

# SigmaPipe as an Education Tool for Engineers

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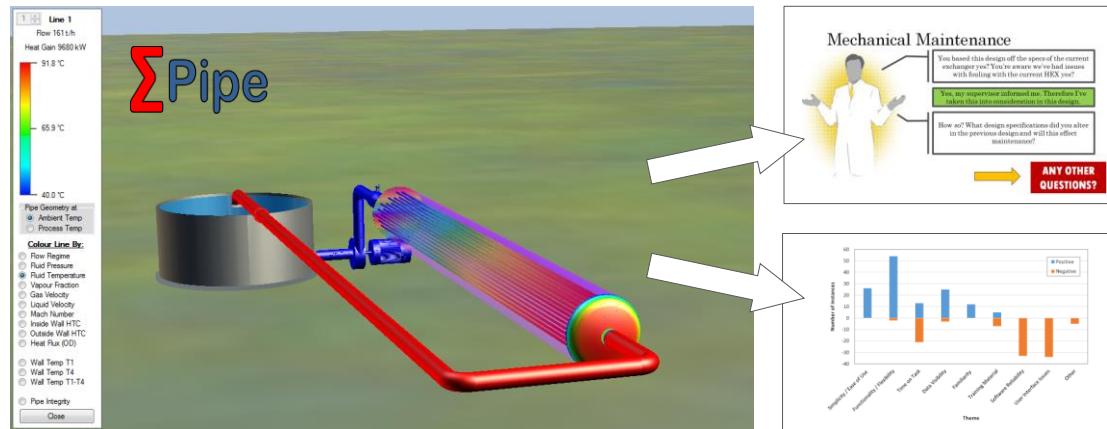
## Highlights

- SigmaPipe is free 3D software for flow and heat transfer simulations in pipes
- Software usability evaluations by students reveal positive and negative aspects
- An activity based on SigmaPipe was evaluated for teaching third-year Process Design
- Changes were made to the software as a result of student feedback

## Keywords

Fluid mechanics; Heat transfer; Software; Case study; Scenario-based learning; Process design

## Graphical abstract



## **Abstract**

Chemical engineering students are trained to solve problems involving pipe flow and heat transfer at a fundamental level. However, when they confront such problems as graduates, they often do not have time to perform such calculations. Although many commercial software packages exist, most (i) require licence fees and (ii) have a significant learning time. Consequently, commercial packages are generally not a realistic choice for the average plant engineer wanting to solve a quick, "once off" problem.

SigmaPipe is a new simulation tool that blends video game-like 3D pipe geometry with pressure drop / heat transfer calculations. It was developed as a "community service" project specifically to fill the abovementioned gap: it is free, universal and easy to use. It is envisioned that a key factor supporting SigmaPipe's uptake in industry will be creating a bond between the software and the student during undergraduate education.

Accordingly, to assess SigmaPipe's potential use in education, evaluation projects were conducted at Curtin University (WA, Australia) and Monash University (Victoria, Australia). The different methodologies and outcomes of the projects are presented here. Student feedback was generally positive and valuable ideas were generated. Importantly, the feedback has already been incorporated into the next version of SigmaPipe.

## **1. Introduction**

Engineers often need to address issues associated with fluid flow and heat transfer in piping systems. Traditional approaches involving hand calculations and/or spreadsheets are largely giving way to smart applications that reduce the time requirement and the potential for errors. This type of software tool is generally able to simulate piping flow systems to determine factors such as pressure drop, maximum possible flow, temperature/phase changes and installed valve characteristics for a given system. Commercial software in this area is reasonably well established – packages currently on offer include the following:

1. Pipe Flow Expert from Pipe Flow, UK ([www.pipeflow.com](http://www.pipeflow.com)). This system deals very well with pipe flow situations and has been available since about 2004. It has a Windows-style interface that includes piping isometrics, but not a full 3D visualisation. A “lite” version user licence will cost around \$US800 and full versions more than \$US2000.
2. Korf Hydraulics from Korf Technology, UK ([www.korf.co.uk](http://www.korf.co.uk)) has broadly similar capabilities, including a general Windows-style interface with piping isometrics. A single-user licence will cost around \$US2000 and a site licence around \$US8000.
3. AFT Fathom from Applied Flow Technology Corp, USA ([www.aft.com](http://www.aft.com)) performs a similar function and includes capability for dealing with non-settling slurries. Licence fees are thought to be broadly similar to those quoted above.

This is not an exhaustive list – Korf Technology (2015) lists some 40 fluid flow packages – the intention is merely to illustrate the type of software landscape a graduate engineer might encounter when investigating options for this type of calculation. These are commercial packages with significant licence fees. Sometimes this approach does not quite fit because the combination of cost and learning requirements renders it unattractive. Under such circumstances, SigmaPipe (as reported here) represents a possible alternative. To place this in context, it is helpful consider how the perceived need for SigmaPipe arose.

In the engineering support section of an operating plant (HIs melt Kwinana 2003–2008) there were several young engineers who, from time to time, needed to perform calculations for orifice sizing and/or pressure drop estimation. An overriding consideration was always time: they needed reliable results fast. There was no question of buying a commercial package and learning how to use it. In any case, the engineers in question might not need such a calculation again for six months or more. If they had bought and mastered a commercial package, they would (six months later) most likely have forgotten how to use it.

How, then, could these engineers get the job done? In this particular case, it became known that one individual (the lead author) had some, albeit not particularly user-friendly, Excel software for performing such calculations. It became easier to ask this person to do the calculations, and this soon became the default mode of operation. Of course, all is well if such a person is available and willing to help when needed. However, this cannot always be the case. Hence there was a gap — what piece of software would allow these young, time-poor engineers to do such calculations themselves with confidence and a minimum of fuss?

Apart from the need for zero cost and a high level of user-friendliness, the greatest requirement is familiarity. If a piece of software has not been used for an extended period, then there is an “activation hump” to get over before it can be used efficiently again. If this hump is perceived to be

too great, then the solution breaks down. This is why it was thought that exposure to suitable software during the engineer's undergraduate education would be critical. If teaching were to incorporate SigmaPipe as a normal part of the course, in the same way that process simulators like Aspen Hysys and Aspen Plus are, then activation issues are dealt with outside the pressurised, on-the-job, graduate environment. It would become quite natural for the young engineer to reach for and use a familiar tool with confidence and competence. Even if such a tool were needed only occasionally, it does not really matter if sufficient familiarity were retained from undergraduate days.

Setting aside graduate concerns for the moment, Campbell and Latulippe (2015) point out two benefits of incorporating commercial-quality software in undergraduate fluid mechanics teaching compared to the use of manual calculations alone. First, it may lead to a deeper understanding of fluid flow concepts and consequently an improved ability to solve practical problems. Second, it allows the convenient analysis of much more complicated, realistic systems. Fraser et al. (2007) also argue the benefit of using fluid flow simulation software early in the course for concept development, which is distinct from its use as a calculation tool by more senior students. It should be noted that teaching commercial heat transfer and pipe flow software, like the abovementioned packages, appears to be uncommon in undergraduate chemical engineering courses (Campbell and Latulippe, 2015).

With the preceding context in mind, SigmaPipe was developed by the lead author with the following key design principles:

- It is essentially a community service project (the engineering community in this case).
- It is designed as a standard Windows application in terms of menus, editing and so on.
- The user must be able to create and manipulate pipe-related objects in 3D space with ease.
- Flow solutions are essentially 1D in nature – it is not a CFD package.
- As far as possible, physical reality must be reflected (e.g. if pipes heat up, they expand; if sonic limitations like choked flow occur, they must be dealt with seamlessly).
- Common elements (e.g. valves, pumps and heat exchangers) must be included.

Based on these guiding principles, coding started in early 2009. The first major release version, a free download from [www.sigmapipe.com](http://www.sigmapipe.com), went online in January 2013 and the second (SigmaPipe 2.0) in January 2014 as a Windows-based application suitable for Windows 7 or later (it will also run on Windows 8 and Windows 10). The two evaluation projects reported in this article were performed using Version 2.2. Improvements to the software have been made as a result of the evaluation projects, and these are discussed later.

The aims of this study are to:

1. Provide a high-level overview of SigmaPipe, noting particularly its user interface features, calculation and reporting capabilities, and its underlying assumptions;
2. Evaluate the software usability of SigmaPipe as perceived by undergraduate chemical engineering students for the purpose of guiding its future development;
3. Evaluate a scenario-based learning activity featuring SigmaPipe aimed at developing high level problem solving skills in a third-year undergraduate Process Design unit;
4. Implement improvements to the software based on the evaluation projects and reflect on possible further developments.

The second and third aims were addressed in projects conducted at Curtin University and Monash University, respectively, both in 2014.

