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Determination of the Convection Heat Transfer Coefficients for Multiphase Flow on Different Sections of a Closed Piping System

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Abstract

The continuous demand for petroleum-based energy as well as the increased need for geothermal energy has led to higher demands of piping systems transporting multiphase flows at high pressures and temperatures. As a result, the research of multiphase heat transfer throughout the piping system is inevitable, much of which the intricate details are still unknown. Multiphase flows and heat transfer have been studied in a wide range of applications such as mechanical, chemical, nuclear, and mineral engineering. The data from this project should prove useful in industries all over the world, especially industries that deal with refrigeration and with piping oil. Also, engines are massively important and their efficiency is becoming more prominent than ever before, and this research could aid in their efficiency. Also, the longevity and performance of these multiphase-flow piping systems, amongst other things, depend greatly on the heat transfer rates they obtain. In this experiment, results were found showing the correlation between the orientation, input temperature, input air pressure, and flow rate of the liquid, with the flow rate showing to make the largest difference.

Keywords: *Convection Heat Transfer Coefficients, Multiphase Flow, Closed Piping System, flow rate of the liquid*

1. Introduction

Why do we study heat transfer and what is it? Heat transfer is defined as “any or all of several kinds of phenomena, considered as mechanisms, that convey energy and entropy from one location to another.”[1] The movement of that energy and entropy is all due to the energy in the system moving as close as it can to equilibrium.

While heat transfer makes up half of our studies in the experiments we will be running, heat always needs a source. The source we will be using is a multiphase mixture of air and water running through a pipe. This means that the other half of our research is aimed at fluid mechanics.

Fluid mechanics is the study of fluid behavior (liquids, gasses, and plasmas) at rest and in motion. The uses of fluid mechanics are just as vast and broad as those of heat transfer. Commonly, this field focuses on mechanical engineering, chemical engineering, industrial engineering, aerospace engineering, and biology. Still, fluid mechanics are present in almost everything that exists in the universe, from something as vast and significant as a star, busting with energy, to something as mundane as water and air, flowing through a pipe.

The report and experiment was primarily focused on these two fields of study, especially on heat transfer. We've created this paper to show our findings on the effect of angle on heat transfer of multiphase flow through a pipe. Many disciplines in mechanical engineering use fluids in pipes to move heat from place to place. Specifically, areas like energy plants, computers, and casting production couldn't exist in their current forms without this technology and research.

In this experiment, the aim was to create a model of the internal pressure and temperature associated with a piping system (like that of oil extraction) which allowed testing and improvement upon existing systems through recommendations of increased efficiency and minimal waste. Water in the system represents the liquid, while air will represent the gas. The focus was placed on the change of temperature at the heating sections with a change with vertical, 45o, and horizontal orientations through the use of thermocouples, NI9211, computers, and Labview software in order to obtain and record the data. This paper will explain, step by step, the theory, the apparatus, and the experimental procedure used to find our end results. The results shown, both theoretical and experimental, will be discussed in detail.

2. Materials And Methods

2.1. Materials

A water pump is essentially the heartbeat of our experiment. It is responsible for getting the water out of the tank and circulating it within the closed-loop system. A variable frequency pump is used which allows control of the flow rate with the circuit. The frequency ranges from 0-60 Hz which translates into a maximum flow rate of 9.5 gallons per minute when the frequency is at its peak. 110/220 volts are required for the operation of this device.

The circuit is constructed using straight 1 inch and 1.5 inches Schedule 80 clear walled PVC pipes. The maximum heat threshold of the material is 140^o F and up to 200 psi at 72^o F. Pipe fittings in this circuit were used to create the 45 and 90 degree angled sections respectively. The accompanying elbow fittings have similar heat and pressure thresholds as the pipes.

A C2002, 6-Gallon, Oil-Free, Pancake Compressor was the air compressor being employed. The pancake-style compressor was selected for better stability. A water drain valve, as well as tough rubber legs, were featured on the compressor. Air delivery of the compressor at 60 psi is 3.5 SCFM whereas 2.6 SCFM is at 90 psi.

