

**INTERACTIVE AND REAL-TIME DYNAMIC
SIMULATION OF A HEAT EXCHANGER USING
PYTHON**

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INTERACTIVE AND REAL-TIME DYNAMIC SIMULATION OF A HEAT EXCHANGER USING PYTHON

by

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LIST OF SYMBOLS

m	mass of fluid = $\rho A_{cross-sectional} \Delta z$	kg
C_p	heat capacity of fluid	J/kgK
F	volumetric flow rate of fluid	m^3/s
ρ	density of fluid	kg/m^3
T_{inlet}	inlet temperature of fluid	K
T	outlet temperature of fluid	K
U	overall heat transfer coefficient	W/m^2K
A_i	heat transfer area between shell and tube	m^2
Q	heat transfer	W
LMTD	log mean temperature difference	K
N_{tp}	number of tubes per pass	-
NS	number of shells	-
D_s	shell external diameter	m
D_{otl}	tube bundle diameter	m
N_t	number of tubes	-
N_b	number of baffles	-
d_{ex}	tube outside diameter	m
d_{in}	tube inside diameter	m
P_t	tube pitch	-
L	length of tube	m
h_s	shell-side film coefficient	W/m^2K
h_t	tube-side film coefficient	W/m^2K

LIST OF ABBREVIATIONS

HYSYS	Hyprotech Systems
VR	Virtual Reality
3D	Three Dimensional
MIT	Massachusetts Institute of Technology
ISA	iLab Shared Architecture
IDE	Integrated Development Environment
LTE	Thermal Equilibrium Model
LTNE	Non-thermal Equilibrium Model
GUI	Graphical User Interface
CFD	Computational Fluid Dynamics
NTU	Number of Transfer Units
NDG	Nitrogen-doped Graphene
PFC	Predictive Functional Control
SDG	Sustainable Development Goals
UN	United Nations

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SIMULASI DINAMIK PENUKAR HABA INTERAKTIF DENGAN MENGUNAKAN PERISIAN PYTHON

ABSTRAK

Pandemik semasa telah mengubah landskap pendidikan bidang sains kejuruteraan oleh kerana keperluan untuk penjarakan sosial telah meningkatkan keperluan makmal maya kerana amalan makmal tradisional tidak boleh dilaksanakan. Namun begitu, kandungan yang terdapat dalam makmal maya yang sedia ada masih tidak meliputi bidang kejuruteraan kimia yang luas. Oleh itu, dalam kajian ini, simulasi dinamik penukar haba dimodelkan dengan penggunaan perisian Python, sistem perisian sumber terbuka yang percuma. Model matematik yang digunakan dalam kajian ini untuk menganalisis perubahan suhu saluran keluar aliran proses telah disahkan dengan jayanya, dengan peratusan penyelewengan 0.69% untuk aliran panas dan 0.33% untuk aliran sejuk, jika dibandingkan dengan nilai teori yang diperoleh daripada sastera. Simulasi Penukar Haba Python kemudian dibina dan kebolehlaksanaannya diuji dengan menjalankan kajian berdasarkan keadaan mantap, yang didapati bahawa peratusan penyelewengan untuk aliran panas adalah 0.71% dan aliran sejuk adalah 0.33%, dan juga dari segi simulasi dinamik, yang didapati bahawa peratusan penyelewengan tertinggi adalah 1.3% untuk aliran panas dan 1.1% untuk aliran sejuk. Pengaruh pembolehubah proses terhadap suhu saluran keluar aliran proses juga dilakukan, dari segi analisis kepekaan, untuk memerhati tindak balas simulasi terhadap perubahan tersebut. Ia didapati bahawa suhu masuk kedua-dua aliran mempunyai kesan yang ketara terhadap tindak balas suhu saluran keluar dalam simulasi penukar haba berbanding dengan perubahan dalam kadar aliran jisim.

INTERACTIVE AND REAL-TIME DYNAMIC SIMULATION OF A HEAT EXCHANGER USING PYTHON

ABSTRACT

The current pandemic has rapidly changed the landscape engineering education as the need for social distancing has opened up uncharted areas such as the necessity for virtual laboratories, due to traditional laboratory practices not being a feasible option. However, the existing online lab modules still do not cover the extensive field of chemical engineering as it lacks in areas such as heat transfer and thermodynamics. In this study, a heat exchanger simulation is modelled with the use of the Python programming language, which is a free open-source software. The mathematical model implemented in this study to analyze the changes in the outlet temperature of the process streams was validated successfully, with a small deviation percentage of 0.69% and 0.33% for the hot and cold streams respectively, when compared with theoretical values obtained from literature. The Python Heat Exchanger Simulation was then developed, and its feasibility was tested by conducting studies based on the steady state, which had an error percentage of 0.71% and 0.33% as well as the dynamic behaviour, which had an error percentage of 1.3% and 1.1% for the hot and cold streams respectively, when compared with literature. The effect of manipulating process variables on the outlet temperature of both process streams were also performed, in the terms of sensitivity analysis to observe the simulation response to these changes. It was found that the inlet temperature of both streams had a significant effect on the transient temperature response of the heat exchanger simulation as compared to change in mass flowrate.

