Case Studies in Thermal Engineering 28 (2021) 101689

Contents lists available at ScienceDirect

Case Studies in Thermal Engineering

journal homepage: www.elsevier.com/locate/csite

Case study of liquid cooling of automotive headlights with hollow fiber heat exchanger

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ARTICLE INFO

Keywords:
Automotive headlight
LED cooling
Plastic heat exchanger
Hollow fiber
Thermal management

ABSTRACT

Thermal performance of small liquid cooling systems based on polymeric hollow fibers was experimentally studied for the cooling of automotive lighting components integrated with high power Light Emitting Diodes (LEDs). Firstly, the tests with control electric heaters on a printed circuit board (PCB) were performed to precisely measure the thermal performance. The cooling effect of liquid cooling system installed on the PCB board of Skoda Octavia 4 (SK38) and Skoda Enyaq (SK316) was tested as the second step. Results of the testing show that the proposed plastic radiators ensure efficient and uniform cooling of the PCBs and keep the LEDs operation temperature much below the recommended 110 °C. As the heat generation is relatively small for liquid cooling (tens of watts), there is only 3–10 l/h flow rate of coolant needed, allowing to operate the plastic radiator with low velocity and pressure drops (below 1 kPa). Additionally, apart from excellent cooling, the tested polymeric radiators are about ten times lighter than their aluminium passive finned competitors.

1. Introduction

LEDs (Light Emitting Diodes) have been used as various lighting and indicator elements in cars for many years. In the last decade, they are entered in use as light sources of car headlights and began to compete with xenon and the best halogen headlamps. A huge advantage of LED headlights is the possibility to variate design by applying more LEDs, sectioning the light source, creating adaptive lighting, etc. The lifetime of a LED headlight is considered even longer than the lifetime of a modern vehicle. This is another significant benefit, as LED headlight does not require change of the light emitting element. However, this lifetime can be ensured only if the LEDs are operated at reasonable conditions and with proper thermal management. In today's headlights, the LED systems are based on electronic control boards and printed circuit boards (PCB) that include advanced technologies to provide light generation and lighting control.

In the available literature, there is a lot of research the on thermal management of PCBs with LED components. High power LED packages were experimentally and numerically analyzed using temperature measurements and infrared scanning [1]. High-brightness multi-LED packages were also investigated in terms of thermal performance [2]. Different cooling methods, such as heat sink, heat pipe, and liquid micro-jet were also investigated for high power LED applications and active radar systems [3]. In the subsequent study

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https://doi.org/10.1016/j.csite.2021.101689
Received 24 September 2021; Received in revised form 23 November 2021; Accepted 3 December 2021

[4], optimization of the micro-jet diameter, mass flow rate of the coolant and block material type was performed by numerical analysis. Automated LED cooling device based on heat pipes and fan was presented in experimental and numerical study [5]. One of alternative methods is direct liquid cooling. In the study of Alvarado et al. [6] dielectric coolant was used directly and the cooling performance of LEDs was investigated in terms of flow behavior and coolant type. The optimization of different blocks based on micro-jet cooling was investigated to obtain a minimum LED temperature [7]. Cooling of LED car headlights by heat pipes was investigated in a comprehensive study [8].

Heat exchangers and heat sinks are commonly made of metals such as various steel grades, aluminium alloys, and copper. Recently, composites and plastics have entered the scene, offering several outstanding features such as being chemically stable, corrosion/ erosion resistant, electrically non-conductive, etc. In addition, non-metallic coolers are also often substantially lighter, cheaper and exhibit a reduced ecological footprint [9].

As demonstrated in Ref. [10], polymeric hollow fibers are a promising alternative to finned-tube heat exchangers, as the tiny fibers (ø1 mm) have high surface-to-volume ratios. Despite of the low thermal conductivity of polymers, the thermal resistance of the fiber wall is very small thanks to its thinness. A hollow fiber of a small diameter has very high internal heat transfer coefficient (1000–5000 W/m2K), independent of the flow velocity (constant Nusselt number) because of the laminar flow [9]. Low flow velocities are beneficial as the pressure loss becomes more favorable. Heat exchangers with hollow fibers were recently tested in various automotive industry and HVAC applications and showed a promising potential [11–14].