Silicone heating tape was used as a heating source in order for convection to take place. The tape is wrapped around the 1.5-inch pipe. Additionally, the heating tape covers the circumference of approximately 8 inches of piping. The maximum heat capacity of the heating tape is 200^{0}F which is regulated by the use of a controller knob. Accompanying the heat tape will be 2 type-K thermocouples which are responsible for reading the exact temperature of the PVC pipe surface.

The equipment used in order to acquire data from the closed system. consists of 2 type-k thermocouples which are placed at the surface of the pipe and then wrapped by the heating tape in order to calculate the pipe's surface temperature. These thermocouples are connected to the NI-9211 component which is responsible for data storage and recording. The NI-9211 component is attached to a computer, by which LabView is used to access the data. Additionally, there are 2 type-J thermocouples that are placed before and after the heating sections. These thermocouples are used to record the multiphase temperature before and after heat is applied. The type-J thermocouples are also connected to the NI-9211 component. This combination holds true at all three heating sections of the closed system which translates to a total of 3 NI-9211 components, 1 computer, and 6 type-J and type-K thermocouples needed.

The 6-foot wired type-k thermocouples in this project are used to record the temperature coming into and leaving each section of pipe and to measure the temperature of the heat tape. These measurements are then sent to the NI-9211 and used in data analysis. There are eight total thermocouples; two for each section and 2 for the heating tape. Diagrams of the piping system and DATAQ system shown in Figures 1 and 2.

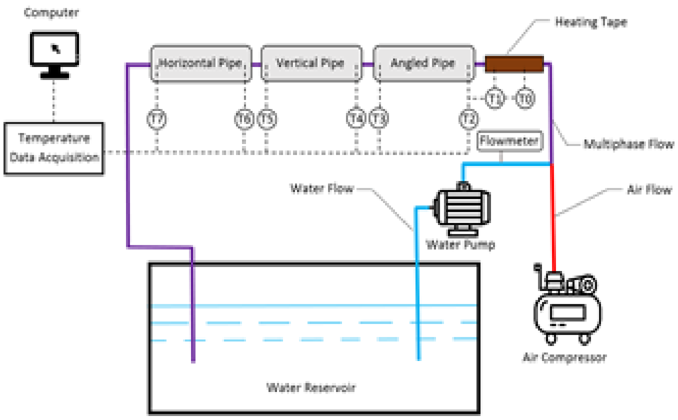

Figure 1: Thermocouple Dataq Flow Circuit

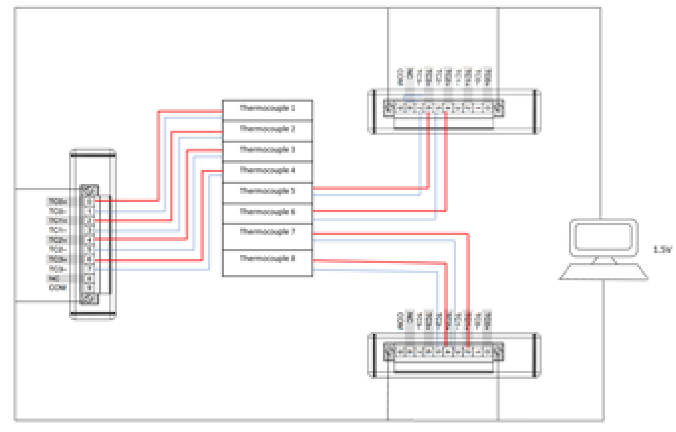

Figure 2: Thermocouple Dataq Electric Circuit

Six pressure transducers are also present in this closed-loop circuit. Each transducer is powered by the DATAQ logging instrument, which draws power from a computer via USB connections. Pressure readings are collected by the transducer which relays the information to the DATAQ logging instrument. These readings are then relayed onto the computer which accesses the data through the WinDaq software.

2.2 Procedure

The main objective of this experiment is to determine the effect that inclined, vertical, and horizontal piping orientations have on the heat transfer convection coefficient of a multiphase system. To achieve this goal, the experiment will be separated into three separate phases. The first of which is running water alone through the system, the second is running air alone, and the third is running of the multiphase flow. The heat transfer coefficient will be recorded and compared for all three phases at the various piping orientation. The heating tape will be set to the same temperature at all three phases. The experimental procedures are as follows:

- A Lab View program able to read the temperatures detected by the thermocouples was created. Ensure results are written to a file that can be detected via Microsoft Excel.
- The water tank was filled to a capacity of 25 gallons and red dye was added to the water.