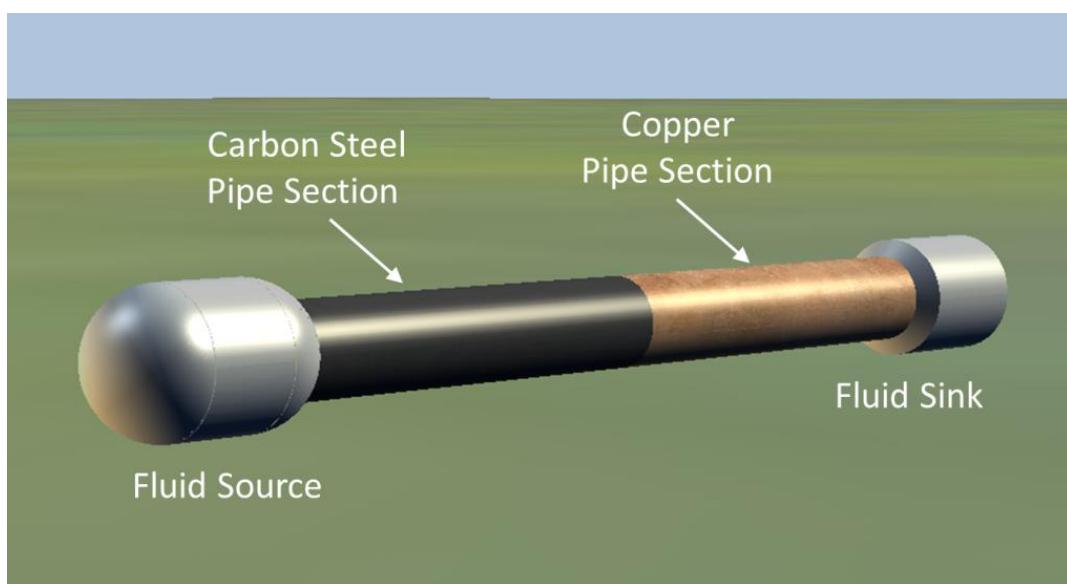
The framework employed in this project is the Case Study, which is used when there is a need for the validation of findings emerging from an analysis of a single case or phenomena (Case and Light, 2011; Flyvbjerg, 2001). It is an in-depth examination of a distinct, single instance of a class of phenomena such as an activity, group, individual or event and often involves a small sample size to allow the researcher to look into situations for logical deductions of the type “if this holds for this case, then it will hold for other cases” (Shepard and Greene, 2003).

## 2. Features, capabilities and methods of SigmaPipe

This section, which expands on previous work by one of the authors (Dry, 2014), gives an overview of the typical workflow of setting up and solving problems in SigmaPipe. It gives an insight into some of its basic and advanced features, sets out the principal calculation methods, and summarises the current training materials.

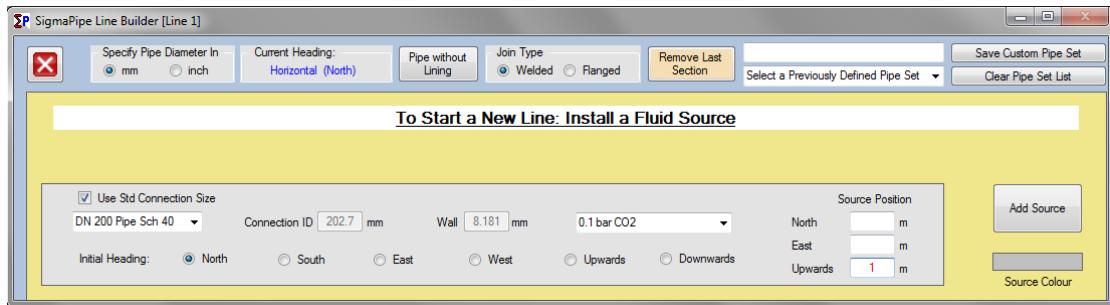
### 2.1 Setting up a pipeline

At its most basic level a SigmaPipe simulation consists of a fluid source, a collection of pipe sections and a fluid sink. Fig. 1 shows a simple system involving two pipe sections, one in carbon steel and the other in copper. Note that all 3D figures shown in this paper are screen shots from SigmaPipe’s main user interface. This interface is fully 3D in the sense that objects can be rotated, zoomed and viewed from any angle.

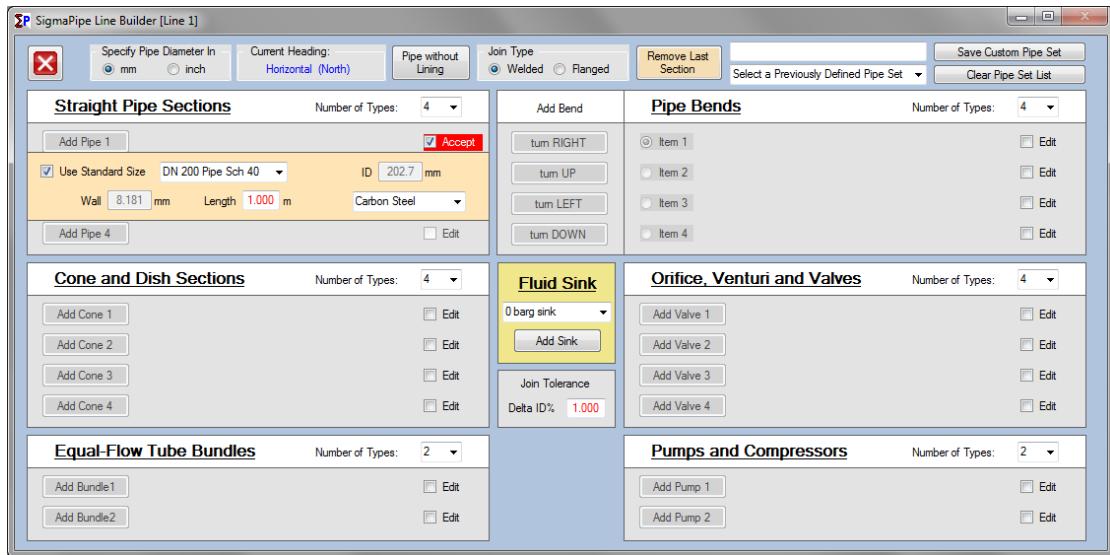


**Fig. 1 – A simple pipe system in SigmaPipe, illustrating the 3D environment and the basic elements needed: a fluid source, pipe sections and a fluid sink (Dry, 2014).**

To enter these items, the user starts by defining a fluid source object via a “Line Builder” interface as shown in Fig. 2. Once this has been done, pipe objects of various types can be defined as shown in Fig. 3. The user is then able to add them to the source, and subsequently to the open end of the growing line, by simply clicking on the relevant “Add” button. Finally, a fluid sink object is added by similar means.



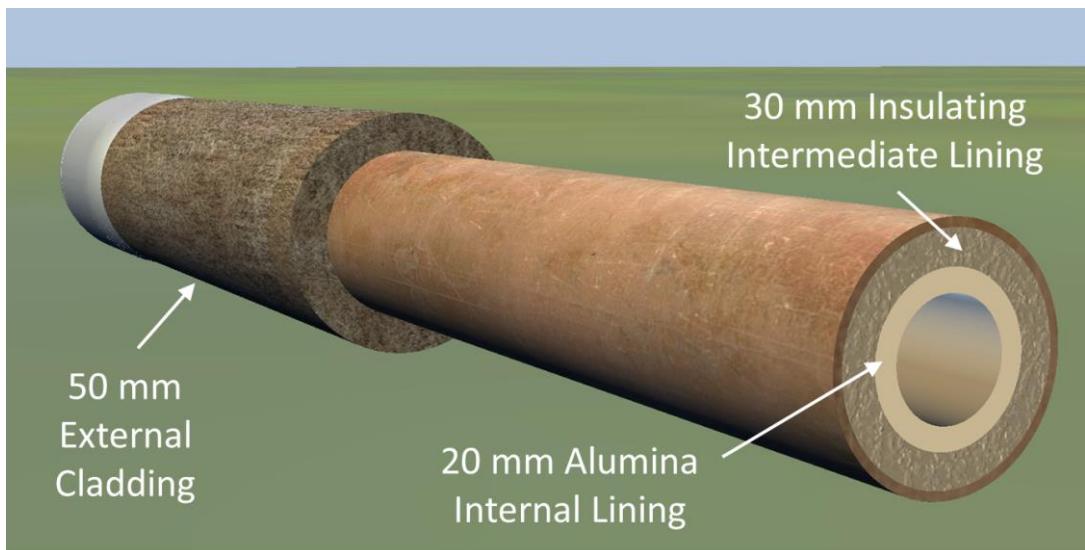
**Fig. 2 – SigmaPipe’s Line Builder interface: installing a new fluid source.**



**Fig. 3 – SigmaPipe’s Line Builder interface: defining a new pipe section.**

Pipe sections may be constructed from any of 21 standard materials (e.g. carbon steel, 316 stainless steel, copper, cement, PVC plastic, etc.). User-defined materials of construction can also be used. For example, if a user would like to specify carbon steel with a given wall roughness ratio, then a new material can be defined based on the existing carbon steel and the wall roughness can be set to the desired value.

Pipe diameters (ID and OD) can be defined (i) in terms of standard sizes (e.g. DN200 Sch 40) or (ii) as a user-defined ID and wall thickness. Internal lining and external cladding options are shown in Fig. 4 – the user can define a single external cladding layer and a single or double layer internal lining.

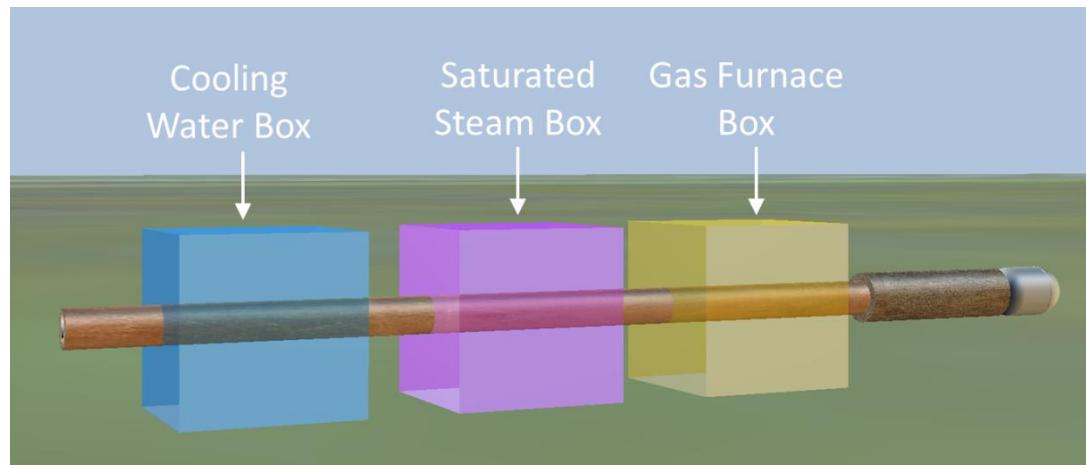


**Fig. 4 – Examples of SigmaPipe's pipe lining and cladding options (Dry, 2014).**

Conditions outside the pipe (ambient air) can be defined by specifying temperature, pressure, humidity and wind speed, and the pipe will interact with this set of global ambient conditions for radiation and natural convection heat transfer calculations. Wall temperature gradient and wall heat flux will be monitored and reported, together with wall stress generated as a result of the wall heat flux. This will lead, in general, to the pipe wall temperature being different from ambient temperature. As a result, the physical size of the pipe, its length in particular, could change due to thermal expansion. This geometry change is monitored and shown in 3D in the results.