In the present case study, laboratory tests of cooling units with hollow fibers were performed in two stages. As the first stage, the tests with calibrated electric heating elements as source of heat were performed to precisely measure the heat performance of plastic cooler. As the second stage, the proof-of-concept tests were performed to evaluate the proposed liquid cooling of high beam light units SK38 (Skoda Octavia unit) and SK316 (Skoda Enyaq unit). For both light units (see Fig. 1), the passive aluminum heat sink was replaced by the relevant plastic cooler.

2. Experimental section

2.1. LED automotive lights

LEDs are placed on a printed circuit board (PCB) together with the controlling electronics in modern automotive lighting. An example of the light units with LEDs is shown in Fig. 1. Even if the LED is efficient source of light, the generated heat is typically 20–30W and the tendency is to use even higher number of LEDs producing over 50W of heat. Heat generated by a LED increases its temperature rapidly. The temperature increase in the uncooled (removed cooler) unit is shown in Fig. 2. It is obvious that the main heat source are LEDs. The control electronics has a negligible effect on the heat generation. The temperature of LEDs is 140 °C after only 10 s after turning the light on.

Typically, the rear side of the PCB plate is bonded with the aluminium finned radiator, to ensure sufficient PCB cooling. The SK38 cooler at the Skoda Octavia LED headlamp uses a small electric fan to enforce the cooling by air forced convection. The cooler is made by aluminium injection moulding and its weight is 163 g. The electric vehicle SK316 in Skoda Enyaq does not have a ventilator and the cooling is associated only with natural convection. The cooler is made of thin aluminium fins welded to the cold plate base and weighs 94 g.

2.2. Use of polymeric hollow fibers to cool the PCBs

Polymeric hollow fibers made by extrusion are used as a heat transfer surface in this study. Due to the manufacturing technology, the fiber surface is very smooth and causes good fouling resistance. Fibres are typically extruded with an outer diameter 0.3–1.2 mm and a wall thickness 5–25% of the outer diameter.

Fibers for electronics cooling can be made from polymers such as polyamides (for instance automotive-used PA11, PA612), polyphthalamide (PPA), polyphenylenesulfide (PPS), or polyetheretherketone (PEEK). The peration temperature of such fibers varies from 90 °C for PA to 230 °C for PEEK. The fiber advantage is low weight, flexibility, and high resistance to in aggressive and corrosion environment. In some applications, electrical non-conductivity can be an additional benefit.

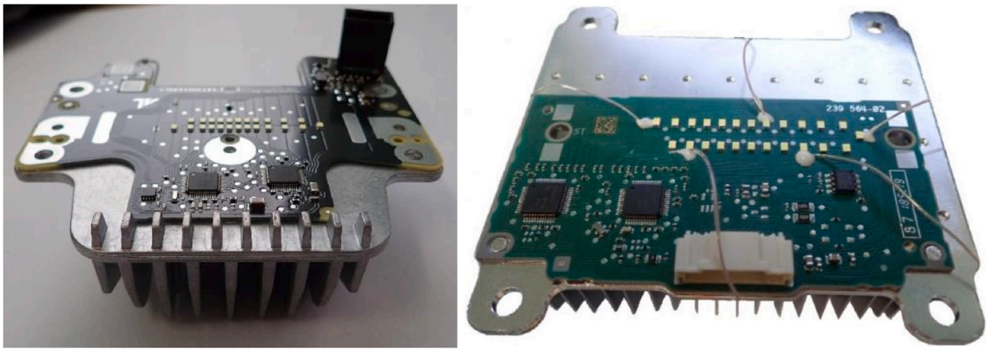

Fig. 1. Skoda Octavia lighting unit, SK38 (left); Skoda Enyaq lighting unit, SK316 (right).

