^S (W/m^2K)</td>
<td>11460</td>
<td>11520</td>
<td>11480</td>
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<td>11350</td>
</tr>
<tr>
<td>h_i^W (W/m^2K)</td>
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<td>3860</td>
<td>7670</td>
<td>10070</td>
<td>11500</td>
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<tr>
<td>h_i^S (W/m^2K)</td>
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<td>4120</td>
<td>8050</td>
<td>10430</td>
<td>11900</td>
</tr>
<tr>
<td>( \delta t ) (m x 10^{-5})</td>
<td>19.6</td>
<td>14.5</td>
<td>7.3</td>
<td>5.6</td>
<td>4.9</td>
</tr>
</tbody>
</table>

Figure 4. Temperature profile over cross section of heat exchanger at Z = 19 cm.
Implementation and Evaluation

We used the heat exchanger simulation as part of the pre-lab experience for the first time in the Fall 2006 offering of our Unit Operations Laboratory course. Students in one lab section who used the simulations were compared to those in a control section who did not. A five question, multiple choice diagnostic was given to students in both sections at the beginning of the course to gage their knowledge of heat exchangers and heat transfer coefficients. Student teams in the control section wrote a standard pre-lab report for each experiment they encountered during the lab including the heat exchanger experiment. The intervention section students wrote standard prelab reports for each experiment except the heat exchanger. For the heat exchanger, they worked through what proved to be a rather lengthy tutorial that explained not only the simulation and step by step procedures for how to run it at several operating conditions, but also the theory behind the equations, including the turbulent flow model, as well as the Wilson plot method. After completing the tutorial that we expected to require about two hours of study, intervention students took a 10 question multiple choice online quiz designed to ensure that they learned the important concepts from the tutorial. After taking the online quiz individually, each intervention student team completed a short answer questionnaire designed to prepare them for physically running the heat exchanger lab, since they didn’t write a prelab report with a procedure section. Both sections, control and intervention, redid the 5 question diagnostic after completing their prelab work. Both sections also conducted the physical lab exercise and collected data to generate a Wilson plots, wrote standard final reports, and prepared and presented oral reports.

The diagnostic given before and after the prelab provided a quantitative measure of improvement in learning via the prelab experience for both groups. Content analysis of written and oral reports was used to measure any difference in understanding of fundamental concepts and in higher level thinking demonstrated by the two groups. At the end of the course both sections completed our standard course evaluation forms, but the intervention students also completed final simulation surveys and in-depth interviews conducted by an external consultant to provide feedback on the simulation experience. The intervention students also completed the VARK learning style diagnostic\footnote{VARK learning style diagnostic} to help us determine if differences in learning or attitudes towards the simulations can be attributed to differences in learning styles. We are also seeking to determine if differences in learning or attitudes can be attributed to differences in gender or ethnicity.

In addition to evaluating the effectiveness of our first implementation of a simulation in the lab, assessment results are being used to improve the simulation and our ongoing development of simulations for other experiments and the next round of implementation scheduled for Fall 2007. Senior thesis projects are currently underway to develop simulations for a gas permeation membrane unit and a fluid flow experiment.