- It was ensured that all valves in the system were opened.
- The water Pump and Air compressor were turned on.
- The heating tape was then turned on, set to desired temperatures of 40, 50, and 60 degrees Celsius respectively and allowed to heat up for 3 minutes.
- The system maximum number of iterations was set to a desired value.
- The program was activated to ensure that the heat is set to the wanted temperature.
- Multiphase system was then allowed to run for 40 minutes in order to achieve a steady state at the respective temperature
- The average temperature at each iteration was then calculated.

2.3 Experimental Set-up

The experimental techniques used in the system consist mainly of the observation of multiphase flow and the calculation of its heat transfer convection coefficient. This will be achieved by heating up various sections along the piping circuit at various orientations being inclined, vertical and horizontal respectively, as is the norm within the Petroleum industry.

Figure 3: Picture of Apparatus

2.4 Theory

The formula for finding the convective heat transfer coefficient is as follows:

$$Q_{conv} = VI = (T_d - T_u)C_p\dot{m} \qquad (1)$$

Where,

V Voltage

I Current

C_p Specific Heat at Constant Pressure

$\dot{m}$ Mass Flow Rate

T_u Upstream Water Temperature (Average Water Temperature)

T_d Downstream Water Temperature

In line with this formula, we can find the heat generated by dividing Q_{conv} by the volume. This comes out to:

Heat generated in heating area =

$$Qconv/V \quad (2)$$

Where,

V $\pi/4(D_o^2 - D_i^2)L$

D_o Outer Diameter

D_i Inner Diameter

The heat transfer coefficient can now be found. To find it, we are assuming that the flow is steady, the pipe surface temperature is equal to outlet flow temperature, and the surrounding temperature is 20^{o}C. The formula that we can use for that is:

$$Qconv = hA(T_s - T_\infty) \quad (3)$$

Where,

A πLD

T_s Temperature of Surface

T_{surr} Temperature of Surroundings

The forced convection formula is as follows:

$$h_f = \frac{k}{D} Nu \qquad (4)$$

Where

k	Thermal conductivity of the cylinder
D	Cross-section diameter
Nu	Nusselt number

$$Nu = \frac{0.3 + (0.62 Re^{0.5} Pr^{0.33})}{(1 + (\frac{0.4}{Pr})^{0.66})^{0.25}} (1 + (\frac{Re}{282000})^{0.5}) \qquad (5)$$

Where

Re	Reynolds number based upon Pr
Pr	Prandtl number

$$Re = \frac{V_e D}{v} \qquad (6)$$

Where

V_e	Effective Velocity (=1.22×V_a)
V_a	Average Velocity

A final useful thing to find for us is the difference in the heat transfer coefficient as the percentage of water to air changes. The results from using equation 7 give a linear relation.

$$h = \frac{\dot{m}_{mixture}\, Cp_{mixture}\, (T_{out} - T_{in})}{A_S (T_S - T_\infty)} \qquad (7)$$

3. Results and Discussion

3.1 Obtaining the Results

In this experiment, some of the most important aspects was the use of softwares to aid us with our mathematics and data retrieval and analysis. The primary softwares that we used were SolidWorks, LabVIEW, Matlab, and Google Sheets. With SolidWorks, we designed our apparatus and planned out how we would lay out the components. This gave us a good grasp of what to expect as we moved closer to getting and analyzing our results. LabVIEW was our pathway of data retrieval. Everything in our results came directly from the measurements that LabVIEW took from the thermocouples that were added to the apparatus. Matlab was then used to convert the data through mathematical formulas into usable values that can foster conclusions from the experiment. Lastly, Google Sheets was used for simple mathematics for very large sets and to plot the data that LabVIEW and Matlab obtained. These processes led to the results immediately below.

