# "INVESTIGATE THE THERMAL EFFECTS ON FLOW RESISTING PROPERTIES OF HYDROCARBONS IN A PIPELINE [EXPERIMENT]"

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**DISSERTATION REPORT**

**FINAL YEAR PROJECT 2**

SUPERVISOR: IR. DR. MOHD SHIRAZ BIN ARIS

Submitted to the Petroleum Engineering Programme

In Partial Fulfillment of the Requirements

For the Bachelor of Engineering (Hons) Degree in Petroleum Engineering)

MAY 2012

**Investigate the Thermal Effects on Flow Resisting Properties of Hydrocarbons in a Pipeline [EXPERIMENT]**

By

Wan Izzul Fathi Bin Hamdan

Dissertation submitted in partial fulfillment of

the requirements for the

Bachelor of Engineering (Hons)

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Universiti Teknologi PETRONAS

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# CERTIFICATION OF APPROVAL

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**Bachelor of Engineering (Hons)**

**(PETROLEUM ENGINEERING)**

Approved by,

___________________________________

**(Ir. Dr. Mohd Shiraz Bin Aris)**

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

SEPTEMBER 2012

## CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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(Wan Izzul Fathi Bin Hamdan)

# ABSTRACT

Pipelines are among the most important element in oil and gas industry and can be located on either onshore or offshore depending on the project requirements. Pipelines are either buried or placed on the ground (seabed for offshore applications) and can reach up to hundreds and thousands of kilometers. One of the problems that are faced in pipelines is its flow assurance when the medium being transported in the pipelines acquire a flow resisting properties. Oil companies face these inevitable problems frequently because of the nature of the hydrocarbon itself. Most of the flow resisting hydrocarbons are paraffinic oil that contains wax (also known as heavy crude). One of the factors that contribute to blockage in pipelines is when this heavy crude encounter low temperature region in the pipeline. Wax depositions will cause pressure drops across the pipeline, causing low production rate at the receiving end. It is known that the heavy crude will react to difference in temperature thus this project will investigate the thermal effect on the flow resisting properties of hydrocarbons in a pipeline. This project aims at studying the thermal interactions between the production lines and heating lines to prevent the deposition of wax in the pipeline. This dissertation report will cover the introductions, literature review, research methodology, results, discussions, recommendations and the conclusion of the project.

## ACKNOWLEDGEMENT

Alhamdulillah, Thanks to Allah SWT, whom with His willing gave me the opportunity to complete this Final Year Project "Investigate the Thermal Effects on Flow Resisting Properties of Hydrocarbons in a Pipeline [EXPERIMENT]". This project serves as one of the requirements to finish the degree in Petroleum Engineering (Hons.) in Universiti Teknologi PETRONAS (UTP)

Deepest thanks to my supervisor, Ir. Dr. Mohd Shiraz Bin Aris, whom without his illuminations I would never be able to finish this project. He has provided and advised in great achievements of the project. He has also been a great role-model to the fellow students under his supervision including me. His expertise in the field has always been an inspiration for me to finish this project which takes about 28 weeks to complete.

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# 1.0 INTRODUCTION

## 1.1 BACKGROUND STUDY

The oil and gas industry these days have developed at a tremendous rate since the day one when oil was found underground. The searches for oil have ever since caught up with the research and development because fossil fuels are one of the main energy sources in the world and since it is a non-renewable source of energy, more exploration have taken place, including the search for oil at the arctic region as well as deepwater environment.

As the technology is going modern and keep advancing, there are a large number of problems that were encountered during these searches and production for oil in deepwater environments. One of the examples is the transportation of crude oil in a pipeline connecting the production rig and the processing plant with a distance of 200-300km away from each other. Oil transportation has become a complex and highly technical operation (M.T. Ghannam, 2009) as the exploration is reaching extreme conditions environments such as ultra-deepwater and the arctic region (G. Jaremko, 2008).

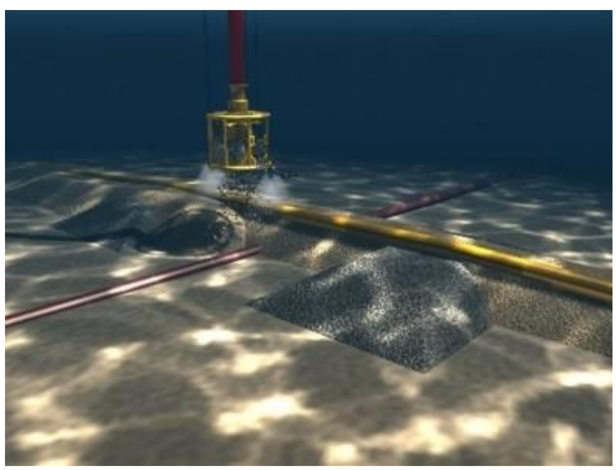

**Figure 1-1: Illustration of subsea pipelines (Source: www.yourindustrynews.com).**

Productions from a deepwater oil field are facing problems because of the colder temperature at the bottom of the sea as well as pressure losses caused by the long distance pipelines from the well to the shore. Even more threatening to the production is when the reservoir is producing a type of crude that contains wax (paraffin). Heavy crude are not pumped easily through the pipelines because of the concentrations of sulfur and metals (e.g. nickel and vanadium) as well as the appearance of paraffinic wax (J.G. Bomba, 1986). In simple words, the waxy crude will become a solid form when its temperature is low, and becomes immobile in the pipeline. The same situation happens to pipelines carrying heavy crudes as well.

**Figure 1-2: A cup of heavy oil produced at Conklin, Alberta (Source: www.sunnewsnetwork.ca)**

The only way to keep producing these waxy crudes is by ensuring the crude to stay at its liquid form by preventing heat loss as well as adding up heat to the pipeline system. Thus, this project will aims at keeping the production line in a carrier pipeline to be above the Wax Appearance Temperature and Pour Point; by studying the thermal interactions between the production line and heating lines in a carrier pipeline.

## 1.2 PROBLEM STATEMENT

A flow resisting hydrocarbon (generally known as paraffin/wax crude) is one of the serious and long standing problems in the petroleum industry and has attracted the attention of many researchers. The number of research papers that have appeared on the subject simply highlighted the complex nature of the problem. Major difficulties are faced by the operators of the process plants handling are the waxy crudes due to the deposition of paraffin waxes. Similar problem are also encountered in the field of oil transportation by pipelines.

Some of the effects of developing fields that possess such deposition of solids are:

1) Changes in reservoir fluid composition - wax present in petroleum crudes consists of paraffin hydrocarbons (C18-C36) and naphthenic HC (C30-C60). When the wax freezes it forms crystals (macro crystalline) [tigger.uic.edu]

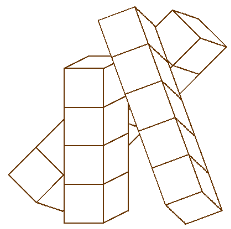

**Figure 1-3: Macro Crystal (Source: tigger.uic.edu)**

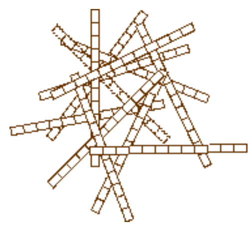

**Figure 1-4: Micro Crystal (Source: tigger.uic.edu)**

2) Permeability reduction with formation damage.
3) Deposition of solids in surface facilities reducing separator and tank volume.
4) Alterations of reservoir rock wetability (wetability reversal).
5) Reduction of the interior diameter that leads to plugging of production strings - when the temperature of a waxy crude is lowered, the heavier fractions of its wax content start to freeze out, causing arterial blockage..
6) Reduced flow and possible plugging of subsea pipelines - as the waxy crude flows through a cold pipe or conduit, crystals of wax form on the wall. Wax crystals will grow in size until the whole inner wall is covered. Wax thickness increment will result in pressure drop across the pipe.
7) Increase service costs and lost production during downtime - pressure drops across the pipe will cause the pumping power to be increase to maintain a constant flow rate. Thus, the power requirement for the crude transport will increase.
8) Decreased pipe diameter – a major contributor of increase in pumping costs; oil transportation companies try to avoid.

