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# Variation on hydraulic diameter for the different PETG condenser tube thickness

Elmer Dollera [1,*], Roel Jeznar Cañeda [1], Clifford Clint Cuerquis [1], Narfred Egar [1], Karl Andree Olaivar [1] and Kristian Jon Dotdot [2]

[1] *Mechanical Engineering Department, Xavier University, Cagayan de Oro City, Philippines.*
[2] *Department of Public Works & Highways, Regional Office 10, Cagayan de Oro City, Philippines.*

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## Abstract

One of the four major components of a refrigeration system is the condenser. It is where the refrigerant releases the heat it absorbed by condensing from vapor to liquid form. This study aimed to design a condenser made of Polyethylene Terephthalate Glycol (PETG) and analyze the effects of varying its hydraulic diameter, wall thickness of the PETG tube, and the addition of fins. The PETG condenser shines in other aspects, like its low weight and low material cost. Different data were gathered including the outlet temperature of the refrigerant, pressure developed inside the PETG tube, and the maximum temperature of the solid PETG material. The results showed that by varying the hydraulic diameter, the wall thickness, and the addition of fins indeed have an effect in the cooling ability of the PETG condenser. The best non-finned condenser is the 3DT2 model while the best finned condenser is the 3DT3. When compared to their copper counterparts, the PETG condensers performed a little bit lower in their efficiency but were able to make it up with the lightweight and lower material cost. It is observed that the 1.0 mm hydraulic diameter PETG condenser consistently resulted in the higher solid temperature across the different hydraulic diameters ranging from 66.47 °C to 67.27 °C followed by the PETG condensers with 3.0 mm hydraulic diameter and solid temperature ranging from 64.05 °C to 65.25 °C, and the 5.0 mm hydraulic diameter with solid temperature ranging from 60.02 °C to 63.16 °C which is well below of the PETG melting temperature of 260.0 ºC.

**Keywords:** PET Glycol condenser; Hydraulic diameter; Tetrafluoroethene refrigerant; Thermoplastic material

## 1. Introduction

Refrigeration works by transferring the heat from an assigned space and moving it to somewhere else, thus lowering the temperature or maintaining the temperature of the assigned space [1]. There is a wide array of applications for refrigeration which can commonly be seen in households, industrial cooling, and air conditioning [2]. It is also very useful in the field of medicine for storing and preserving drugs, vaccines, blood, organs, and many more. Refrigeration in the medical field is also used to ensure that the stored item is in proper condition for treatment [3].

One of the four major components of a refrigeration system is the condenser. This receives the high-pressure and high-temperature gaseous refrigerant from the compressor. As the refrigerant travels throughout the condenser, it releases heat and changes its phase from gas to liquid [5,8]. In short, the condenser is the heat rejector of the refrigeration system.

The performance of each condenser set will then be based on different parameters including the interior pressure delivered by the compressor, minimum and maximum temperature of the refrigerant, minimum and maximum temperature of the solid material, and the rate of heat transfer [6,7].

* Corresponding author: Elmer Dollera, email:edollera@xu.edu.ph

Instead of using the traditional material for condensers, which is copper, this study will utilize PETG or Polyethylene terephthalate glycol. PETG is a thermoplastic polyester that is commonly used in 3D printing applications. Polymers as a material for heat exchangers is not new and have already pointed out that polymer heat exchangers are promising because of their advantageous factors including being low weight, low cost, antifouling, and anticorrosion properties [9]. Moreover, PETG is also recyclable. With that, it is also the aim of this study to provide some groundwork about the possibility of the utilization of PETG condensers in the design of portable vaccine carriers

## 2. Material and methods

This study focused on obtaining the minimum and maximum temperature, internal pressure developed, and heat transfer rate using different condensers with varying internal hydraulic diameter and thickness. The effect of the addition of fins will also be investigated. The result of this study is useful for the development of a portable vaccine carrier [14].

### 2.1. Designing and modelling of the PETG condensers

The authors used SolidWorks to conceptualize and design condensers. The different sets of condensers have identical tube lengths of 3.0 meters. The hydraulic diameter of the tubes are 1.0 mm, 3.0 mm and 5.0 mm with a wall thickness of 1.0 mm, 2.0 mm and 3.0 mm.

The addition of fins will differentiate the resulting fluid temperature in each set from the other. The tube will follow the same pattern, construction and observe an adequate spacing to allow the air to pass through. Figure 1 through Figure 5 show the specifications of the PETG condensers.