CHAPTER 1

INTRODUCTION

1.1 Introduction

This study is aimed to simulate a heat exchanger for the potential use in virtual laboratories. With the need for accessible learning in times when social distancing is mandatory, the resources needed for this implementation is limited in engineering education, especially to conduct online laboratories. This study is intended to change that perception and to contribute in terms of the resources needed for the study of heat transfer and thermodynamics in virtual experiments via the simulation of a heat exchanger. The simulation will be carried out using Python programming language and evaluated based on its performance of producing relevant data needed to promote inquiry-based learning among students.

1.2 Background

Since the beginning of the year 2020, the COVID-19 pandemic has dramatically and very rapidly changed the landscape of higher education. The need for social distancing in these to contain the spread of the virus in these trying times has affected the modus operandi of teaching and learning. Institutions around the world had to adapt quickly to online pedagogical methods and assessments during lockdowns of many levels of stringency. These emergency measures had to force higher education institutions to revise their conventional teaching and learning techniques and come up with innovative solutions to deliver high quality education as well as engage students to learn from the comfort of their home. This was particularly a challenge for engineering education as engineering is a practical discipline. It is a hands-on profession

in which doing and gaining practical knowledge is the key to being an ideal engineer in the workforce.

The applied sciences discipline such as engineering requires both theory and practical knowledge to be able to fully understand the governing concepts and apply them to real life. While theoretical knowledge can be gained in classrooms and lectures, its practical counterpart can only be learned and practiced by physical doing experiments in a laboratory. The laboratory practice is the closest representation to what students will encounter in the real world as professional engineers. The engineering profession requires engineers to function as team members, discuss the planning and execution of projects and share ideas about the analysis and interpretation of data – all of which is experienced by a student in a laboratory. Hence why the laboratory practice has become a significant part of engineering education as it is the ideal place for active learning, which is demanding the active use of knowledge and skill.

In order to assess the effectiveness of practical work, the objectives of this course should be clearly identified. The aim of laboratory practices should not only focus on specific course outcomes but also have a holistic approach. Edward (2002) has classified the objectives of experimental work into four categories, which are listed below:

- Cognitive learning
- Inquiry methodology
- Vocational aims
- The development of personal skills

Cognitive learning is the ability of students to integrate the learned theory with practice. It is a form of active learning that teaches students critical thinking with the use of their senses, experience and thought. It gives the students the chance to reflect

on what they have learnt in the classroom and how it applies to engineering problems. This also helps students develop their problem-solving skills needed to understand and create connections between what they learn and its applications in real life. Inquiry methodology is the essence of experimental practices, which is why the latter is also known as a form of inquiry-based learning. Inquiry methodology incorporates the designing of experiments, forming of hypothesis and evaluation of results. Students are encouraged to use the creativity in designing systems using specific materials and methods. In this way, students are motivated to explore the given material, ask questions and share their ideas with peers, which is a better way of ensuring what is learnt remains firmly in their memory.

Vocational aim is the ability for students to be aware of current practices and cultivate professional ethics in a group setting. Ethics include reporting information objectively and interacting with integrity in the laboratory. Lastly, the development of personal skills is to promote teamwork, by assigning roles and responsibilities as well as effective communication among peers. These soft skills are necessary as they are needed to communicate and maintain good relationships with colleagues in the future.

In the current global situation, restricted physical interaction imposes a challenge for ensuring the successful implementation of these objectives. A viable solution to address this challenge would be the implementation of virtual lab and simulations to help students understand and apply their theoretical knowledge practically, without engaging in physical experiments. However, the presently available resources for the use of virtual labs, especially in chemical engineering, lacks the extensiveness needed to cover all courses in the syllabus.

1.3 Problem Statement

The uncertainty in the times we live in, creates chaos and may alter some of the conventional ways of doing things. The current COVID-19 pandemic has caused disruption in many sectors including the education sector, which has been heavily affected due to the need for social-distancing to curb the virus across the globe. With that said, from an engineering education point of view, laboratory practices can no longer be only traditionally conducted, through face-to-face interaction. Hence, it is important for engineering syllabus to enhance the existence of online laboratories. Although studying an engineering course online from anywhere in the world at any time has become a possibility in recent years, it still lacks the extensiveness needed to be inclusive for all disciplines of engineering education, especially in terms of heat transfer processes in online laboratories. In this study, an interactive and real-time simulation of a heat exchanger unit operation will be simulated for its potential use in online laboratories. The simulation code and performance will be studied in this project.