Preliminary Results

At press time for this draft paper, analysis of our assessment data is not yet complete. Further analysis will be available at the conference. Based on an initial review of the data, it appears that due to a small sample size and an imperfect initial implementation, firm conclusions about the effectiveness of using simulation in the lab will have to await the results of our future implementations. Problems arose in the initial implementation because of the length of the
tutorial, the delivery of the online quiz, and the lack of a standard prelab report for the heat exchanger. There were only 15 control students and 14 intervention students in the initial implementation. Our next implementation will expose more students to simulation by using simulations of other experiments in addition to the heat exchanger. A control will be maintained since one section will use the heat exchanger simulation, but do the membrane experiment without simulation, while the other section will use a membrane simulation, but do the heat exchanger experiment without simulation, for example. Of the 14 students in the intervention group, none reported spending as much as the expected two hours studying the tutorial and the simulation. Five students claimed they spent between 1 and 2 hours but three reported that they spent between 15 and 30 minutes; much less than we believe necessary to gain the full benefit. Several students admitted that they discovered that the online quiz could be taken multiple times prompting them to simply guess and retake until all the questions were answered correctly. Some even complained that this loophole hindered them from making full use of the tutorial information. Some intervention students also complained that failure to prepare a standard prelab report left them less prepared for conducting the experiment and writing the final report than they were on other experiments where a prelab report was written. There also appeared to be a mismatch between our expectations of the simulation promoting better conceptual understanding (visualization of the solution to differential equations and prediction of experimental results from theory) and the student’s desire to have a prelab experience with a more immediate impact of preparing them for the physical lab session (showing them which valves to turn and which gages to read). Consistent with this point, some students noted that the simulation was more useful at the final report stage than the prelab stage. These concerns will be addressed in subsequent implementations. It may be best to use the simulation in addition to a prelab report rather than instead of one. It is interesting that these concerns were raised in the final simulation survey and in the interviews when the students were specifically asked about their simulation experience yet there was no mention of the simulation in open responses on our standard course evaluation form. There were also no significant differences in responses on our standard course evaluation between the control and intervention groups; both groups reported an overall favorable response to the course similar to what we have received in recent years.

Despite the concerns noted above, the intervention students did no worse, and perhaps slightly better, than the control students with regard to quantitative and qualitative measures of improved learning. The final course grades and the grades obtained oral and written reports for the heat exchanger were similar between groups and did not appear to depend on the type of prelab experience. Both groups improved in the diagnostic from pre to post. On average the control group got 1.5 more of the 5 questions correct, while the intervention group got 1.6 more correct, the second time around. Our three-faculty-member team in the course, two of whom are not involved in the simulation development and implantation, determined that intervention students showed slightly better understanding of fundamentals regarding the definition of the heat transfer coefficient and the factors that it depends on than control students. One student in particular appeared to have benefited form visualization of the boundary layer in the simulation when he tried to explain why the heat transfer coefficient increases with increasing water flow rate.

The final simulation survey and interviews also indicated that the simulation was effective in promoting understanding through visualization. All the students reported that the simulation helped them understand the fundamentals of heat transfer although responses were, more or less,
evenly distributed between “just a little”, “somewhat”, and “much”; none chose “very much”. Paraphrasing one student interview “The simulation gives you a chance to break down slices of the heat exchanger itself rather than just looking at a pipe in the lab and not be able to visualize what is going on. The simulation allows you to see the temperature and pressure profile – so you can see what’s going on”. Another stated “You get to see what’s happening in the heat exchanger before doing the experiment”. Yet another student who self identified as being visually oriented noted that “This one was more fun than [a standard prelab]. I don’t like textbooks and dry reading. The visuals and the interaction helped. I remember altering the files/images. It gave me something to do besides just reading.”

Future Work

Although we still believe that using computer simulation to set up and solve the partial differential equations that describe momentum, energy, and mass balances and also to visualize the velocity, pressure, temperature, and concentration profiles within the equipment will reinforce fundamental concepts and help “bring to life” not only the experiments but also the mathematics, we are reconsidering how and when the simulation should be introduced. The initial implementation of using simulation as a substitute for writing a prelab report proved problematic due, in part, to the length of the tutorial students were asked to study and to the student’s desire to prepare themselves for the practical aspects of the laboratory session at the prelab stage. The heat exchanger tutorial length was based on the need to introduce the modeling software to students with no modeling experience and also to the complexity of modeling turbulent flow. In our next implementation we may introduce the modeling software separately and require students to conduct the fluid flow lab with an associated turbulent flow simulation before they encounter the heat exchanger lab. We will complete the detailed analysis of our evaluation data and present those results at the conference along with our plans for an improved second round implementation.

The simulations we are developing are being used in our senior chemical engineering laboratory, but they can also be used in fundamental courses in fluids, heat transfer, and mass transfer and the approach can be applied to other disciplines in science and engineering. Since future undergraduate engineering students will use finite element models instead of empirical equations to analyze and design heat exchangers as well as other equipment and processes, we are starting with the senior lab course, but are seeking to determine when and where in the curriculum it is appropriate to introduce finite element modeling to underclass undergraduate engineering students.

Acknowledgement

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