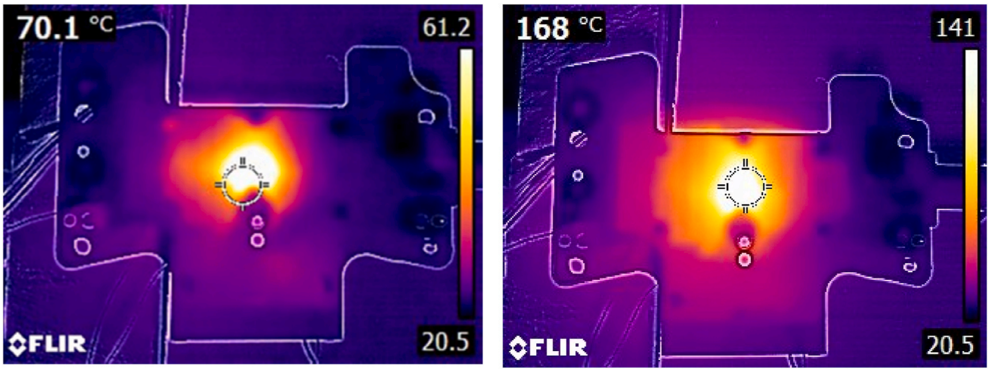

Fig. 2. Temperature distribution on rear side of lighting unit SK38 with removed cooler after 3 (left) and 10 s after switching on.

In the present study, hollow fibers made of polyamide 612 with outer diameter 1 mm and wall thickness 0.1 mm (10% of diameter) were used and the tested heat exchangers were made of fibers connected on both sides into small manifolds made of carbon epoxy composite (see Fig. 3). The small thickness of the wall can lead to belief that heat transfer surface is very delicate, but the opposite is true. This fiber withstands the pressure over 100 bar at room temperature and pressure of 60 bar at temperature of 80 °C. Polyamide 612 is already used in automotive industry to make the pressure cable jackets, hoses and other components and can be operated in the related range of temperatures including below zero. Proper fiber wall thicknesses and connection of tubes must be of course insured, but the material itself can be considered a right choice.

2.3. *Tests of cooling performance of heat exchanger*

The PCB plate (100 × 60 mm size) with two electric heaters (30 × 36 mm size each) placed in the middle of the plate was used as a test sample. Both sides of the plate were covered with thin (52 μm) copper foil and the plastic heat exchanger was bonded to the rear side of the PCB plate by the epoxy resin with improved thermal conductivity (1.2 W/m K). The plastic heat exchanger was made of 57 hollow fibers. Two thermocouples (micro thermocouples, type K) were placed in the middle of the PCB plate to measure the temperatures and calibrate the results of the temperature distribution obtained by the infrared camera. The PCB plate (the side of the heating elements) was insulated with the mineral foam to eliminate the heat loss to the surroundings.

The tests were carried out with increasing the heating power of the heaters and the coolant (tap water) flow rate was controlled to set a constant water temperature difference of 10 K. Such a temperature difference was chosen to ensure low temperature gradients across the PCB plate. The required coolant flow rate increased linearly with the increasing power of electric heaters. However, the maximum flow rate applied was low (only 3 l/h) because the maximum heat power of the headlight was only 35 W.

2.4. *Tests of PCBs in light units*

The original SK38 light unit is shown at Fig. 1 on the left. The aluminium heat sink was removed and the heat exchanger with 33 hollow fibers was attached. The width of the heat exchanger covers only the central part of the light unit. The adhesive with the copper microparticles was used to bond the heat exchanger to the PCB plate. The thermal conductivity of the glue was 1.5 W/m K. Four micro-thermocouple type K were attached to the PCB near the LEDs. The test sample prepared for measurement is shown in Fig. 4 left.

The SK316 light unit was prepared in a similar way. The heat exchanger with 48 fibers was used. The heat exchanger covers full size of the PCB plate. The installation of the headlight unit SK316 with heat exchanger is shown in Fig. 4 right.