1.4 Objective

The prime objective of this project work is to model, develop and perform a real-time simulation of a heat exchanger using Python programming language, for its potential use in virtual laboratories. The stepwise objectives are as follows:

- i. To model and develop a code for the simulation of a heat exchanger using Python programming language and validate the simulation results obtained with published results from literature.
- ii. To create a real-time temperature graph for the process simulation of the heat exchanger.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to Simulation

The development of technology in this 21st century has seen a rapid advancement in worldwide communication networks in just a span of two decades, with the emergence of the internet. In the various areas of progress that we have seen, it has also significantly redefined the conceptualization of distance education and the means of delivering the content of engineering education. Distance learning, which has been provided through video media as well as correspondence courses, has been predominantly replaced by online education as the world's advancement in technology is ever-growing.

The vision of bringing education to anyone at anywhere, in terms of online education, was realised by Frank Mayadas and Ralph Gomory in 1993, with the inception of the "Learning outside the classroom" program (Mayadas, 2001). More than two decades later, the foresight of accessible education has been partially implemented as higher education begins to grasp the importance of online education and its integration with conventional in-person teaching methodologies.

Engineering education has always been focused on content and design, in the intent of developing critical and analytical thinking as well as problem-solving skills. With the presence of laboratory courses in the syllabus, collaborative problem-based learning and team-building techniques have been added. However, engineering education needs to fulfil special requirements when offered in the form of virtual learning. This includes the consideration of effectively providing laboratory experiences by means of distance learning, in terms of online laboratories.

A research by Zacharia *et al.* (2008) has studied the advantages of the investigative approach to learning science, in which students conduct experiments and analysis rather than instructional-based teachings and demonstrations. With inquiry learning, students are given the opportunity to interact and apply their knowledge in the physical world by using models, devices, data collection techniques, and theories of science. Typically, hands-on experiments fulfil this necessity. However, the evolution of technology in the past decade has resulted in the inception of online laboratories, where experiments involve the simulation of material and apparatus. The advantages of physical laboratories are well-known, but the advantages of virtual laboratories are not, due to its lack of extensiveness in engineering education.

Both physical and virtual laboratories can attain similar purposes. This includes fostering team building, encouraging conceptual understanding and inquiry skills as well as promoting an interest in science. Virtual laboratories provide a unique benefit in which reality can be altered or adapted. In other words, virtual laboratories can be designed to simplify learning by emphasizing on the important information and omitting unnecessary details (Trundle *et al.*, 2010). Moreover, virtual laboratories triumph over physical ones in terms of efficiency, as they are cost-effective and require less set up time, while providing experiment data immediately (Zacharia, 2008). This gives students the chance to conduct more experiments thus absorbing more information in the same amount of time it would take to complete a physical experiment.

A study of simulator-based learning in chemical engineering showed that simulation-based learning using Aspen and HYSYS reached significantly higher success compared to traditional experiments as students were able to understand learning outcomes more easily (Borreguero *et al.*, 2019). More than 95% of students were able to interpret complex problems and simulate industrial processes as well as

discuss the data obtained. It was also observed that the simulation software used were suitable for students as both simulations obtained identical results.

Another study of virtual laboratory used to support a Chemical Reaction Engineering course identified that through simulation, students were able to solve problems taken from real-life engineering situations (Ramírez *et al.*, 2020). The approach taken in this study was different from other simulation studies because the real-life situation is provided using industry-oriented software that did not necessarily contain all the syllabus of an undergraduate degree in chemical engineering. In this way, the students needed to adjust to interfaces that were not solely academic-oriented. It was concluded that a full class of 45 undergraduate students described the virtual experiment as similar to their expectations of real engineering.

Granjo *et al.* (2020) did a study using LABVIRTUAL software, and students found that the software supported their self-study, simulated chemical processes and performed equipment sizing. Students also noted LABVIRTUAL as user-friendly and a valuable learning tool. This was believed to be due to the integration of teaching methodologies that exists in the software which complements lectures in classrooms as well. Furthermore, students also noted that conducting experiments in virtually enhanced their ability to make their own decisions and the capability to solve problems autonomously. It was measured that most students have used the software to support their self-regulated study and equipment sizing (80%). Students also gave positive feedback about the user experience of LABVIRTUAL, since more than 72% of the responses agreed or strongly agreed that it was well-organized, user-friendly as well as perked their interest and had a positive impact on their learning experience.