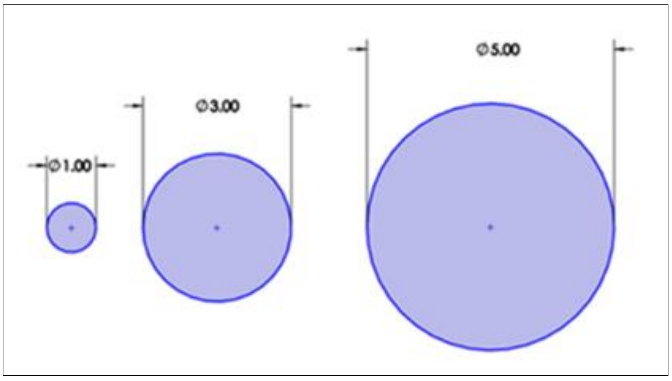


**Figure 1** Dimension of hydraulic diameters

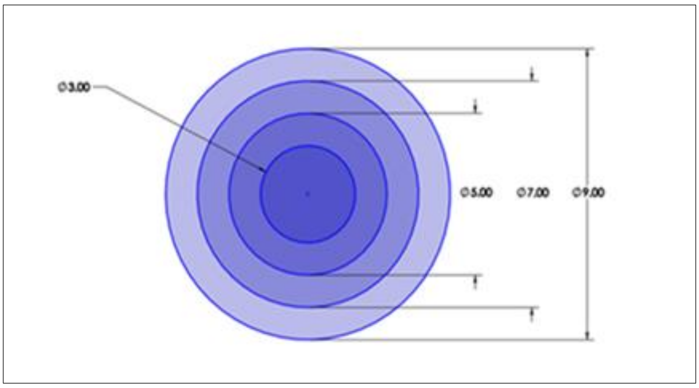


**Figure 2** Wall thickness for 3.0 mm PETG tube

Figure 1 illustrates the dimensions of the PETG condenser tubes under study. The first PETG tube has a hydraulic diameter of 1.0 mm. The second PETG tube has a hydraulic diameter of 3.0 mm and the third PETG tube has a hydraulic diameter of 5.0 mm. Figure 2 shows the wall thickness for the 3.0 mm hydraulic PETG tube. This PETG tube has a wall thickness of 1.0 mm.

The dimension of the fin is shown in Figure 3. For a 5.0 mm PETG tube, a hole is drilled on the fin with a diameter of 7.0 mm. This 7.0 mm hole is just enough to accommodate the 5.0 mm hydraulic diameter PETG tube with a wall thickness of 1.0 mm. The flat fin dimension is 15.00 mm in width and 325.60 mm in length. The hole should be drilled 10.0 mm from the top and 7.50 mm from both sides.

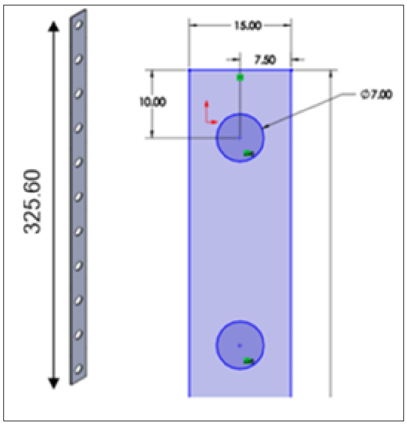


**Figure 3** Location and dimension of fins

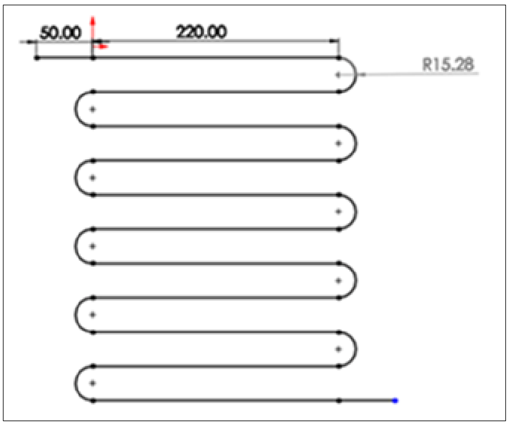


**Figure 4** Tube arrangement on PETG Condenser

Figure 4 shows the PETG condenser tube arrangement and dimensions. The radius of curvature on the return bend is 15.28 mm and the distance between the return bends is 220.0 mm. The PETG tube is extended at both ends with a length of 50.0 mm. This tube extension is necessary for fastening and mounting the PETG condenser to the refrigeration system [11,12].

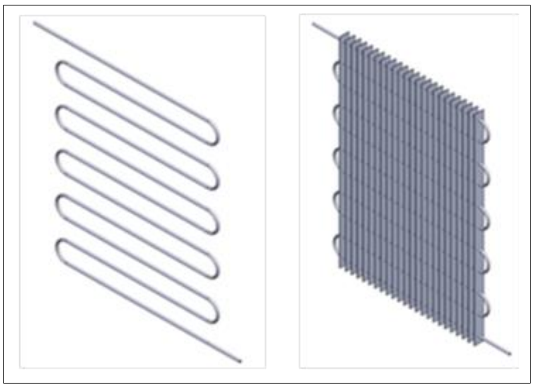

**Figure 5** The 1.0 mm hydraulic diameter with and without fins

The first figure in Figure 5 shows the 1.0 mm hydraulic diameter PETG condenser without fins. The second figure in Figure 5 also shows the 1.0 mm hydraulic diameter PETG condenser with the addition of fins to the condenser coil.

