Flow Patterns of Tetraflouroethane Refrigerant in Different Small Diameter Tubes Used for Vaccine Delivery Boxes

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Abstract
This study aims to determine the flow patterns of tetrafluorethane refrigerant in different small diameter tubes. It attempts to establish a relationship among the temperature, pressure drop, volumetric flow of tetraflouroethane refrigerant in a 900 mm long small diameter tube. Tests are conducted to determine the effect of varying hydraulic tube diameter to the temperature and pressure drop of tetraflouroethane refrigerant in different flow rate. A copper tube with hydraulic diameter of 0.20 mm, 0.25 mm, 0.30 mm, 0.35 mm, 0.40 mm and 0.45 mm were used in this study. For every known hydraulic diameter, there are six (6) test points located in every 150 mm interval. The experimental rig is composed of six (6) pieces of 900 mm long copper tubes for the given hydraulic diameters. Each tube is marked with 150 mm, 300 mm, 450 mm, 600 mm, 750 mm and 900 mm. The markings represent the length of capillary tubes in millimeters where test points are located. A pressure transducer is attached to every test point and is used to measure the pressure drop at every length of the small diameter capillary tube. The result shows that pressure drop increases as the tube hydraulic diameter decreases and attained an evaporator temperature as low as -5 ºC. The smaller the diameter of the tube, the more it is effective to give pressure drop for the design of a handy vaccine delivery box refrigeration system.

Keywords: Capillary tubes, Pressure drop, small diameter tube, Tetraflouroethane

Introduction

During medical missions, most of the temperature-sensitive vaccines in the Philippine archipelago are to be stored in a vaccine delivery box with a temperature range from 2 ºC to 8 ºC. These vaccine delivery boxes must be able to maintain this temperature before the vaccine can be injected to the potential recipients (Kimberlin et al. 2018). This temperature is very low compared to the ambient temperature of Filipino villages and mostly located in the hinterlands. There is a need for a low temperature storage delivery box which can maintain the storage temperature for the vaccines. This is technically needed for the delivery of basic health services in far-flung Filipino communities not only for vaccines but also with other temperature-sensitive medicines needed for the medical mission in far-flung Filipino communities. This storage temperature of 2 ºC to 8 ºC can be best attained by using a miniature basic vapor compression refrigeration system (Kandlikar, 2002). The conventional vapor compression refrigeration system may not be advisable especially when the vaccines or other temperature-sensitive medicines are going to be transported to remote provinces and hinterlands without adequate source of electricity (Dittus et al. 1930). Thus, the design of the miniature solar compression refrigerator is highly recommended for this problem (Dollera et al. 2019).
One of the basic parts of vapor compression refrigeration system is the metering device (Stoker et al. 1982). Its primary purpose is to provide pressure drop as well as temperature drop of the flowing refrigerant in the system. However, for every purpose or use of a refrigeration system, it has different capacities depending on the field of its use (ASHRAE, 2009). And for every capacity, physical size of the system is one of the primary things that matters to achieve the desirable capacity for a specific function of the system (Sonntag et al. 2013).

Mini, micro, and nano technology are rapidly getting advancement in different fields and practices. People in their different specialization are trying as much as possible to fit the world in the smallest dimension that they can imagine. However, this could be very challenging since most of the engineering applications on cooling systems are still in a very young stage of development. This study will analyze a system of metering device that could run in such manner that its part should be as small as possible to fit in a mother system which is a mini vapor compression refrigeration system (Faires et al. 2013). This metering device should be in line with the application of a capillary tube to be used in a miniature refrigeration system.

A capillary tube is commonly used as an expansion device for low-capacity vapor compression refrigeration systems where the cooling load is constant (Moran et al. 2011). The capillary tube serves almost all small refrigeration systems, and its application extends up to refrigerating capacities of the order of 10 kW. A capillary tube is one (1) meter to six (6) meters long with an inside diameter generally from 0.5 to 2.0 mm (Stoker et al. 1982). In the arrangement of the flow of the refrigerant, the refrigerant often comes out from the capillary tube in a sub cooled condition. As the liquid refrigerant enters the capillary tubes, the pressure of the refrigerant drops linearly due to friction and as the pressure falls below the saturation pressure, part of the refrigerant flashes from liquid phase to vapor phase (Sonntag et al. 2013). This causes an increase in fluid velocity as well, which causes more friction and acceleration of the pressure drops resulting in flashing of more liquid from liquid phase to vapor phase.

