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Polymeric Hollow Fiber Heat Exchangers for Automotive Applications

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Abstract **-** This paper explores the potential of polymeric hollow fiber heat exchangers (PHFHE) in the automotive industry by examining their use in three different applications. The first application involves using PHFHE as a radiator for vehicles with internal combustion engines. The second application explores the use of small liquid cooling systems based on PHFHE to cool automotive lighting components integrated with high-power LEDs. Research has shown that PHFHE offer several benefits over traditional metallic heat exchangers, such as higher heat transfer efficiency, lower production costs, and reduced weight. These advantages make PHFHE a promising solution for improving vehicle efficiency and sustainability in the automotive industry. By utilizing PHFHE, the automotive industry can potentially reduce fuel consumption and emissions, while also improving vehicle performance and handling.

Keywords**:** heat exchangers, polymeric hollow fiber, automotive, battery cooling, engine cooling, LED cooling

1. Introduction

Metal heat exchangers are widely used nowadays. An alternative to these devices polymeric heat exchangers have gained popularity in recent years, particularly in industrial chemical applications and for use with highly corrosive surroundings. Typically, commercially available heat exchangers are made of polymeric tubes with a diameter of 5-50 mm and a wall thickness of 1-3 mm. However, the polymeric heat exchangers discussed in this paper are unique in that their heat transfer surface is composed of polymeric hollow fibers with a outer diameter about 1 mm and a wall thickness of about 0.1 mm. In such a heat exchangers, the heat transfer surface is made up of several thousand of these tiny tubes. This type of heat exchangers was first introduced in [1], and since then, significant efforts have been made to study the different properties of this type of heat transfer surface.

The smooth surfaces of the extruded fibers provide excellent resistance to fouling, which has been studied both for air-liquid heat exchangers with dust in the air and for liquid-liquid heat exchangers with waste water[2,3]. It has been shown that fouling on plastic tubes is about four times slower when compared to fouling on louvered fins of a similar size. In addition, fouling deposits can easily be cleaned from a polymeric fiber surface due to its smoothness and weak adhesion forces.

Polymeric materials cannot be considered as good heat conductors, but very thin wall of hollow fibers and large heat transfer area allows PHFHE to compete with metal heat exchangers in terms of heat transfer intensity. [4] shows that thermal performance and overall heat transfer coefficients of PHFHE were competitive with similar metal heat exchangers. One of the positive factors of Heat exchangers made completely of polymeric materials is that they are electrical nonconductive, making them useful for electrical devices. The use of these Heat exchangers for computer cooling has been discussed in [5]

Despite the wall thickness being about 0.1 mm, the hollow fibers can accommodate a high pressure due to the small diameter of the microchannel [6]. Fibers can survive surprisingly high inner pressures from 50 to 150 bar.

Polymeric heat exchangers offer a significant advantage over their metal counterparts in terms of environmental friendliness. Their production requires considerably less energy than that of metal heat exchangers, while also being easy to recycle. This makes them a more sustainable option for cooling systems for example in automotive application, as they not only offer efficient heat transfer but also contribute to reducing the environmental impact of the manufacturing process.

This article will describe the use of heat exchangers made of polymer hollow fibers as cooling systems for automobiles.

2. PHFHE in Automotive Application
2.1. Automotive Radiator

This chapter will describe laboratory prototype of a polymeric hollow fiber comparison with a commercially available aluminum radiator [7]. In the Heat Transfer and Fluid Flow Laboratory, a novel type of polymeric heat exchanger has been developed and built for automotive use. This heat exchanger is comprised of 12,240 polyamide hollow fibers, each with a length of 720 mm, resulting in a total heat transfer surface area of 12.92 m2. The fibers are arranged in 34 layers, with each layer containing 360 fibers woven together with textile fiber and a polypropylene tube with an outer diameter of 0.6 mm. These tubes are perpendicular to the active hollow fibers and also provide spacing between the heat exchanger layers. PHFHE was designed and build to replace radiator of Skoda Octavia, 3rd generation, gasoline engine 1.4 l TSI, maximum power 110 kW. Overall view of commercially available metal radiator and a novel polymeric heat exchanger with their structures showed on Figure 1.