A study on the comparison of physical and virtual laboratories suggested that both methods complement each other (Zendler *et al.*, 2020). In terms of practical work

and problem-solving, physical laboratories were more effective for developing the skills required to thrive in a group setting. On the other hand, simulation was also shown to be advantageous, especially for students who were less familiar with conducting experiments. The study concluded that the physical and virtual laboratories can be characterized into two learning theories: the cognitivist learning theory for the physical approach and the constructivist learning theory for simulation. From a cognitivist point of view, physical experiments ensure students focus on the task at hand, while also helping students link information with their prior knowledge of the topic. From the perspective of a constructivist, virtual laboratories give importance to stimulation and encouragement for students while also promoting self-directed learning in terms of learning techniques and self-motivation. However, it was noted that students failed to reflect on what they have learned before performing simulation experiments. The author believes this could be due to the “no consequence” mindset with virtual laboratories being significantly higher compared to physical laboratories.

2.2 Types of Simulation

With the ever-growing presence of the internet, online and distance learning have become much more advanced. Online learning environments are providing opportunities and more accessible ways of education. It is enabling higher education institutions to develop creative and innovative teach methodologies via online learning tools. These online pedagogical methods for engineering laboratory learning can be categorized into two, which are virtual laboratory and remote laboratory. These types of laboratories have become the focus of many researchers due to the current landscape of technological and communication advancement.

2.2.1 Virtual Laboratory

A virtual laboratory is essentially programs simulated to replicate a laboratory environment in which students can access and carry out experiments in a virtual space, without the need and use of physical experimental apparatus and tools. A virtual laboratory can also be interchanged with a simulation laboratory. Virtual labs play a significant role particularly in engineering education as experiments can be simulated to obtain specific objectives. Simulations are already established in engineering industries such as petroleum, nuclear, chemical, aviation and many more. Virtual labs have an advantage in the sense that costly equipment needed for engineering education such as unit operations do not have to be physically available to be used as pedagogical tools. In this way, students and also researchers can have access to costly equipment that may have not been accessible otherwise. Another added advantage to the implementation of simulation lab is that it can be scaled up, which allows participation of a large number of students at one time. Taking this observation to account, one virtual lab can be accessible to all engineering students around the world, which is a far cry from the feasibility of having multiple physical labs in multiple engineering institutions globally.

Having said that, the implementation of virtual labs also come with a set of challenges. It is important to note that, practical training and experience gained in a simulation environment is dependent on the capability and limitations of the existing. Software constraints such as pre-designed initialization and outcomes may limit a student's creativity when it comes to solving problems in a virtual setting. This shows that the competence of the simulation depends heavily on the software criteria. Balamuralithara *et al.* (2009) have discussed the list of software criteria needed for the

successful implementation of virtual labs. Some of the important criteria are highlighted as follows:

- Modularity
- Multi-platform portability
- Hardware and software compatibility
- Extendable libraries
- Intuitive Graphical User Interface (GUI)
- Performance

Modularity is the ability to test single modules to speed up the development of applications. This criterion is important for a software to be able to modify experiments so that it can be catered to multiple levels of advancement in engineering education. For example, a simple heat transfer simulation experiment for a first-year undergraduate class can be modified to teach thermodynamics to a class of third-year undergraduates. The ability for the simulation to be modified and developed quickly is a unique advantage that can only be implemented in a setting. In addition, multi-platform portability, the ability for many simulation designers to work on individual components of an experiment and merge them all in one platform is also a significant way to ensure that quick modification and development of the simulation is being done.

Hardware and software compatibility are apparent in ensuring that the simulation is capable of running on various hardware interfaces and also with previous software versions. Ensuring the availability of extended libraries in the software can help simulation designers bridge the gap between creating libraries of low-level routines and linking them in higher-level systems. One of the most important criteria for the use of software in simulation is to ensure that the GUI guarantees an interactive user experience, one that is easy to be used. Lastly, the performance of the software for the

required simulation ensures that the execution (development) is able to meet the final outcome (simulation environment).

Interestingly, the mode of using virtual lab can be categorized into two – client processing and server processing. Client processing is when the simulation can be run on individual students' computers. This type of mode mainly uses software that are compatible in JAVA applications which can run on universally available Web browsers. On the other hand, server processing is when the simulation is run on a server in which students are able to access remotely via a Web browser interface. Some notable simulation programs currently available are MATLAB/SIMULINK, P-Spice and ChemLab, HOPSAN, DYNAST (Balamuralithara, 2009). These simulation programs have been on the forefront of establishing effective virtual labs in engineering education.

The very foundation of virtual labs is a software that programs the simulation environment to represent a mathematical model of the system. Hence, it can be refuted that virtual lab do not provide real results. Moreover, knowledge and experience gained by students participating in lab experiments goes beyond the scope of the particular experiment objectives. Lab ethics and safety procedures are indirectly instilled into students every time a lab session commences. However, students might ignore these in a virtual lab as most simulations do not contain these aspects (Zendler, 2020). Due to this, students may not be fully equipped to approach unit operations in a real-life situation as one might hope, because virtual settings can also establish a mindset of unreality. This is one of the main downsides of virtual labs.