Capillary tubes have been used in vapor compression refrigeration systems since the late 19th century. The effects of capillary tubes in refrigeration systems have been investigated experimentally and theoretically. Different types of capillary tubes with different lengths and diameters have been tested. The hydraulic diameters of capillary tubes used for typical vapor compression refrigeration system are normally higher than 0.45 mm.

In this study, the 0.45 mm hydraulic diameter of capillary tubes down to 0.20 mm small diameter tube is investigated. The right choice of refrigerant depends on the situation at hand. Of these refrigerants, tetraflouroethane or R134a, together with R-22 and R-502 refrigerants account for over 90 percent of the market in the United States (Cengel et al. 2008). The local market has an abundance supply of R134a refrigerant so that the experimental rig will use tetraflouroethane refrigerant as the working substance in all the small diameter capillary tubes (Dollera et al. 2015).

Statement of the Problem: In the world of medicine, refrigeration systems are very important especially in most pharmaceutical products that need a lower storage temperature compared to the ambient temperature of the surroundings. In the Philippine archipelago, the medical mission is particularly challenging for the hinterland regions. People living away from the town centers only receive medical attention from medical practitioners few days in a year or not at all through organized medical missions. And in these medical missions, products with lower temperature such as ice or solidified carbon dioxide which are commonly known as dry ice are used for the storage of vaccines and medicines and other tools to be used in the medical mission that need a lower temperature for storing and transporting vaccines and other related medicines. However, it would be uneconomical and unreliable to use these kind of cooling products for the preservation of vaccines and other temperature sensitive medicines. These cooling products will only be reliable for a few hours and inefficient to be used especially for a longer period spent for the mission. For such difficulty and the question of reliability of the cooling products, the use of refrigeration cooling technology would be very useful for the preservation and maintaining the storage temperature of many temperature-sensitive vaccines, medicines, and other medical products (Stoker et al. 1982). This technology will be driven by a portable source of power such as batteries or even solar panels.

The aim of the study is to provide an analysis for the metering device that could be used in handy vaccine delivery boxes. This study will analyze the metering device of a vapor compression refrigeration system, called capillary tube. This capillary tube must have hydraulic diameters lower than what is conventionally used for vapor compression refrigeration system.

To make the temperature-sensitive vaccines and medicines delivery boxes to be handy, the conventional vapor compression refrigeration system must be miniaturized to reduce the weight of the handy vaccine delivery boxes. To miniaturize the whole system will lead to the reduction of the size of the cooling compartment and reduction of the size of the evaporator. In such a case, the miniaturization of the evaporator will also lead to the miniaturization of the metering devices or the coiled capillary tubes.

General and Specific Objectives: The general objective of this study is to design and fabricate a test rig where the flow characteristics of tetraflouroethane refrigerant can be measured and establish a relationship between pressure drop of the refrigerant and the diameter for a given flow rate in a 900 mm long small hydraulic diameter coiled capillary tube.

The following statements are the specific objectives of this study:

1. To design coiled capillary tubes with an equivalent hydraulic diameter of 0.20 mm, 0.25 mm, 0.30 mm, 0.35 mm, 0.40 mm, and 0.45 mm.
2. To fabricate the designed coiled capillary tubes and the experimental rig.
3. To measure the temperature, pressure, and the volume flow rate of the tetraflouroethane refrigerant flowing through the coiled capillary tubes.
4. To evaluate the effects of temperature, pressure drops, and the volume flow rate of tetraflouroethane refrigerant flowing through the coiled small diameter capillary tubes.

Conceptual Framework: The study is based on the existing concepts from the vapor compression refrigeration system. Knowledge on fluid mechanics, college physics, refrigeration engineering, subjects on heat transfer and thermodynamics, as well as knowledge on the properties of tetraflouroethane refrigerant are needed on this study as depicted in Figure 1.