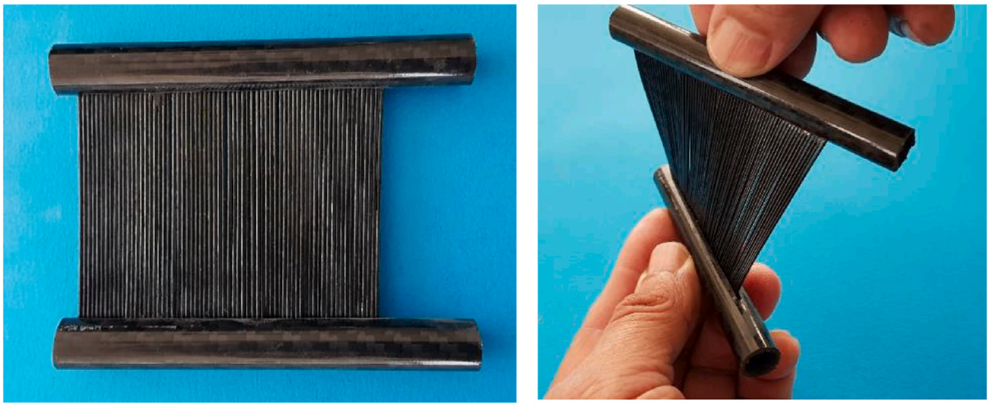

Fig. 3. Heat exchanger made of layer of polyamide fibers used as the LED headlight cooler.

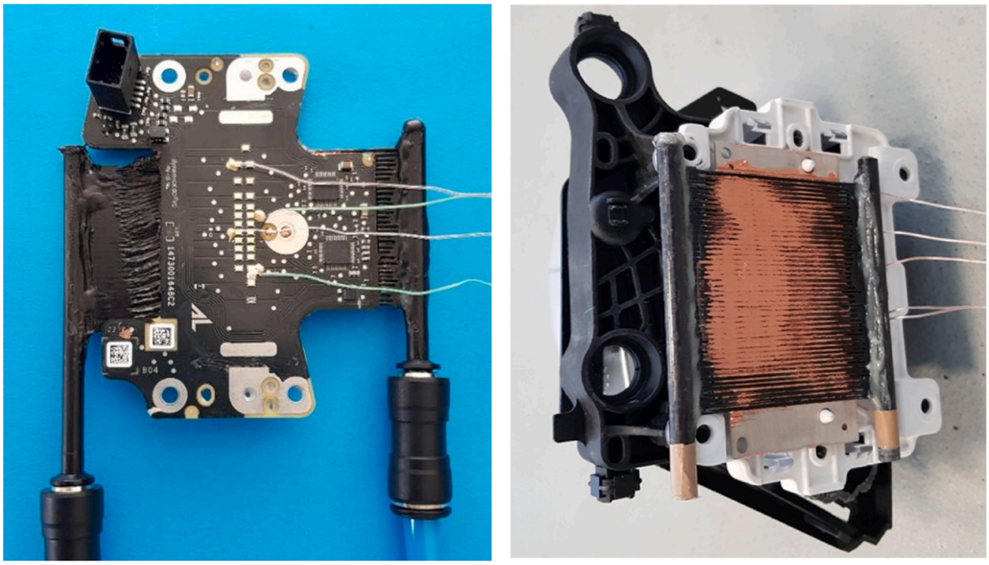

Fig. 4. Left: PCB of Skoda Octavia SK38 with attached heat exchanger; Right: Headlight of Skoda Enyaq SK316 with attached heat exchanger.

Both light units were built into the optical system of the head lamps and electrically connected to the automobile control system of the automobile. The tests were carried out with the maximum light performance, but the heat power was not identical as the headlamp electronics has its own built-in control of the LEDs temperature. It reduces the lighting power in high temperature regimes where a LED overheating is indicated.

The experiment arrangement is shown in Fig. 5. The heat exchanger is connected to the water cooling system, where the input and the output temperatures and flow rate of coolant are measured. The proof-of-concept tests were done with an input coolant temperature of 17 °C and 40 °C. Temperature 40 °C was chosen as the second test temperature because it is a typical temperature available in a car from a low temperature car radiator. Experiments were done with the defined temperature difference ΔT between the input and output cooling water temperatures and the flow rate was adjusted to obtain the defined ΔT. The data were recorded for stationary regime when stable temperatures and flow rate were set.