The advancement of computer programming and graphical technology this past decade have introduced the implementation of virtual reality (VR) in the form of 3D simulation labs. The application of VR in virtual labs could be the solution to address

the unrealistic element of a simulation environment, by creating realistic conditions similar to a traditional lab setting (Ertugrul, 2000). One of the latest and most innovative improvement to the 3D simulation labs in recent years is the inception of gamification, which is a virtual activity developed in the form of game-based learning. This is an interesting concept that can be used in engineering education to promote participation and encouragement for students to learn about difficult concepts such as heat transfer and thermodynamics, which was seen in the work of (de la Flor *et al.*, 2020).

2.2.2 Remote Laboratory

A remote laboratory is interpreted as a physical experiment being conducted away from the student. The experiment is carried out in a traditional lab setting and the equipment is remotely connected to students via online. Therefore, students are able to conduct a physical experiment from any remote location in real-time.

Remote lab is another useful and practical solution in order for students to get the full experience of physical experiments at anytime and anywhere. This type of lab gives authority to the user (student) to send commands that will enable real experiments to be carried out via a server. The experiment results will also be notified to students on their interface almost immediately. There are many ways of implementing remote labs such as shared remote lab, localized remote lab, distant remote lab and technical review lab (Balamuralithara, 2009). Shared remote lab is an added advantage for remote lab learning as expensive equipment from one laboratory could be shared among students and also various engineering institutions at any place. A prime example can be seen by the iLab project, implemented by MIT. They have developed the iLab Shared Architecture (ISA), a web service infrastructure which serves as a platform that gives remote access to a range of online laboratories available globally. This initiative gives

students the opportunity to access various types of experiments by only the use of the internet (Harward *et al.*, 2008).

Localized remote lab helps students to refresh their memory by allowing them to re-do experiments as it is accessible at any time via online. This enables students to improve their practical skills at their own convenience. The distant remote lab is relevant for the use of distance learners and also specifically part-time students. Part-time engineering students do not usually have access to experimental learning, and this might hinder their understanding of certain theories and concepts. The use of distant remote lab can give them access to experiments without having to physically be present and also allowing them the convenience of doing these experiments at their own time (Colton *et al.*, 2004). Additionally, technical review lab is reserved for engineering industry professionals who need to test certain systems or equipment from their workplace. This would give them the benefit of saving cost that would be required to test a system on a larger scale.

In order to build an effective remote lab, a few technicalities are required (Balamuralithara, 2009). The basic necessity would be the client stations, which is a computer with strong internet access, and the internet support needed to connect the different computers from various locations to the remote lab server. Furthermore, depending on the scale of the remote lab, the server needs to be able to withstand the network traffic that will occur when students are accessing the experiment to avoid the server from crashing, which would be an unpleasant experience for the user. An effective remote lab is also one with experimentation and instrumentation units that are well-maintained so that experiments can run smoothly, and experiment readings are collected in real-time.

Having said this, remote labs also come with a set of challenges that need to be addressed in order to form a benchmark that is necessary for successful implementation (Balamuralithara, 2009). Firstly, for the aim of providing users the full hands-on experience, the interface should have a clear view from the video camera of all apparatus and measuring devices used in the experiment. It should be ensured that the experiment settings cater for students of various skill levels. This could be done with the installing an automated error detection which would notify students when they have made a mistake and are able to learn from them. Flexibility and reliability are key to implementing an ideal remote lab. There should be no constraints as the remote lab should be accessible at any given time and place. The cost is also an important factor to consider. Students should not have to bear the cost of software or other devices which should be provided by the institution. The remote lab system should be well supported by individuals who are qualified to ensure its reliability. Most importantly, the learning experience of students is one that should be meaningful and enjoyable and knowledgeable. There should be a demonstration done before the students are allowed to conduct the experiments on their own, similar to any traditional lab settings. This would give students the confidence needed to solve the problems given.

2.3 Heat Exchanger Simulations in Virtual Laboratory

Heat exchangers have a significant role in chemical processes. In a chemical plant, heat exchangers are used to transport the feed stream to a desired temperature before it enters reactors, and cool end-product streams before storage and shipping. In terms of condensers and reboilers, heat exchangers also produce reflux streams in vapour or liquid form in the event of separation and purification of product streams. The uniqueness of a heat exchanger lies in the fact that a similar type can be used in various

auxiliary services in a chemical plant and many other areas such as a chiller in refrigeration and air-conditioning systems, an aftercooler for gas pipelines, and also as vapor condensers and generators in solar, geothermal and nuclear power plants (Stephen Hall, 2017).