Figure 1. Conceptual Framework

The conceptual frameworks of this study are based on the tetraflouethane refrigerant, the power input, and the fabricated small hydraulic diameter capillary tubes. This study aims to assemble an experimental rig that caters for the data gathering from the fabricated small hydraulic diameter capillary tubes. Testing and data gathering will be done on the assembled experimental rig that is made of a miniature vapor compression refrigeration system.

The expected output of this study is the evaluation of the changes in temperature, pressure drops and volume flow rate of tetraflouroethane refrigerant as it flows through the different small hydraulic diameter coiled capillary tubes.

The parameters to be gathered are the pressure drop, temperature, and volumetric flow of tetraflouroethane refrigerant inside the coiled capillary tube. Test points are designated along the coiled capillary tubes. These characteristics should be enough to be able to provide correlations and analysis and to draw an overall conclusion about the study.

The working pressure of tetraflouroethane refrigerant should be suitable for the applications for the design of a handy vaccine delivery boxes for medical products. The required average temperature for medical supply storage ranges from 2 ^{o}C to 8 ^{o}C and it is appropriate that the tetraflouroethane refrigerant should have a lower temperature than what is needed by the product (Dollera et al. 2019). This pressure drop is then used as the basis for the evaporating pressure of the system and for the condensing pressure for tetraflouroethane refrigerant which is 150.0 psig.

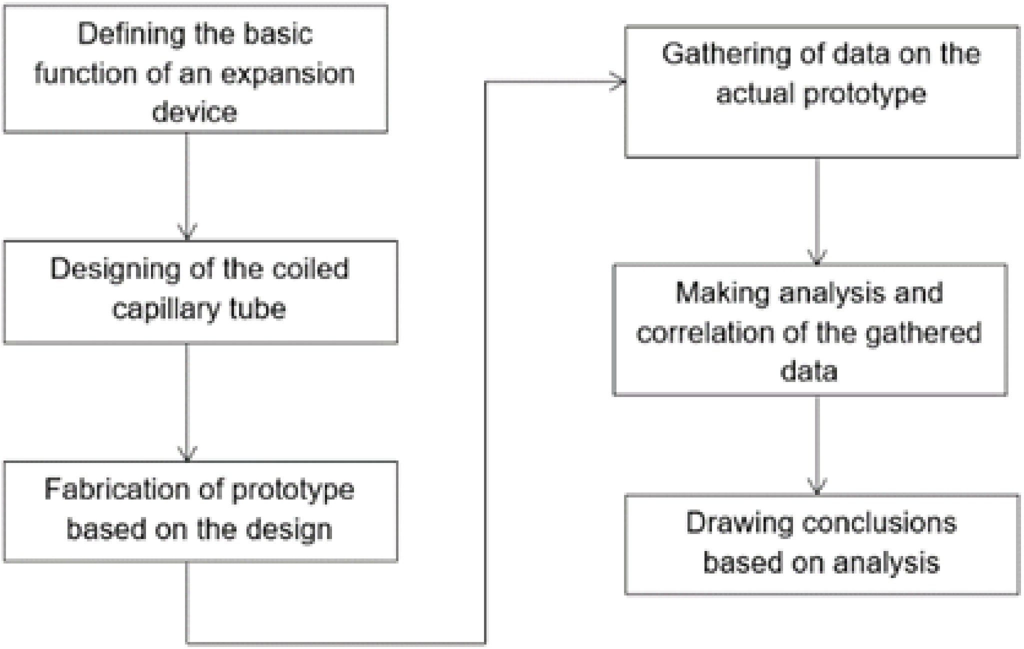
Significance of the Study: This study aims to analyze the effects on the cooling medium which is the tetraflouroethane refrigerant as it flows through the small hydraulic diameter coiled capillary tubes. This study is most useful in future studies for miniature cooling devices such as a miniature vapor compression refrigeration system for the preservation of temperature-sensitive vaccines and medicines. This is also useful for the design of portable mobile storage of medical materials and pharmaceutical products that will need miniature size technology. Portable devices should be handy and easy for transport, and for this reason, the refrigeration system of this device should be smaller compared with the conventional vapor compression refrigeration system.