**Figure 1-5: Wax formations reduced the interior diameter of a pipe (Source: PhillipsPetroleumCo.com)**

9) Decreased oil quality and loss of throughput.

## 1.3 SIGNIFICANCE OF THE PROJECT

This project will investigate the thermal effect to the flow resisting properties of the hydrocarbon in a pipeline from where the results and conclusion from this study can be used to further upgrade and enhance the pipeline system in the oil and gas industry in transporting these waxy crudes; specifically in the design of the carrier pipeline. The production line is expected to work above the Wax Appearance Temperature (WAT).

The project findings and results can be used as one of the stepping stones to further upgrade and enhance the transportation technologies in the oil and gas industry by these means:

- Better understanding on how to transport different types of crudes – light, medium to heavy crudes.
- Decrease the pumping costs by introducing insulation and active heating options in the pipeline – maintenance of optimum temperature in pipeline prevents blockage in the system, thus preventing unnecessary increase in pumping power.
- Further studies on how to improve the carrier pipeline design can be done by using the results and findings from this project.
- The understanding of the science and physics of transporting these mediums in a pipeline will decrease the possibilities of lost production during downtime.

Although there are many research paper that have appeared on the subject (Mohammad A. Haq), this project will also give impact on the continuing studies about the transportation system – also the contents are directed towards eliminating catastrophic failures in an operation.

## 1.4 OBJECTIVE OF THE STUDY

- Investigate the thermal effects on the various properties of analog fluid in an experimental setup simulating the flow of crude oil in a pipeline.
- Study the thermal effects on the viscosity behavior of the analog fluids (mixtures of polymers that resemble the properties of heavy crude) – the flow rate in a pipeline is heavily dependent on the viscosity of the medium flowing inside the pipe line.
- Investigate the wax appearance temperature (WAT) of different mixtures of analog fluids and wax content – important as to maintain the temperature of the pipeline above the WAT to prevent wax appearance that can cause blockage.
- Study the thermal interactions between the copper pipe and hot water supply lines. (co-current & counter current)
- Correlates the result from the experiment with a computer simulation model using the Computational Fluid Dynamic (CFD) software.
- Improve the design of carrier pipelines by using the results from the experiment and simulating with software.
- Further discuss any other significant data that will give impacts on the result of the experiments.

## 1.5 SCOPE OF THE STUDY

The scope of the study will be focusing on:

- The properties of the flow resisting hydrocarbons (waxy crude).
- Experimental setup of 2-inch copper pipe with insulations and hot water supply lines together with pumps, valves and other pipes.
- Mixing the analog fluid to form different mixtures of polymers that resembles light oil, medium oil and heavy oil – measuring the API gravity after each mixture.
- Studying the thermal effects on the different properties of the analog fluid – e.g.: viscosity, density, rheology, wax appearance temperature.
- Validating the data from the experiment with the CFD calculations to successfully simulate the conditions in the pipeline.
- Propose further recommendation to improve the outcome of this study.
- Submitting and reporting the study in a full final report.

# 2.0 LITERATURE REVIEW

## 2.1 FLOW-RESISTING HYDROCARBONS

A flow-resisting hydrocarbon is often called waxy crude, which carries properties such as a high pour point, low API gravity, often containing paraffin wax (John G Bomba, 1986), and a high wax appearance temperature (Fouad Fleyfel, 2004). Waxy crude can be easily distinguished by a non-Newtonian viscosity behavior at temperature below about 20°F above the pour point (John G Bomba, 1986).

One of the characteristic of waxy crude to be identified is acquiring the characteristic of a Bingham plastic after gelling; which means a specified yield stress must be exceeded before the fluid can start to flow. The viscosity of a Bingham plastic will depend on the rate of shear and time (John G Bomba, 1986).

In a laminar flow condition, the effective viscosity of the fluid will depends on the uniform rate of shear; a function of flow rate and pipe inside diameter. However in a turbulent flow, there will be a presence of a thin boundary layer adjacent to the pipe wall; subject to a rate of shear under laminar conditions. At this stage, oil will rapidly mix with the bulk of the oil in the centre of the pipe. The appropriate rate of shear to determine the effective viscosity is at this high rate of shear in the boundary layer; generally obtained by multiplying a correction factor depending on the Reynolds number with the uniform rate of shear during laminar flow condition (John G Bomba, 1986).

The entire mass of crude oil will become a gel once the wax crystallize; a condition which occurs once the waxy crude is cooled below its pour point with no flow in a pipeline (static condition). Which such knowledge of the gelling effect, it is important to operate the pipeline at temperature above the pour point of the crude. It is important however, to note that if the fluid is kept in motion, transporting the waxy crude below the pour point should be a no problem.

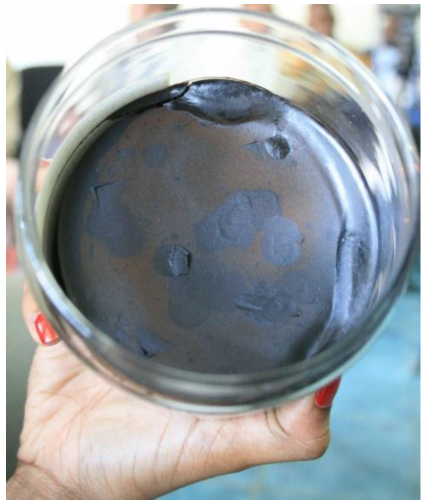

**Figure 2-1: Waxy Oil Samples from Heritages Kingfisher 1 site (Photo by: Devapriyo Das)**

When waxy crude are flowing below its pour point and later forced to shut down (enters static condition), it will enter a gelled state. Once the gelled state is achieved, more pressure (known as restart pressure) is required to put back the fluid into motion. This additional restart pressure however, are less required if the crude was flowing above its pour point, got shut down and are allowed to cool down statically.

## 2.2 EXPORT OF WAXY CRUDE OIL

The process where establishing an overall system pressure in a waxy crude pipeline are complicated; the pressure drop calculation in a section of pipeline is dependent on the data of the temperatures of the crude oil as it passes through. For improved accuracy, a heat loss calculation integrated over a certain number of segments of the line is required.

There are three modes of heat transmission: conduction, convection and radiation. In the case of crude oil pipeline heat loss, conduction is the primary consideration (John G Bomba, 1986). A heat flow will take place from a high temperature region to a lower temperature region within a fluid or solid that is in direct contact. In the case of pipeline at a seabed will lose its heat through the pipe wall and contact with the seawater. The heat lost however is compensated by the heat that was generated by the friction during oil flow.

Additional mechanism for heat transfer such as the various coatings are applied to the submerged pipelines and sea water is flowing around, along and over the pipe lines; further complicates the heat loss calculation because of the various heat transfer rate.