The common and straightforward application of a heat exchanger in a process plant is heating or cooling a liquid or gas product, which is called the process fluid, to a desired temperature for further processing or storage. The most common utility used in the process is saturated steam or water. No phase change occurs in the heat exchanger if none of the streams reach their melting or boiling point. A heat balance equation is used to relate the inlet and outlet temperatures of the two streams, with their specific heat and mass flow rate. The stream temperatures are linear functions of the heat exchanged between the streams (Stephen Hall, 2017). In other words, there will be a steady increase or decrease in temperature for both streams in the heat exchanger as the heat transferred directly heats or cools the product stream. It is thermodynamically impossible for both streams to have a higher or lower temperature than the inlet conditions.

Heat exchangers typically have different types of configurations. Their surface area can range up to 100,000 m². The commonly noted heat exchangers which are taught in chemical engineering education are the shell-and-tube, double pipe, and finned-tube. These heat exchangers are also part of the laboratory experiment syllabus used to expose students to further understanding of thermodynamics and heat transfer, which are among the fundamentals of chemical engineering. There have only been few simulations of the heat exchanger for its use in virtual laboratories. This can be due to conventional pedagogical methods still being needed to fully grasp the initial understanding of thermodynamics and heat transfer mechanisms in a thermal system.

However, the studies conducted on the simulation of heat exchangers for virtual use have been promising.

A study on the experience of part-time adult learners using a web-based shell-and-tube heat exchanger found that the virtual and online features were useful for these learners as it could be readily used during night-time classes a high number of users can use the software simultaneously (Byrne *et al.*, 2012). The design of the virtual heat exchanger experiment consisted of two stages. The first being the modelling, design and operation (data collection) of a laboratory model shell-and-tube heat exchanger. Then, the development of an online virtual laboratory software interface using Adobe Dreamweaver IDE, CorelDraw and Flash. The feedback from the students were generally good, with a positive response of 83%. Students found the web-based experiment to be user-friendly and usefully complement existing lectures about the topic. Over 70% of students felt that the virtual experiment was more effective in terms of gaining better understanding of the operation and design of a heat exchanger compared to a physical laboratory experiment.

To combat the common negative perception of students when it comes to thermodynamic and heat transfer as both are difficult topics to comprehend, innovative pedagogical methods have been introduced to motivate and enhance students' participation in these courses. Such was the work of de la Flor (2020) escape lab-room, which is a game-based simulation of a heat exchanger. The general outline of the escape lab-room was a team-based game in which students were required to complete tasks in a limited amount of time. These tasks were based on their knowledge of thermodynamic and heat transfer. A storyline with related clues and puzzles is presented prior to starting of the game. Students are encouraged to work collaboratively in their groups to complete the different tasks to win the game. Based on a survey done after the game, it

was found that the participation rate of the students was at 100%, despite it being a voluntary activity. This showed that students were motivated and interested to learn due to the nature of the game-based activity. It can be further noted that 90% of students found the escape lab-room to be motivational to study thermodynamics and heat transfer. Furthermore, 98% identified the activity to be the correct way of evaluating the knowledge gained. The author also confirmed that the activity encouraged cooperation and collaborative learning between the students.

Another study on a web-accessible heat exchanger via remote access to the real equipment garnered favourable responses from students (Colton, 2004). As part of the I-lab project at the MIT, the author had collaborated with Armfield Ltd. (known for marketing laboratory-scale heat exchangers) to develop a remotely controlled heat exchanger experiment. The heat exchanger unit with a software driver for the Windows operating system. It is specifically designed to operate from a computer which operates on Windows. All the parameters are controlled via computer, without manual interference except setting up and turning on the equipment on site. LabVIEW 6.1 software was the core graphical programming language, which was used to develop the Graphical User Interface (GUI). It communicated with the heat exchanger and also made data accessible to the students. Java Client Interface was also used in comparison to the LabVIEW. Through the assessment done to evaluate students' response to the experiment, it was concluded that the tolerance of students for imperfections and problems that may arise during the virtual laboratory session was low. Students identified that it was harder to visualize that laboratory equipment are likely to malfunction. In addition, there is also intriguing evidence from the study which suggests that students' experience with an experiment is strongly related to the circumstances in

which the experiment is performed. When assessed to compare both interfaces, students preferred the LabVIEW interface in contrast to the Java Client Interface.

2.4 Heat Exchanger Simulation Modelling

Heat exchangers have always been an interesting area of research due to its various innovative advancements in enhancing its heat transfer capabilities, as this is very much needed to optimize processes in a real chemical plant. Parameters such as variation in temperature and flowrate, type of fluid as well as insert systems have been researched with the main objective of enhancing the performance of the heat exchanger through studying its transient behaviour. However, research done on the transient behaviour of heat exchangers via simulation have only been few. The investigation of transient behaviour can be subdivided into two methods – numerical and analytical.

