EXPERIENCES OF USING A WEB-BASED VIRTUAL SHELL AND TUBE HEAT EXCHANGER EXPERIMENT BY ADULT CONTINUING LEARNERS

Edmond Byrne*1, John Barrett1, Tomáš Jiříček2, Alan Kelly3, Colm O'Sullivan4

1Department of Process and Chemical Engineering, University College Cork, Republic of Ireland
2Institute for Nanomaterials, Advanced Technologies and Innovation, Technical University of Liberec, Czech Republic
3School of Food and Nutritional Sciences, University College Cork
4Department of Physics, University College Cork

Abstract: This paper describes the experiences of adult continuing learners at University College Cork (UCC) in employing a virtual web-based shell and tube heat exchanger experiment. The experiment was developed at UCC as part of a ‘ComLab’ European project. The development of the virtual experiment consisted of two stages; stage 1 involved the design and build of the model heat exchanger and the collection of experimental data, while stage 2 consisted of the development of the virtual online experimental interface. The learners using the experiment are engaged in a two-year part-time evening Diploma in Process and Chemical Engineering and the experiment forms part of an assessment exercise for a module on Heat Transfer and Applied Thermodynamics, taught by the principal author, which incorporates the principles of heat exchanger design.

The virtual and online nature of the laboratory were useful features for these learners as it could readily be used during the night-time classes (and by a high number of users simultaneously) and could be accessed remotely outside of class time, unlike a real laboratory experiment. Feedback was obtained on a longitudinal basis from learners over a number of iterations of the experiment and was generally very positive, with learners preferring the virtual online experiment to a real laboratory experiment, as well as universally finding it both useful in developing their understanding of heat exchanger design and operation and highly user-friendly. The virtual shell and tube heat exchanger experiment can be accessed online at: http://cs1.ucc.ie/~jb7/exch/

Keywords; virtual lab, experiential, heat exchanger, adult, remote, e-learning, heat transfer.

*Correspondence to: E.P. Byrne, Department of Process & Chemical Engineering, University College Cork, Ireland. E-mail: e.byrne@ucc.ie

1. INTRODUCTION

Virtual laboratory experiments involve the use of technology, in particular computer technology, to simulate and/or replicate actual laboratory experiments. Indeed, the use of technology to simulate physical phenomena predates the development of the computer, and Edwin Link’s ‘link
trainer’ flight simulator from 1928 with its pneumatic and electrically based instrumentation, probably represents the first serious exemplar (Feisel and Rosa, 2005).

Given the practical and applied nature of the profession, it is hardly surprising that engineering education has found a wide range of applications for virtual laboratory experiments (Selmer et al., 2007; Granjo et al., 2009; Balamuralithara and Woods, 2009; Rasteiro et al., 2009; Martin-Villalba, 2010). The pedagogical basis for virtual laboratory experiments is no different to that for general laboratory experiments, in that they can help provide a framework for experiential learning (Kolb, 1984) and hence facilitate learning and professional development. Indeed while the particular experimental system described here is a determinate one, the prevalence of complex and indeterminate systems in engineering practice (Ulanowicz, 2008, Byrne and Fitzpatrick 2009; Byrne 2012) across natural and societal spheres emphasises the requirement for an appreciation of experiential learning among engineering graduates. This has been increasingly recognised in fields such as industrial ecology, where the inherent value and necessity of experiential system understanding is recognised and promoted over the mere acquisition of theoretical factual knowledge.

This paper describes the experience of users of a virtual laboratory shell and tube heat exchanger (STHE) experiment developed at University College Cork (UCC) during a part-time evening programme in Process and Chemical Engineering.

### 2. MATERIALS AND METHODS

#### 2.1 Context and rationale

The design of the virtual lab experiment comprised of two stages:

1. The design, construction, operation (including data collection) and modelling of a laboratory scale model STHE (Jiříček, 2007)
2. The development of an online virtual laboratory software interface (Barrett, 2008)

The work was prompted though a European Commission Leonardo da Vinci pilot project entitled ComLab (Computerised Laboratory in Science and Technology Teaching – part 2; [http://e-prolab.com/](http://e-prolab.com/)). The aim of this project was ‘to integrate different ICT tools in science and technology teaching’ through both ‘real laboratory’ and ‘virtual laboratory’ exercises and activities. The virtual heat exchanger project described here resided under the ‘Principle of Heat Exchangers’ node, which was part of the ‘Experiments in food science and technology’ section of the project as a ‘ComLab 2 course’.

#### 2.1 Design and construction of the STHE

A single-pass three tube STHE unit was designed and fabricated. The shell side was constructed of transparent polycarbonate, and helical static mixer elements were inserted into the stainless tubes to help promote heat transfer. A second identical model was constructed entirely of polycarbonate for visualisation purposes and this was used to build a 360° rotatable image on the ‘Apparatus’ section of the virtual laboratory website using an Object VR (Video Recording) type interface created with Flash, using 40 images of the apparatus rotating captured at 9° intervals (Figure 1) (Barrett, 2008).
The heat exchanger contained three tubes, each of effective length 20 cm, arranged in a triangular formation within the shell, which had two cutaway baffles with a 25% cut (Jiříček, 2007). Dimensions are shown in Figure 2.