Scope and Limitation: The scope of the study is to provide analysis on the temperature, pressure drop, and the volumetric flowrate of tetraflouroethane refrigerant as it flows through the small hydraulic diameter coiled capillary tubes with an equivalent hydraulic diameter of 0.20 mm, 0.25 mm, 0.30 mm, 0.35 mm, 0.40 mm, and 0.45 mm. The aesthetics of the experimental rig will not be considered in the presentation of the result and evaluation of this study.

Methodology

The purpose of the study is to give an analysis for the different small hydraulic diameter capillary tubes where limited studies have taken place. The figure below shows the flow process of the study.

Figure 2. Process Flow of the Study



The first and second steps of the study start with the review of related studies on small diameter capillary tubes followed by the design of the small diameter coiled capillary tubes as shown in Figure 2. The third step is the fabrication of the test rig based on the design. In this step, a vapor compression refrigeration system from a commercial water dispenser unit will be used as a mother unit for the experimental rig. The fourth step is the data gathering from the fabricated experimental rig. The fifth step is to analyze the collected data, and it includes the determination of the change in temperature, the pressure drops and the mass flow rate of tetraflouroethane refrigerant as it flows through the small hydraulic diameter copper tubes. And the final step is to draw a conclusion based on the analysis from the collected data from the experimental rig.

The major function of a metering device or an expansion device for a vapor compression refrigeration system is to provide pressure drops for the tettraflouroethane refrigerant before it will be subjected to absorb heat by evaporation in the compartment called evaporator. The process occurs when the temperature of the surface exceeds the saturation temperature corresponding to the liquid pressure (Incropera et al. 1996). As the pressure drops, the temperature will also drop thereby absorbing heat from the surroundings. This pressure drop should be synchronized to the demand of the load of the miniature refrigeration system.

The fabricated experimental rig is composed of a vapor compression refrigeration system from a commercial water dispenser unit with 1/12 horsepower compressor capacity and this system is used as a mother unit of the refrigeration system for the experimental rig (Dollera et al. 2019). The basic components of the commercial water dispenser were removed from the original casing and a new platform is fabricated. The hermetic compressor, condenser, metering device and the evaporator were fastened and mounted to the new platform. In addition to the basic components, a new liquid receiver was fabricated after the main condenser and a new liquid separator was fabricated before the compressor (Rajput, 1999). These two fabricated components served as the junction to the main header of the experimental rig.

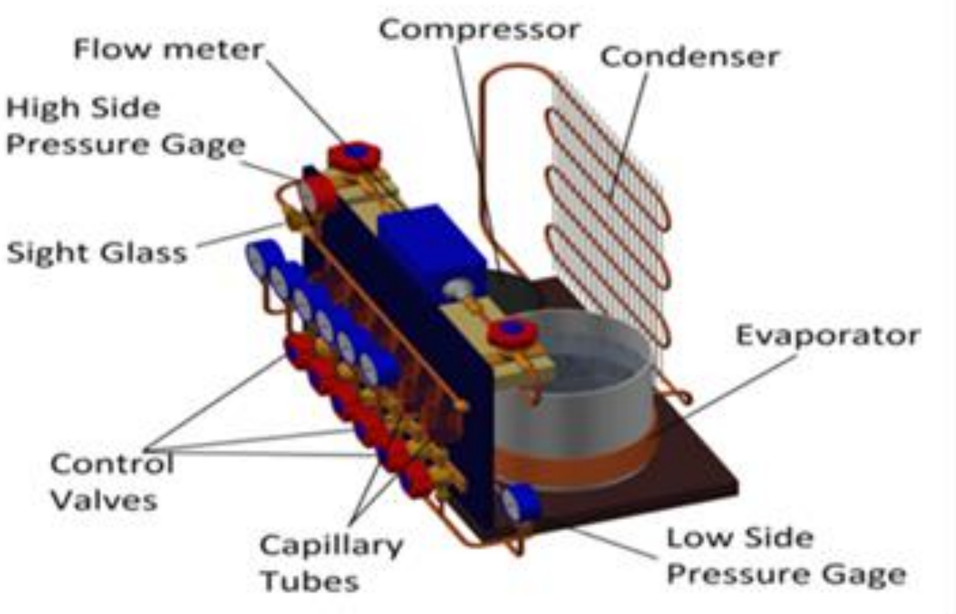
After assembling the small hydraulic diameter capillary tubes, the main header is connected to the fabricated liquid receiver and liquid separator. Testing for tetraflouroethane refrigerant leakages were conducted by evacuation and charging of refrigerant to the mother system. When the system has stabilized, the experimental rig is now ready to conduct the physical measurements of the pressure drops, temperature and the flow rate of the tetraflouroethane refrigerant as it flows inside the different small diameter tubes. Each small diameter tube has its own control valve that allows the refrigerant to flow from the liquid receiver to the liquid separator (Dollera et al. 2020).