### 2.2. 3D Printing and Fabrication of the System

The design of the PETG condenser is done through AutoCAD software available in the Mechanical Engineering Laboratory. Fabrication of the condenser assembly, including the addition of fins, is done through 3D printing [13] which is also available in the laboratory. A test rig has been constructed for this study using the available materials and methods in the Mechanical Engineering Laboratory for the next phase of the study [14]. Simulation of the heat exchange between the refrigerant and the surroundings was done using SolidWorks Flow simulation software.

SolidWorks is used to simulate the refrigerant flow inside the PETG condensers. The data provided to the software are as follows:

*Physical Features*

Heat Conduction in Solids: On

Gravitational Effects: On

Material Settings

Fluid: Air (Default), Refrigerant R-134a

Solids: PETG

*Ambient Conditions*

Static Pressure: 101 325 Pa

Temperature: 25 C

Velocity in X direction: 0 m/s

Velocity in Y direction: 0 m/s

Velocity in Z direction: 1 m/s

Default material: PETG

Initial Solid Temperature: 25 C

Turbulence Intensity: 2%

Turbulence Length: 0.00006 m

*Boundary Conditions*

Inlet Mass Flow (0.0001 kg/s, 70 C, 2 013 000 Pa)

Static Pressure (30 C, 2 013 000 Pa)

The properties of the refrigerant R134a were used as a basis of the boundary conditions listed above. Under these boundary conditions are the inlet and outlet pressure and temperature of the refrigerant and its mass flow rate [4,10]

## 3. Results and discussion

There were two main parameters collected and served as dependent variables in the simulation process using SolidWorks software. The refrigerant data which are the temperature and pressure of the inlet and outlet of the refrigerant were simulated and recorded. The condenser data which shows the temperature of the solid material and the rate of heat transfer [15,17]. The data from each model would be compared to determine its performance.

After gathering the data, it is then interpreted and analyzed to identify correlations and recognize defining features that should differentiate the parameters of the different condenser passes to establish a comparative analysis [16,19]. Different goals were set in the SolidWorks Fluid Flow Simulation. These goals served as the baseline data that will be used in the comparison of the different condenser sets.

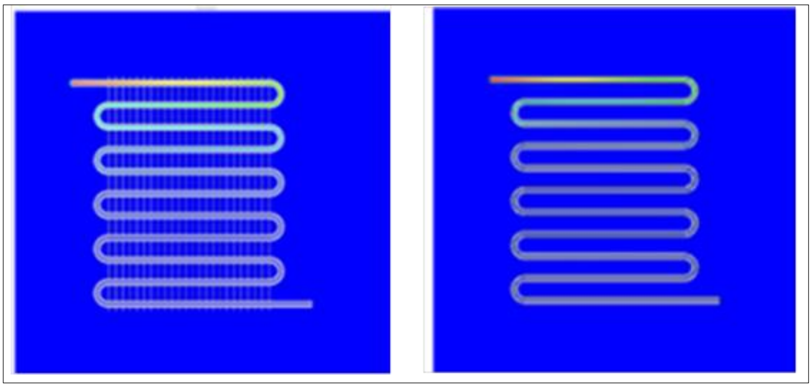

**Figure 6** Fluid flow simulation process

The following figures show the relationship between the refrigerant temperature and the type of PETG condenser. The number found after the letter D indicates the hydraulic diameter of the PETG tube while the number found after the letter T indicates the thickness of the PETG tube. The results are as follows:

### 3.1. The effect of fins to fluid temperature

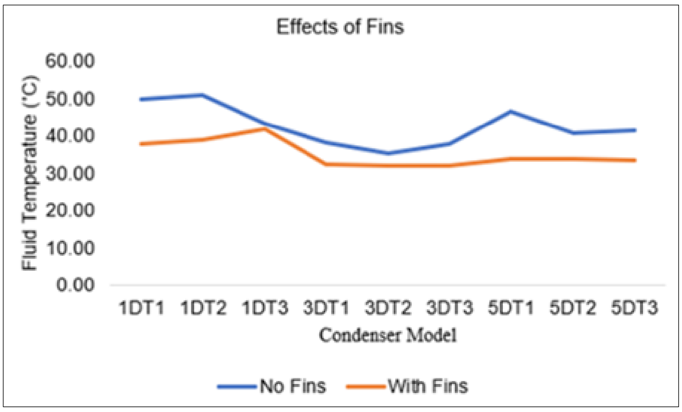


**Figure 7** Outlet fluid temperature difference of the same condenser tube with and without fins

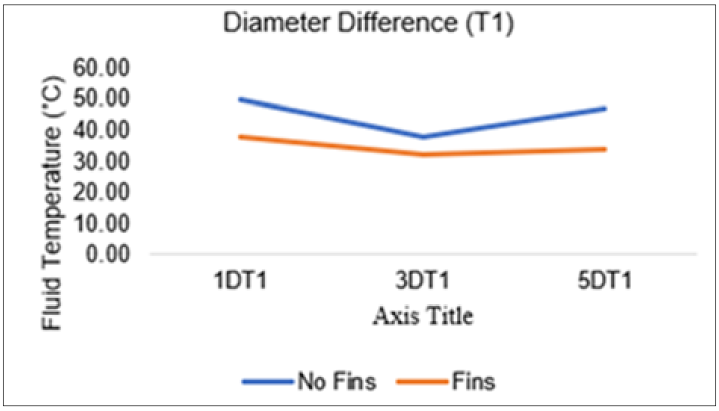


**Figure 8** Outlet fluid temperature difference of the 1.0 mm condensers with different hydraulic diameters

Figure 7 shows the difference in refrigerant temperature at the outlet of the condensers for models with and without the fins. The result shows that the heat transfer in the condenser improves when twenty-four (24) condenser fins were added to the condenser assembly [18], which measures 325.60 mm x 15.0 mm x 1.0 mm. This is mainly because of the addition of fins increases the surface area, thus improving the convective heat transfer rate between the PETG condenser and the surrounding or ambient air.

The greatest improvement in the outlet temperature is observed in the 1.0 mm and 5.0 mm models, but the 3.0 mm model still has the lowest outlet temperature among the PETG tubes. The 3.0 mm hydraulic diameter model consistently had a lower outlet temperature for the finned and no-finned condenser model. The 3.0 mm hydraulic diameter with 2.0 mm thickness has the lowest outlet temperature among the no-finned condenser model and the 3.0 mm hydraulic diameter with 3.0 mm thickness has the lowest outlet temperature among the finned condenser model having a temperature of 35.21 °C and 31.94 °C, respectively. It can be observed that the 3.0 mm hydraulic diameter model is more optimal for higher heat transfer rate compared to 1.0 mm and 5.0 mm hydraulic diameter PETG condensers.

### 3.2. The fluid temperature changes due to diameter difference

Figure 8 shows the outlet fluid temperature difference of the PETG condenser with different hydraulic diameters having 1.0 mm wall thickness.

In Figure 9, it is shown that the refrigerant outlet temperature differences are lower for PETG condensers with the addition of twenty-four (24) fins compared with the refrigerant outlet temperature differences for PETG condensers without fins installed in the condenser assembly.

Figure 10 shows the characteristics of the outlet refrigerant temperature differences of the PETG condensers with different hydraulic diameter but with the same PETG tube thickness.

The preceding figures show the effects of varying the hydraulic diameter of the PETG condenser to the outlet refrigerant temperature differences while maintaining the wall thickness of the PETG tube. It can be observed that the 3.0 mm hydraulic diameter PETG condenser consistently performed as the most efficient PETG condenser across the different wall thickness followed by the PETG condensers with 5.0 mm and 1.0 mm hydraulic diameter. In addition, the PETG condensers with a hydraulic diameter of 3.0 mm resulted with the highest temperature drop in the refrigerant where it recorded a temperature of 35.21˚C for the non-finned model and 31.94˚C for the finned PETG condenser model.

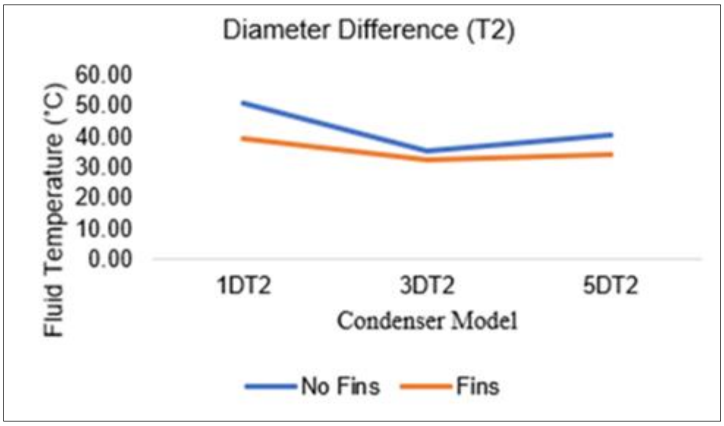


**Figure 9** Outlet fluid temperature difference of the 2.0 mm condensers with different hydraulic diameters

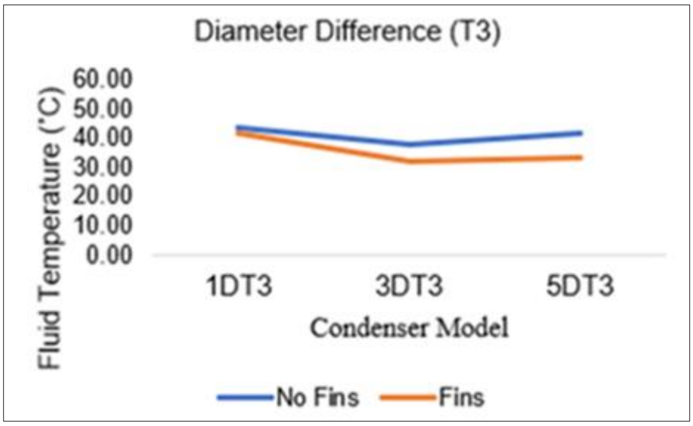


**Figure 10** Outlet fluid temperature difference of the 3.0 mm condensers with different internal diameters

These results indicate that the variation of the hydraulic diameter of the PETG condenser tube affects the flow rate of the refrigerant passing through the PETG tube. In the 1.0 mm hydraulic diameter tube, the refrigerant flow rate is too high causing the transfer of heat to the surroundings to be at a lower rate. Thus, the 3.0 mm hydraulic diameter PETG condenser tube remained the optimal design for the three (3) PETG condenser models.