In a particular application, parts of the external pipe could be exposed to something other than the global ambient conditions. As shown in Fig. 5, SigmaPipe allows for three different types of external “process container” to accommodate some common external heat transfer environments:

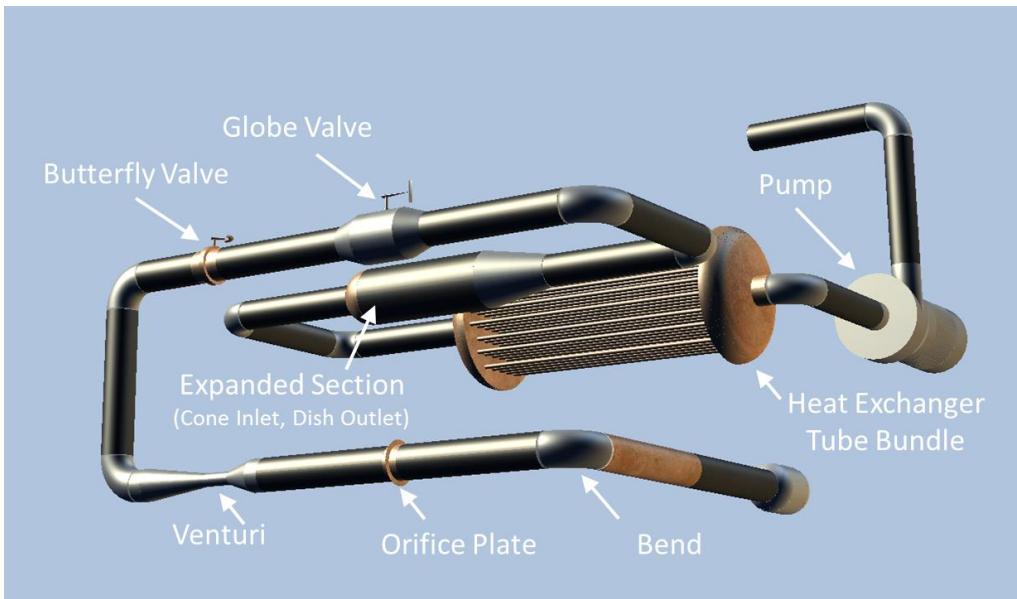
- Gas furnace box – typically hot flue gas with a given temperature and velocity;
- Saturated steam box – saturated steam at a given pressure;
- Cooling water box – water with a given temperature and average velocity.



**Fig. 5 – Three types of external process containers can be used in SigmaPipe to specify a pipe’s environment in addition to the default, ambient air (Dry, 2014).**

The pipe section inside each box will experience “local ambient” conditions as defined by the box object, not by the global ambient settings. Any pipe section that is outside a process box will experience the normal, global ambient conditions.

These, then, are the basics of how SigmaPipe deals with pipe sections. Of course, plain straight-pipe objects are not enough – some of the other standard object types are shown in Fig. 6. The user can assemble these pipe element types in any desired combination. After assembly it is also possible to edit individual elements and, if necessary, to resize the whole line.



**Fig. 6 – A selection of other element types – beyond straight pipe, source and sink – that are available in SigmaPipe (Dry, 2014).**

After specifying the pipe system and external environment, the next issue is selection of a fluid type. Currently available fluid types are:

- Argon
- Oxygen
- Nitrogen
- Water/steam
- Carbon dioxide
- Carbon monoxide
- Methane
- Ethane
- Ethylene
- Propane
- n-Butane
- Ammonia
- Hydrogen sulphide
- Sulphur dioxide

The user may nominate any mixture of these types, along with the supply temperature and pressure. In the current version of SigmaPipe, only Raoult’s Law interactions between components are assumed – this is an area for future development. For each fluid type, a wide range of thermodynamic and transport properties are stored in a database, including thermal conductivity, speed of sound and

similar. For water/steam the full range of ASME97 steam table equations (Parry et al., 2000) is used, and for the other species NIST data (NIST, 2014) are generally used. Where necessary, extrapolation is performed to allow simulation over the temperature range 100–3000 K (−173 to 2727°C) and pressure range  $10^{-12}$  to 500 bar absolute.

In the current version of SigmaPipe, it is not possible for the user to add other fluids. Adding another fluid is not a simple matter: data consistency and range are major issues, and significant testing is needed to ensure the integrity of the calculations. Adding further fluid types is a matter for future development. The current fluid database is aimed at typical plant systems involving utilities, combustion/gasification, steam cycles and natural gas processing. It is expected that these will adequately cover a fair proportion of situations encountered by plant process engineers.

The final selection item for the user is defining a fluid sink. In SigmaPipe a fluid sink object may be regarded as a constant-pressure “black hole” into which fluid disappears. The pressure of the sink is the only item the user needs to specify.

## **2.2 Calculation methods**

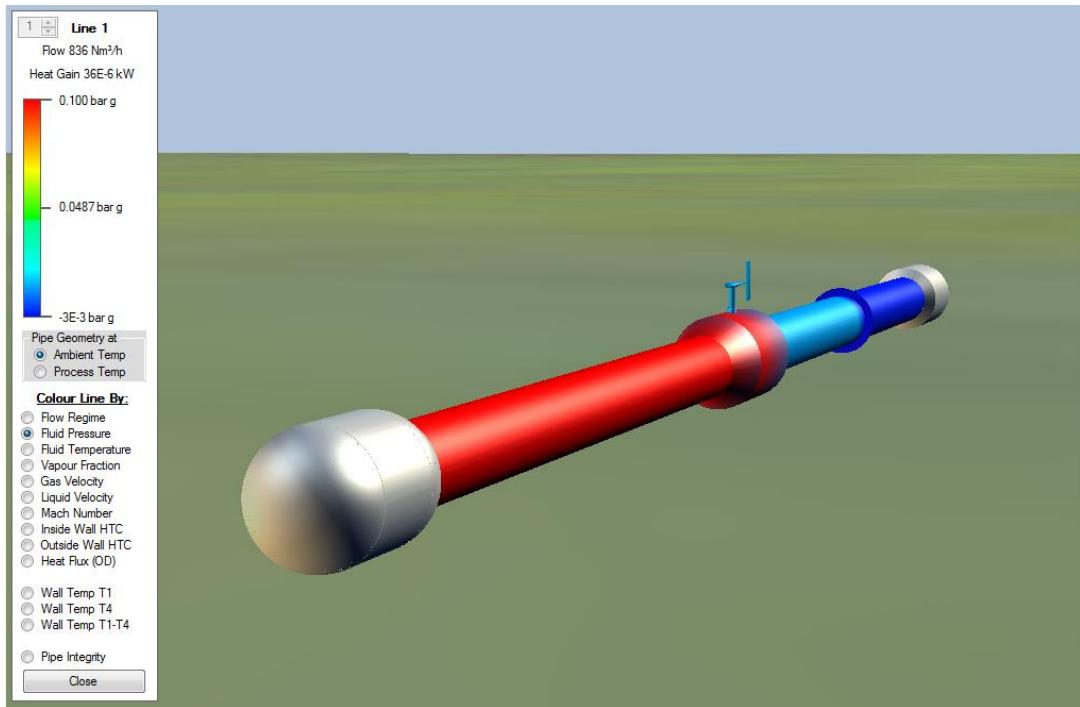
The methods used to calculate pressure drop and heat transfer are generally the same as those typically taught in the undergraduate curriculum. In particular, the following methods and assumptions are used:

1. For single-phase pressure drop, the wall friction contribution is determined via the full-range Fanning friction factor equation of Churchill (1977).
2. Loss factors recommended by Coulson and Richardson (1977) are used for pressure loss in pipe bends and other fittings.
3. For two-phase flow pressure drop, the equations of Lockhart and Martinelli, as presented by Coulson and Richardson (1977), are used.
4. Bernoulli’s equation as described in Coulson and Richardson (1977) is used to track static, elevation, velocity and frictional head components of the flow.
5. Every fluid has an associated speed of sound at the prevailing pressure and temperature, with mixtures using a molar average. The calculation procedure checks for velocities in excess of Mach 1 and, when necessary, limits the solution to this value.
6. For single-phase flow, laminar heat transfer coefficients are evaluated using the Hausen correlation and for turbulent flow the Sieder-Tate equation is used as reported in Perry and Green (1984), equations 10-49 and 10-50, respectively.
7. For transitional flow (between laminar and turbulent) the heat transfer coefficient expression from Coulson and Richardson (1977) given by equation 7.60 is used.
8. For boiling heat transfer, the method described in Shah (1976) is used.
9. For condensing heat transfer, the methods used are those outlined in Section 2.6 of Hewitt (1996).