The basic physical problems as well as the rheologic characteristics of waxy crudes that will affect pipelines were also identified (John G Bomba, 1986). The solutions to those problems are: preventing the wax from depositing, keep the crude heated and in a moving (flowing) state.

## 2.3 CHALLENGES IN TRANSPORTING HYDROCARBON FLUIDS

In deepwater oil and gas production, there are many challenges associated with transporting hydrocarbon fluids. As per mentioned before, wax precipitation in the pipeline due to the cold temperature is a serious problem. Insulation is one of the expensive solutions in preventing wax precipitation. Other methods for wax controlling method include:

- Pigging
- Internal coatings
- Chemical injection
- Thermal management strategies

Pigging refers to the passing of solids through a pipeline to clean and/or to inspect its condition. These solids are carefully engineered to scrape the wax deposits on the pipeline walls, collect deposits on the lower half of the pipelines, etc. Pigging is considered a “must-use’ technology for long-distance tiebacks.

Internal coatings are used to prevent wax crystals and particles from precipitating onto the internal walls of pipelines. Examples of internal coatings include (Buck, 2006):

- Phenolics,
- Epoxies
- Phenolic-epoxies
- Polyurethanes,
- Nylon
- Teflon

In a particular one study has shown that the nylon coatings succeed in decreasing wax deposition at high flow rates and temperatures close to the cloud point temperature (Hsu, 1997). But further studies need to be done to determine if the deposition reduction is applicable for slurries transporting below its pour point.

In coiled tubing and active heating technology, the pipeline dimensions and geometry always limits this technology to be applied within. The dual insulated flow lines, is a standard in managing wax problems. Single insulated buried lines are also seen. For a single insulated line, it is uncommon to see a subsea pig launchers in the design. In some cases, dual flow lines which are heated are used. The active heating procedure is by circulating a mixture of glycol-water mixture.

In other cases, a direct electrical heating (DEH) is supplied through an electrical current; this is to generate heat through the steel pipeline wall. The fluid temperature generated by DEH was maintained at greater than the equilibrium temperature of hydration formation.

## **3.0 METHODOLOGY**

For this study, it will include three main processes which are the research background, experimental setup and comparing the result with the CFD calculations.

For the research part, the author will be studying journals, books, technical papers and the internet for a better understanding and background about the flow assurance topic. Most of the sources were found from ScienceDirect.com, Scopus.com and Society of Petroleum Engineers (SPE) technical papers that were found at OnePetro.com. The books and journals were also found from the Information Resource Centre at Universiti Teknologi PETRONAS (UTP).

The background research is a continuous learning process throughout the project to ensure a better baseline reference. The Gantt chart I (*Refer APPENDIX I)* was designed which consist of many milestones and project activities to ensure a smooth and planned flow of project.

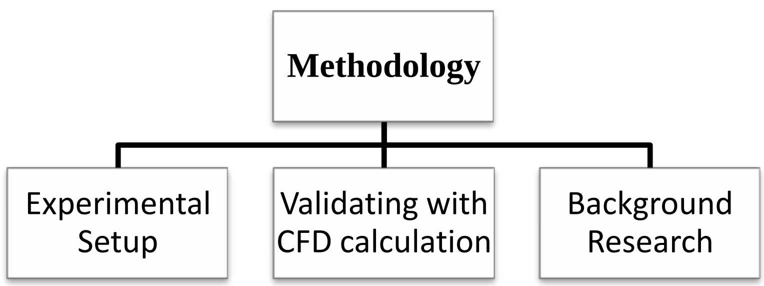


**Figure 3-1: Methodology**

A test rig will be setup which consists of 50L & 100L tanks, flow meters, pumps, thermocouples, ball & globe valves, heater, 2-inch inner diameter of copper pipe with insulations, co-current & counter current hot water lines, and strainers. These are all supplied by SOLTEQ Polymer Flow Loop Test Rig (Model: BP 591).

## 3.1 PROJECT ACTIVITIES

The project activities will include as per below:

- Continuous research on technical papers and journals that are related to the current scope of study.
- Setting up the experiment according to the diagram of the tube bundle system.
- Gathering the data from the experimental setup. (e.g.: readings from thermocouples, flow meters)
- Using different mediums of fluid in the flow-loop system in the following order: water, polymer, analog fluid, and mixture of wax and analog fluid.
- Deliver the data from the experiment to the CFD calculations. (to colleague working on the simulation project)
- Further research on previous technical paper and thesis that correlates with the current field of study.

## 3.2 TOOLS REQUIRED

The tools required for the experimental setup are the:

- Analog fluid (developed by a group working on different project, the fluid resembles the properties of a crude oil – crude oil is too dangerous to be used in the experiment as a safety precaution)
- SOLTEQ Polymer Flow Loop Test Rig (Model: BP 591) that consists of: A 50L & 100L tanks, flow meters, pumps, thermocouples, ball & globe valves, heater, 2-inch inner diameter of copper pipe with insulations, co-current & counter current hot water lines, and strainers.
- Computational Fluid Dynamic (CFD) software to validate the experimental data for simulation purpose.


**Figure 3-2: SOLTEQ Polymer flow loop system Control Panel**

The following figure at the next page is the diagram of the SOLTEQ (Model: BP 591) polymer flow loop system as viewed in LabView software program.