In the design of the capillary tubes for vapor compression refrigeration system, the pressure must be based upon the working pressure of the mother system. In many types of power or refrigeration cycles, one is interested in changing vapor to a liquid, or a liquid to a vapor, depending on the part of the cycle under study (Holman, 2010). In this refrigeration system, the liquid must evaporate so that the experimental rig will reach 150 psig on the high side and 20 psig on the low side to evaporate the tetraflouroethane refrigerant. In this process, the experimental rig and the tetraflouroethane refrigeration system should be designed at these working pressures, and for the tetraflouroethane refrigerant to flow through the capillary tubes (ASHRAE, 2009) and throughout the whole system. Some criteria for data gathering of the significant parameters should be considered both on the design of the capillary tube and to the refrigeration system, such as the selection of strategic test point on the small hydraulic diameter coiled capillary tubes and the insertion of the strings with different sizes. Proper number of strings is considered to achieve the desired hydraulic diameter of the capillary tubes (Rin et al. 2006).

When the normal running condition of the experimental rig is attained, the collection of data will start using a data logger for the collection and recording of the temperature, pressure drops, and volume flowrate of tetraflouroethane refrigerant (Dollera et al. 2019).

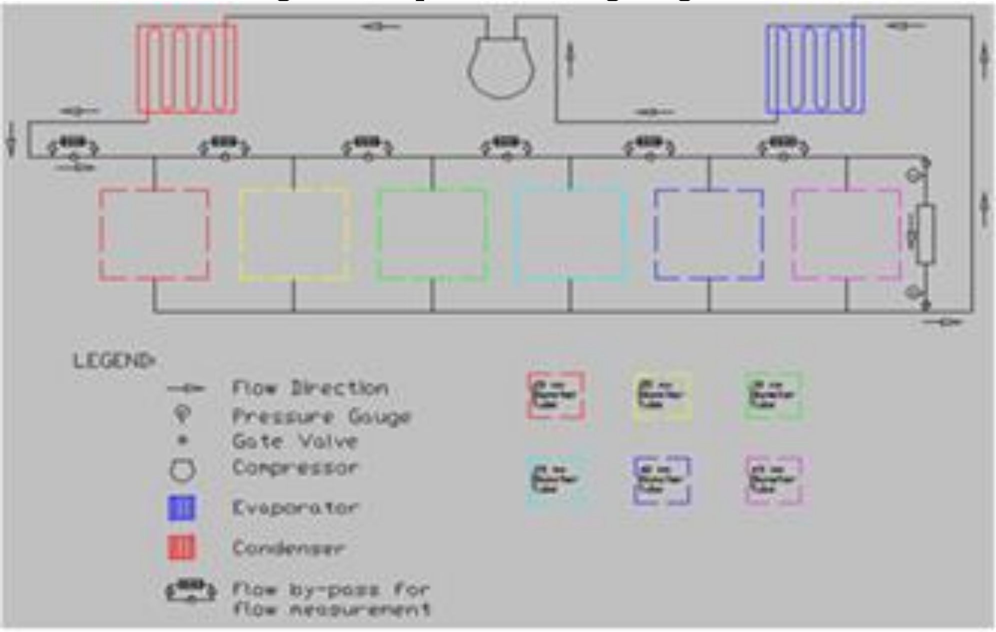
Figure 3 shows the set-up of the system and there will be no auxiliary devices that will be added to the system, except for the pressure gages and flow meter by-pass line which is essential for the measurements of any parameters to be taken for the analysis.

Figure 3. The Experimental Rig Assembly



The system will be composed of an evaporator, compressor, condenser and the capillary tube which is the subject of the study. In the capillary tube set-up, for every tube for a given diameter, the value of pressure is taken at a certain point. The schematic diagram of the proposed set-up is shown in Figure 4.