The tested unit was electrically connected to the car headlamp, and the light control functions was managed by the computer

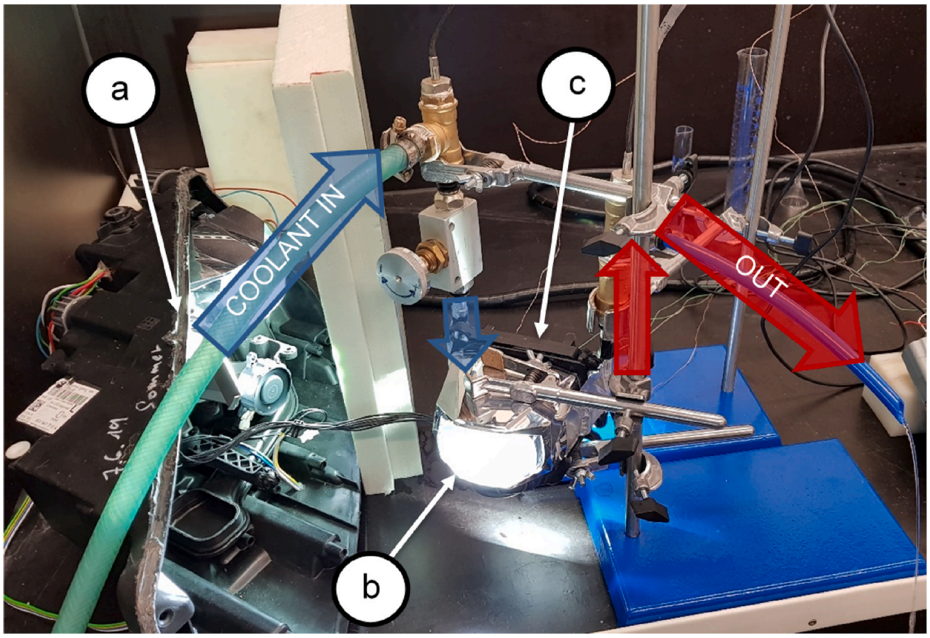

Fig. 5. Arrangement of laboratory experiment, a – cover of the head lamp with the lighting unit rower wiring and controlling electronics, b – light unit consisted of the PCB with lighting LEDs, the body and the lens, c – polymeric heat exchanger.

simulator, which replaces the car control system. The electric power was measured by the digital multimeter, and micro-thermocouples monitored the temperature of LEDs.

The temperature of rear side of the heat exchanger was monitored by means of the infrared camera FLIR E4. The temperature obtained from the thermocouple attached to the heat exchanger was used to calibrate the emissivity of the FLIR infrared camera and obtain the right temperature field with thermography.

Micro-thermocouples of type K, wire diameter of 0.1 mm, were attached to the PCB plate near the LEDs. The tips of thermocouples were placed in drilled holes 0.5 mm deep under surface of the PCB. Thermocouples installed in unit SK38 are shown in Fig. 4 (left) and thermocouples in unit SK316 are shown in Fig. 1 (right).

LEDs are located on PCBs in lines, but thermography picture (see Fig. 2) shows that heat generated by LEDs forms a hot spot in the centre of LEDs line. The temperature reading from micro-thermocouples is averaged for the central part of the LEDs line (values T LED centre) and for side thermocouples (values T LED side).

2.5. Uncertainty analysis

In the case of experiments with LED light units, four values are reported in the results (temperature difference, LED temperatures, flow rate and electric power). The uncertainty intervals of these values will be now described.

Temperature difference of the coolant in the inlet and outlet of the heat exchanger was measured by the Pt 100 sensors. The total relative uncertainty of the sensor and the dataloger *OM-DAQPRO 5300* is in the range 1.0–1.6% for the measured temperatures in the range 17.0–50.0 °C. Temperature of LEDs was measured by the thermocouples of type K with absolute error ±1.5K. For the temperature range 30.8–103.3 °C, it means relative uncertainty 1.5–4.9%. The flow rate was calculated as ratio of liquid volume collected in a graduted cylinder during a time period measured by a stopwatch. Three types of cylinders were used (25 ± 0.5 ml, 100 ± 1 ml, 500 ± 5 ml). The time of measurement was adjusted in order to achieve values of 90% of a cylinder maximal range to minimize the relative uncertainty. The measured time was in the range 30–120s. We assume the human factor error during using stopwatch to be 1%. The relative uncertainty of flow rate $\delta Q/Q$ can be determined using the methodology presented in Ref. [15]. It is calculated based on the relative uncertainties of volume measurement $\delta V/V$ and time measurement $\delta t/t$:

$$\frac{\delta Q}{Q} = \sqrt{\left(\frac{\delta V}{V}\right)^2 + \left(\frac{\delta t}{t}\right)^2}$$

Therefore, the flow rate in the range 2.0–10.1 l/h has a relative uncertainty from 1.5 to 2.3% depending on the used graduated cylinder. The electric power of the LED headlights was determined by the electric power supply *BK Precision 1688B* with absolute uncertainty of 1.0 W. The measured electric power was in the range 23.0–35.1 W with relative uncertainty in the range 2.8–4.3%.