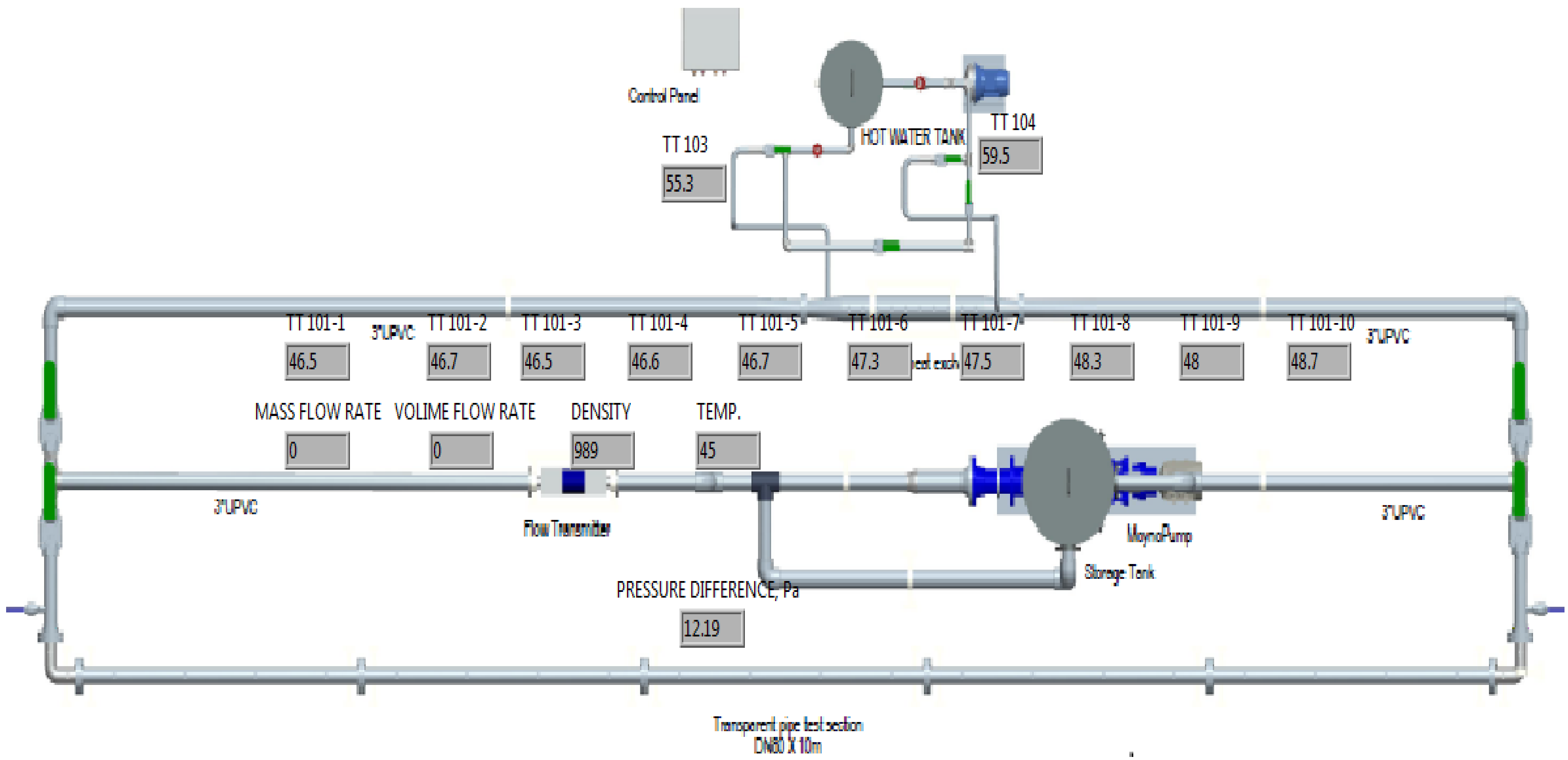


**Figure 3-3: Diagram of the SOLTEQ (Model: BP 591) system**

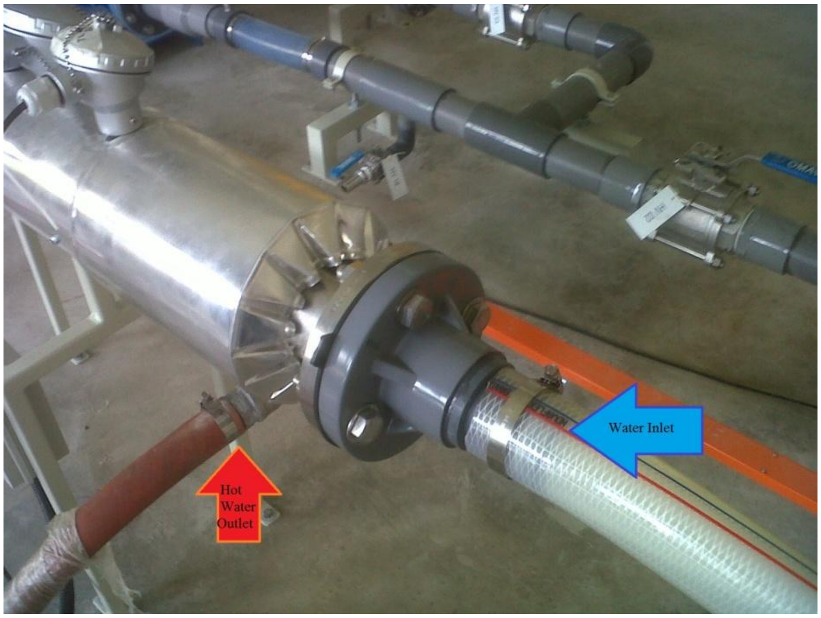


**Figure 3-4: Heat Exchange section of Water Inlet and Hot Water Outlet**

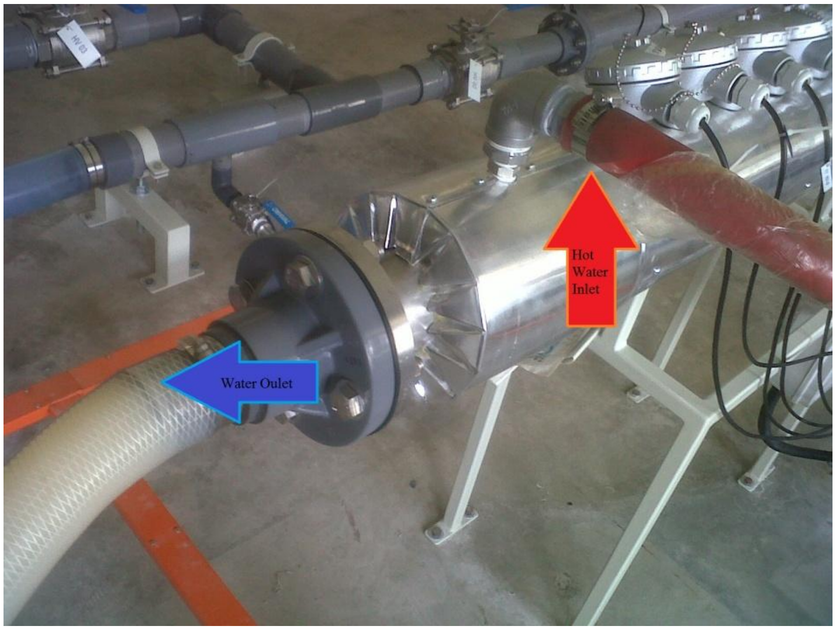


**Figure 3-5: Heat Exchange section of Water Outlet and Hot Water Inlet**

## 3.3 KEY MILESTONE

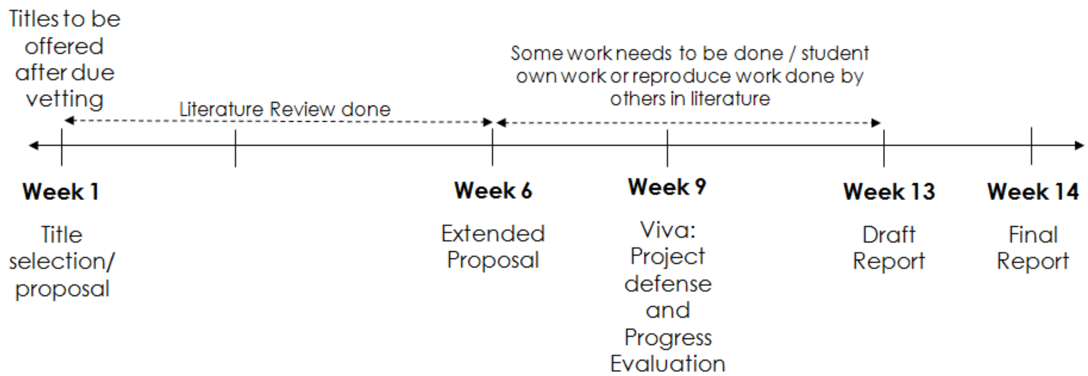


**Figure 3-6: Key Milestone for FYP I**

This is the milestones for Final Year Project I. All of the key milestones have been completed. The remaining of the project will be continued during Final year Project II.