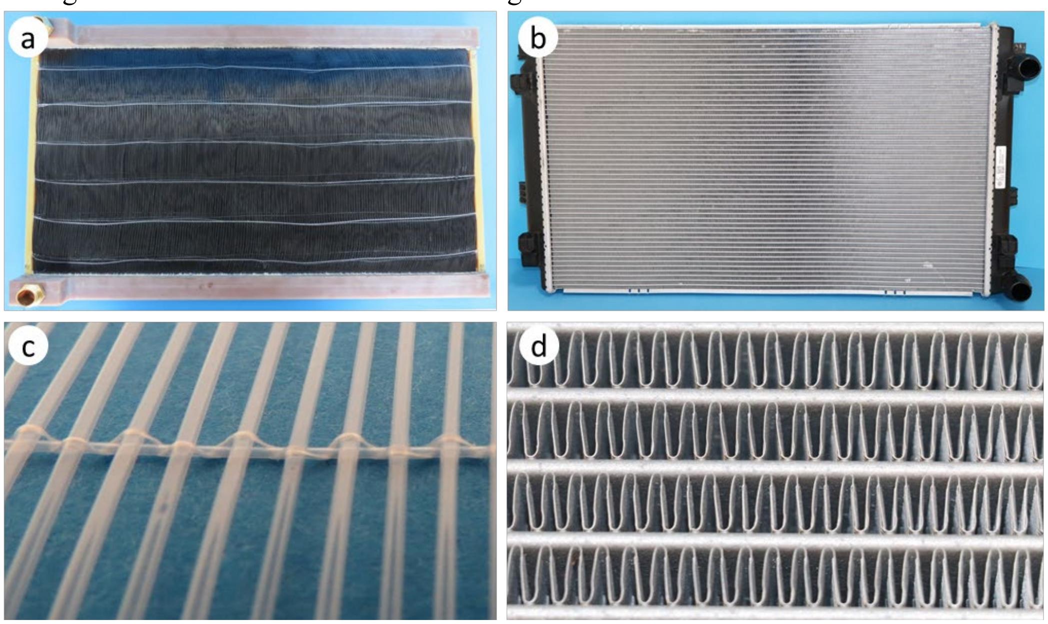

Fig. 1: Overall view of PHFHE (a) with with its structure (c) commercially available metal HE (b) with its structure (d).

In the test, a radiator coolant comprising a 50% water and 50% ethylene glycol mixture was utilized. The heat exchanger liquid input temperature was 90°C, while the inlet air temperature was 30°C. The tests were conducted on a polymer radiator with air velocities of 1, 2, 3, and 4 m/s, and liquid flows of 15, 30, 45, and 60 l/min. The tests for the metal radiator were carried out at air velocities of 2, 4, and 6 m/s and liquid flows of 30, 60, and 90 l/min. The results are presented in Figure 2, showing that the polymer heat exchanger exhibited superior thermophysical properties across the entire measurement range at the same air velocities. The maximum thermal performance for PHFHE was 70 kW at a liquid flow rate of 60 l/min and an air velocity of 4 m/s, which was 1.4 times higher than the metal heat exchanger.

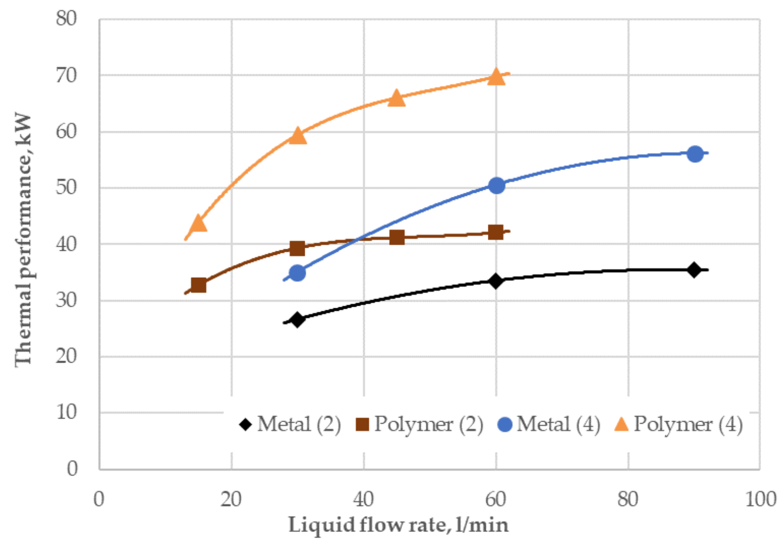

Fig. 2: Caption for figure goes at the bottom.

