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Polymer Hollow Fiber Oil Cooler for a Racing Car

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Abstract - Heat exchangers constructed from polymer hollow fibers create the potential for a possible replacement of conventional metal heat exchangers. Polymer hollow fibers are chemically resistant, corrosion-resistant, lightweight, easy to shape, and less energy-consuming than conventional metal heat exchangers (lower CO_2 production during production). This study focuses on the possibility of using a polymer hollow fiber heat exchanger (PHFHE) for oil cooling in a race car. There is minimal free space in the engine part of the racing vehicle. Therefore, the dimensions of the initially used oil cooler must be respected, so a cooler with a high specific heat flux is needed. The heat exchanger was manufactured on the X-Winder winding machine, which is not designed for the production of heat exchangers, so the software was developed to control the winding device based on user-specified parameters to achieve optimal geomemetry and therefore high heat flux. Measurements were made comparing the thermal performance of the designed heat exchanger and a real-life oil cooler for a racing car. The cooler had a satisfactory thermal performance at all measurement points.

***Keywords*:** heat exchanger, hollow fiber, heat transfer, oil cooler

1. Introduction

Most heat exchangers are made of metals such as aluminum, copper, steel, etc. Polymer hollow fiber heat exchangers were introduced in 2004 by Zarkadas and Sirkar [1]. In this study, they were presented as an alternative for low-temperature applications. The overall heat transfer coefficient for polypropylene fibers achieved 647-1314 and 414-642 Wm2k-1 for water-water and water-ethanol systems, respectively.

Polymer fibers in heat exchangers typically have an outer diameter between 0.8 and 1.2 mm with a wall thickness of 10-15 % of the outer diameter of the fibers. The fibers used are usually made of polyamide (PA), polypropylene (PP), and polyetheretherketone for applications with higher temperature working medium.

Polymer materials have significantly lower thermal conductivity than metals. According to [2], the thermal conductivity of PP at 50 °C is 0.22 Wm-1K-1 and of PA6 is 0.29 Wm-1K-1. In comparison, the thermal conductivity of aluminum at 0 °C is 236 Wm-1K-1 and of copper is 401 Wm-1K-1. However, the disadvantage of the lower thermal conductivity of polymers compared to metals is overcome by the minimal wall thickness, which ensures low thermal resistance of the heat exchanger wall. PHFHE are also characterized by a high ratio of heat transfer surface to heat exchanger volume.

In a study [3], the bursting pressure of hollow fibers was investigated for six different polymers over a heat range of -40 to 160 °C. The fibers showed outstanding durability no matter the temperature, as the lowest burst pressure was approximately 40 bar at 160 °C.

Fouling has a significant effect on the overall thermal performance of the heat exchanger. Polymer hollow fibers are characterized by their smooth surface and low adhesion, ensuring a favorable fouling characteristic. In [4] was studied the effect of fouling on polymer hollow fibers and concluded that the decrease in heat transfer coefficient is in the range of 5-20 %, depending on the flow regimes. The fouling fluid was a suspension of TiO2 in tap water. Fiber fouling by air dust was studied in [5]. According to this study, the smooth polymer surface has considerably better anti-fouling properties than conventional metal heat transfer surfaces with a similar density. Metal louver exchangers achieved a 50% increase in pressure loss with three times less dust in the test air than polymer heat exchangers.

The use of a PHFHE for a car radiator was studied in [6]. In the study, two heat exchangers with PP fibers with outer diameters of 0.6 and 0.8 mm were constructed. A heated ethylene glycol-water mixture flowed inside the fibers at 60 °C, and air at 20 °C flowed outside the fibers. The values of overall heat transfer coefficients (335 $Wm^{-2}K^{-1}$), heat transfer rates (up to 10.2 kW), and pressure drop were competitive with conventionally used aluminum finned heat exchangers. A specific comparison of a polymer hollow fiber cooler with a conventional aluminum radiator was the subject of a study [7] presented in 2021. PHFHE achieved higher thermal performance by about 20 % on average, and it's about 20 % lighter.

Specific applications take advantage of the chemical resistance of polymer hollow fibers. In studies [8] and [9] PHFHEs are used for desalination. Their use for the desalination process is promising for several reasons, such as compactness, anti-corrosion, high efficiency and anti-fouling.