### 3.3. The fluid temperature changes due to thickness difference

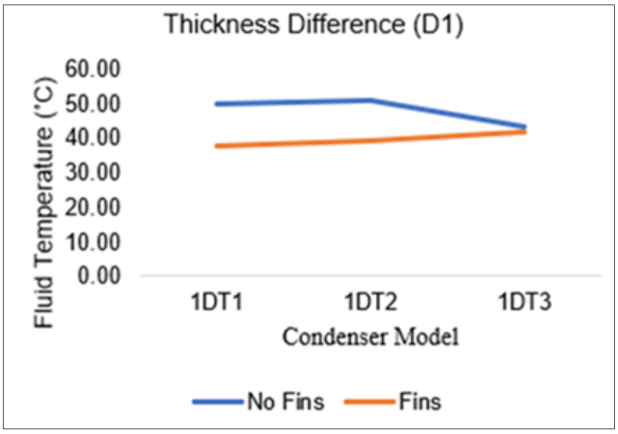


**Figure 11** Outlet fluid temperature difference of 1.0 mm condensers with different wall thickness

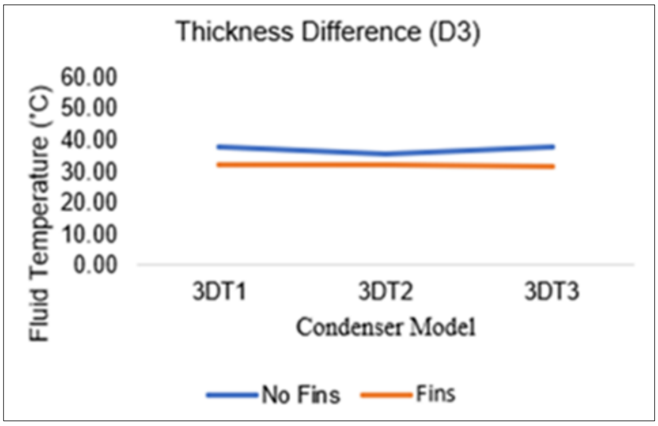


**Figure 12** Outlet fluid temperature difference of 3.0 mm condensers with different wall thickness

Based on Figures 11, 12, and 13, the variation of the wall thickness of the condenser tube influences the output of the temperature of R134a refrigerant.

Figure 11 shows the 1.0 mm hydraulic diameter PETG condenser with no fins, and the 1.0 mm hydraulic diameter PETG condenser with fins. The refrigerant temperature is always at the lower value for the finned PETG condenser, irrespective of the hydraulic diameter of the PETG tube.

Figure 12 shows the outlet refrigerant temperature differences of the PETG condensers with 3.0 mm hydraulic diameter tube. This PETG condenser model performed better than the other two (2) PETG condenser models.