Both radiators exhibited a similar pressure drop on the liquid side of the heat exchanger. However, the polymeric radiator had a considerably higher pressure drop on the air side (refer to Figure 3). On one hand, this results in a reduction in the hydraulic resistance of the vehicle. On the other hand, there is a risk that, under real conditions, the cooling air may not be able to flow through the radiator in the required quantity. Therefore, a further comparison is made based on the relationship between the air mass flow through the heat exchanger and its pressure loss coefficient.

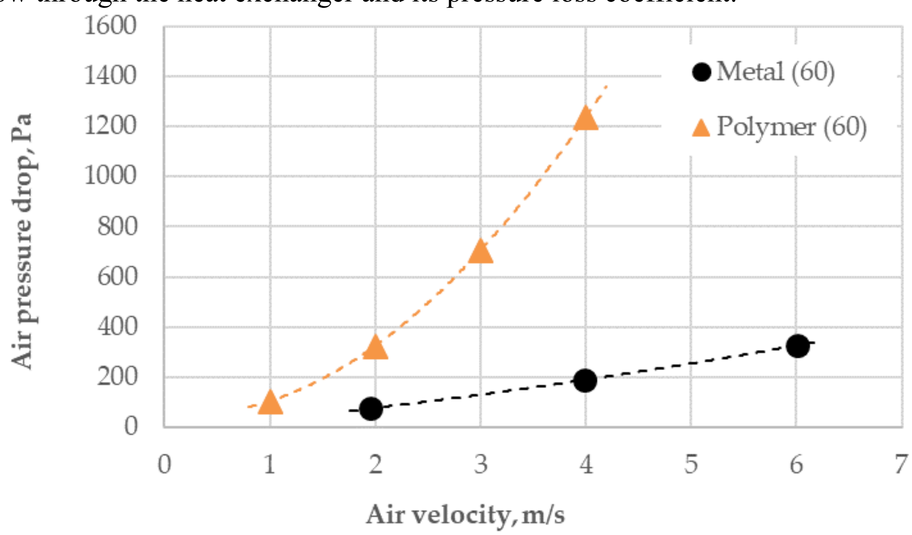

Fig. 3: Air side pressure drop of compared radiators.

The comparison of the thermal performance of a PHFHE with a common aluminum heat exchanger is determined by the relationship between the air mass flow through the conventional heat exchanger installed in the vehicle and its pressure loss coefficient. This relationship was established in a full-scale aerodynamic tunnel for the tested vehicle. Figure 4 illustrates the dependency of air velocity on the pressure loss coefficient, which was obtained by fitting the experimental data with a rational function. Using this function, the air velocity for the compared heat exchangers is estimated

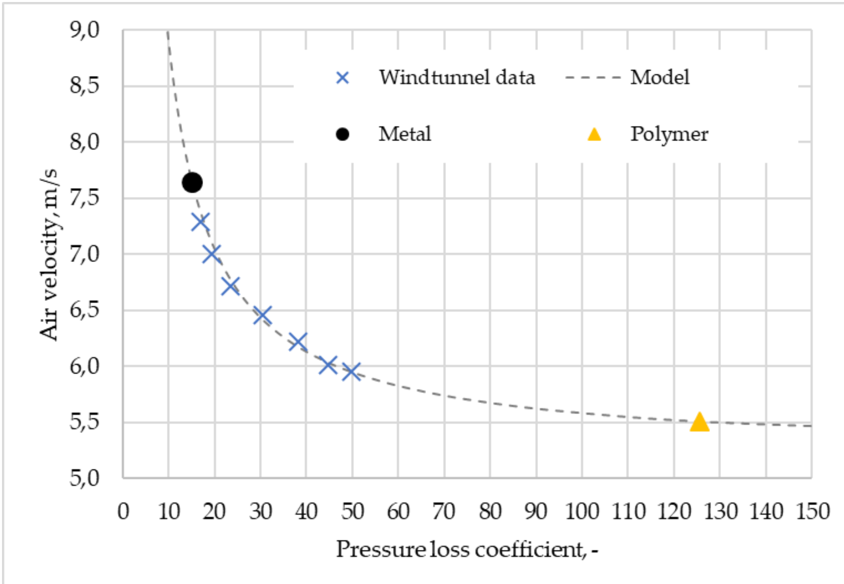

Fig. 4: Theoretical air mass flow computation.