3. Results and discussion

The results of the experiments for light units SK38 and SK316 are summarized in Table 1 and Table 2, respectively. The value T_{IN} is the water input temperature, ΔT is the water temperature difference and P is the electric power of the light unit.

An example of a heat exchanger temperature field is shown in Fig. 6. Decreasing the flow rate of the cooling water through heat exchanger increases the surface temperature. The flowrate for ΔT = 3K is four times higher than for ΔT = 10K. It is obvious that the highest thermal load is in the centre of the unit, as shown in Fig. 2 as well.

The flow inside of the small-diameter hollow fibers is laminar with Reynolds number ranging 20–136. Due to the laminar flow, the inside Nusselt number and the heat transfer coefficient are constant and velocity-independent. The calculated heat transfer coefficient is 2387 W/m^2K for water at 17 °C, 2522 W/m^2K for water at 40 °C and 1684 W/m^2K for 50% glycol/water liquid at 40 °C (typically used as automotive coolant).

Thermal conductivity of polymers is generally low. For polyamide, the conductivity is considered 0.24 W/mK. However, the fiber wall thickness is only 0.1 mm, and therefore the low conductivity does not significantly reduce the heat conduction from the hot PCB plate. Considering the heat transfer efficiency of this cooling system, high thermal conductivity of the adhesive bonding of the polymeric heat transfer surface to the PCB plate is very important. Thus, epoxy resin with copper microparticles with an increased conductivity of 1.5 W/m K was used.

Measurements of temperature field on the PCB plate with LEDs showed that the low thermal conductivity of the PCB plate prevents heat distribution from the overheated hot spot in the centre to the sides of the LEDs row.

Cooling of the headlight unit is substantial even with low coolant flowrates. For example, flowrate of 3 l/h and temperature difference of 7K is sufficient for majority of headlights where approx. 25W of heat is generated. It has to be noted that even the maximum flowrate of 10 l/h used in the experimental program is negligibly small compared to the flowrates in automotive radiators (hundreds

Table 1
Parameters of experiment with light unit SK38.

Experiment	T_{IN} (°C)	ΔT (°C)	T LED side (°C)	T LED centre (°C)	Flow rate (l/h)	P (W)
1	17.0	3	37.5	67.1	6.6	23.0
2		5	39.9	63.0	4.3	25.1
3		7	50.2	80.9	3.0	24.4
4		9	59.4	90.3	2.3	23.8
5		10	53.2	103.3	2.0	23.0

Table 2
Parameters of experiment with light unit SK316.

Experiment	T_{IN} (°C)	ΔT (°C)	T LED side (°C)	T LED centre (°C)	Flow rate (l/h)	P (W)
6	17.0	3	30.8	41.2	10.1	35.1
7		5	41.7	50.6	6.0	34.8
8		7	46.2	58.8	3.4	27.3
9		10	61.2	72.5	2.2	25.8
10	40.0	3	54.5	67.1	9.7	33.9
11		5	56.1	67.8	4.8	27.8
12		7	63.0	73.0	3.1	25.4
13		10	64.2	74.6	2.4	27.9