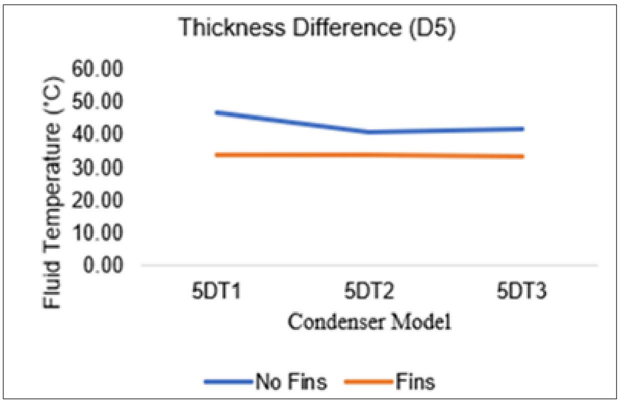


**Figure 13** Outlet fluid temperature difference of the 5.0 mm condensers but different thickness

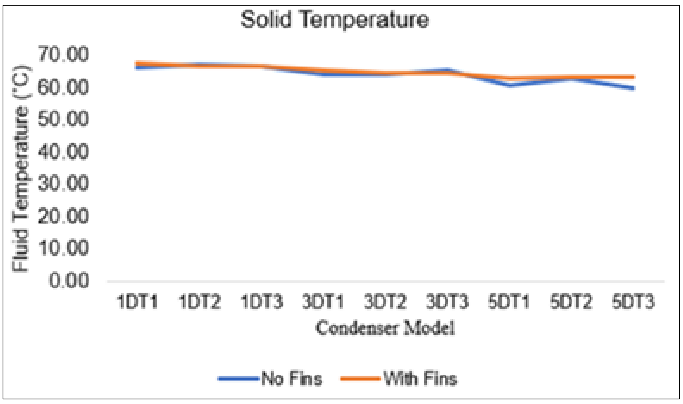


**Figure 14** Maximum solid temperature difference

Figure 13 shows the outlet refrigerant temperature difference of the 5.0 mm PETG condenser model with different wall thickness. This PETG condenser model with twenty-four (24) fins has a better performance compared with the same hydraulic diameter PETG condensers without fin assembly. It is also observed that for the 3.0 mm and 5.0 mm hydraulic diameter without fins, the PETG condenser having a 2.0 mm wall thickness had the better performance. This could be attributed to the fact that changing the wall thickness affects the conductive heat transfer rate in the walls and the external surface area for a better convective heat transfer rate of the PETG condenser. Thus, a 2.0 mm wall thickness PETG tube resulted in an optimal temperature difference. On the other hand, when the fins were added, the temperature gap among the three (3) PETG condensers became negligible.

### 3.4. The maximum solid temperature

The maximum solid temperature of the material is measured at the surface of the PETG tube. Figure 14 shows the difference in the maximum temperature of the solid material of the same PETG condenser model with and without fins.

It is observed that the addition of fins did not have a significant effect on the maximum temperature difference of the solid material since the recorded temperature of the set-up with fins and without fins were close to each other.

It could be observed that the 1.0 mm hydraulic diameter PETG condenser consistently resulted in the highest solid temperature across the different hydraulic diameters ranging from 66.47 °C to 67.27 °C followed by the PETG condensers with 3.0 mm hydraulic diameter and solid temperature ranging from 64.05 °C to 65.25 °C, and the 5.0 mm hydraulic diameter with solid temperature ranging from 60.02 °C to 63.16 °C.

Although the 1.0 mm hydraulic diameter PETG condenser has the highest maximum temperature among the three models, it did not reach the solid maximum temperature, even more to reach its melting temperature. PETG tube has a glass transition temperature of 67.0 °C – 81.0 °C and a melting point of 260.0 °C. This indicates that even at 1.0 mm hydraulic diameter, the PETG condenser is still usable for prolonged periods, without significant change in its properties.

### 3.5. The comparison of PETG and copper condenser

Figure 15 illustrates the difference in the outlet temperature of R134a refrigerant when used in the different condenser models without fins. These condensers were made of copper material and PETG thermoplastic. It is observed that the copper condensers performed consistently better than their PETG counterparts by giving lower outlet refrigerant temperatures.

This could be attributed to the fact that copper has a higher thermal conductivity of around 400 W/(m-K) compared PETG with only 0.29 W/(m-K). Still, the PETG condensers were able to bring down the temperature of the refrigerant way below its saturation temperature at the given pressure, thus successfully condensing it from gas to liquid. In addition, the copper condensers performed relatively identical to the PETG condenser in the sense that the condensers with 3.0 mm hydraulic diameter performed the best, followed by PETG condensers with 5.0 mm and 1.0 mm hydraulic diameter.

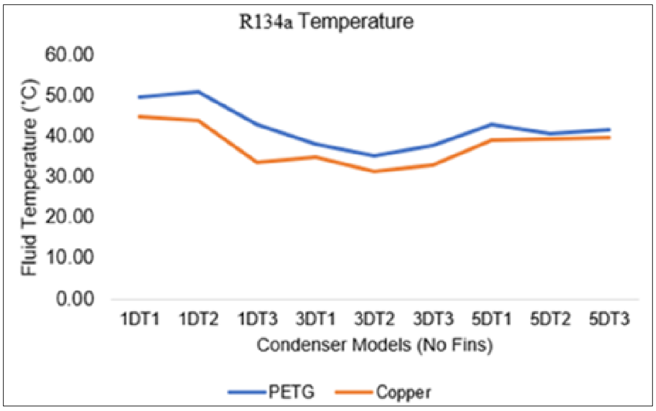


**Figure 15** Comparison of the R134a temperature using the PETG and Copper condenser models with no fins

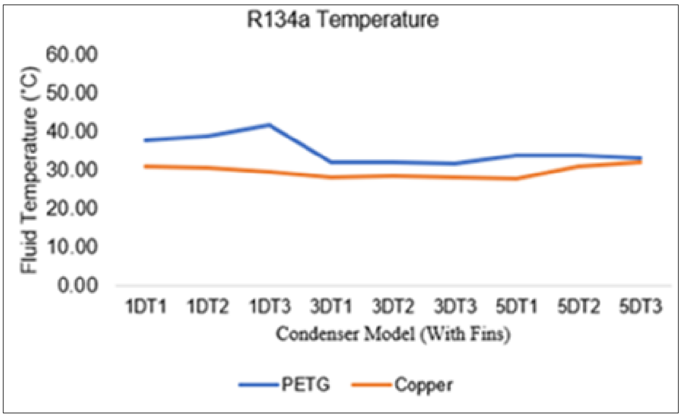


**Figure 16** Comparison of the R134a temperature using the PETG and Copper condenser models with fins

Figure 16 shows that, just like the PETG condenser models without fins, the copper condensers consistently performed better than those made of PETG mainly because of the difference between their thermal conductivity values. And, when compared to the outlet refrigerant temperature in the condensers without fins, the condensers with fins, both PETG and copper condensers, performed considerably better. This underscores the importance of adding condenser fins, which increases the surface area for a better convective heat transfer rate. It should also be noted that of all the condenser models, the ones with 1.0 mm hydraulic diameter benefited the most from the change of material from PETG to copper.