The potential use of PHFHE is also considered in the electrical industry. A study [10] uses polymer hollow fibers for cooling automotive LED headlights. The LED is a very efficient light source but still produces a significant amount of heat in the headlamp, 25 to 30 W. Currently, passive or active finned aluminum heat sinks are used to cool the LED board. A polymer heat exchanger replacing a conventional metal solution is approximately ten times lighter. This study has shown that this system has significant potential, especially regarding the trend of increasing LED headlight power.

Battery cooling was studied in [11], a polymer hollow fiber liquid cooling system for Li-ion cylindrical batteries is shown. This system brings significant advantages over traditional thermal management systems. The traditional thermal management system for batteries in electric vehicles consists of an aluminum heat exchanger with liquid cooling. The conventional aluminium heat exchanger must be separated from the batteries by a non-conductive element to prevent short circuiting. The advantage of PHFHEs is therefore also their electrical non-conductivity, low weight and cheap materials.

2. Heat Resistance in Polymer Hollow Fibres

The total thermal resistance of the heat exchanger fibers is the sum of the three resistances. The first is the thermal resistance inside the hollow fiber (R_{in}), the resistance between the flowing fluid inside the fiber and the inner wall of the fiber. The second is the resistance of the hollow fiber wall (R_{wall}), and the last is the thermal resistance outside the fiber (R_{out}), the resistance between the working fluid flowing past the fibers and the outside wall of the hollow fiber.

The inner diameter of the fibers is very small and the fibers are considered as capillaries with laminar flow. According to [12], the heat transfer coefficient inside the fiber is high. Therefore, the effect of R_{in} on the overall thermal resistance is relatively small. R_{wall} depends on the wall thickness of the hollow fiber and the thermal conductivity of the material. Despite the low thermal conductivity of the polymer, the R_{wall} is low due to the very small thickness. For this application, a wall thickness of 0.1 mm has been designed. Further reduction of the wall thickness could adversely affect the reliability of the heat exchanger. Study [12] also states that R_{out} significantly affects the overall thermal resistance.

3. Oil cooler design

The proposed cooler in the thesis was compared with an oil cooler designed for racing cars, specifically for the Škoda S2000 (Fig. 1) and the designed cooler respects the dimensions of the original oil cooler.

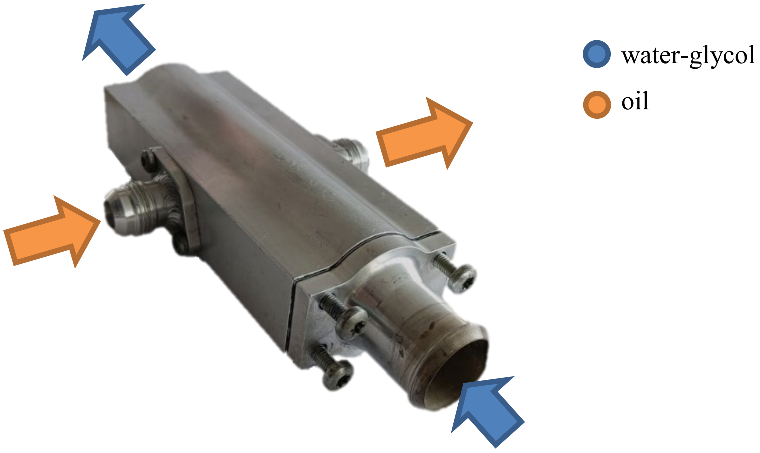

Fig. 1: Original oil cooler for racing car.

The design of the proposed heat exchanger is similar to the shell and tube heat exchanger and tube-in-tube heat exchanger. Fig. 2 shows the function principle of the designed cooler. The cooled medium (oil) enters the heat exchanger through a carbon tube. A plug is provided in the carbon tube to disallow direct flow of the heat transfer medium through the tube. Eight holes have been created in the wall of the tube. The first four holes allow the oil to enter the active part of the exchanger, where the heat is transferred from the oil (flowing outside the fibers) to the coolant (flowing inside the fibers). The remaining four holes are used to drain the oil from the active part into the carbon tube.