It is understood that application of these types of engineering correlations will not always give a precise result. In most cases this is of little concern, as long as the solution is approximately correct and trends in behaviour from one case to another can be compared. However, in some instances a more precise base-case calibration is needed; e.g., setting up a SigmaPipe model to agree with an actual set of measurements before simulating different operational or design alternatives. SigmaPipe accommodates this by providing a set of transport factor parameters that the user can adjust to tune individual components of pressure drop and heat transfer. In this way it is possible to calibrate the pressure drop and heat transfer predictions when there is a need to do so.

### 2.3 Solving and viewing results

Once a fluid source, a pipeline (that is, a combination of pipe elements) and a fluid sink are in place, the user can solve the model. The user can then examine the results (i) as a colour gradation along the pipe wall as illustrated in Fig. 7 or (ii) as a result graph as shown in Fig. 8.



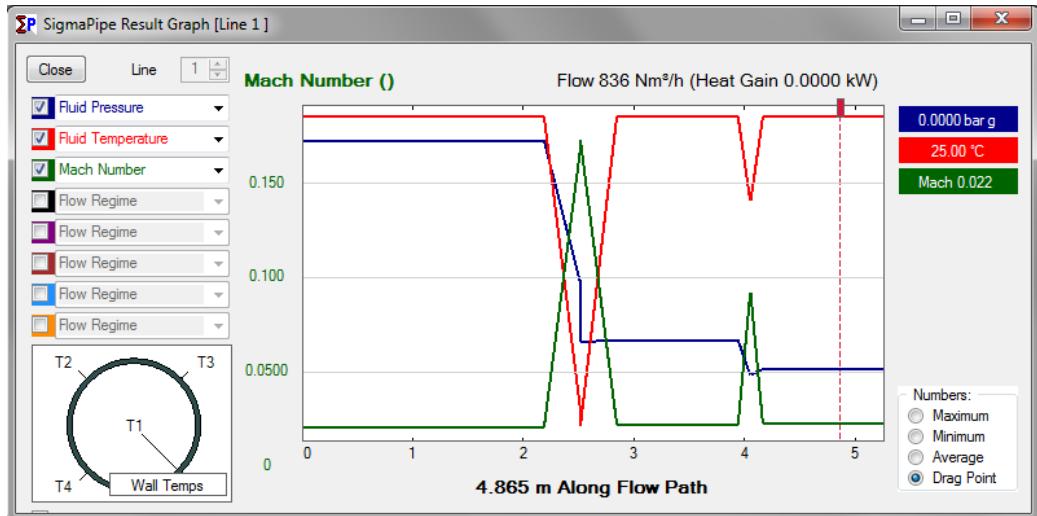
**Fig. 7 – Example of SigmaPipe results using colour gradation to show the fluid pressure distribution along a pipe system with a globe valve (upstream) and an orifice plate (downstream) (Dry, 2014).**

To help visualise the results, the user can select from the following parameters for colouring the pipe wall:

- Flow regime (gas, liquid, stratified horizontal, bubbly flow, etc.)
- Fluid pressure
- Fluid temperature
- Vapour fraction
- Gas velocity
- Liquid velocity
- Mach number
- Inside wall heat transfer coefficient

- Outside wall heat transfer coefficient
- Pipe wall heat flux
- Inside wall surface temperature
- Outside layer outer wall surface temperature
- Temperature difference between innermost and outermost wall surfaces
- Pipe integrity (in terms of wall stress as a function of maximum allowed stress)

For each of these parameters, where appropriate, the user is able to select his or her preferred units of measure; e.g., for pressure: bar absolute, bar gauge, kPa, mbar, psi, mm Hg, etc.



**Fig. 8 – Example of SigmaPipe result graph showing pressure, temperature and Mach number for the same system as shown in Fig. 7 (Dry, 2014).**

Other output features include an ability to toggle the pipeline between ambient and process temperatures in order to visualise the degree of thermal expansion. Fixed points and linear thermal expansion compensators can also be defined to assess movement allowances and mechanical integrity strategies.

Each material of construction has a stress versus temperature curve that defines the yield point. When a fluid flow solution is calculated, SigmaPipe automatically computes wall stress as a percentage of yield stress at the prevailing process condition. If yield stress, or more precisely, yield stress divided by a user-defined safety factor, is breached, SigmaPipe reports this as a pipe wall integrity failure. Pipe wall integrity is included as a standard output that may be viewed in the same way as any other output variable.

## 2.4 Training materials

Training material is available on the SigmaPipe website ([www.sigmapipe.com](http://www.sigmapipe.com)) in the form of downloadable PowerPoint modules and related YouTube video links. While this material is primarily a self-guided introduction to the software, it also demonstrates some of the range of SigmaPipe's capabilities. A summary of the current training modules is shown in Table 1. They start in Module 1 with a simple, pre-defined example that needs little user input. Module 2 is a broad presentation of the many features and capabilities of the software that users would find helpful. Subsequent modules cover a variety of particular topics and skills. Most modules guide the user to develop a base

case simulation and then the user is prompted to examine or change the simulation to answer questions that are typical of plant operations; for example:

- What is the pump power requirement at the design conditions?
- What is the maximum water flow through this system when the valve is 100% open?
- If a fouling layer equivalent to 1 mm of cement is present on the cooling water side of the tubes, what is the expected reduction in steam condenser capacity?

**Table 1 – Summary of available SigmaPipe training materials.**

Module	Main new topics covered
1	<ul style="list-style-type: none"> <li>• Software installation</li> <li>• What is SigmaPipe?</li> <li>• Pre-defined Quick Start simulations of nine simple configurations</li> </ul>
2	<ul style="list-style-type: none"> <li>• User interface – toolbar, keyboard and 3D environment</li> <li>• An overview of capabilities for setting units, fluid, materials of construction, ambient conditions, source, sink, pipe sections, fittings, heat exchange tube bundles and process boxes</li> <li>• Editing, duplicating and removing pipe sections</li> </ul>
3	<ul style="list-style-type: none"> <li>• Worked example: choked flow of nitrogen through an orifice</li> <li>• Using a Quick Start option, editing fluid source, line and fitting sizes</li> </ul>
4	<ul style="list-style-type: none"> <li>• Worked example: water flow through a valve and orifice with an elevation change</li> <li>• Adding bends to allow for an elevation change, specifying a valve characteristic curve and viewing results in a graph and in the 3D environment</li> </ul>
5	<ul style="list-style-type: none"> <li>• Worked example: pump characteristics and flow through a long, elevated pipe</li> <li>• Specifying a pump characteristic curve and setting flow solver options</li> </ul>
6	<ul style="list-style-type: none"> <li>• Worked example: steam condenser with and without fouling</li> <li>• Simulating a tubular heat exchanger, adding tube lining to simulate fouling, hiding / revealing elements in the 3D environment</li> </ul>
7	<ul style="list-style-type: none"> <li>• Worked example: gas compressor with intercooler and aftercooler</li> <li>• Repositioning pipework, and copying and pasting an existing heat exchanger</li> </ul>
8	<ul style="list-style-type: none"> <li>• Overview of structural elements: foundations, support beams, plates and similar</li> <li>• Cutting slabs into different shapes, creating multiple copies and grouping elements</li> <li>• Worked example: creating a shed consisting of foundation, roof and roof support columns</li> <li>• Worked example: creating a bank of water-cooled solids injection lances for a smelter vessel</li> </ul>

### **3. Curtin University SigmaPipe Project 2014**

#### **3.1 Curtin context**

A research project was conducted in the Chemical Engineering Department at Curtin University in 2014 to investigate how engineering students perceived SigmaPipe. The project was principally

undertaken by one of the authors (HR) as his fourth year research project (Research Projects 411 and 412), which corresponded to 25% of his final year workload.

The aim of the project was to investigate *the usability of SigmaPipe software* with a view to providing evidence to inform future development work. The ultimate goal is to embed the software as part of the engineering curriculum so that it becomes known and readily used by graduate engineers. Usability was defined as “the capability of a software product to be understood, learned, used and be attractive to the end user, when operated under specified conditions” (International Organisation for Standardisation, 2001).

### **3.2 Curtin methodology**

Evaluation of usability for any system or software is a significant part of its development. Commonly used methods for usability evaluation in educational research are observations, questionnaires and interviews (Dix et al. 1998; Nielsen, 1993). Dix et al. (1998), however, recommend using the thinking aloud method to evaluate software usability, and it is the method employed in this study. The thinking aloud technique has been proven to be one of the most effective ways to assess higher level thinking processes and to study one’s thoughts while doing a particular task (Charters, 2003).

Thinking aloud is where the test user is encouraged to talk while she/he is carrying out set tasks given by the observer. This type of observational technique is simple, but the information provided by the user will be subjective and selective (Dix et al., 1998). As the test users are verbalising, the researcher observes how they view the software and identifies their difficulties (Nielsen, 1993). The goal of the researcher is to be “invisible” to the test user and to create an environment as close as possible to the real world conditions present when the software is used.

Two challenges of this method are choosing the level of difficulty of the set tasks and the communication with the users. The selected task was hard enough that the user would not stop verbalising thoughts as his/her actions become near automatic or automatic (Charters, 2003), but not too demanding to create a large cognitive load, which has been found to interfere with verbalisation. As suggested by Gibson (1997) and Olsen et al. (1984), the test users were briefed about the study’s aim, the thinking aloud technique and what they would be required to do.