Respective input and output fluid stream temperatures were measured and recorded with four type K thermocouples and a Pico TC-08 data logger connected to a computer for both shell and tubeside streams. Water was used as both the shell and tube side fluid. Four different temperatures were used in the hot tube inlet stream fed from a heating bath through flexible hoses (35°C, 50°C, 65°C and 80°C), while the cold shell-side stream comprised of water taken from the mains water supply at 18°C. Experimental data for both co-current and counter current configurations were taken. Flowrates of between 1 kg/min and 5 kg/min were employed at both shell side and tube side, using gate valves and variable area flowmeters at increments of 1 kg/min and 0.5 kg/min, respectively. In total, data was collected from 360 successful experiments. The actual experimental set up is shown in Figure 3.

2.2 Online software development
The online virtual laboratory experiment was conceived with the intention of replacing or enhancing a real laboratory session, and so the design of the online website was modelled on the typical experience of a student attending a practical. The pages of the site are therefore each
based on different sections of a typical laboratory handout, and the site thus consists of four principal sections: ‘Introduction’, ‘Apparatus’, ‘Procedure’ and ‘Experiment’.

Figure 3 Actual laboratory set up

The ‘Apparatus’ section includes sub-pages which employ multimedia devices to provide a 360° rotatable image of the heat exchanger and a video demonstrating flow patterns in both the shell and tube. The actual virtual experiment is located in the ‘Experiment’ section. This includes manual click and drag sliders to control flowrate and temperature and an intuitive lever to switch between co-current and counter current flows (Figure 4), as well as a data recording and exporting function. Adobe Dreamweaver IDE, Flash and CorelDraw were used in the construction of the site and its elements.

Figure 4 Screenshot from ‘Experiment’ page online
2.2.1 Data Modelling

This virtual laboratory experiment is different from many virtual experiments in that it does not simulate or predict output data using a relevant algorithm. Instead it uses real experimental data gleaned from stage 1. It thus shares elements in common with an ‘interactive screen experiment’, though it differs from this in the critical aspect that it does not present an ‘interactive movie of an experiment, filmed as that experiment was being performed’ (Hatherly et al., 2009) (Figures 3 and 4). However, to generate a user impression of real laboratory conditions, changes in the inlet and outlet temperatures (T2 and T3 or T4) on the screen and on the associated plot of temperature against time were fitted with an algorithm which produced asymptotic curves. This prevented discrete changes in output data once input settings were altered. A function of the following form (called ‘tempLag()’) was used to create this artificial transitional period after any change in experimental conditions:

\[ T_{\text{present}} = T_{\text{previous}} + K (T_{\text{final}} - T_{\text{previous}}) \]  

where \( T_{\text{previous}} \) is initial temperature and \( T_{\text{present}} \) is temperature one time interval later. Values for the constant \( K \) were calculated using the solver tool in Microsoft Excel by performing a least squares regression fit to experimental data expressed over time. For output temperatures, it was found that \( K \) values calculated from reliable experimental data varied in the range 0.247- 0.272, and a mean calculated \( K \) value of 0.254 was used. An arbitrary value of \( K = 0.5 \) was used in the model for input temperatures. An example of actual experimental data for output temperatures and the fitted curve are shown in Figure 5.

![Figure 5 Curve fitted using the algorithm used in the tempLag() function.](image)

3. APPLICATION

3.1 User group

The online virtual laboratory was incorporated into a module on Heat Transfer and Applied Thermodynamics as part of a two year part-time evening Diploma in Process and Chemical Engineering at University College Cork. The module was developed and delivered by the principal author of this paper. The laboratory complemented students’ exposure to STHE design
principles as part of the heat transfer section. The virtual and online nature of the laboratory were particularly suitable features for this group of part-time learners, as it could be easily used during the night time classes (and by a high number of users simultaneously) when real laboratories and associated support were off limits, while they could also be accessed remotely outside of class time. The students were introduced to the software in the computer laboratory, when they gathered the experimental data (as they would a real experiment), and began to develop the necessary spreadsheets from which relevant performance plots could be constructed and conclusions/reflections drawn. This latter part was completed by the students remotely out of class as part of their continuous assessment. The experimental procedure is shown in Table 1.