The coolant enters a flange at the edge of the heat exchanger, from which it is then distributed to the individual polymer hollow fibers. After passing through the fibers, the fluid enters the flange on the other side of the heat exchanger, and the coolant is returned to the car radiator.

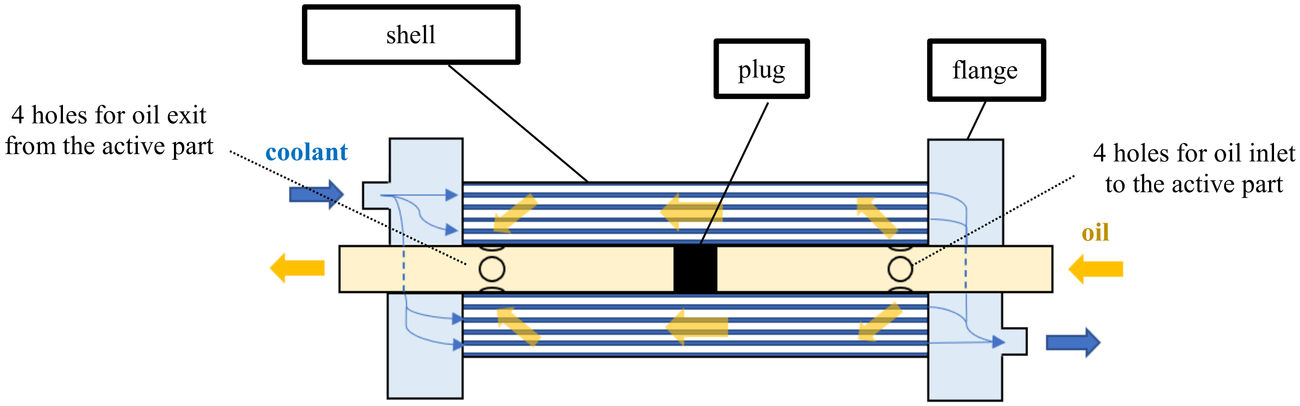

Fig. 2: Functional principle of the designed PHFHE.

Polyamide hollow fibers were used to construct the proposed heat exchanger. The internal diameter of the fibers is 0.8 mm and the outer diameter is 1 mm. The PHFHE was designed based on the geometrical parameters of a real cooler used in a racing car. The space for the oil cooler is limited in the engine part of the car. Therefore, it is necessary to keep the geometric parameters. The designed cooler has 610 hollow fibers.

The cooler is designed with the combined flow. The cooling substance enters the active part of the heat exchanger by cross-flow, and then the working substance streams are directed against each other, thus creating a countercurrent flow. Countercurrent exchangers generally achieve higher heat outputs and are used in most applications, according to [13].

According to [12], the angle between the hollow fibers and the axis of flow of the working medium (α) passing outside the fibers (Fig. 3) has a significant influence on the overall heat transfer coefficient. The study shows that an inclination of $\alpha = 5$ ° leads to a significant increase in the heat transfer coefficient outside the hollow fibers. The inclination angle of the fibers considerably affects the heat transfer coefficient up to 30°. Further increasing the angle has no significant effect on the heat transfer. Therefore, the angle of inclination of the fibres was chosen as $\alpha = 30°$.

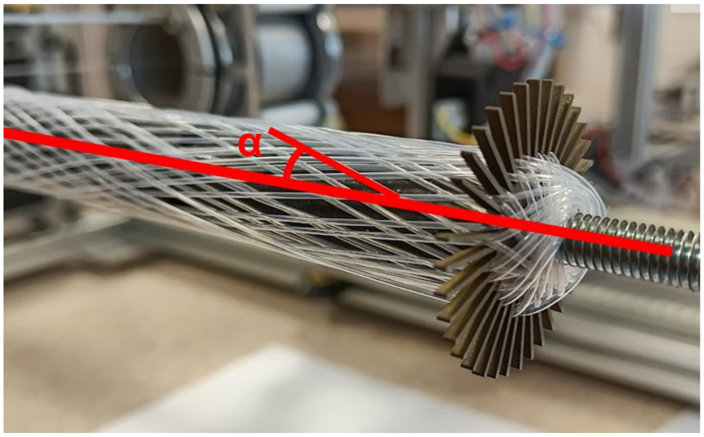

Fig. 3: Slope of the heat exchanger fibers.