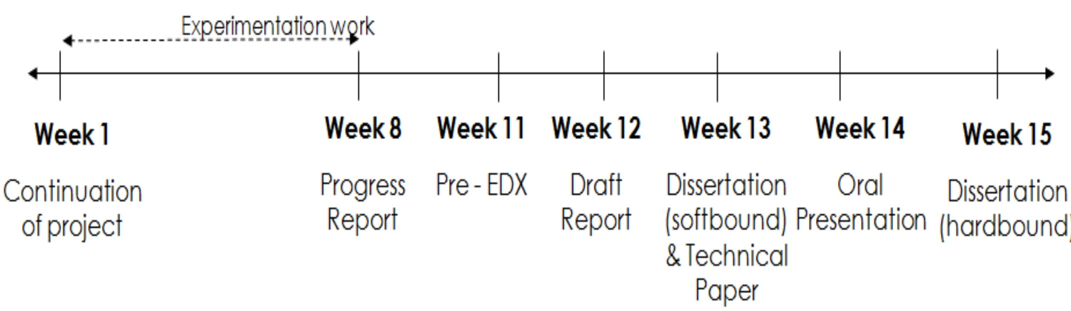


**Figure 3-7: Key Milestone for FYP II**

# 4.0 RESULTS AND DISCUSSIONS

## 4.1 RESULTS

The first data gathered during the experiments are done by using water as the medium in the flow loop. The graph was obtained (Temperature at y-axis, Distance at x-axis): *Refer APPENDIX II Figure 1*

From these results, it was found that as the distance increases, the heat transfer process is less thus resulting in the lower reading of temperature at the end of the heat exchanging section. The heat transfer does not include the heat transfer inside the production line because the usage of water does not represent the non-Newtonian behavior of crude oil.

The next graph (*Refer APPENDIX II Figure 2)* shows the average temperature of each thermocouple at different flow rates vs. distance. This is the supporting evidence that shows the heat distribution at the heat exchanging section where the hot water is flowing in a counter-current direction. The heat exchange occurs greatly at TT101-10 where it is the first contact point when the water is at the hottest point. Whereas at TT101-01, the temperature is the lowest because of the heat transfer to the flowing water as the water flows in a counter-current direction.

These data were obtained (*Refer APPENDIX II*) by taking measurements at different flow rates with increment of around 10-11 cubic meters/second, with counter current hot water supply line. This proves that as the flow rate increases, the heat exchanging process is faster and the average temperature of water in the flow loop increases as well.

All of these graphs were generated using the data from the experiment obtained (*Refer APPENDIX III).* These data were then averaged and scatter plot graphs from APPENDIX II were obtained.

Based on the simulation part of this project, it is found that the error percentage between the experimental part and simulation part from CFD software is at 3.5209%.

| VOLUME FLOW RATE ($m^3/s$) | TT 101-1 (°C) | TT 101-2 (°C) | TT 101-3 (°C) | TT 101-4 (°C) | TT 101-5 (°C) | TT 101-6 (°C) | TT 101-7 (°C) | TT 101-8 (°C) | TT 101-9 (°C) | TT 101-10 (°C) | TT 103 (°C) | TT 104 (°C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 84.00 | 32.53 | 32.35 | 32.43 | 32.55 | 32.43 | 32.93 | 32.73 | 33.75 | 33.88 | 33.32 | 51.90 | 56.07 |
| 94.00 | 34.95 | 34.92 | 35.02 | 35.32 | 35.08 | 35.27 | 35.53 | 36.60 | 36.58 | 36.15 | 53.73 | 57.57 |
| 104.00 | 37.42 | 37.35 | 37.38 | 37.82 | 37.52 | 37.83 | 37.90 | 39.00 | 39.10 | 39.00 | 54.38 | 57.85 |
| 114.00 | 39.45 | 39.45 | 39.40 | 39.85 | 39.75 | 40.02 | 40.10 | 40.92 | 40.95 | 41.12 | 54.83 | 58.15 |
| 124.00 | 41.33 | 41.28 | 41.22 | 41.70 | 41.65 | 41.82 | 41.97 | 42.80 | 42.75 | 43.08 | 55.00 | 57.77 |
| 134.00 | 42.90 | 42.88 | 42.80 | 43.18 | 43.10 | 43.42 | 43.53 | 44.37 | 44.28 | 44.67 | 55.52 | 58.17 |
| 144.00 | 44.15 | 44.28 | 44.05 | 44.43 | 44.52 | 44.77 | 44.87 | 45.77 | 45.58 | 45.88 | 55.73 | 58.27 |

**Table 1: Average readings of thermocouples with different flow rates**

# 5.0 CONCLUSIONS

## 5.1 CONCLUSIONS

Based on the results and discussion obtained from the experimental and simulation work, it is found that transportation of waxy/paraffinic crude can be further enhanced by reducing the spaces/distances between the production line and the heating lines. Better active heating system will ensure the production line to maintain the temperature above the Wax Appearance Temperature (WAT) and the Pour Point of the crude.

Moreover, the small error percentage between the experimental result and the calculation obtained from the Computational Fluid Dynamic (3.5209%) validates the thermal analysis from the simulation part.

## 5.2 RECOMMENDATIONS

This project only covers the thermal interaction between the pipes. The heat transfer also simulates between the void spaces in the carrier pipe. The heat transfer inside the production line cannot be simulated by using water in the flow loop since the production line is carrying a non-Newtonian fluid; crude. Thus the result from this experiment is limited to the outer section of the production line.

However the result can be further improvised by using a type of polymer in the flow loop. A type of polysaccharide can be used, Xanthan Gum. This polymer is also known as E415 and used as a thickening agent in the food industry. This polymer is known to have a non-Newtonian behavior; similar to the crude oil properties. Using Xanthan Gum in the flow loop can further break through the boundary line which is set upon the production line.

Other type of fluid (e.g.: Analog fluid) can also be used in the experiment. An analog fluid is a type of fluid which can have the exact similar properties with the crude oil from a specific field. However further developments of the analog fluid shall be researched first before proceeding to the experiment section. For this experiment, three models of analog fluids were developed by a group of postgraduate students by mixing benzene and dodecane. However they have found out that their best model were having a 300% difference with the crude from Angsi-C Field. Hence, a replacement model shall be developed before proceeding with the experiment section.

In the future, this experiment can be further studied in order to get a better coverage and understanding of the thermal interaction between the pipes. Take note that crude oil must not be used in the polymer flow loop system since crude oil have a flammable properties which is highly dangerous to be used in the system.

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APPENDIX I: Final Year Project Gantt Chart

Several targets and key milestones have been set for the Final Year Project I as per indicated at the Gantt chart below:

| No | Detail / Week | 1 | 2 | 3 | 4 | 5 | 6 | 7 | | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Selection of project topic | | | | | | | | M | | | | | | | |
| 2 | Preliminary research work | | | | | | | | I | | | | | | | |
| 3 | Literature review | | | | | | | | D | | | | | | | |
| 4 | Submission of extended proposal | | | | | | | | | | | | | | | |
| 5 | Proposal defence | | | | | | | | S | | | | | | | |
| 6 | Project planning | | | | | | | | E | | | | | | | |
| 7 | Submission of interim draft report | | | | | | | | M | | | | | | | |
| 8 | Submission of interim report | | | | | | | | | | | | | | | |

**Table 2: Project Activities and Key Milestones for FYP I**

Legends:-

Project activities

Key milestones

Several targets and key milestones have been set for the Final Year Project II as per indicated at the Gantt chart below:

| No | Detail / Week | 1 | 2 | 3 | 4 | 5 | 6 | 7 | | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Design Test Rig | | | | | | | | M | | | | | | | | |
| 2 | Research work | | | | | | | | I | | | | | | | | |
| 3 | Commissioning Test Rig | | | | | | | | D | | | | | | | | |
| | Data Gathering | | | | | | | | | | | | | | | | |
| 4 | Analyze and verify result | | | | | | | | | | | | | | | | |
| 5 | Preparation & submission of progress report | | | | | | | | S | | | | | | | | |
| 6 | Pre-SEDEX | | | | | | | | E | | | | | | | | |
| 7 | Preparation & submission of draft report | | | | | | | | M | | | | | | | | |
| 8 | Preparation & submission of soft bound | | | | | | | | | | | | | | | | |
| | Preparation & submission of technical paper | | | | | | | | | | | | | | | | |
| | Preparation of oral presentation | | | | | | | | | | | | | | | | |
| | Preparation & submission of hard bound | | | | | | | | | | | | | | | | |