3.2 Causes of Temperature Reading Differences

While the primary goal of this project was to find the heat transfer coefficient differences between horizontal, inclined, and vertical piping, the data found was also useful for finding other empirical differences between each section of pipe. Part of this empirical data is the effect of flow rate, air pressure, and applied temperature on the temperature losses. Looking at these effects and how they change with the effect of orientation can help broaden our understanding of heat transfer in multiphase flow.

3.2.1 The Effect Of Flow Rate

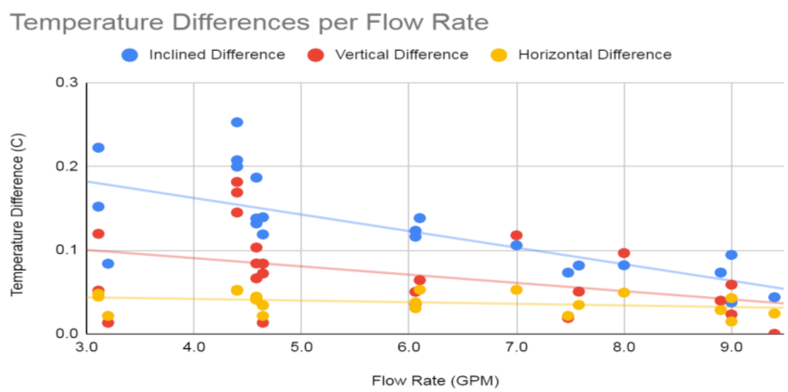

Figure 4: Temperature Difference Per Flow Rate

Analyzing the results visualized in Figure 4, it can be seen that flow rate makes a significant difference in the temperature difference of a section. The faster the flow rate, the lower the difference in inlet and outlet temperatures. This is because the multiphase flow is losing energy, and therefore heat, at the same rate as it moves. Because it moves faster with higher flow rates, there is less time between the two thermocouples, and therefore, the heat has a lower chance of escaping. Just looking at the inclined data, the trendline temperature difference at 3 GPM is about 0.1819^{o}C and is about 0.0637^{o}C at 9 GPM. If the GPM has a linear relation with the temperature difference, each of these values should have the same ratio. Dividing 9 by 3 gives back 3:1 and diving 0.1819 by 0.0637 gives back about 2.9:1. Since these values are so close, this data shows a direct relation between the flow rate and temperature difference and shows that any change due to the orientations is very small. Doing the same to the vertical and horizontal sections, ratios of about 2.4:1 and 2.7:1. While these have larger errors, it is determined that they also follow the same rule. A closer study of the flow regimes of each section would be required to understand if these errors are caused by the orientations or another variable condition.

3.2.2 The Effect of Air Pressure

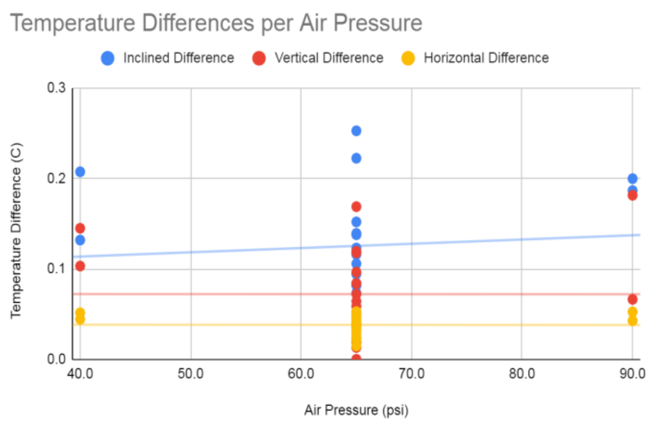

Figure 5: Temperature Difference Per Air Pressure

Looking at Figure 5, it becomes clear that changing the pressure at which the air enters the system has very little effect on the temperature differences at each section of pipe orientation. It has been concluded that this is most likely caused by the miniscule role that the air plays in the total mass of the system. Since water is about 814 times denser than air, the air just doesn't have enough of an impact on the system for a change of about 1.25 times the starting pressure to effect any significant change.