The designed heat exchanger is manufactured on the X-Winder 4X-C winding machine. X-Winder is not designed to produce heat exchangers. Therefore, using the original software is very complicated to produce a PHFHE. For this reason, the software generating the control code based on the parameters specified by the user was developed as part of the study. Fig. 4 shows the structure of the exchanger fibers during winding on the X-Winder.

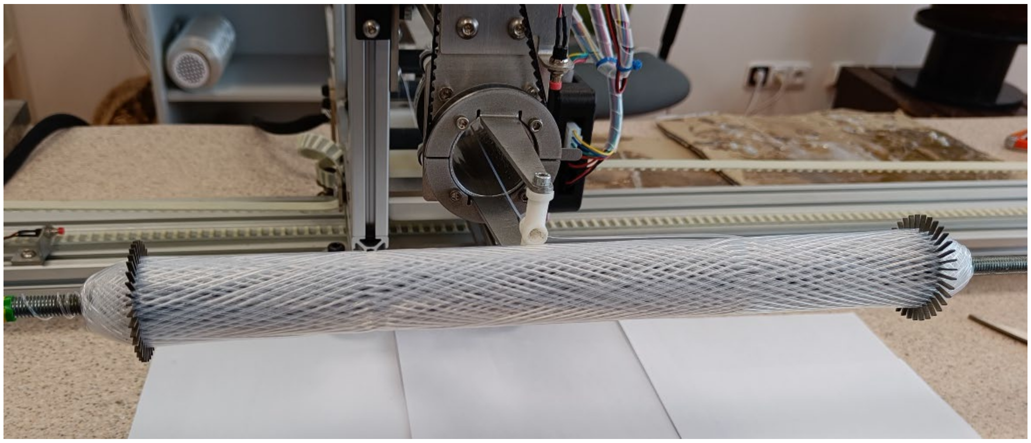

Fig. 4: The structure of the fibers during winding on the X-Winder.

The program enables the regular structure of the heat shell to be created, thus achieving higher heat flux. The repeatability of the created structure also allows for easier evaluation of the results and application of implementations based on the measured data.The produced heat exchanger is shown in Fig. 5.

Fig. 5: Produced cooler.

4. Experiment

The measurements were carried out sequentially for both heat exchangers. The first measurement was performed on a real oil cooler designed for racing cars and the second measurement was performed on a PHFHE. A simplification was used in the measurements by using water as the working medium on both sides of the heat exchanger (instead of oil and glycol-water mixture). It is assumed that if higher heat power are achieved for the proposed PHFHE, the heat exchanger will achieve sufficient heat power also if the correct working media is used.

The original metal cooler has two structural arrangements: a baffled and an unbaffled (Figure 6). The baffle forces the working fluid to flow in an intercooler finned channel. In this arrangement, heat transfer is more intense, but on the other hand, pressure losses are higher. In case of lower cooling demand, the baffle can be removed. In this case, the flow cross-section is considerably increased, leading to a reduction in the flow rate of the working fluid. Under these conditions, the pressure loss is reduced.

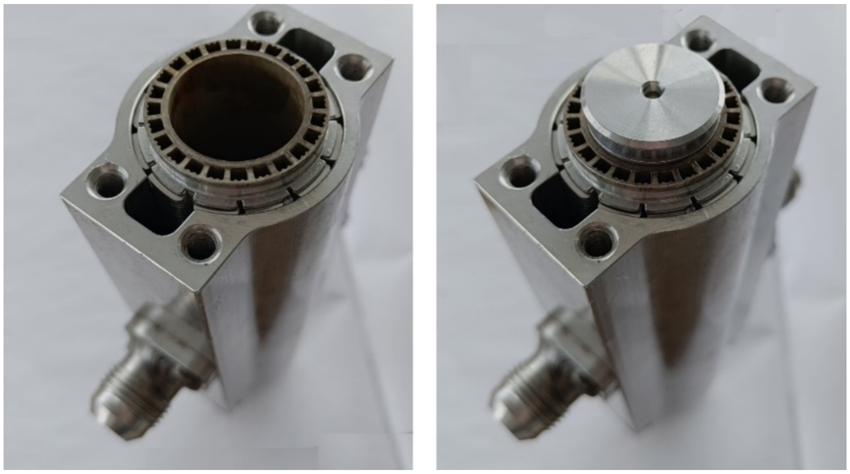

Figure 6: A unbaffled (left picture) and an baffled (right picture) arrangement of oil cooler.