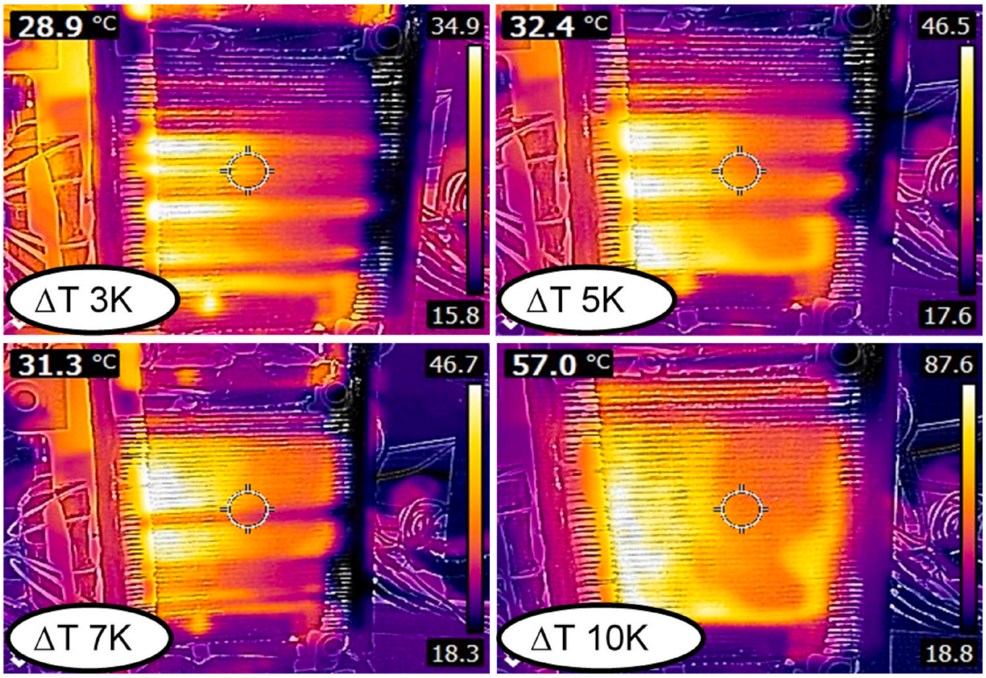

Fig. 6. Temperature distribution on heat exchanger for exp. 6–9 with inlet temperature of 17 °C.

and thousands of litres per hour).

Fig. 7 shows the influence of flowrate and temperature of the cooling water on the temperature of LEDs of the SK316 light unit. For the higher flowrates, a large temperature difference can be observed between the central hot spot and the sides of the LEDs row. However, even an elevated coolant temperature of coolant of 40 °C provides sufficient cooling of LEDs, as 120 °C is considered as operation temperature limit of LEDs (higher temperatures reduce the durability of the headlight).

Laboratory tests were done with setting the light unit to maximum intensity. Table 2 shows that the measured power is not constant. This is due to a built-in system which reduces the power of the light unit with increasing temperature.

Pressure losses in the heat exchanger are low because of low flowrate and low velocity in fibers. Fig. 8 shows the calculated pressure losses for the heat exchanger at the light unit SK316. The pressure drop was calculated as a function of fibre internal diameter, fibre length, number of fibres, coolant flow rate and viscosity (please see Ref. [12] for details on pressure drop calculation). Due to the laminar flow inside fibers, the pressure losses grow linearly with flowrate. Even a relatively small difference in temperature changes the water viscosity. The pressure loss when using 17 °C water is approximately twice as high as when using 40 °C water. The pressure loss of the 50/50% water/glycol mixture at 40 °C is presented also as an example because this coolant is typically used in automotive cooling systems.

4. Conclusions

Car headlight systems with LEDs are currently the most typical type of headlight in the automotive industry. Even if the LED is an efficient source of light, a typical contemporary headlight generates 25–35 W of heat. Overheating of LEDs reduces the lifetime and durability of light unit. Currently, passive or active finned aluminium heat sinks are used for cooling the board with LEDs. A liquid cooling system using hollow polymeric fibers as a heat transfer surface is used in this case study. The tested polymeric heat exchangers are about ten times lighter than the aluminium ones. It is possible to implement this heat exchanger into an existing vehicle thermal