The participants (test users) involved in this study were five chemical engineering students in their third or fourth year. They had completed Fluid Mechanics and Process Heat Transfer subjects. This means that they would understand the theory behind SigmaPipe. They were experienced computer users, but had not previously used SigmaPipe. The researcher aimed to have participants with a range of Course Weighted Averages (CWAs). One student had a CWA of 60–69, two had CWAs of 70–79, and the final two had CWAs over 80. The participants were gathered by advertising the opportunity to help evaluate SigmaPipe for its potential use in chemical engineering projects. The selection was not based on gender, age or cultural characteristics. In contrast to the Monash University project (Section 4), this study was not focussed on a particular teaching unit. The study was approved by the Curtin University Ethics Committee (Approval Number ENG-26-14).

The testing was done in four-hour sessions, on a one-to-one basis, with breaks when needed. Three hours were allocated for learning SigmaPipe 2.2 using the supplied training modules (Table 1), and one hour was allocated for carrying out a set task. The same computer was used in all sessions. The test users were assured that the aim was to evaluate the software, not the user.

The set task was framed as a plant troubleshooting exercise – to explain why a lower flow rate was experienced through an existing section of pipework when the upstream fluid temperature was increased. The following problem statement was provided:

*A scrubber discharges water at 0.1 barg and 72°C into a DN 300 Sch 20 carbon steel pipe. The pipe run is as follows:*

- (i) horizontal for 2 m then
- (ii) turn (horizontally) through 90° (smooth bend)
- (iii) run a further 40 m (horizontally)
- (iv) turn 90° downwards (smooth bend)
- (v) run vertically down 8 m.

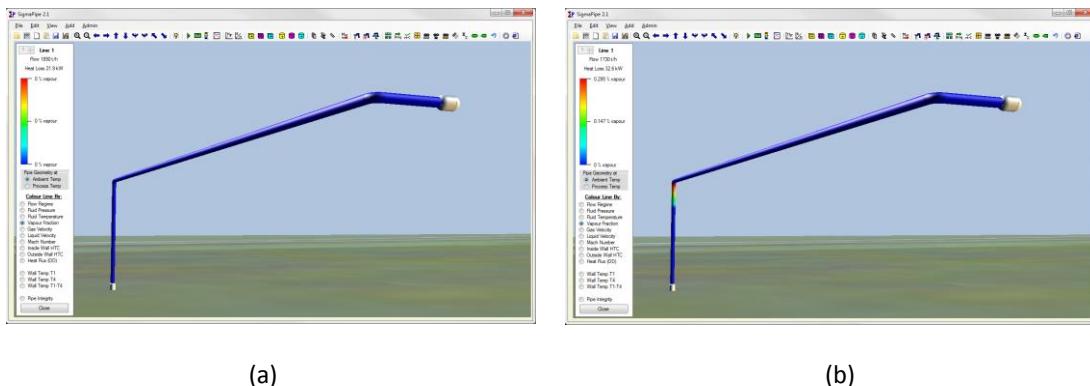
*This pipe then discharges 0.3 m below the open surface of a water clarifier tank (i.e. the sink pressure is 0.03 barg and the pipe is always full of water).*

*This scrubber has been operating well for years. The flow of water in the discharge line was usually close to 1900 t/h. Recently, a process change associated with plant debottlenecking has resulted in water entering this line at 82°C (same pressure as before).*

*The flow of water was expected to remain about the same (within 1%), but plant measurements show it has actually dropped by about 8–9%. There is speculation about the cause – could it be an obstruction of some kind, or is it something else?*

*Your challenge is to analyse this and decide what is causing it.*

The test users needed to simulate the system for the original upstream temperature then increase the upstream temperature and use the visualisation facilities to help uncover why the flow rate had dropped. Fig. 9(a) shows the simulation that the students would construct for the first part of the set task. When the upstream temperature is increased, some flashing occurs after the second bend (Fig. 9b), causing a reduction in the flow rate – the source and sink having fixed pressures in this scenario.



**Fig. 9 – Set task used in the Curtin University case study: (a) simulation of an existing pipe system with the fluid source in the foreground and the sink in the background, and (b) simulation for an increased upstream temperature that shows flashing near the second bend.**

Throughout the session, the test user's voice and computer screen were recorded. If the test users fell silent for 1–2 minutes, they were reminded to keep talking (Ericsson and Simon, 1993). The researcher observed any actions and body language by the participant that were not recorded by the microphone. Having more than one source of data from the testing increases the reliability and accuracy of the results (Sugirin, 1999). If the test users asked questions the researcher answered very briefly. When occasional technical problems arose, the researcher rectified them.

The voice recordings were transcribed and matched, where needed, with images of the user's screen. Positive and negative statements relating to software usability were identified in the transcriptions then the statements were examined for emerging themes.

### **3.3 Curtin case study results and evaluation**

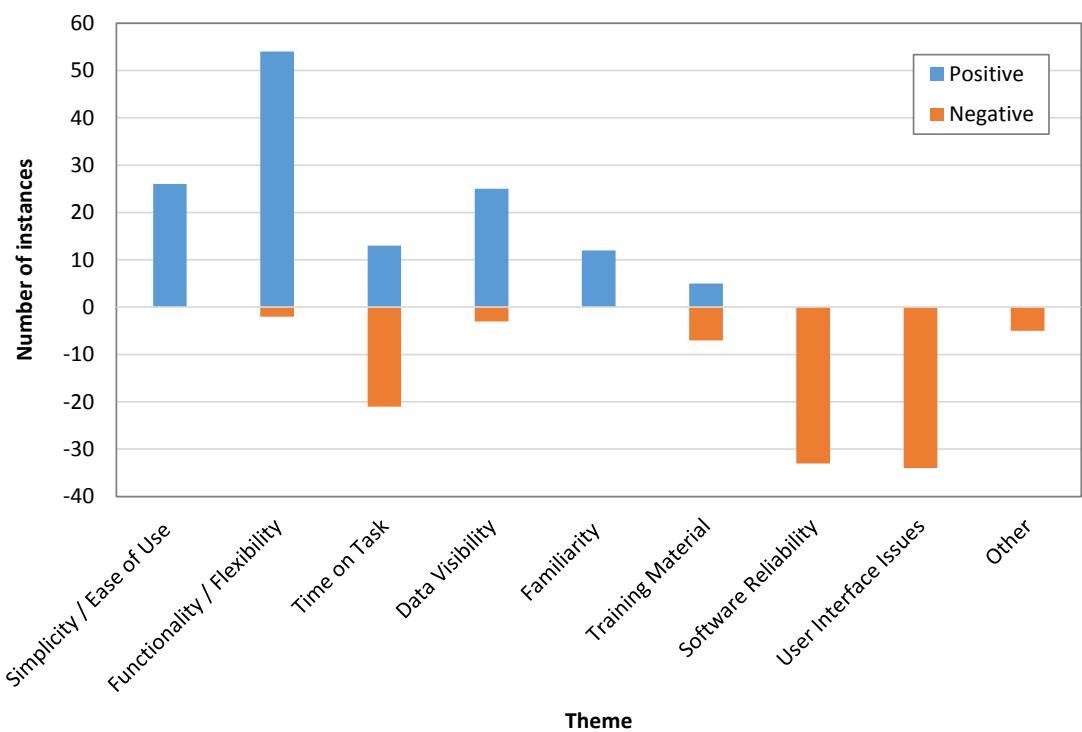
The five test users made a total of 184 statements relating to usability, 93 classified as positive and 91 as negative. From these statements, eight main themes were identified as reported in Table 2, which also includes an "Other" category for a small number of statements that were ambiguous.

**Table 2 – Classification of test users' comments on software usability from the Curtin University case study.**

Theme	Description	Examples of user statements
Simplicity / Ease of Use	Software features and actions needed are easy to understand; concepts are easy to grasp.	<ul style="list-style-type: none"> <li>• "I find it easy to use the mouse."</li> <li>• "It's convenient that you can copy one heat exchanger and copy downstream near the outlet... Simple procedure."</li> </ul>
Functionality / Flexibility	Being able to alter settings and default inputs easily or not; the ability to choose according to the user's preference; general comments on software functions.	<ul style="list-style-type: none"> <li>• "Define the properties of the materials... You can make your own materials if you want... That's good."</li> <li>• "With the texture, you can't have your own one."</li> <li>• "That's pretty useful, having a split screen... I like that."</li> </ul>
Time on Task	When using a certain function or when carrying out a certain action, time is saved or wasted.	<ul style="list-style-type: none"> <li>• "I like that feature – it'll automatically find that point on the graph."</li> <li>• "It would be just annoying, if you were given the values in a different unit and would have to go back to another screen to change that."</li> </ul>
Data Visibility	How well or not information is shown; numerical data, error messages, graphical displays of inputs and results.	<ul style="list-style-type: none"> <li>• "If the axis is intersecting the object then it can be hard to move or even find."</li> <li>• "You can look anywhere along the graph and see different values... that's good."</li> </ul>
Training Material	While using the training materials, the direct comments about it and statements said while using it.	<ul style="list-style-type: none"> <li>• "Would have liked it to have the tool strip button page earlier on [in the training material], because sort of... I'd have gone through each one before reaching this."</li> <li>• "The actual pipework seemed good and I see it being used... Simple to replicate the pipes..."</li> </ul>

		Liked the step by step guide... Easy to follow."
Familiarity	Actions and features that are familiar to the user; past experiences from other software.	<ul style="list-style-type: none"> <li>“So yeah deleting things is pretty standard, like any program.”</li> <li>“Mouse movements seem straightforward and pretty similar to what I used before.”</li> </ul>
Software Reliability	Instances where the software behaved out of the norm; where functions or actions are not carried out properly.	<ul style="list-style-type: none"> <li>“Changing material to glass, and then the sheet location altered automatically.”</li> <li>“Double clicks on pipe item... Error message appears.”</li> </ul>
User Interface Issues	When there are graphical and technical issues while using the software; general comments on the appearance of menus and control of the software.	<ul style="list-style-type: none"> <li>“I guess that's too big for the screen.” [referring to Transport Factors menu]</li> <li>“Bit hard to click on the pump, for some reason.”</li> <li>“Be nice if you could use keyboard as well to move things...”</li> </ul>
Other	Ambiguous statements that could not be categorised in the themes above.	