This suggests that even though the refrigerant flowed at high velocity in those condenser models due to the smaller hydraulic diameter, thus limiting the contact time between the fluid and inner condenser wall, the thermal properties of copper were able to overcome this problem. Based on Figures 17 and Figure 18, the maximum solid temperatures of the copper condenser models are consistently lesser than their PETG counterparts. This is mainly because copper is more efficient when it comes to convective heat transfer because of its higher convective heat transfer coefficient. Moreover, the larger surface area due to the thicker profile resulted in a better convective heat transfer rate. This explains why thicker condenser models performed better than condensers with the same hydraulic diameter but different in wall thickness.

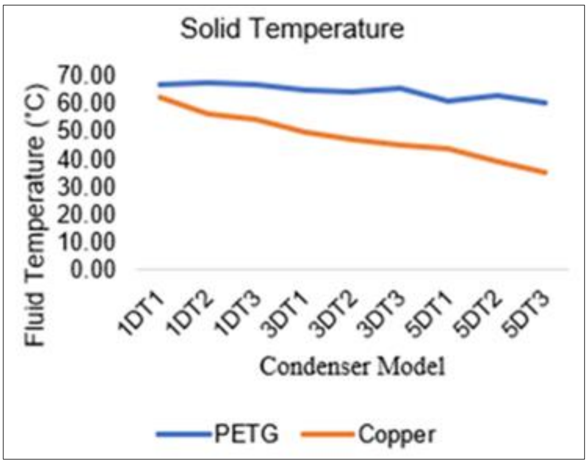


**Figure 17** Comparison of the solid temperature using the PETG and Copper condenser models with no fins

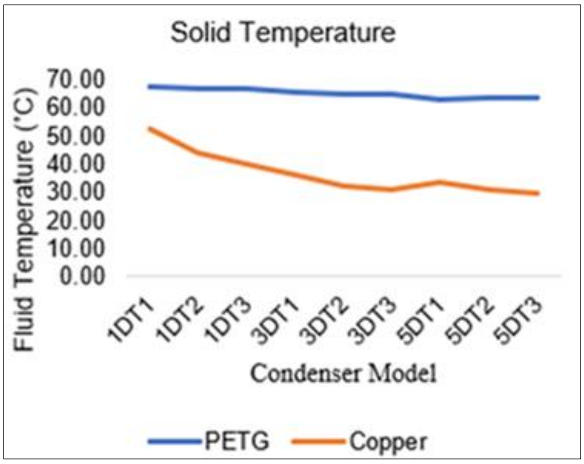


**Figure 18** Comparison of the solid temperature using the PETG and Copper condenser models with fins

### 3.6. The volume, mass, and cost comparison of the PETG and copper condensers

Table 1 shows the comparison of the cost between the PETG condenser and the copper condenser. The addition of fins considerably increases the mass and consequently increases the cost of the condenser model, but as a result, the outlet refrigerant temperature is reduced. When compared to the copper models, the PETG condensers are about seven times lighter than the copper condenser.

But when the fins were added, the difference between the temperature drop of the PETG condenser and the copper condenser, especially in the models with 3.0 mm hydraulic diameter, becomes almost negligible with PETG condenser maintaining its lightweight property compared with the copper condenser.

**Table 1** Mass and cost comparison of the PETG and Copper condensers

| MODEL | Without Fins | | | | With Fins | | | |
|---|---|---|---|---|---|---|---|---|
| | Mass (kg) | | Cost (₱) | | Mass (kg) | | Cost (₱) | |
| | PETG | Copper | PETG | Copper | PETG | Copper | PETG | Copper |
| 1DT1 | 0.02 | 0.17 | ₱30.14 | ₱76.00 | 0.17 | 1.20 | ₱214.58 | ₱541.09 |
| 1DT2 | 0.07 | 0.51 | ₱90.42 | ₱228.00 | 0.21 | 1.51 | ₱269.56 | ₱679.72 |
| 1DT3 | 0.14 | 1.01 | ₱180.84 | ₱456.01 | 0.27 | 1.97 | ₱352.03 | ₱887.66 |
| 3DT1 | 0.05 | 0.34 | ₱60.28 | ₱152.00 | 0.18 | 1.34 | ₱239.42 | ₱603.72 |
| 3DT2 | 0.12 | 0.84 | ₱150.70 | ₱380.01 | 0.25 | 1.80 | ₱321.88 | ₱811.66 |
| 3DT3 | 0.21 | 1.52 | ₱271.26 | ₱684.01 | 0.33 | 2.42 | ₱431.84 | ₱1,088.91 |
| 5DT1 | 0.07 | 0.51 | ₱90.42 | ₱228.00 | 0.20 | 1.47 | ₱261.60 | ₱659.65 |
| 5DT2 | 0.16 | 1.18 | ₱210.98 | ₱532.01 | 0.29 | 2.08 | ₱371.56 | ₱936.91 |
| 5DT3 | 0.28 | 2.03 | ₱361.68 | ₱912.02 | 0.39 | 2.85 | ₱509.00 | ₱1,283.47 |

### 3.7. The efficiency based on the outlet temperature

In Figure 19, it is shown how the efficiency of the system can be compared with the PETG condenser to that of the copper condensers, both with no fins.