Both measurements were performed for a constant flow rate on the coolant side of the oil cooler, namely for a flow rate of 1 m^3h^{-1} at a constant inlet temperature of 7.6 °C. The flow rate was successively set in the oil cooler side to 0.03 m^3h^{-1}, 0.05 m^3h^{-1} and 0.07 m^3h^{-1} at a constant inlet temperature of 70 °C.

5. Results and discussion

The measurement results are summarized in Table 1. The parameter T stands for temperature and the index o stands the oil side of the cooler. The index in indicates the inlet of the working fluid and the index out indicates the outlet of the working fluid from the heat exchanger. $\dot{V}$ represents the volumetric flow rate.

Table 1:Measured parameters on the oil side.

	original cooler, design with baffle		original cooler, design without baffle		designed cooler	
$\dot{V}_o$ [m^3/h]	$t_{in,o}$ [°C]	$t_{out,o}$ [°C]	$t_{in,o}$ [°C]	$t_{out,o}$ [°C]	$t_{in,o}$ [°C]	$t_{out,o}$ [°C]
0,03	70,02	12,90	70,03	25,30	70,13	11,16
0,05	70,13	17,00	70,19	33,60	70,32	14,03
0,07	70,23	21,70	70,05	39,63	70,12	18,15

In Fig. 7 we can see the comparison of the thermal performance of oil coolers when the flow rate of the coolant is varied. The effect of the baffle in the metal cooler on its thermal performance is significant. It can also be seen that the polymeric cooler achieves higher performance at all measurement points compared to the metal heat exchanger.

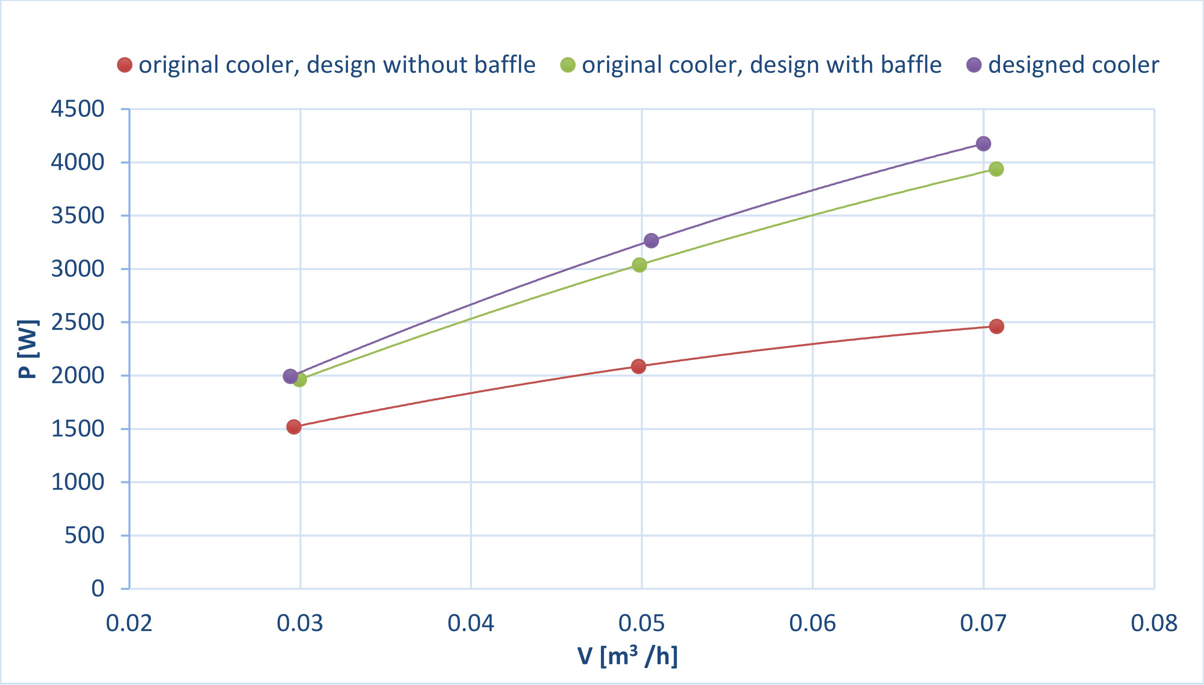

Fig. 7: Thermal performance of coolers.