Figure 4. Experimental Rig Diagram



The purpose of separating each tube for every point of measurement is to minimize the pressure drops due to fittings from the by-pass lines and the pressure gages specially that the capillary tubes have very small diameter, and that the study only focus on the pressure drop due to the capillary action of the tetraflouroethane refrigerant inside the tubes.

Materials and method: Data gathering will be done for one (1) minute interval in a continuous run for ten (10) trials for each tube. For every small diameter capillary tube, there will be at least six (6) test points. Each small diameter capillary tube will have six (6) test points where the measuring instruments are mounted; each segment will represent a single test point. The first test point will be mounted 150 mm from the header and the remaining test points will be determined by the increment of 150 mm from the first point until the last test point reaches 900 mm.

For every test point, there will be at least three (3) parameters that should be measured, namely, temperature, pressure drops, and flowrate of tetraflouroethane refrigerant. These parameters are significant in obtaining a realistic analysis of the flow characteristics of the tetraflouroethane refrigerant at any point of the capillary tube. The testing procedure of the experimental rig and the collection of data will be as follows:

1. After the system is charged with tetraflouroethane refrigerant, the system will run for at least five (5) minutes before the testing starts.
2. After the system has stabilized, data gathering will start at the first test point by attaching the data logger to the test point.
3. Data measurement on each test point will consist of ten (10) trials with the testing for a given small diameter capillary tube, the refrigerant should flow through the capillary tube being tested and the remaining tubes should be closed.
4. After gathering and storing the necessary data, the process will be repeated for the next segment of the capillary tube.

Recharging of refrigerant would be necessary if the pressure on the high side and the low side of the mother system does not reach 150 psig and 20 psig, respectively.

After data gathering, the analysis of the data must be conducted. In this part the question of what happened to the refrigerant inside the capillary tube must be clarified and answered clearly. A correlation between each parameter must be provided.

Data and Results

The scope of the study is the measurement and testing of six (6) different small diameter capillary tubes, with the hydraulic diameters of 0.20 mm, 0.25 mm, 0.30 mm, 0.35 mm, 0.40 mm, and 0.45 mm having an equal length of 900 mm. Each tube consists of six (6) test points located for every 150 mm interval of its total length. The data gathered for the six (6) small diameter capillary tubes with different hydraulic diameters is remarkable. During the gathering of data, each small diameter capillary tube was marked with 150 mm, 300 mm, 450 mm, 600 mm, 750 mm and 900 mm. The markings represent the length of tube in millimeters where test points were located. In each segment, a pressure transducer and a thermocouple are installed to monitor the real time data as shown in Figure 5.

Figure 5. Temperature Measurement

Data gathering consists of ten (10) trials. A one (1)-minute time interval was maintained for every trial and a five (5)-minute stabilization system was observed before starting the measurement of each tube. All the data gathered was analyzed with the aid of computer software. In this method, data analysis was made easier, faster, more precise, and more accurate.

Table 1. Pressure for 0.20 mm

DIAMETER - 0.20mm										
LENGTH	PRESSURE (Psi)									
	TRIAL 1	TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 6	TRIAL 7	TRIAL 8	TRIAL 9	TRIAL 10
0 mm	120	120	120	120	120	120	120	120	120	120
150 mm	110	110	110	110	110	110	110	109	109	109
300 mm	95	95	95	95	95	95	94	94	94	94
450 mm	80	80	80	80	80	80	79	79	77	77
600 mm	68	68	68	68	68	66	66	66	66	65
750 mm	46	46	46	46	46	46	45	45	45	44
900mm	12	12	12	12	10	10	10	9	9	9