3.2.3 The Effect of Applied Temperature

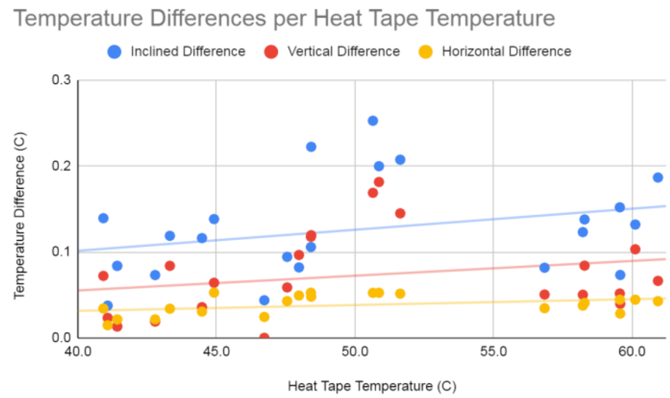

Figure 6: Temperature Difference Per Heat Tape Temperature

When Studying The Results Found In Figure 6, It can be seen That, While The Results Tend Higher As The Temperature Tends Higher, Which Is Expected By The Exponential Way That Things Cool, There Is A Problem Near The Middle Of The Graph. This Part Has An Unprecedentedly High Value For What Is Expected. Looking At The Data, All But One Of These Unusually High Values Are At 4.4 GPM. Because Of This, We Have Concluded That There Was Most Likely Some Kind Of Error When The Heat Tape Was Around 50° C And The Flow Rate Was Around 4.4 GPM. With Or Without This Probable Error, The Conclusion Is The Same: As The Temperature Rises, The Temperature Change Rises With It, But The Slope Of That Rise Is Not Very Steep.

3.3 Heat Transfer Rate Changes with Differing Variables

While the data above provides a great insight to the effects of different variables on the temperatures at the beginning and end of each piping section, determining the effect on the heat transfer rates of each orientation of pipe is our true goal for this project. Using mathematics in Matlab, the values of the Prandtl Number, Reynold's Number, and Nusselt Number were found so that the Heat Transfer Coefficients could be determined.

3.3.1 The Effect of Flow Rate

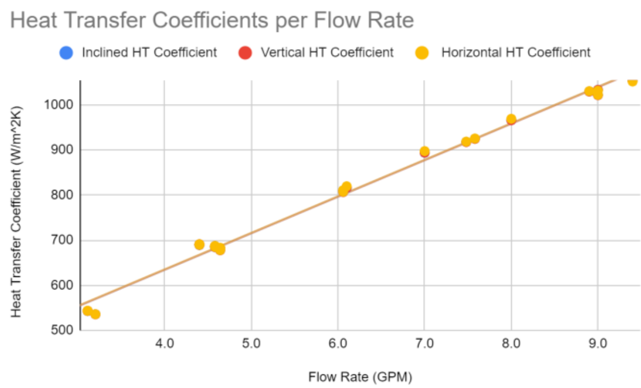

Figure 7: Heat Transfer Coefficient per Flow Rate

Looking at Figure 7, it can be seen that every point that was calculated came out to practically the same exact value. They are so close in fact, that the inclined and vertical heat transfer coefficients are almost completely covered by the horizontal values. This implies that the effect of orientation had very little effect on the heat transfer coefficient. As for the effect of the flow rate on the heat transfer coefficient, there is a very clear correlation between the two. As the flow rate rises, as does the heat transfer coefficient. In our data, it seems that the heat transfer coefficient just about doubles as the flow rate triples. This is due the fact that convection is a combination of conduction and advection where advection is considered as energy transferred because of the bulk movement of a fluid. Therefore increasing the flow rate consequently increased the rate of advection and thus the convective heat transfer coefficient.