Numerical methods use numerical approximation for mathematical analysis. It is a faster approach as the results are approximated and not exact. However, the computational aspect is time consuming. Analytical method is used to present formula expressions that can then be used to present numerical solutions. The added advantage of analytical methods is that it can provide exact solution to the mathematical problem. This section will review various literature of heat exchanger simulation with the use of both methods.

2.4.1 Numerical Method

A study was conducted on the temperature transient response of a single-phase fluid in a heat exchanger for two transient situations – when the second fluid of constant temperature was subjected to a step change in temperature and when the single-phase fluid was subjected to a step change in mass flowrate (Yin *et al.*, 2003). The aim of the work was to solve the transient temperature distributions of the single-phase fluid

and the wall of the heat exchanger, along the heat exchanger after the step change was introduced. In this work, the integral method was used to express the transient behavior of the heat exchanger. This paper is distinctive as the results produced can be used for various types of heat exchangers due to the fact that flow arrangement becomes irrelevant when one of the fluids in the heat exchanger is of constant temperature. The governing equations of numerical solutions were solved by Modelica modelling language with Dymola as the dynamic simulator. As a benchmark, the results were validated by numerical results of two similar works prior, and they were of excellent agreement. The numerical results were then used to verify the approximate analytical model done by the study. The research concluded that the analytical model had a good accuracy with the numerical solution in the overall system of the heat exchanger but not exactly at each point in the system. A generally average agreement was obtained between the numerical solution and the analytic model.

Another study on the effect of step change in flowrate on a counter-flow double-pipe heat exchanger gathered interesting insights about modelling approach. Instead of mathematical modelling based on overall heat transfer coefficients, Abdelghani-Idrissi and Bagui (2002) performed a modelling approach based on the average convective heat transfer coefficients of both the hot and cold fluids. In other words, this modelling approach was based on the approximation of the exponential factor of the temperature distribution. The governing equations of the double-pipe heat exchanger were expressed in terms of partial differential equations. The equations were then solved numerically to predict the transient behavior with exact solutions obtained for time constants for both fluids. An experimental setup was done and the best linear fit from the experimental data was used to validate the analytical solution. The accuracy of the experimental data was said to be approximately 5%. In terms of exponential factor, the

difference error between the experimental results and the numerical solution was only 1.1%. This showed that the numerical solution corroborated with the results of the best fit. In terms of dimensionless temperature along the length of the heat exchanger, both results only had a differential error of less than 10% for both fluids.

Additionally, a study by Ch (2015) utilized MATLAB in a Graphical User Interface (GUI) form to model and simulate a single shell and tube heat exchanger. The dynamic behaviour of the heat exchanger was modelled using ordinary differential equations (ODE). To get an updating value for the model, the numerical approach via Euler's method was used for solving ODEs with a given initial value. To simplify the ODEs based on the energy balance of process streams, the thermal parameters of the heat transport fluids such as density, heat capacity and heat transfer coefficient were remained constant. The study developed an end-user simulator to model the temperature of the output stream by varying the flowrate of either cooling or heating fluid and the disturbances such as the change of inlet temperature and ambient temperature were also analysed and simulated.

2.4.2 Analytical Method

A research done by Ansari *et al.* (2007) investigated the transient response of a double-pipe heat exchanger with co-current flow through a variation of inlet temperature with time. The work done by these authors is particularly interesting as it was a combination of both analytical and numerical methods to simulate the transient response. The governing equations were linearized and solved via analytical method to obtain the temperature distribution equations. Then, the temperature distribution equation derived were solved by numerical method for the entire length of the heat exchanger. The numerical solution was verified by the finite-volume method also used

in the study. The finite-volume method was then subsequently validated by a previous experimental study done using the finite-volume method on the transient behavior of a similar heat exchanger to any disturbances in terms of parameters, which in this case was the inlet temperature change. When compared, the results showed that the solution obtained was competent in realistically predicting the transient behavior of the heat exchanger. It was also noted that the model solution obtained converged with the finite-volume solution quickly, inferring that the solution has potential to be applied for a greater variation of elements as it decreased the computational calculation time needed.

The analytical method was utilized in a research done by Abdelghani-Idrissi *et al.* (2001). The prime motivation of this work was to investigate the unsteady-state response of the tubular counter-current heat exchanger. Hence, the transient behavior of the heat exchanger was observed when the hot fluid was subjected to a step change in mass flowrate and the effect of initial and final mass flowrates were studied. The analytical solution was validated by an experimental setup also done by the study, in which temperature sensors were strategically positioned along the length of the insulated heat exchanger to record the effects of the manipulated variable on the temperature. The mathematical modelling used in the study were obtained from partial differential equations derived from the energy balance equations. The transient behavior of the heat exchanger from the step change in mass flowrate was expressed in a first order system by an exponential response. The transient response was then solved analytically for both the hot and cold fluid. The effect of the time constant on the spatial variation of temperatures along the heat exchanger and the step magnitude of flowrate were graphically shown. The results from the study proved that there was good agreement between the analytical solution and the experimental data obtained for both

fluids. However, there was a slight variation of 15% between the analytical solution and experimental data.