Figure 5 depicts the thermal performance comparison based on laboratory tests, where the results were computed for a liquid flow rate of 60 l/min and air velocity corresponding to a vehicle speed of 160 km/h. Under the same conditions of heat power from the vehicle engine and internal flow of coolant (60 l/min), the polymer heat exchanger exhibited a higher heat rejection of 10 kW.

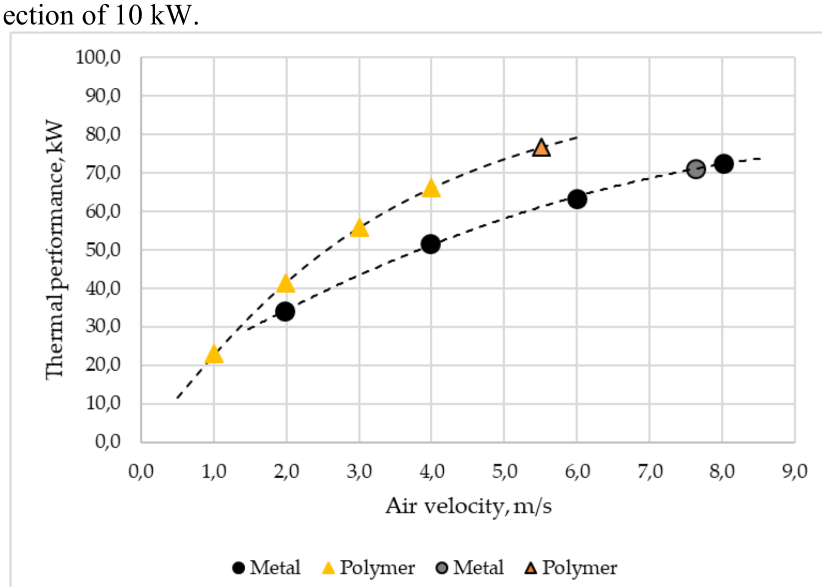

Fig. 5: Theoretical performance of car built-in radiators.

The findings indicate that despite the polymer heat exchanger's high air resistance, it is capable of effectively dissipating heat at the same vehicle speed. In fact, in some cases, as demonstrated in Figure 5, it can even outperform a metal heat exchanger in terms of heat removal. Moreover, the increased air resistance in the engine compartment enhances the car's aerodynamic properties, resulting in reduced CO_2 emissions per kilometer.

2.2. Automotive headlights cooling

Chapter describes a small liquid cooling systems based on polymeric hollow fibers for cooling of automotive lighting lighting components integrated with high power Light Emitting Diodes (LEDs) [9]. In modern automotive lighting, LEDs LEDs are mounted on a printed circuit board (PCB) alongside the controlling electronics. Despite LEDs being an efficient efficient source of light, they typically generate between 20-30W of heat, with a trend toward using even more LEDs that that produce over 50W of heat. This rapid generation of heat causes an increase in temperature particularly in uncooled units. units. The main source of heat is the LEDs, as the control electronics have a negligible effect on heat generation. In fact, after only 10 seconds of turning on the light, the temperature of the LEDs reaches 140°C. To ensure adequate cooling of the PCB, the rear side of the PCB plate is typically bonded with an aluminum finned radiator. For example, the SK38 cooler in the Skoda Octavia LED headlamp utilizes a small electric fan to enhance cooling through air forced convection. The cooler is made of aluminum injection molding and weighs 163 g. In contrast, the SK316 in the Skoda Enyaq does not have a ventilator, and cooling is associated solely with natural convection.