**Table 3: Project Activities and Key Milestones for FYP 2**

**Legends:-**

Project activities

Key milestones

APPENDIX II: Project Results and Data

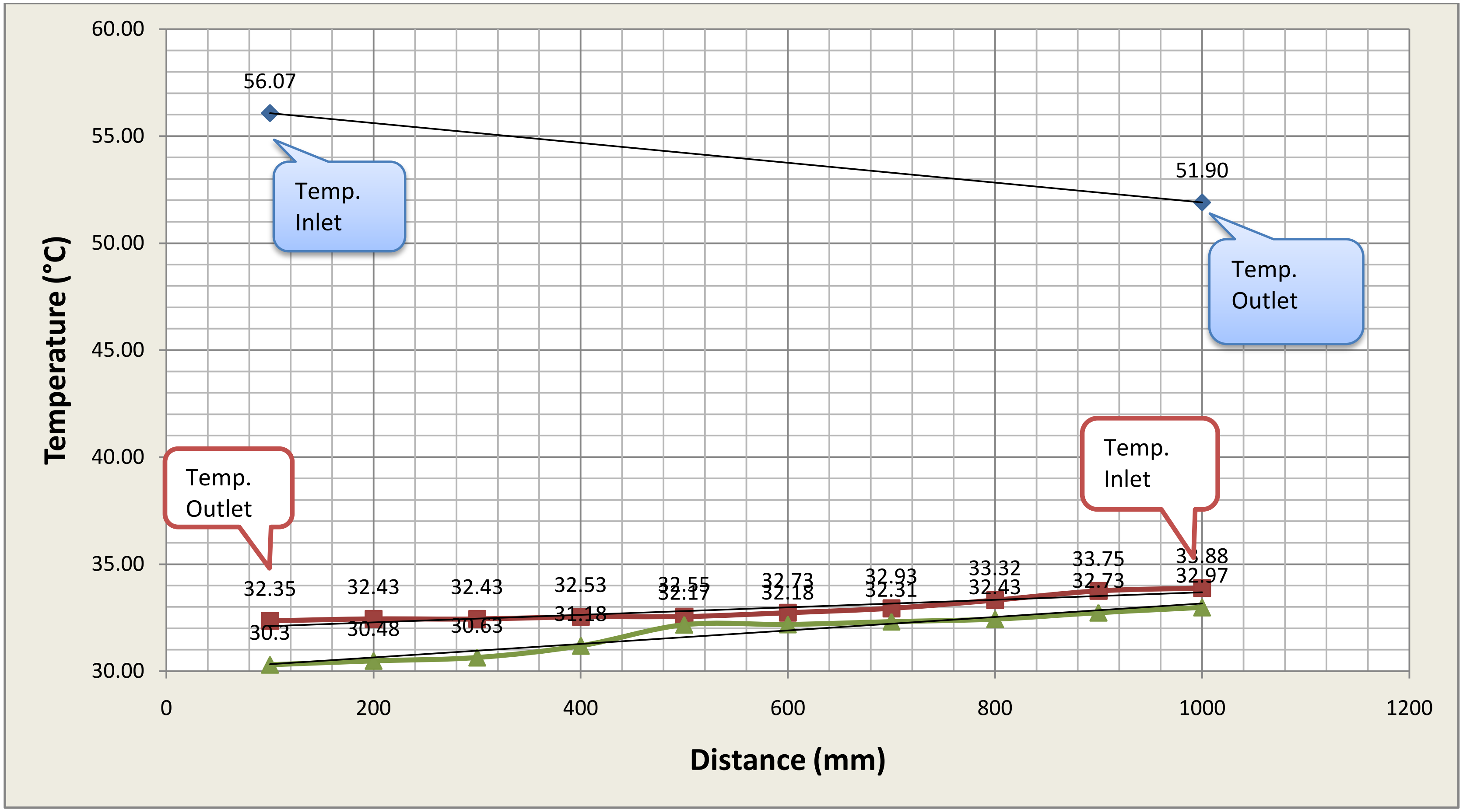


**Figure 1: Graph showing the temperature distribution at different distance between hot water lines and flowing water loop at 84 liter/min.**

The red line showing the plot from the simulation whiles the green line showing the plot from the experimental data. The error percentage is calculated to be 3.5209%