3.3.2 The Effect of Air Pressure

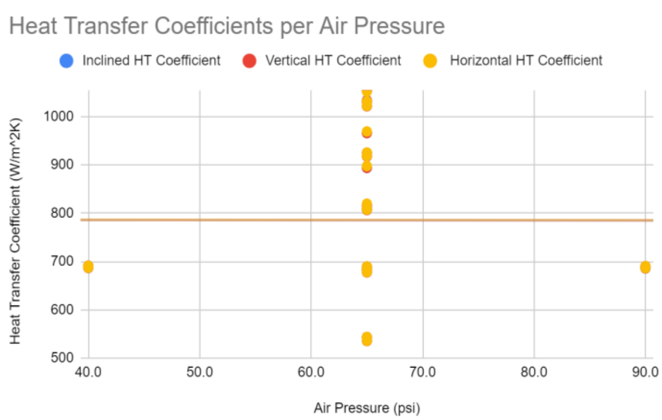

Figure 8: Heat Transfer Coefficient per Air Pressure

Analyzing the plot of the heat transfer rate change with air pressure changes, it can be inferred that the air pressure has practically no change of the heat transfer rate of the multiphase flow. For all three orientations of pipe, the trendline is practically horizontal, and on top of that, they are all at the same value, showing orientation has just as negligible an effect.

3.3.3 The Effect of Applied Temperature

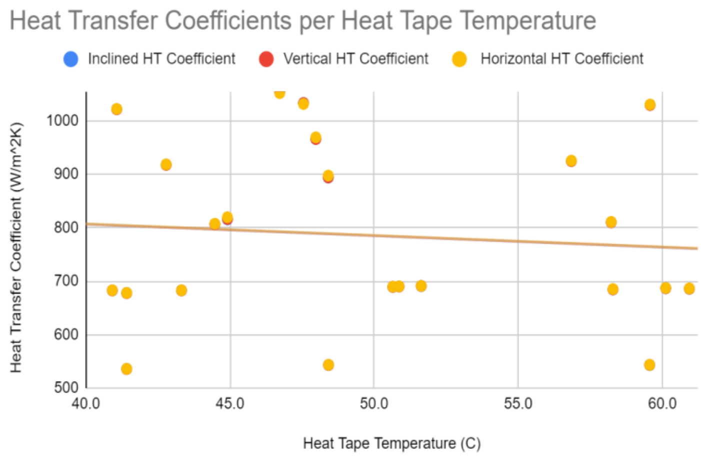

Figure 9 : Heat Transfer Coefficient per Heat Tape Temperature

Figure 9 shows the change in heat transfer coefficient in relation to changes in heat tape temperature. While a trendline was added to this graph, it does no justice in explaining what the plotted points show; a negligible effect. Looking into the formulas for finding the Prandtl, Nusselt, and Reynold's Numbers, and therefore the heat transfer coefficient, there is no input for temperature anywhere. Because of this, an effect due to the change in input temperature is not expected, and the graph complies with this logic. Also, the effect of orientation, again, shows itself to be negligible for the conditions in which we found our results.

3.4 Findings On The Effect of Orientation On Heat Transfer

Going back and studying the graphs above, there are some conclusions that can be made about orientation effects and some conclusions to be made about our experimental setup and apparatus. First, by looking at the heat transfer coefficients of each piping orientation, the results show that the differences in the values are negligible, with readings varying by 0.005%-0.082% on average.

The differences are far more obvious when studying the variances in temperature change, but all of those differences may be caused by other factors. In all three temperature difference graphs, the inclined difference is the highest, followed by the vertical difference, and ending with the horizontal difference. This could be caused by the orientation of the pipe, but it is far more likely that this is caused by the placement of the piping sections, the inclined section is first, then the vertical section, and then the horizontal section. Since objects, including fluids, cool exponentially, the temperature readings imply that the positioning of the sections caused the differences in the values for each section, not the orientation of that section.

Because of this finding, a change to the experimental process or a change in the apparatus would be recommended if a study of temperature differences is to be done again. Creating a three-way split leading to each orientation at the same distance would likely get rid of the error caused by these distances and would result in more accurate values. As for the primary subject of this experiment, the apparatus worked quite well. As expected, the heat transfer coefficients were practically the same. A further study of each section's flow regimes and variance in the pipe diameters would be recommended for further experimentation.