The present study utilizes polyamide hollow fibers for the tested heat exchangers. These heat exchangers are made up of fibers with an outer diameter of 1 mm and a wall thickness of 0.1 mm, which is 10% of the diameter. The fibers are connected on both sides to small manifolds made of carbon epoxy composite, as shown on the left in Figure 5. The original aluminum heat sink from the SK38 light unit was removed, and a heat exchanger with 33 hollow fibers was attached in the center, as shown in the middle of Figure 5. The width of the heat exchanger only covers the central part of the light unit. To bond the heat exchanger to the PCB plate, adhesive with copper microparticles was used, with a thermal conductivity of 1.5 W/mK. To measure the temperature, four micro-thermocouple type K were attached to the PCB near the LEDs, as shown on the left of Figure 4. The light unit SK316 was prepared in a similar way, with a heat exchanger containing 48 fibers, as shown on the left of Figure 5. The heat exchanger fully covers the size of the PCB plate.

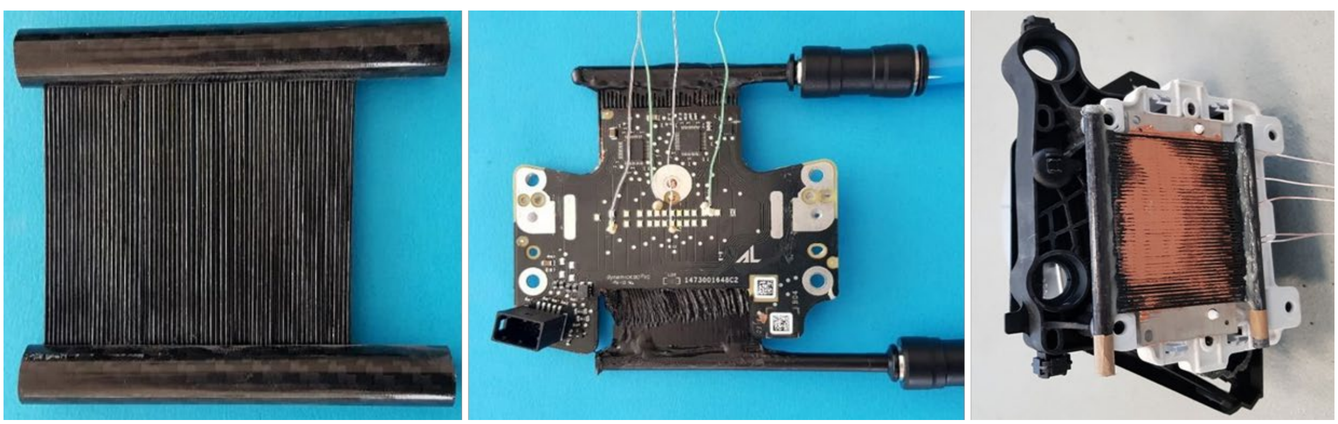

Fig. 5: Heat exchanger made of layer of polyamide fibers used as the LED headlight cooler (left), PCB of Skoda Octavia SK38 (center) and Headlight of Skoda Enyaq SK316 (right) with attached heat exchanger

The Both light units were integrated into the optical system of the headlamps and connected to the control system of the vehicle for testing. The tests were conducted at maximum light performance, although the heat power was not identical due to the built-in control system of the headlamp's electronics, which regulates the temperature of the LEDs. This control system reduces the lighting power in high-temperature regimes to prevent LED overheating. The heat exchanger is connected to a water cooling system, where the input and output temperatures and flow rate of coolant are measured. Proof-of-concept tests were conducted with input temperatures of 17°C and 40°C, with 40°C being chosen as the second test temperature because it is a typical temperature available in a car from the low-temperature car radiator. Experiments were conducted with a defined temperature difference (ΔT) between the input and output cooling water temperatures, and the flow rate was adjusted to achieve the defined ΔT. The data were recorded for the stationary regime when stable temperatures and flow rates were set. The tested unit was electrically connected to the car headlamp, and the light control functions were managed by a computer simulator that replaced the car control system. The electric power was measured using a digital multimeter, the temperature of the LEDs was monitored using micro-thermocouples.