<table>
<thead>
<tr>
<th>Table 1 Experimental Procedure: Online Virtual Shell and Tube Heat Exchange Laboratory</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Choose any shell-side (cold) fluid mass flowrate.</td>
</tr>
<tr>
<td>2. For this mass flowrate, select the lowest available tube-side mass flowrates for the hot fluid</td>
</tr>
<tr>
<td>3. Press the ‘Start’ button and select any one of the four possible inlet temperatures for the hot fluid.</td>
</tr>
<tr>
<td>4. When the flowrates and temperatures have reached steady state, press ‘Record’ to record the relevant associated data.</td>
</tr>
<tr>
<td>5. Repeat for all the next tube-side flowrate and again press ‘Record’ when equilibrium has been reached.</td>
</tr>
<tr>
<td>6. Repeat for all higher tube-side flowrates and save your results onto an Excel spreadsheet (to do this use the ‘Printer friendly data sheet button’ and then cut and paste).</td>
</tr>
<tr>
<td>7. Do this for both co-current and counter current flow (this can be changed by turning the valve just below the heat exchanger by clicking and dragging your mouse over it).</td>
</tr>
<tr>
<td>8. Repeat the above for a second shell-side fluid mass flowrate.</td>
</tr>
<tr>
<td>9. From the data collected estimate the Overall Heat Transfer Coefficient, U for each of the settings you’ve considered.</td>
</tr>
<tr>
<td>10. For heat exchanger setting (co-current or counter current) and at the hot fluid inlet temperature chosen, draw plots which show how the U value changes (y axis) with mass flowrate (x-axis) of the hot fluid for each of the cold fluid mass flowrates chosen (on the same graph).</td>
</tr>
<tr>
<td>11. Identify and express the trends in U values that exist over different (hot and cold) flow rates and suggest why these are so.</td>
</tr>
<tr>
<td>12. Make sure to label all tables and charts clearly and correctly, including all the relevant appropriate units.</td>
</tr>
</tbody>
</table>

**4. RESULTS AND CONCLUSIONS**

**4.1 User survey**
The virtual laboratory experiment was designed with the intention of replacing or enhancing a real laboratory session. It was of interest therefore to see how this succeeded from the user, i.e., learner perspective, and to answer the following questions:

1. Did participants find the virtual laboratory user-friendly?
2. How did it aid understanding of the principles of heat exchanger design and operation relative to the lectures?
3. How did it aid understanding of the principles of heat exchanger design and operation compared with a real laboratory experiment?
4. Would learners actually prefer the virtual laboratory to a real lab experiment?

A survey was developed which sought to ascertain the answers to these questions, and feedback was obtained on a longitudinal basis among learners over a four-year period between 2009 and 2012. Students were also invited to provide qualitative feedback on how the virtual laboratory affected their learning experience.
4.2 Feedback results
Response rates to the survey were good, with 9 out of 10 (90%), 11/13 (85%), 11/16 (69%) and 7/7 (100%) responding over each of the respective years, giving a total response rate of 83% (38/46). Table 2 presents the aggregated quantitative feedback along with the survey questions. There was little deviation in the responses over each of the years.

On a scale of 1 to 5 (where 5 is maximum), please indicate the rating you would propose for each of the following.

<table>
<thead>
<tr>
<th>With respect to the Heat Exchanger Virtual Lab Experiment, how did you consider the following:</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>User friendliness</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>17</td>
<td>21</td>
</tr>
<tr>
<td>Usefulness in gaining a better understanding of heat exchanger design and operation compared with lectures alone</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>17</td>
<td>20</td>
</tr>
<tr>
<td>Usefulness in gaining a better understanding of heat exchanger design and operation compared with a real laboratory experiment</td>
<td>-</td>
<td>1</td>
<td>10</td>
<td>19</td>
<td>8</td>
</tr>
<tr>
<td>In this module, to what degree would you prefer the HE VLE to a real lab experiment? (3 equals no preference)</td>
<td>-</td>
<td>5</td>
<td>11</td>
<td>13</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 2 Virtual lab experiment users aggregated feedback

Users overwhelmingly found the virtual lab experiment both to be user friendly and to usefully complement lectures. A good majority (over 70% answered 4 or 5) also reckoned that this virtual lab experiment was actually more useful than a real laboratory experiment in helping them gain a better understanding of the design and operation of a STHE. Consistent with these findings, a majority (57%) also suggested that they would prefer the virtual lab to a real one. From a pedagogical perspective, while showing impressive support for the online lab, it should be noted that these responses were in the context of a cohort of evening part-time students and the associated constraints. The latter finding may also reveal a degree of comfort among contemporary learners (even adult learners) with using computers as simulators.

The qualitative feedback was no less supportive of the virtual lab experience, with the following being a representative selection of comments made:

‘Excellent tool. Gives better understanding of heat exchange.’
‘Very good that the program is online and I was able to finish the assignment at home.’
‘Extremely useful in demonstrating the principles of heat exchangers’
‘Being able to complete the experiment online means you can work on it at your own pace and you have access to it when it suits you. A real experiment may also be of benefit but I would choose the online version if I had to choose.’

In conclusion, this project has demonstrated that a well designed virtual laboratory experiment, when used in the right context, can offer significant benefits as a learning tool, even compared with real experiments.

4. ACKNOWLEDGEMENTS

The authors wish to acknowledge support for this project from the EU Leonardo da Vinci Community Vocational Training Action Programme, project SI-05-B-F-PP-176008 Computerised Laboratory in Science and Technology Teaching – PART 2.
5. REFERENCES


Byrne, E.P., 2012. Educating fit for purpose 21st century chemical engineers; appreciating complexity, inherent uncertainty and a broader perspective. 14th Asia Pacific Congress Chemical Engineering (APCChE 2012), Singapore, 21-24 February 2012.