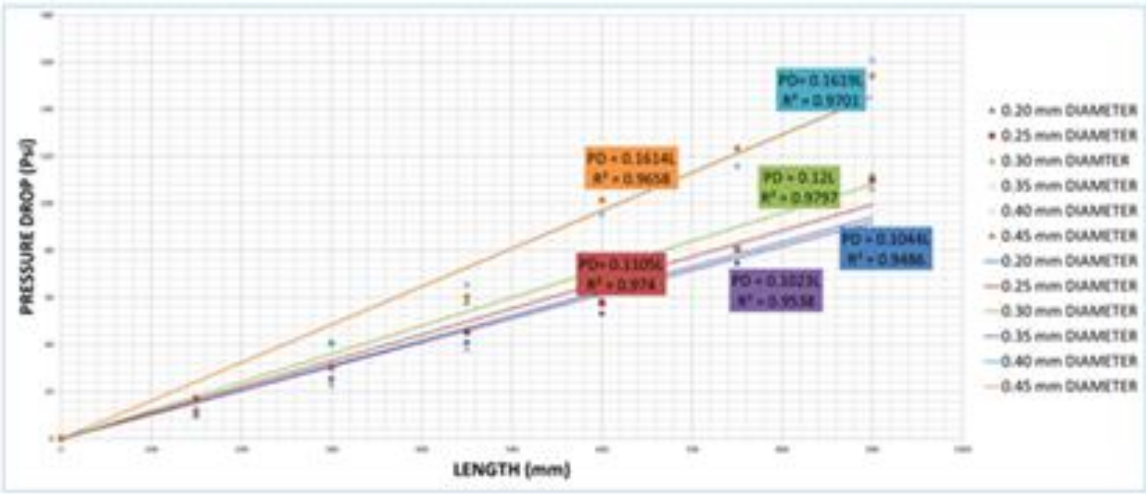
Table 1 shows the correlation of the pressure drop of tetraflouroethane refrigerant through the total length of the small diameter capillary tube. Minitab 14 is used to analyze the data and to acquire correlation between the length and pressure drops.

Discussion of Results

The flow characteristics of tetraflouroethane refrigerant displayed unique physical properties in every capillary tube being tested. Each of the six (6) small diameter capillary tubes has its own unique physical characteristics in terms of temperature, pressure drop and flowrate.

In Figure 6, the 0.25 mm small diameter capillary tube displayed the highest pressure drops among the six (6) small diameter capillary tubes followed by the 0.30 mm small diameter capillary tube. The pressure drops of the 0.20 mm small diameter capillary tube are not clear because of some leaks of tetraflouroethane refrigerant. The smaller the capillary tube, the more difficult it is to eliminate the problem of a leaking tetraflouroethane refrigerant.

Figure 6. Pressure Drops in Capillary Tubes



Since the pressure drop of the refrigerant is directly proportional to the length of the tube, therefore an increase in the tube length would mean an increase also in pressure drop of the refrigerant. But the correlation on how the pressure drop of the tetraflouroethane refrigerant increases as the length increases is very difficult to determine. The best correlation that it can have as far as the result is concerned is a linear equation. This is true based on the square of R, the closer the value of R^2 to 1 the more accurate the correlation can be generated. Since the result shows that R^2 is greater than 0.94, the deviation of these samples is not too large as shown in Figure 6.

Table 2 shows the mean flow rate of tetraflouroethane refrigerant inside the different small diameter capillary tube. The 0.45 mm small diameter capillary tube displays the highest volumetric flow rate as compared to the other small diameter capillary tube. The 0.20 mm small diameter capillary tube displayed the lowest mean volumetric flow rate.

There is a presence of scientific correlation being established with the gathered volumetric flow rate. This correlation can be expressed in terms of the equation, $y = 1.6617x$ with a value of $R^2 = 0.9463$.