A follow-up study was done by Arbaoui *et al.* (2007) on the unsteady-state response of the counter-flow heat exchanger and its effect on model-based predictive control. The heat exchanger was set in heater configuration and the control on the outlet temperature were observed. The inlet mass flowrate of the hot fluid was manipulated to observe its effect on the outlet temperature of the cold fluid. The governing equations were also taken from the previous study and derived to be expressed as partial differential equations. An analytical model solution of temporal evolution of the cold fluid along the heat exchanger with step change of mass flowrate of hot fluid was expressed as a first order system. Then, predictive functional control (PFC) was applied to test experimentally the effect of the variation of flowrate on the outlet temperature. In terms of process control and instrumentation, the analytic model estimated the gain and time constant with the change in mass flowrate of the hot fluid, while the PFC estimated the manipulated variable in real-time and controlled the outlet temperature of the cold fluid. The study concluded that the analytic model and PFC were in good agreement as the controller rejected the disturbance (manipulated variable) and maintained the desired outlet temperatures for the cold fluid.

An analytical model was created to evaluate the transient temperature distribution in a double-pipe heat exchanger of both parallel and counter-flow configurations (Un *et al.*, 2017). The governing equations were expressed in a set of partial derivatives. The analytical solution method was solved using the separation of variables, also known as the Fourier method. Interestingly, a numerical solution was also formed from the governing equations, in this study, in order to validate the analytical solution. The numerical solution was solved using the finite-volume method

and the analysis was performed via CFD with ANSYS-FLUENT software. The analytical solution was then compared with the simulation results. The outcome of the study showed that the analytical solution was appropriate as it was in agreement with the simulation results, with the highest error difference being 9% for parallel and 7% for counter-flow configuration. This was inferred due to a sudden increase in temperature of the wall of the heat exchanger as high temperature of fluid was found in the outlet region of the inner pipe, which caused the simulation (numerical) results to differ from the exponential curve expressed by the analytical model.

The same study done on the modelling approach of the counter-current double-pipe heat exchanger further expanded into investigating its analytical transient response of temperature when the mass flowrate of hot fluid was subjected to a step-change (Abdelghani-Idrissi, Bagui, *et al.*, 2002). The analytical solution was derived from the numerical solution done in their previous research, to form the transient response to a step-change in flow rate. This solution was estimated as an exponential expression of temperature distribution similar to a first-order system, with the evolution of time-constant as its main criteria. An experimental setup was also done to validate the analytical solution. From the graphical results, it was deduced that the analytical solution was in good agreement with the experimental solution. Since the accuracy of the experiment was said to be approximately 0.06%, the difference between the experimental results and analytical solution did not exceed 2%.

Furthermore, mathematical modelling done on an industrial heat exchanger system by Emhemed *et al.* (2012) found an identical trend of simulated response compared to the real plant data obtained. This heat exchanger mathematical model was constructed with the use of real parameters through dynamic modelling. The mathematical model was derived under the assumption that the heat exchanger was fully

insulated and simulation was performed via MATLAB to obtain the process response. The responses between the real plant data and simulation had an error of no more than 10%, which validated the dynamic modelling for design purposes and also control.

2.5 Python Programming Language and Its Engineering Applications

Python is a high-level, modular programming language which acts as a platform to host a broad range of standard extension modules and components that perform specific functionality and applications. Python's ability to host a large number of numeric extensions enables it to efficiently store and process massive volumes of numerical data. Not only known as a programming language for general purposes, Python also has a syntax which is easily comprehensible. However, the most important feature of Python is that its free and open source, making it easily accessible as it can be run on any modern computer or laptop by anyone (Sanner, 1999).

The Atomic Simulation Environment (ASE) is a built-in software package in Python which deals with the fundamental properties of atoms and calculators (Hjorth Larsen *et al.*, 2017). It is intended to set up, control, visualize and analyze simulations at the atomic and electronic scales. The tasks in ASE which are programmed in Python allows for the fast generation of complex simulation such as setting up, guiding and analyzing the simulation. The ASE is dependent on external libraries which facilitate the systematic execution of numerical algorithms such as:

- NumPy – A multidimensional array class which performs fundamental arithmetic calculations as well as other mathematical operations on normal arrays such as matrix multiplication, fast Fourier transformations and eigenvalue computation.