Fig. 8 shows a comparison of the pressure losses of the heat exchangers when the working fluid flow rate is changed on the oil side.

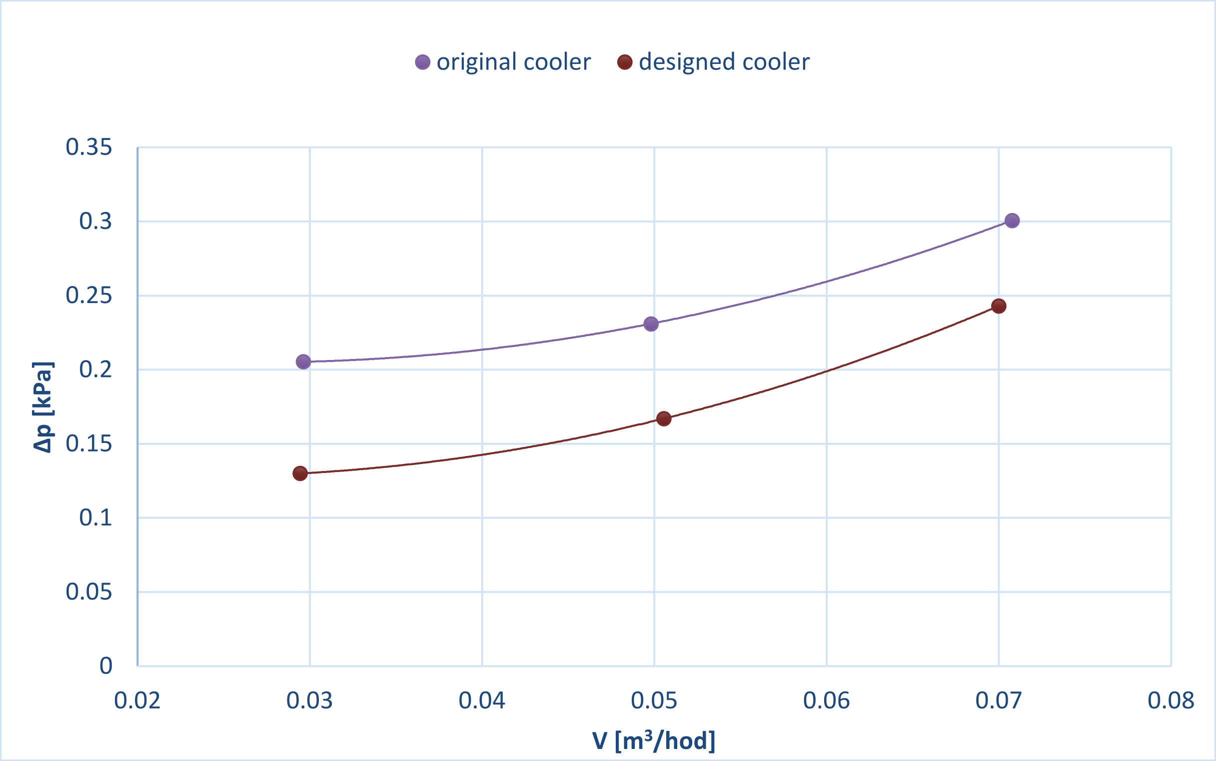

Fig. 8: Pressure losses of heat exchangers.

5. Conclusion

The oil heat exchangers used in cars today are made of metal. The present study shows a possible alternative, the use of PHFHE. Study shows that the proposed heat exchanger achieves higher thermal performance and lower pressure losses than the original metal heat exchanger. The designed heat exchanger was able to cool the hot medium more than a conventional metal oil cooler in a comparative measurement. At a flow rate of 0.05 m^3h^{-1} in the oil side of the cooler, the designed cooler was able to cool the hot medium from 70 °C to 14.03 °C, compared to the conventional metal cooler, which cooled the medium to only 17.00 °C. The measurements showed that the designed cooler has the potential to compete with the conventional metal oil cooler.

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