Fig. 6 depicts the influence of cooling water flow rate and temperature on the temperature of LEDs in the SK316 unit. For higher flow rates, a significant temperature difference can be observed between the central hot spot and the of the LED row. However, even at an elevated coolant temperature of 40°C, the LEDs are sufficiently cooled, as 120°C considered the operational temperature limit for LEDs. Higher temperatures can reduce headlight durability. The laboratory tests were conducted with the light unit set to maximum intensity, and each light unit has a built-in system that reduces power as the temperature increases.

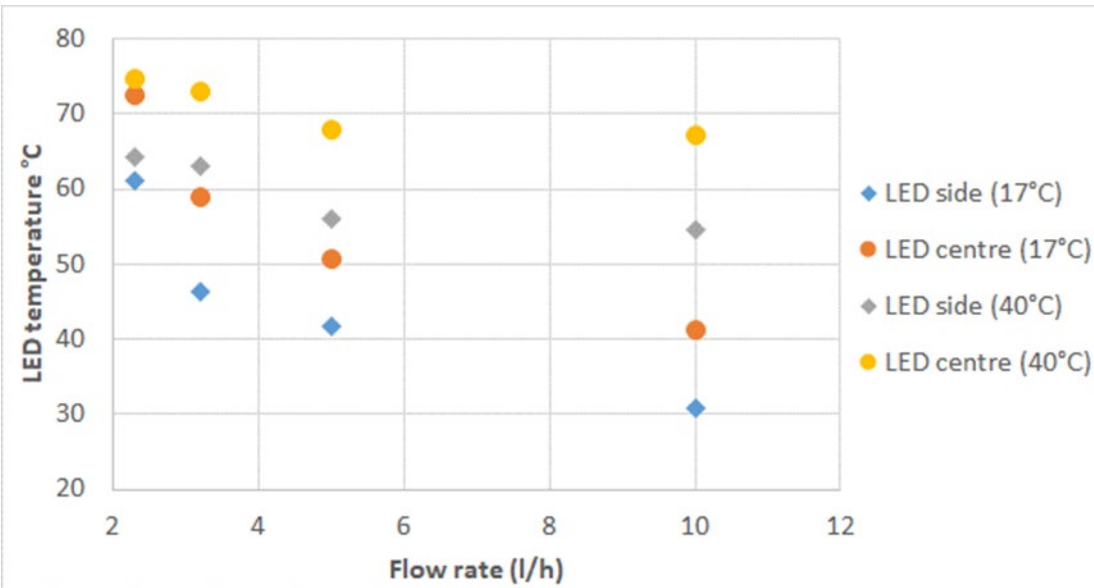

Fig. 6: Fig. 7 Average temperature of LED components with changing the flowrate in heat exchanger for unit SK316

The tests showed that polymer heat exchangers are capable of fully meeting the requirements for LEDs thermal regulation. The tested polymeric cooling systems are approximately ten times lighter than their aluminum counterparts. Additionally, the electric non-conductivity of the polymeric cooler can be considered an advantage.

4. Conclusion

Hollow fiber polymer heat exchangers have emerged as a promising alternative to traditional metallic heat exchangers in the field of automotive engineering. These heat exchangers are made up of a bundle of hollow fibers made of polymer materials such as polypropylene, polyamide and others. PHFHE utilize a polymeric microchannel as a heat transfer surface.

Compared to their metallic counterparts, polymer heat exchangers have several advantages. Firstly, they exhibit higher heat transfer efficiency due to their high surface area-to-volume ratio. This means that they can transfer heat more effectively, resulting in better overall performance of the vehicle's systems. Secondly, they are more environmentally friendly as the production costs of polymers are lower than those of metals, and polymers can be recycled.

Furthermore, the use of polymer heat exchangers not only provides the benefits of being lighter and less energy-demanding, but it also enhances the car's aerodynamic properties. This is a significant advantage in the automotive industry where reducing weight and improving aerodynamic is crucial for improving fuel efficiency and reducing emissions. Lighter heat exchangers can also contribute to a decrease in the overall weight of the vehicle, resulting in positive impacts on its performance and handling.

Overall, the use of hollow fiber polymer heat exchangers in the automotive industry has several benefits, including improved performance, increased efficiency, and reduced environmental impact. As such, they represent a promising solution solution for meeting the increasingly stringent requirements for vehicle efficiency and sustainability.

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