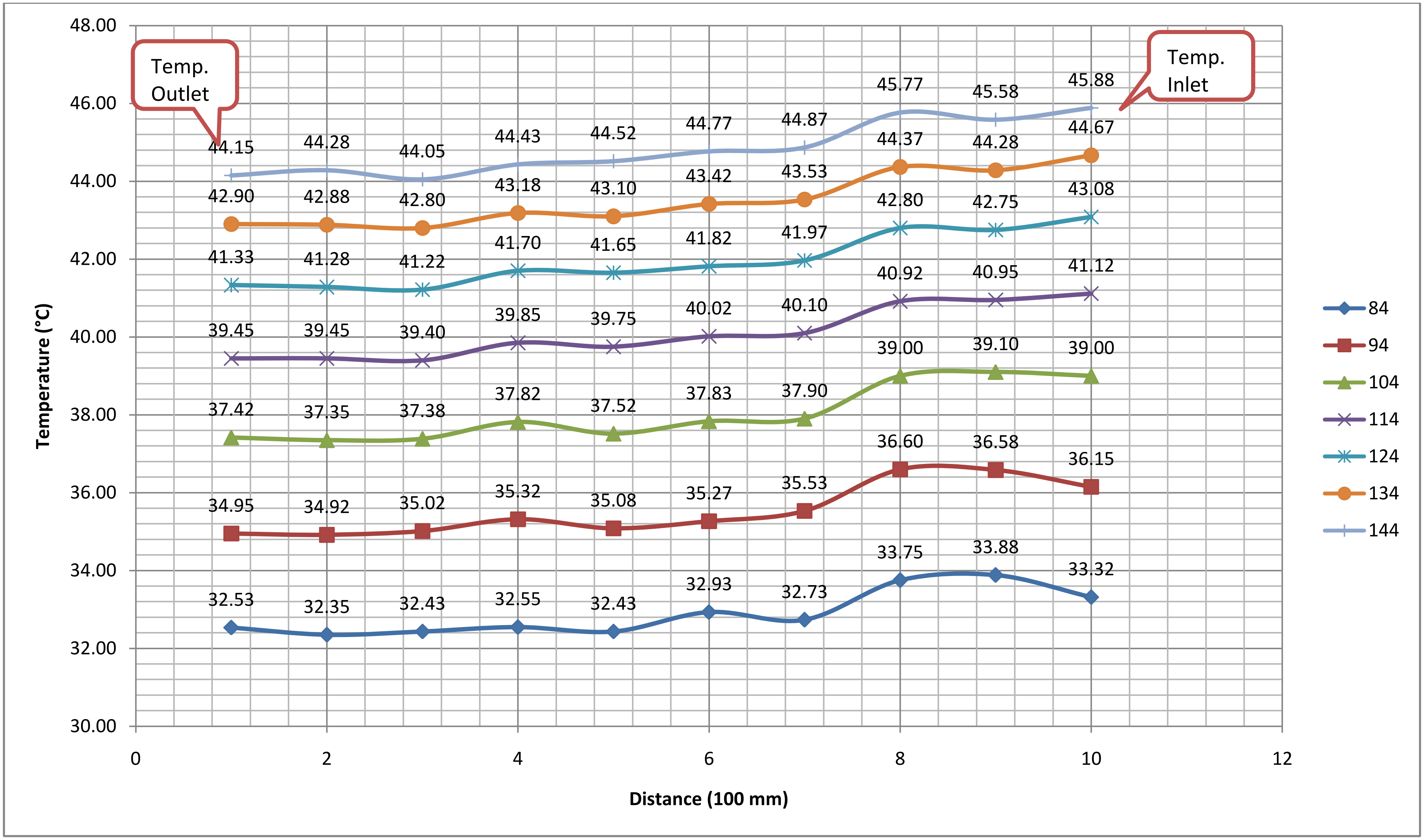


Figure 2: Results of temperature at different flow rates

# APPENDIX III: Experimental Data

| TIME | TT 101-1 (°C) | TT 101-2 (°C) | TT 101-3 (°C) | TT 101-4 (°C) | TT 101-5 (°C) | TT 101-6 (°C) | TT 101-7 (°C) | TT 101-8 (°C) | TT 101-9 (°C) | TT 101-10 (°C) | TT 103 (°C) | TT 104 (°C) | MASS FLOW RATE (kg/s) | VOLUME FLOW RATE ($m^3/s$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2:25:08 PM | 31.7 | 31.3 | 31.2 | 31.2 | 31.4 | 31.9 | 31.5 | 32.6 | 32.6 | 32 | 47.2 | 51 | 84 | 84 |
| 2:28:26 PM | 32.1 | 31.7 | 31.8 | 31.9 | 31.8 | 32.3 | 32 | 33.1 | 33.2 | 32.6 | 50.7 | 55.3 | 84 | 84 |
| 2:31:05 PM | 32.4 | 32.2 | 32.3 | 32.4 | 32.2 | 32.8 | 32.5 | 33.5 | 33.7 | 33.1 | 52.7 | 57.3 | 84 | 84 |
| 2:33:37 PM | 32.6 | 32.5 | 32.7 | 32.8 | 32.6 | 33.1 | 32.9 | 33.9 | 34.1 | 33.6 | 53.3 | 57.2 | 84 | 84 |
| 2:36:11 PM | 33 | 33 | 33.1 | 33.3 | 33.1 | 33.6 | 33.6 | 34.5 | 34.6 | 34.1 | 53.6 | 57.8 | 84 | 84 |
| 2:38:45 PM | 33.4 | 33.4 | 33.5 | 33.7 | 33.5 | 33.9 | 33.9 | 34.9 | 35.1 | 34.5 | 53.9 | 57.8 | 84 | 85 |
| | 32.53 | 32.35 | 32.43 | 32.55 | 32.43 | 32.93 | 32.73 | 33.75 | 33.88 | 33.32 | 51.90 | 56.07 | | |

| TIME | TT 101-1 (°C) | TT 101-2 (°C) | TT 101-3 (°C) | TT 101-4 (°C) | TT 101-5 (°C) | TT 101-6 (°C) | TT 101-7 (°C) | TT 101-8 (°C) | TT 101-9 (°C) | TT 101-10 (°C) | TT 103 (°C) | TT 104 (°C) | MASS FLOW RATE (kg/s) | VOLUME FLOW RATE ($m^3/s$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2:42:03 PM | 34 | 33.9 | 34.1 | 34.4 | 34.2 | 34.4 | 34.6 | 35.5 | 35.8 | 35.2 | 53.4 | 57.3 | 94 | 94 |
| 2:44:38 PM | 34.4 | 34.4 | 34.5 | 34.8 | 34.5 | 34.7 | 35 | 35.9 | 36.2 | 35.6 | 53.4 | 57 | 94 | 94 |
| 2:47:16 PM | 34.7 | 34.8 | 34.8 | 35.1 | 34.9 | 35 | 35.4 | 36.4 | 36.2 | 35.9 | 53.9 | 57.5 | 94 | 94 |
| 2:49:49 PM | 35.2 | 35.1 | 35.2 | 35.5 | 35.3 | 35.5 | 35.7 | 36.8 | 36.7 | 36.3 | 53.7 | 57.5 | 94 | 95 |
| 2:52:22 PM | 35.5 | 35.5 | 35.5 | 35.8 | 35.6 | 35.8 | 36.1 | 37.3 | 37 | 36.7 | 54.1 | 58.1 | 94 | 94 |
| 2:54:57 PM | 35.9 | 35.8 | 36 | 36.3 | 36 | 36.2 | 36.4 | 37.7 | 37.6 | 37.2 | 53.9 | 58 | 94 | 94 |
| | 34.95 | 34.92 | 35.02 | 35.32 | 35.08 | 35.27 | 35.53 | 36.60 | 36.58 | 36.15 | 53.73 | 57.57 | | |

| TIME | TT 101-1 (°C) | TT 101-2 (°C) | TT 101-3 (°C) | TT 101-4 (°C) | TT 101-5 (°C) | TT 101-6 (°C) | TT 101-7 (°C) | TT 101-8 (°C) | TT 101-9 (°C) | TT 101-10 (°C) | TT 103 (°C) | TT 104 (°C) | MASS FLOW RATE (kg/s) | VOLUME FLOW RATE ($m^3/s$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2:58:47 PM | 36.6 | 36.6 | 36.6 | 37 | 36.7 | 36.8 | 37.1 | 38.3 | 38.2 | 37.9 | 54.2 | 57.7 | 103 | 104 |
| 3:01:20 PM | 36.9 | 36.9 | 36.9 | 37.3 | 37 | 37.3 | 37.4 | 38.6 | 38.6 | 38.3 | 54.2 | 57.6 | 103 | 104 |
| 3:03:52 PM | 37.2 | 37.2 | 37.2 | 37.6 | 37.3 | 37.6 | 37.7 | 38.9 | 38.9 | 38.9 | 54.4 | 57.7 | 103 | 104 |
| 3:06:33 PM | 37.6 | 37.5 | 37.5 | 38 | 37.7 | 38.1 | 38 | 39.1 | 39.3 | 39.3 | 54.3 | 58.1 | 103 | 104 |
| 3:09:05 PM | 37.9 | 37.8 | 37.9 | 38.3 | 38 | 38.5 | 38.5 | 39.4 | 39.6 | 39.6 | 54.7 | 58 | 103 | 104 |
| 3:11:39 PM | 38.3 | 38.1 | 38.2 | 38.7 | 38.4 | 38.7 | 38.7 | 39.7 | 40 | 40 | 54.5 | 58 | 103 | 104 |
| | 37.42 | 37.35 | 37.38 | 37.82 | 37.52 | 37.83 | 37.90 | 39.00 | 39.10 | 39.00 | 54.38 | 57.85 | | |