Most statements were coded to one theme; however, a portion of statements were coded to two or three themes. For positive statements, 57% had a single theme, 37% contained two themes and 6% spanned three themes. For negative statements, 87% were single-themed and 13% had two themes. Consequently, while 184 statements on usability were recorded, there were 240 instances of comments related to the identified themes.



**Fig. 10 – Number of positive and negative user comments on software usability classified according to theme from the Curtin University case study. Note: negative numbers are used for negative comments.**

Fig. 10 shows the breakdown of positive and negative comments by theme. Two of the themes were associated only with positive comments, three only with negative ones and the remaining four themes contained a mixture of positives and negatives. Functionality / flexibility was the most common theme overall with 54 instances, or around one fifth of the total comments. Positive comments on functionality / flexibility outnumbered negative ones by a factor of nearly 30. The users' statements included:

- “It’s good the way you can put the structural stuff in and remove or hide it when you want to see the pipes only.”
- “The pump graph, it tells you that it’s cavitating or not.”
- “Kind of cool that you can scroll and open the valve.”
- “I like how it has heaps of quick start options.”

Simplicity / ease of use and data visibility also featured strongly in the positive comments, each being referred to about 25 times. Positive comments were also made about time-saving features, its similarity with other software and about the training materials. The users seemed to appreciate most the software's functionality, ability to visualise the input data and calculation results, ease of use and its intrinsic familiarity because of software they already knew.

The test users had mixed views about the time taken to perform tasks and the training materials, with both positive and negative comments being made. For these two aspects of usability, there were around 50% more negative comments than positive ones. It should be noted that there were fewer comments about the training materials compared to time on task. Overall, the users indicated that there were certainly time-saving features, but there were also aspects of the software that took up more time than they felt should be necessary. Further examination of the statements related to time on task revealed possibilities for changes to the current version of the software, such as the ability to define or change several items at the same time, rather than individually, and to change units using a local drop down list instead of the main menu. Around one third of the negative comments on the time taken to perform tasks were also associated with themes of user interface design and perceived reliability of the software.

Software reliability problems and user interface issues were perceived as the most negative aspects of the software's usability, each receiving around 30 comments. The problems included:

- Difficulty viewing, moving, selecting or grouping items from time to time
- Not understanding error messages
- The use of CTRL-Z for an action aside from “Undo”
- The need, on occasion, to fix a problem by deleting temporary files

In a few cases, the user interface design of SigmaPipe was compared with that of the commercial flowsheet simulator Aspen Hysys, which they had been exposed to in second and third year. Detailed analysis of these user comments on the perceived negative aspects of usability of SigmaPipe 2.2 has helped guide the further development of the software. Many of the issues raised have been addressed in SigmaPipe 2.3 as outlined in Section 5.

## **4. Monash University SigmaPipe Project 2014**

### ***4.1 Monash context***

A parallel research project into undergraduate student experiences with SigmaPipe was carried out in the Department of Chemical Engineering at Monash University as part of a Final Year Research Project (CHE4180) by one of the authors (DF). The project constitutes half of a full semester enrolment.

The Chemical Engineering course at Monash University includes the use of simulation packages (e.g. Hysys, Matlab) across a range of units, mostly focussed in the area of chemical engineering design. However, in most cases, students have to spend a significant amount of time learning how to use the simulator even when tackling simple problems, such as flow in networks of pipes. Furthermore, it becomes difficult to maintain a balance between the time students invest in learning to use a simulation tool and the time they have for developing skills in “high-level problem solving”, which requires them not only to analyse and solve a problem but also to evaluate its solution.

It is universally acknowledged that problem solving and analytical skills are highly valued in engineering graduates and even more perhaps if combined with the use of simulation software (Lucas et al., 2014; International Engineering Alliance, 2013; Male et al., 2010).

In view of this, it was proposed that, as part of a Final Year Research Project, a student would design a learning activity aimed at developing high-level problem solving skills in the context of process design. It was expected that involving a student in the design of the activity would help to make it engaging for other students.

The main objective of the project was to create a meaningful learning activity that develops high-level problem solving skills using an industrial context as a motivational element and that would be suitable for delivery in the third year Process Design unit (CHE3166) at Monash. The activity was also intended to provide an opportunity to reinforce concepts and knowledge already acquired by performing design hand-calculations for problems related to flow in pipes and heat exchanger systems.

Therefore, key to the development of such an activity was the selection of a software tool that would be simple for students to learn while also being able to generate quickly results of long calculations so that students could evaluate alternative solutions. It was proposed to use SigmaPipe for this activity due to its simplicity, accessibility and capacity for object visualisation, which is not least important in the educational context.

### ***4.2 Monash activity design***

In the design and development of the learning activity, focus was placed on three main aspects: the learning framework, suitable pedagogies and the learning context.

As the main aim of the activity was to develop high-level problem solving skills, the learning framework used here to guide the creation and development of the activity was student-centred learning informed by social cognitive theory (Svinicki, 2010). From this perspective the learning should be focused on students’ skills, knowledge, needs and attitudes and result in the development of metacognitive skills through applying their problem solving in a different context, which is also referred to as “problem-solving transfer” by Mayer (1998). The development of metacognitive skills

can be achieved when solving problems in a realistic work setting. Likewise, motivation plays a key role in becoming a good problem solver (Mayer, 1998).

Based on this, Scenario-Based Learning (SBL) and e-learning were considered suitable pedagogies to be used in the development of this activity. SBL simulates a workplace environment with authentic challenges and associated tasks (Errington, 2011). The realistic nature of the scenario provides opportunities to develop skills (e.g. problem solving) that cannot be developed commonly through tutorial questions alone (Rashid and Ventura-Medina, 2012). The method used in the development of the scenario was adapted from the EMERGO method that has been successfully used in the development of scenarios in different contexts (Hulme et al., 2009; Nadolski et al., 2008; Rashid and Ventura-Medina, 2012).

Finally, the following aspects about the learning context were taken into consideration when designing the activity:

- the Process Design (CHE3166) unit's aims and intended learning outcomes, and the context of the activity as the basis for a meaningful engineering experience,
- students' comments from unit evaluations regarding improvement to activities and course delivery,
- format and modes of delivery (e.g. suitable for a wide range of learning styles, on- and off-campus, inside and outside scheduled unit times),
- software capabilities and ease of use.

The aim of the Process Design unit, as described in the course handbook (Monash University, 2014), is to develop knowledge and skills in the interrelated themes of process safety, mechanical integrity, equipment selection and operability. The learning outcomes associated with this unit that were considered key to achieving the objectives of the project were based on the design of heat transfer equipment, as this was an area where students had some prior knowledge and some practice with routine calculations. Moreover, this was an area targeted for further cognitive development within the unit, which included routine practice hand-calculation problems related to heat exchanger design, selection and optimisation. Inherent to equipment design is always the consideration of equipment safety, which was a new knowledge area for the students in this unit. The development of an appreciation of the role of the chemical engineer and his/her relationship with other professionals was addressed by setting the problem in an industrial context. An open-ended problem was created for the activity with particular focus on design optimisation in order to address all the intended learning outcomes (Monash University, 2014).

Students' comments from previous unit evaluations were also considered. One comment indicated that students liked open-ended problems: "*I liked that some tutorials required problem solving, not just calcs.*" In general the comments pointed out the need for more open-ended problems with industrial relevance and more guidance in tutorials.

Students also recognised that there was in general a disparity – between the open-ended assignments and the practice questions in the tutorials – that should be addressed by having more complex problems among the tutorial questions. The data were used only qualitatively to take into consideration the students' learning needs. It was decided to provide opportunities to support different learning styles commonly found in engineering students, as described by Felder and Silverman (1988), by using computer assisted instruction (sensing/active), visual representations (sensing/visual), options to cooperate (active), motivation by relating the material to previous units

and those to come (inductive/global), and the inclusion of materials relevant to practical problem solving (sensing/acting).

The final consideration regarding the learning context was the suitability of SigmaPipe, based on its capabilities and ease of use. To help make this decision, we carried out a preliminary assessment of the software by going through the training modules provided on the SigmaPipe website (Section 2.4) and beyond in order to establish possible avenues of enquiry for a problem-solving activity, in particular on the topic of heat exchanger design. It was concluded that SigmaPipe provides enough features (in regard to heat exchangers) and a user-friendly interface that it could be incorporated in a learning activity with minimal training requirements. As SigmaPipe is under continuous development, some of the limitations found at the time have already been addressed in more recent versions (Section 5).

It was decided to give the problem to the students in the form of an interactive presentation of an industrial scenario in a self-contained file along with some potentially-useful supporting documentation. It was also decided that the activity should be designed to be done in pairs or by an individual over approximately one hour. These characteristics provide flexibility, so the activity could be added within a tutorial session or as an off-campus activity, and at the same time would permit individual or cooperative learning. A detailed description of the activity follows.

#### ***4.3 Monash activity design methodology***

The activity produced was based on a design problem in an industrial context. The materials created to carry out the activity consisted of:

- PowerPoint slides,
- an incomplete equipment data sheet with process data relevant to the equipment to be designed,
- a Conceptual Questions sheet for students to fill in with information that could help them carry out optimisation of the design, and
- a template of the Memorandum they should submit at the end of the activity.