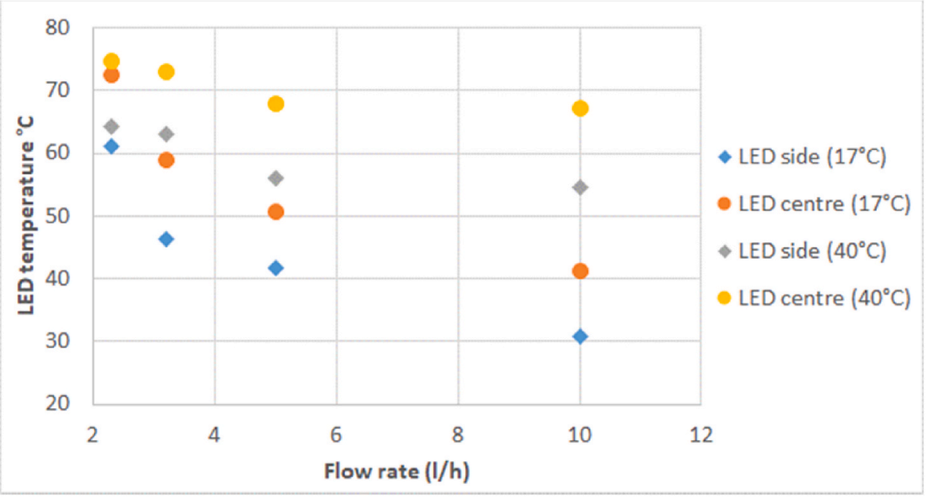

Fig. 7. Average temperature of LED components with changing the flowrate in heat exchanger for unit SK316.

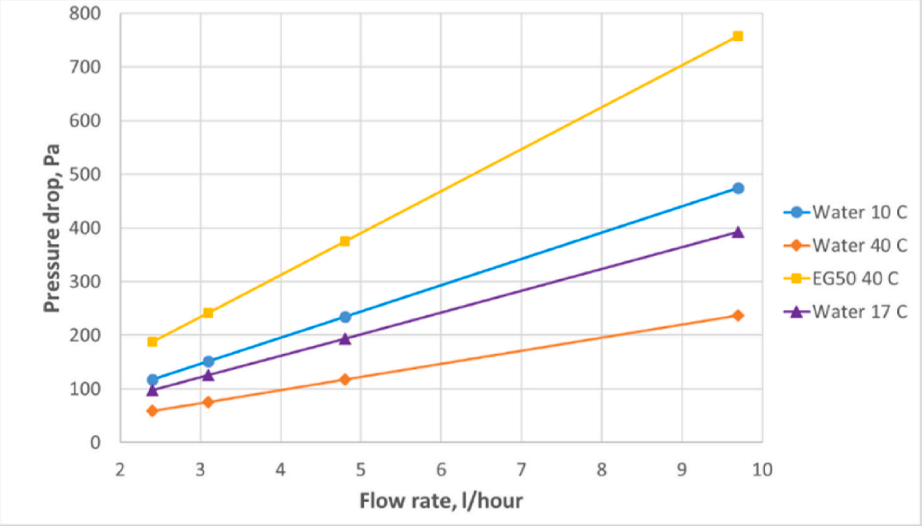

Fig. 8. Pressure losses for increasing flowrate (unit SK316, 48 fibers, length 65 mm).

management system, such as low temperature car radiator. Electric non-conductivity of the polymeric cooler can be considered as an advantage in comparison with the aluminium counterpart. The present study showed that a LED headlight cooling system based on polymer hollow fibres has a significant potential, especially regarding the trend of increasing power of LED headlights.

Further study should be devoted to test the cooling with extremely low coolant flowrates and a partial evaporation of the coolant in capillaries. That system can hold the LEDs temperature slightly above 100 °C which is acceptable temperature. The tested heat exchangers used uniform spacing of the hollow fibers on the cooled surface. Further improvement can be obtained if the fiber spacing is denser in the centre of the LED line, where the main part of heat is generated. The side parts of a PCB plate can be cooled with fibers placed with larger distances.

Author statement

Krystof Mraz:, Project administration, Writing – Original Draft; **Erik Bartuli:** Methodology, Visualization; **Tereza Kroulikova:** Investigation, Formal analysis; **Ilya Astrouski:** Conceptualization, Writing - Review & Editing; **Ondrej Resl:** Validation, Writing - Review & Editing; **Jan Vancura:** Resources; **Tereza Kudelova:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The research has been supported by the project FSI–K-21-6948, Compact Heat Exchangers for Automotive Industry Made of Polymeric Hollow Fibers, funded from the project Quality internal grants of BUT, reg. number: CZ.02.2.69/0.0/0.0/19_073/0016948.

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