3.5 Liquid and Multiphase Flow Heat Transfer Coefficients

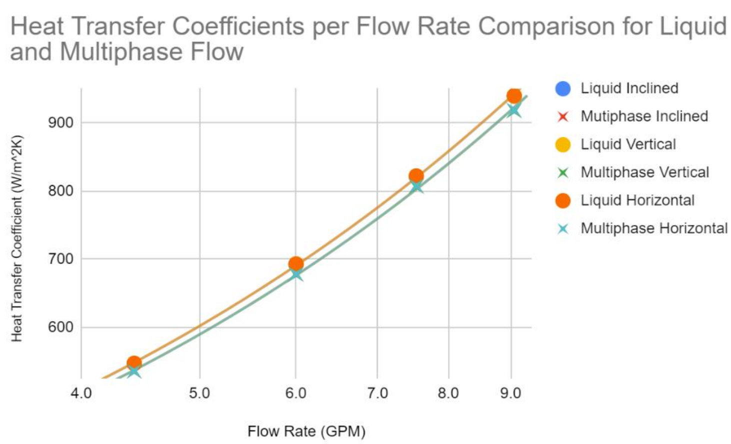

Figure 10: Comparison of Heat Transfer Coefficients for Liquid and Liquid/Air Flow

Figure 10 shows the differences in inclined, vertical, and horizontal heat transfer coefficients for both multiphase and liquid-only flows. These readings are all at 41^{o}C to 45^{o}C and the air pressure in the multiphase flow is at 65 psi. By looking at the graph, one can see that, just as in the graphs above, the orientation of the pipe makes very little difference to the heat transfer coefficient and can be considered negligible. The real pattern to see in the plot is the difference that the addition of air makes to the heat transfer coefficient. While the multiphase flow and the liquid flow have very similar best-fit curves, the multiphase heat transfer coefficient curve stays about 12 to 26 units below the liquid-only curve, a difference of 2% to 2.5%. This is due to the inclusion of the air in the multiphase flow, though making up a very small portion of the flow regime, has a significantly lower heat transfer coefficient than that of the water only as seen in Figure 11. Air flow at 40 degrees celsius and a pressure of 65 psi has a heat transfer coefficient of around 75 W/(M*C), which is at least 7.28 times smaller than the smallest heat transfer coefficient for water only. Hence the inclusion of the air in the multiphase flow makes the heat transfer rate slightly lower than the water.

3.6 The Effect Of Air Pressure On Heat Transfer Coefficients

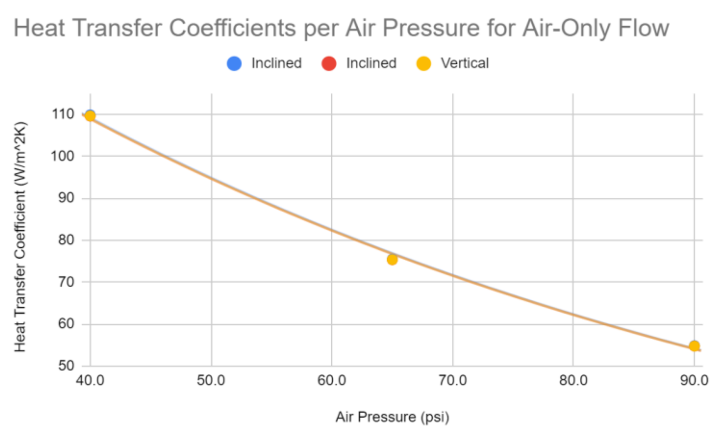

Figure 11: Comparison of Heat Transfer Coefficients for Different Air Pressures

While examining Figure 11, a clear relation between the air pressure and the heat transfer coefficient can be seen. As the air pressure rises, the heat transfer coefficient lowers exponentially. This exponential relation is expected because the Nusselt number, which is used to find the heat transfer coefficient, is found using an equation with exponents. Also, focussing on the values of the heat transfer coefficients, they stay between values of 54 and 110. These are far smaller than the values found in the liquid and multiphase flows, which are 9 to 10 times that of the air flow.

This is because the velocity of the air is far lower than that of the water. With our apparatus, the velocity of the air was between 0.178 m/s and 0.675 m/s, neither of which can compete with the velocity of the water.

4. Conclusion

Using a closed piping system to model the multiphase flow in industrial settings, data was analyzed using LabVIEW software. It was found that the orientation, input temperature, and input air pressure makes a negligible difference to the heat transfer coefficient, but the flow rate of the liquid has a large correlation.

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