The PowerPoint presentation contains the scenario information. Students can navigate around it using hyperlinks that lead to the different parts of the story and that also provide clues for the different tasks and requirements. The rest of the materials referred to within the scenario are provided to the students separately from the scenario itself. The first part of the scenario requires the student to become familiar with the problem and gather enough information to complete the equipment data sheet. The second part of the scenario involves using SigmaPipe to create a simulation for the design base-case and then to carry out an exploration to optimise the design. The Conceptual Questions sheet encourages the student to consider relevant parameters to be explored in the optimisation. The Memorandum template consists of a series of questions that asks the students to reflect upon what they have considered through the scenario. It also acts as a vehicle to communicate the key findings of the task: whether or not a new heat exchanger is required, and its physical and performance characteristics. The use of each handout was prompted throughout the activity.

The background story is that the student is an engineering intern working for an oil and gas company over the summer at one of its facilities. The student is directly supervised by a Process Engineer. The student has already been given two projects to complete over the summer. However, one day, the

Plant Manager meets the student and asks her/him to design a Heat Exchanger to replace one that is nearing the end of its life. The main constraint is that the manager would like to have the job done in a few hours. The manager provides the student with an incomplete Equipment Specification Sheet. In order to complete the task, she/he will need to find out more information from some of the staff in the plant (Fig. 11).

<p><b>Background Information</b></p> <p>You are an engineering intern working for a large oil and gas company. Your direct supervisor is a process engineer who has given several projects for you to complete over the summer.</p> <p>On your way back from an unusually long lunch break you bump into the Plant Manager...</p> <p style="text-align: right;">NEXT</p>	<p><b>Manager</b></p>  <p>Anyway, I heard you were looking for projects from your supervisor..</p> <p>(What? But he's already given me two big projects to do...) Oh, did he mention that to you?</p> <p style="text-align: right;">NEXT</p>
<p>(a)</p>	<p>(b)</p>
<p><b>Finding Information</b></p> <p>CONTROL ROOM OPERATOR      PLANT OPERATOR</p> <p>PROCESS ENGINEER</p> <p style="text-align: right;">NEXT</p>	<p><b>Control Room Operator</b></p>  <p>Hey, you know the 562 heat exchangers on the South West-ish side of the plant next to pumps 86 and 64? Do you know it's operating conditions?</p> <p>It uses cooling water to cool down the process stream. The water comes in at 20°C or thereabouts.</p> <p style="text-align: right;">NEXT</p>
<p>(c)</p>	<p>(d)</p>

**Fig. 11 – Snapshot of the activity scenario in the Monash University study:** (a) the problem is introduced, (b) interaction occurs with the Plant Manager, (c) possible sources of information and (d) part of the dialogue with the operator.

Much of the interaction and dialogue between the student and the plant staff is simulated by way of animated dialogue boxes that appear as the story progresses at the click of the mouse. This helps to bring in some realism about the working environment and common practices in an industrial process facility.

The scenario takes the student on a journey of finding information from staff, putting it together, making sense of it and doing the work to complete the task. Once the student has completed the specification sheet for the base case through some routine hand calculations using the data they have gathered, she/he is prompted to use SigmaPipe for the optimisation of the design. At this point, the student is prompted to create a base-case simulation using SigmaPipe before proceeding with the optimisation. As SigmaPipe is not intrinsically an optimisation tool, the student has to explore manually the effects that changing the design parameters will have on the outlet temperature and velocity of the tube side fluid, as well as on the overall rate of heat transfer. By the end of this part of the activity, the student should have an optimal heat exchanger design (Fig. 12).

TABLE 1 VESSEL DATA			
Type	Shell and Tube (1 Shell Pass, 1 Tube Pass)		
LMTD	°C		
Duty	kW		
Overall Heat Transfer Coefficient	W/m <sup>2</sup> .K		
Heat Transfer Area	m <sup>2</sup>		

Stream No.	Tube Side	Tube Side	Shell Side	Shell Side
Stream Description	Ammonia Inlet	Ammonia Outlet	Cooling Water	Cooling Water
Temperature	°C			
Mass Flow Rate	kg/h	36441	36441	
Vapour Fraction		1	0	0
Specific Heat	kJ/kg.C		0.4559	0.6375
Conductivity	W/m.K	0.03678	0.4559	0.6033
Density	Kg/m <sup>3</sup>	8.299	583.9	1011
Viscosity	cP	0.0107	0.112	1.00

TABLE 3 DESIGN CONDITIONS			
	Tube Side	Shell Side	
Design Temperature (min)	°C	124	100
Design Temperature (max)	°C	-3	-3
Allowable Pressure Drop	kPa g		

Please note that you don't have to take into account every single aspect of the design when modelling the HEX in SigmaPipe. For example, pressure is currently not a property that is easily viewed (you can calculate it from the data given though).

(a)

**SigmaPipe**

Open SigmaPipe software by clicking the following icon



NEXT

(b)

**SigmaPipe Instruction Manual**

RESULTS GRAPH	TUBE SIDE PROPERTIES	FLUID SINK
FOULING LAYER	FLUID SOURCE	SHELL SIDE PROPERTIES
COLOUR SCALE	VALVE PROPERTIES	PUMP PROPERTIES

NEXT

(c)

**Fig. 12 – Snapshot of progress midway through the Monash University student activity: (a) incomplete Equipment Specification Sheet, (b) prompt to the student to start using SigmaPipe, and (c) functionality to be investigated through the SigmaPipe Instruction Manual that is needed to complete the design task.**

The scenario continues with a simulation of a presentation that the student has to give to plant personnel, including the Plant Manager. The presentation component of this activity does not actually take place and the narration of the story skips to a question and answer session that is to occur at the end of the presentation. The question session is simulated through dialogue boxes. The intention of these questions is to make the student reflect upon the various aspects that should have been considered in the design optimisation and to provide support for their reasoning. The questions are in the Memorandum that the students are required to submit to the Plant Manager (Fig. 13). The students were instructed to hand in the Memorandum to the demonstrator at the conclusion of the activity.

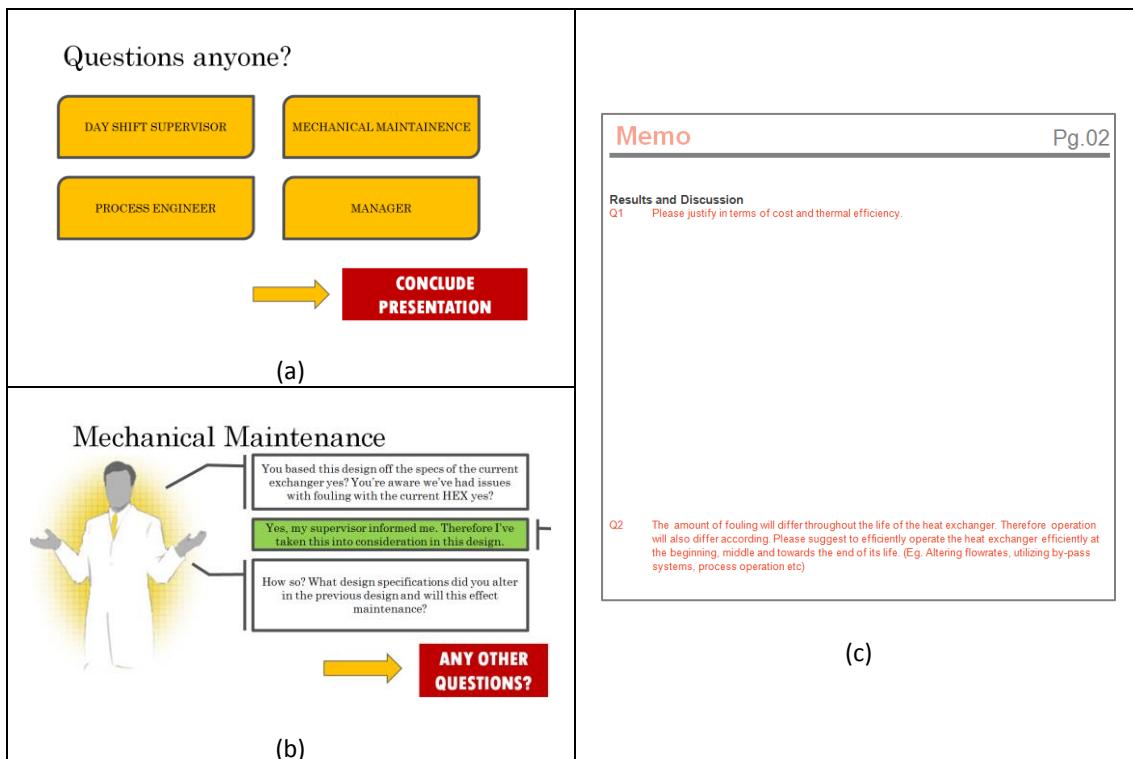


Fig. 13 – Snapshots from the final parts of the Monash University activity: (a) post-presentation questions session, (b) example of a question from the plant maintenance staff, and (c) a section of the Memorandum that the student must complete and submit at the conclusion of the activity.

#### 4.4 Monash activity results and evaluation

A preliminary evaluation was conducted into the students' perception of the potential success of the activity if it were to be embedded in the Process Design unit at Monash. The aim of this preliminary evaluation was only to obtain feedback to troubleshoot the activity's design. A reference group of three student volunteers was used for this purpose.

The only criterion for the selection of the volunteers was that the students must have completed the unit CHE3166 previously. This was decided on the basis that students who had previously taken the unit would have a base line for comparison and would not be confronted with completely new concepts. Hence, the focus of this preliminary evaluation could be on the innovation and the potential for its use in other units.