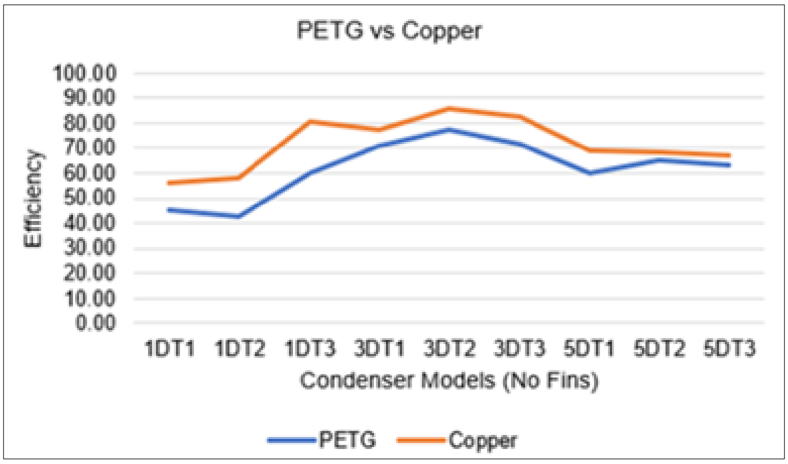


**Figure 19** Efficiency comparison of the PETG and Copper condensers without fins

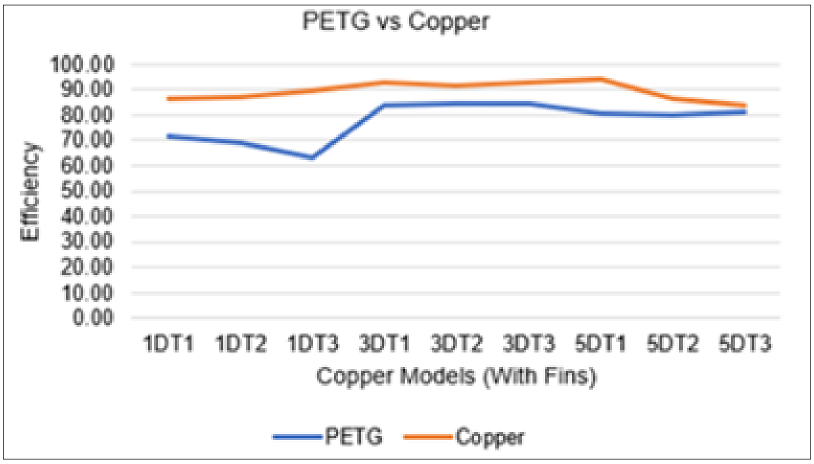


**Figure 20** Efficiency comparison of the PETG and Copper condensers with fins

Figure 19 shows the copper condenser models are consistently performing better than the PETG condensers. At most, the copper condenser is ahead by around 20% over the PETG condenser.

Figure 20 shows the comparison of the efficiency of the system using PETG condenser and copper condenser both with fins. It is observed that the copper condensers are better compared to PETG condenser by 30% at most, in terms of efficiency. This underscores the fact that the difference in the thermal conductivity of copper condenser and PETG condenser is still too big to be overcome by any design variation. But still, if the finned and non-finned PETG condensers are compared, the models with fins performed much better, with the model 3DT3 having the most efficient model.

## 4. Conclusion

Through the utilization of simulation software, the authors were able to test the design and gather significant data from each PETG condenser model. The addition of fins to the PETG condenser resulted in lower temperature of the R134a refrigerant when compared to the non-finned PETG condenser.

It is observed that the addition of fins improved the overall performance of the PETG condenser. When it comes to the variation of thickness, the 3.0 mm and 5.0 mm hydraulic diameter PETG condensers work best when the wall thickness is maintained at 2.0 mm.

Moreover, the PETG condenser model with a hydraulic diameter of 3.0 mm resulted in the highest temperature drop in the refrigerant outlet temperature. Overall, the best non-finned condenser is the 3DT2 PETG condenser model while the best finned condenser is the 3DT3 PETG condenser.

It should also be noted that the maximum temperature of the solid is 67°C, which is lesser than its maximum service temperature. This indicates that PETG condenser can be very effective for this type of condenser design. When compared to a traditional copper condenser, the PETG condensers performed slightly lesser than the copper condenser, but the PETG condensers were able to make it up in terms of the lightweight of the condenser assembly and a lower cost of material used in fabrication.

## Compliance with ethical standards

### *Acknowledgments*

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### *Disclosure of conflict of interest*

No conflict of interest to be disclosed.

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