| TIME | TT 101-1 (°C) | TT 101-2 (°C) | TT 101-3 (°C) | TT 101-4 (°C) | TT 101-5 (°C) | TT 101-6 (°C) | TT 101-7 (°C) | TT 101-8 (°C) | TT 101-9 (°C) | TT 101-10 (°C) | TT 103 (°C) | TT 104 (°C) | MASS FLOW RATE (kg/s) | VOLUME FLOW RATE ($m^3/s$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3:15:14 PM | 38.7 | 38.7 | 38.6 | 39 | 39 | 39.2 | 39.3 | 40.1 | 40.3 | 40.4 | 54.7 | 57.8 | 114 | 115 |
| 3:17:46 PM | 39 | 39 | 38.9 | 39.4 | 39.2 | 39.5 | 39.7 | 40.4 | 40.6 | 40.6 | 54.8 | 58.1 | 115 | 116 |
| 3:20:21 PM | 39.3 | 39.3 | 39.3 | 39.7 | 39.6 | 39.9 | 40 | 40.8 | 40.9 | 40.9 | 54.7 | 58.4 | 115 | 116 |
| 3:22:54 PM | 39.6 | 39.6 | 39.6 | 40 | 40 | 40.2 | 40.3 | 41.1 | 41 | 41.3 | 54.9 | 58.6 | 115 | 116 |
| 3:25:26 PM | 39.9 | 39.9 | 39.9 | 40.4 | 40.2 | 40.5 | 40.4 | 41.4 | 41.3 | 41.6 | 54.9 | 58 | 115 | 116 |
| 3:28:03 PM | 40.2 | 40.2 | 40.1 | 40.6 | 40.5 | 40.8 | 40.9 | 41.7 | 41.6 | 41.9 | 55 | 58 | 114 | 115 |
| | 39.45 | 39.45 | 39.40 | 39.85 | 39.75 | 40.02 | 40.10 | 40.92 | 40.95 | 41.12 | 54.83 | 58.15 | | |

| TIME | TT 101-1 (°C) | TT 101-2 (°C) | TT 101-3 (°C) | TT 101-4 (°C) | TT 101-5 (°C) | TT 101-6 (°C) | TT 101-7 (°C) | TT 101-8 (°C) | TT 101-9 (°C) | TT 101-10 (°C) | TT 103 (°C) | TT 104 (°C) | MASS FLOW RATE (kg/s) | VOLUME FLOW RATE ($m^3/s$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3:31:29 PM | 40.7 | 40.6 | 40.6 | 41.1 | 41 | 41.1 | 41.3 | 42.1 | 42.1 | 42.4 | 54.8 | 57.8 | 122 | 124 |
| 3:34:07 PM | 41 | 40.9 | 40.8 | 41.3 | 41.2 | 41.5 | 41.5 | 42.4 | 42.3 | 42.7 | 54.6 | 57.3 | 123 | 124 |
| 3:36:36 PM | 41.2 | 41.2 | 41.1 | 41.6 | 41.6 | 41.7 | 41.9 | 42.7 | 42.6 | 43 | 54.7 | 57.6 | 123 | 124 |
| 3:39:09 PM | 41.5 | 41.5 | 41.3 | 41.9 | 41.8 | 41.9 | 42.1 | 42.9 | 42.9 | 43.2 | 55.2 | 58.1 | 123 | 124 |
| 3:41:48 PM | 41.7 | 41.6 | 41.6 | 42 | 42 | 42.3 | 42.4 | 43.2 | 43.2 | 43.5 | 55.4 | 57.7 | 123 | 124 |
| 3:44:24 PM | 41.9 | 41.9 | 41.9 | 42.3 | 42.3 | 42.4 | 42.6 | 43.5 | 43.4 | 43.7 | 55.3 | 58.1 | 123 | 124 |
| | 41.33 | 41.28 | 41.22 | 41.70 | 41.65 | 41.82 | 41.97 | 42.80 | 42.75 | 43.08 | 55.00 | 57.77 | | |

| TIME | TT 101-1 (°C) | TT 101-2 (°C) | TT 101-3 (°C) | TT 101-4 (°C) | TT 101-5 (°C) | TT 101-6 (°C) | TT 101-7 (°C) | TT 101-8 (°C) | TT 101-9 (°C) | TT 101-10 (°C) | TT 103 (°C) | TT 104 (°C) | MASS FLOW RATE (kg/s) | VOLUME FLOW RATE ($m^3/s$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3:47:52 PM | 42.3 | 42.3 | 42.2 | 42.6 | 42.5 | 42.8 | 42.9 | 43.8 | 43.7 | 44.1 | 55.2 | 58.1 | 134 | 135 |
| 3:50:24 PM | 42.6 | 42.5 | 42.4 | 42.8 | 42.8 | 43.1 | 43.1 | 44 | 43.9 | 44.3 | 55.5 | 58.2 | 134 | 135 |
| 3:52:55 PM | 42.8 | 42.8 | 42.8 | 43.1 | 42.9 | 43.3 | 43.5 | 44.3 | 44.2 | 44.6 | 55.4 | 58.1 | 134 | 135 |
| 3:55:32 PM | 43 | 43 | 42.9 | 43.3 | 43.2 | 43.5 | 43.7 | 44.5 | 44.5 | 44.8 | 55.7 | 58.2 | 133 | 135 |
| 3:58:05 PM | 43.2 | 43.3 | 43.1 | 43.5 | 43.4 | 43.8 | 43.9 | 44.7 | 44.6 | 45 | 55.5 | 58.1 | 134 | 135 |
| 4:00:38 PM | 43.5 | 43.4 | 43.4 | 43.8 | 43.8 | 44 | 44.1 | 44.9 | 44.8 | 45.2 | 55.8 | 58.3 | 134 | 135 |
| | 42.90 | 42.88 | 42.80 | 43.18 | 43.10 | 43.42 | 43.53 | 44.37 | 44.28 | 44.67 | 55.52 | 58.17 | | |

| TIME | TT 101-1 (°C) | TT 101-2 (°C) | TT 101-3 (°C) | TT 101-4 (°C) | TT 101-5 (°C) | TT 101-6 (°C) | TT 101-7 (°C) | TT 101-8 (°C) | TT 101-9 (°C) | TT 101-10 (°C) | TT 103 (°C) | TT 104 (°C) | MASS FLOW RATE (kg/s) | VOLUME FLOW RATE ($m^3/s$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4:04:02 PM | 43.6 | 43.8 | 43.6 | 44 | 44 | 44.3 | 44.4 | 45.3 | 45.1 | 45.4 | 55.9 | 58.4 | 144 | 146 |
| 4:06:44 PM | 43.8 | 44 | 43.8 | 44.2 | 44.3 | 44.4 | 44.6 | 45.5 | 45.3 | 45.6 | 55.7 | 58.3 | 144 | 145 |
| 4:09:18 PM | 44.1 | 44.2 | 43.9 | 44.3 | 44.4 | 44.7 | 44.8 | 45.7 | 45.5 | 45.8 | 55.7 | 58.1 | 144 | 145 |
| 4:11:53 PM | 44.3 | 44.4 | 44.2 | 44.5 | 44.6 | 44.9 | 45 | 45.9 | 45.7 | 46 | 55.7 | 58.5 | 143 | 145 |
| 4:14:40 PM | 44.5 | 44.6 | 44.3 | 44.7 | 44.9 | 45.1 | 45.2 | 46 | 45.9 | 46.2 | 55.7 | 58 | 143 | 145 |
| 4:17:11 PM | 44.6 | 44.7 | 44.5 | 44.9 | 44.9 | 45.2 | 45.2 | 46.2 | 46 | 46.3 | 55.7 | 58.3 | 144 | 145 |
| | 44.15 | 44.28 | 44.05 | 44.43 | 44.52 | 44.77 | 44.87 | 45.77 | 45.58 | 45.88 | 55.73 | 58.27 | | |