Commonly focus groups for qualitative research are carried out with 6–10 members per group of homogeneous strangers; however, each project might require special considerations (Morgan, 1997). In this case, it was considered that, because the target community for the activity is relatively small, a group of strangers would not suit the purpose of the evaluation and it would also be unrealistic to find such volunteers. Similarly, it was thought that although three volunteers is perhaps not desirable, a smaller number of participants could produce more detailed feedback.

An invitation to participate in the reference group was circulated via email to all students to seek volunteers. The volunteers were asked to sign a consent form and were given instructions at the beginning of the reference group. Firstly, the reference group participants were asked to carry out the

activity as if it were part of a 1-hour tutorial session. Two students worked in a pair while the third one worked alone, but all were in the same room and were able to communicate. After the activity, the participants were interviewed in a focus group. Data were gathered in both instances. The participants were observed while they performed the activity; both their behaviour and any technical procedural issues that they encountered while carrying out the activity were noted. Their answers to a structured interview held during the focus group session were also recorded.

The data gathered were grouped in three themes: the software features (e.g. user friendliness), how the software was incorporated into the activity (e.g. the tasks the student had to do) and the activity itself (e.g. whether it was perceived to have added value in the development of high-level problem solving skills). A summary of the positive feedback aspects is presented in Table 3.

The following aspects were mentioned as needing further development:

- Familiarisation with some words used in the software; e.g. “fluid sink and fluid source were confusing at first”;
- At times the activity required swapping between the PowerPoint activity file and SigmaPipe, which made it difficult to do on a computer with only one monitor;
- The amount of time allocated is possibly not enough to complete the activity in its current form;
- The initial and detailed instructions about setting up the simulation for the base case were not always clear;
- The wording of some of the questions in the memorandum was perhaps vague.

These results have been useful in improving the characteristics of the activity and provided an insight into how it could be used within the Process Design unit.

**Table 3 – Summary of positive feedback gathered from reference group participants in the Monash University study.**

Aspect assessed	Summary of positive feedback
Software features	<ul style="list-style-type: none"> <li>• It is simpler to use than Hysys.</li> <li>• It is easy to change variables and see the effect they have.</li> <li>• The visualisation element.</li> </ul>
Software use within activity	<ul style="list-style-type: none"> <li>• Results are quick to obtain.</li> </ul>
Activity	<ul style="list-style-type: none"> <li>• The activity was interactive (i.e., they had to respond to questions to be able to progress) and it felt similar to a game with dialogue that made it more interesting and enjoyable.</li> <li>• Good to improve understanding of how to carry out the optimisation as it was possible to visualise the system and directly relate output variables to what was manipulated.</li> <li>• The activity was not too difficult to follow.</li> <li>• The activity feels like a real-life situation and relevant to the work of an engineer.</li> </ul>

#### **4.5 Monash project summary**

A learning activity using Scenario-Based Learning was successfully developed in this study at Monash University. The activity used a realistic industrial scenario that required the students to tackle a heat exchanger design and optimisation problem with the assistance of SigmaPipe. The activity was designed to provide enough flexibility to be used in a variety of learning environments and delivery modes. The preliminary data obtained from a small reference group gives encouraging prospects for its use in the Process Design (CHE3166) unit. However, a larger pilot study should perhaps be carried out before releasing the activity to a larger group of students. Similarly, some improvements are necessary before it can be fully embedded into the Process Design unit; in particular, the apparent need to change views on the computer between the simulator and the activity file or to use two computers, as well as some of the limitations associated with the software itself.

### **5. SigmaPipe modifications**

#### **5.1 Changes implemented as a result of the evaluation projects**

The Curtin and Monash University evaluation projects reported in Sections 3 and 4 were performed using SigmaPipe Version 2.2. The feedback to the developer resulted in the following:

1. An independent sub-project was set up to explore further details associated with negative comments from both studies. This was done by two students (not previously associated with either evaluation project) conducting intensive stress-testing, weekly bug-list generation and improvement concept formulation over a three-month period.
2. Solutions to specific issues, such as software stability, ease of 3D navigation and more intuitive access to program options, were implemented. Examples include (i) modifying the Line Builder to deactivate the Windows (top, right) close option, which was found to be a major source of instability; (ii) modifying keyboard navigation (W-A-S-D and arrow keys, plus the provision of “hot” keys) to bring SigmaPipe into better alignment with “natural” user expectations; and (iii) adding access to Units of Measure and related options via the Settings menu, in addition to the original Edit menu option.

These changes have been incorporated in SigmaPipe 2.3, which went online in March 2015.

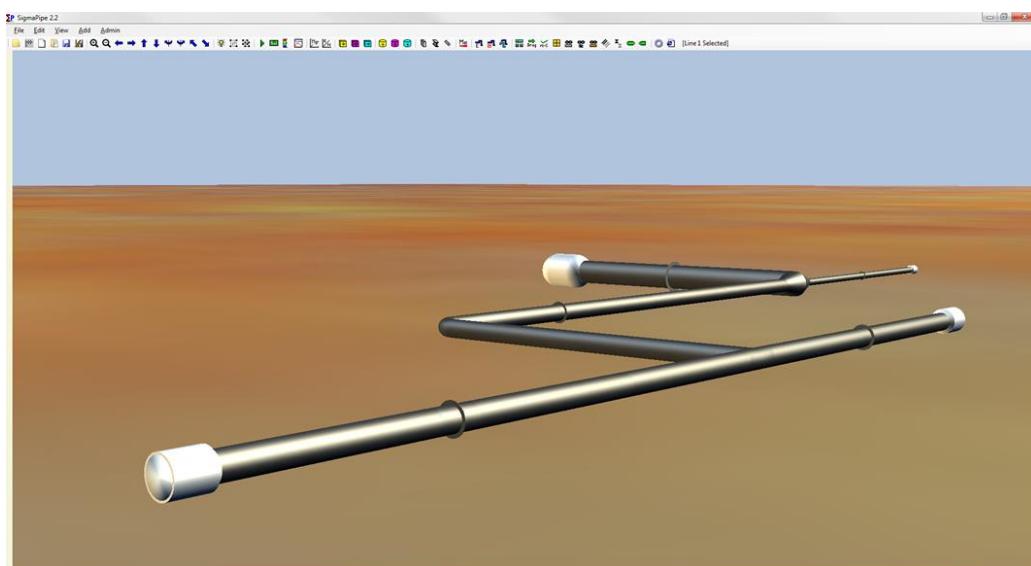
#### **5.2 Current limitations and future development options**

The primary technical limitations relating to the current version of SigmaPipe (2.3) are as follows:

1. User-defined fluids are not currently permitted;
2. Only single-line pipe systems are currently allowed, with no line splitting or mixing.

In general, the problem with user-defined fluid types is that they could give unreliable results due to the uncontrolled nature of the fluid data. New fluid types can certainly be added in future but, as described earlier, this needs to be done at source-code level due to the requirements for data consistency and integrity. Which fluids are added and in what order will depend on user demand.

The next major version of SigmaPipe (3.0) will include line splitting and mixing – a splitting example from the development environment is shown in Fig. 14. Stream splitting naturally calls for component, phase and flash separators. Feedback from current users will determine how and when this is implemented. Introduction of splitting and mixing is a significant step, because it will extend the capability of SigmaPipe into the area of formal plant design. Release of a line splitting version will occur in late 2015 or early 2016.



**Fig. 14 – Example of line splitting in SigmaPipe (currently under development).**

In principle, it is also possible to develop a solids handling capability; for example, to simulate a bin dispensing powdered coal with subsequent pneumatic conveying. Collaboration with at least one bulk materials handling equipment supplier is considered a prerequisite for this. Initial discussions are already underway. After splitting and mixing, this is considered the next logical development step.

Ultimately, there is no reason why chemical reactions cannot be included. The result, in this case, will be a flowsheet development tool with full 3D capability. This option is further in the future compared to the other options outlined above. The primary reason for ordering priorities this way is that all the preceding features will be needed for the chemical reaction version.

A parallel development option relates to user interface language translation. Although SigmaPipe is currently available in English only, the internal code structure allows for the use of other languages, such as Chinese, French or Spanish. The action required to activate another language is quite simple – what is needed is translation of a list of English-language text strings into the language in question. Of course, this translation service, including the iterations to “get it right”, needs to be provided on the same type of “community service” basis that has underpinned the development of SigmaPipe to date. In other words, this will happen quite naturally when a sufficient degree of “user-pull” is present.

## 6. Conclusions

SigmaPipe is a new, free software tool designed to allow students and engineers to interact with pipe flow and heat transfer problems in an intuitive, 3D, highly visual manner. It has been tested via exposure to undergraduate chemical engineering students at Curtin and Monash universities using

different approaches. At Curtin, a case study approach was used to investigate the software usability aspects of SigmaPipe. Five students were observed via the thinking aloud technique learning SigmaPipe from the supplied training materials and then solving an original problem. Their positive and negative comments on usability were classified into eight themes. At Monash the assessment process involved developing a learning activity for a third-year Process Design unit based on the scenario of an intern in an oil and gas company being asked to investigate the replacement of an ageing heat exchanger. The learning activity, which sought to develop high level problem solving skills, was trialled by a small reference group of students. Observations and structured interviews revealed student perceptions about the software features, incorporation of SigmaPipe into the activity and the activity itself.

In an overall sense, the student response from the evaluation projects has been positive. As with any new piece of software there are a few rough edges – trends emerging from the recorded negative comments provide a valuable guide for further development. Although many of the issues raised have already been addressed in the current version (2.3), further activity along these lines is ongoing.

Curtin and Monash evaluation exercises, as described above, constitute a major acceptability test for “cold” introduction to SigmaPipe. Current results support the view that it works well as a software tool that can be readily assimilated to extend the range and depth of problem-solving ability in students. Over time it is expected that the number of university departments using it as a standard undergraduate teaching aid will increase.

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