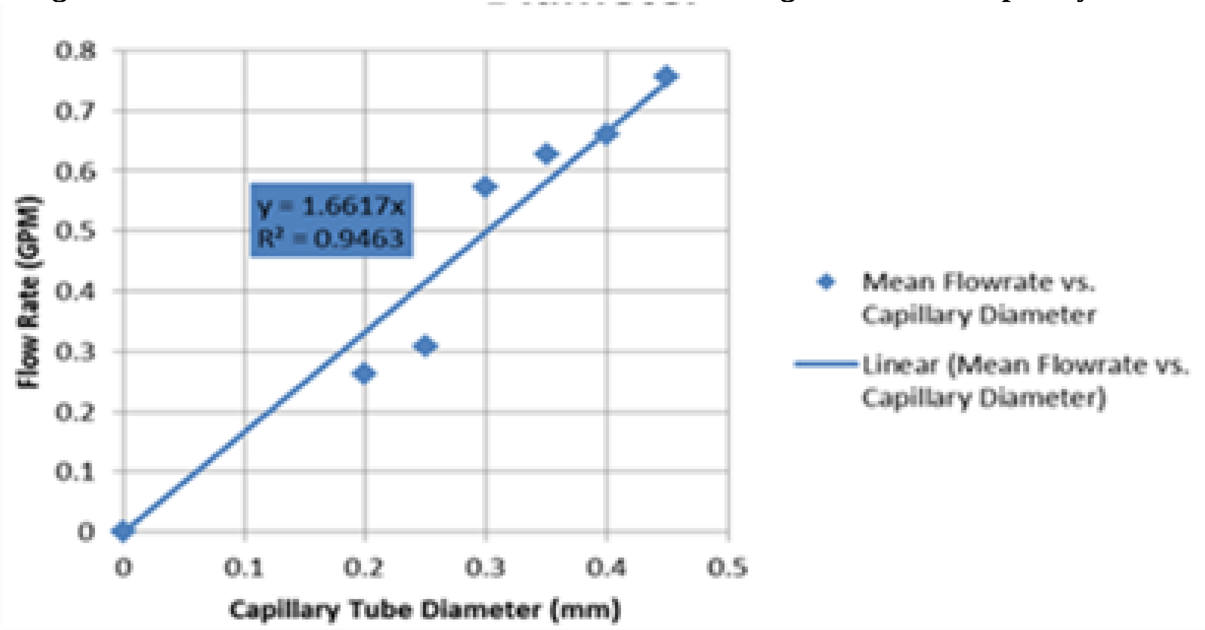
Table 2. Standard deviation of small diameter capillary tube flow rate

DIAMETER (mm)	MEAN FLOWRATE (GPM)	STANDARD DEVIATION
0	0	0
0.2	0.262714	0.049867
0.25	0.308857	0.066148
0.3	0.572	0.118268
0.35	0.626857	0.047351
0.4	0.660857	0.058204
0.45	0.757167	0.075174

With R^2 closer to 1, this correlation is considered statistically valid as depicted in Figure 7. The closer R^2 values to 1, the smaller are the differences between the observed data and the fitted values. So that the equation $y=1.661x$ can be used to model this correlation, where y represents the flow rate in gallons per minute and x represents the small hydraulic diameter of the capillary tubes in millimeters.

However, this could only be true for 0 cm ≤ Length ≤ 900 cm, beyond those limits; an evaluation should be carefully investigated, sample beyond the limit could probably deviate from the equation. The size of the tube can greatly affect the pressure drop in a certain point in the tube. It shows that from 0.20 mm to 0.30 mm, its correlation decreases as the tube size increases, but from 0.35 mm to 0.45 mm, it is the other way around. The flowrate in every tube size increases as its size also increases. This could mean that the pressure drop of the tetraflouroethane refrigerant is not only dependent on the length of the tube but also dependent on the flowrate of the working medium passing through it.

Figure 7. Volume Flow Rate of Tetraflouroethane Refrigerant in Six Capillary Tubes



Conclusion

As a conclusion, there is no significant change in the pressure drop in the overall perspective base on the total length of the capillary tube. Most of the tubes have similar pressure drops from the inlet to the outlet. But if it is divided into certain points as the diameter of the capillary tube increases, the flowrate also increases. If the flowrate could be maintained to a certain amount, it would probably give a difference to the pressure drop with respect to the different capillary tube sizes. Thus, it can be observed that the pressure drop would increase if the diameter of the capillary tube decreased and there is a significant decrease of the flowrate.

The small diameter capillary tube will require lesser flow of refrigerant to obtain the desired pressure drop for a certain refrigeration system. Since the flow is less, the tons of refrigeration would also be less. Therefore, this kind of technology is not applicable to refrigeration systems that require a lot of tons of refrigeration. However, these capillary tubes may be suitable for a certain application where only a small number of tons of refrigeration is needed by the system. These refrigeration systems may be small and handy, where only a small cooling capacity is needed to maintain a certain load at a pressure of 20 psig with a temperature of -5.5 ^{o}C. Therefore, this study may open the realization of the design of a small refrigeration system applicable for handy vaccine delivery boxes.

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