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Review of Vehicle Heating and Ventilation Systems Development Techniques

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Abstract
This paper focuses on the potential for improving vehicle heating and ventilation systems. The automotive industry has undergone a complete technological transformation, introducing various environmentally friendly solutions. In particular, electrification poses further challenges in the context of studies to control and improve internal heat flows around the vehicle's energy source, the battery, so optimum power can be obtained with long battery life. The appropriate level of control of air flows and heat losses is a priority. It is therefore addressed in this publication by discussing the battery thermal management systems (BTMSs), part of HVAC systems, that have been recently used to cope with such thermal issues that affect the vehicle's battery. For example, such systems control the battery temperature to be within 15–35 °C for Li-type batteries. Moreover, new measurement techniques for improving vehicles' HVAC systems and their integration into these systems are highlighted and will be considered for further research. For instance, particle image velocimetry (PIV) and background-oriented Schlieren (BOS) measurements have been developed substantially in the last few years. They become more compact and can be integrated into the vehicle's HVAC systems with minimal effect on the process. Furthermore, they produce high data rates and real-time flow field visualization. This paper explores future development directions for automotive heating and ventilation systems.

Keywords
HVAC, optical measurements, BOS, air flow, heat losses

1 Introduction

Heating, ventilation, and air conditioning (HVAC) systems are among the highlighted topics in the vehicle industry. This is because of their high energy consumption from the energy produced in the vehicles. Another reason is that with car electrification, HVAC becomes more sensitive due to the direct effect of thermal flow on the main powertrain component of the electric vehicle, the battery. This battery is substantially affected by the fluctuating temperature of the vehicle's HVAC. To cope with this, a battery BTMS is used as the vehicle's HVAC brain that can control the energy source, which is the battery, so that its power can be efficiently consumed (Bencs, 2023).

Nevertheless, the need for conventional vehicles is still competing with that of electric vehicles (EVs) due to time-consuming charging, the scarcity of charging stations, and the perception of the customers of EVs (Cvok et al., 2021), which is the other concern of this review. HVAC systems in conventional or electric vehicles can be well optimized and improved with the proper selection of measurement setups to visualize better the flow and thermal losses occurring in such systems. Optical measurements are potent tools in this field and have witnessed rapid development. For instance, particle image velocimetry (PIV) and Schlieren measurements used to occupy a lot of space; however, recently, they have become easily integrated with HVAC systems. Hence, they allow the designers to monitor and test the vehicles' HVAC systems and optimize them in a shorter cycle time. Furthermore, they help users and maintenance engineers monitor the system efficiently so that predictive maintenance can be implemented and system troubleshooting is reduced (LaVision, 2020).

There is a lack of literature regarding integrating optical measurement systems into vehicles' HVAC systems, which have witnessed considerable development with the advance of digital cameras and imaging techniques.

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PIV and background-oriented Schlieren (BOS) measurements witnessed significant development, especially in their compactness and integration within the vehicles' HVAC systems. Table 1 compares the available literature and this paper in this regard.

This article addresses the heat transfer issues in battery-electric vehicles (BEVs) by discussing the BTMSs. Then, some examples of the utilization of optical measurements in HVAC systems that can be applied in vehicles and BTMSs are presented. Finally, the most recent and innovative optical measurement solutions for the HVAC of vehicles are illustrated, which can be utilized in future works.

2 Battery management of electric vehicles

Temperature plays a crucial role in the battery's lifecycle for EVs. For Lithium-ion batteries, the operating temperature range is between 15 and 35 °C. Elevated temperatures decrease the cycles of the Li-ion battery; for example, the number of cycles of this battery type at 45 °C is 3,323 cycles; however, increasing the temperature to 60 °C decreases the cycle's number to 800 cycles. Furthermore, the increase in temperature causes a drop in the performance of this battery type. For instance, more than 60% of the battery's performance is lost after 800 cycles at 50 °C, whereas above 70% of its performance is lost after 500 cycles at 55 °C (Bencs, 2023).

This problem was solved using the battery thermal management system (BTMS) – the battery's brain. The primary function of BTMSs is to maintain the battery temperature at a specific value by cooling. There are many types of BTMSs, and they are illustrated in Table 2 (Bencs, 2023).

Low temperatures also influence Li-ion batteries since their discharge capacity drops. For example, at –10 °C, the capacity of the battery with 2.2 Ah declines to 1.7 Ah at 1 C discharge rate, or otherwise, it decreases to 0.9 Ah to maintain a discharge rate of 4.6 C. The reduction in discharge rate results in lower energy provided by the battery. Different preheating techniques are used to cope with the problem.

1. Liquid heating provides temperature uniformity in battery cells. Furthermore, it has a higher heat transfer efficiency compared to air heating.
2. Conduction heating is when the heating elements are directly connected to the battery cells so that heat loss is decreased in the heat transfer path.
3. Internal heating exploits the high impedance of the battery at a low temperature to produce a considerable amount of heat resulting from the electrochemical reaction when the current passes (Bencs, 2023).

Table 1 Comparison of current review with existing research papers

Reference	Review of BTMSs	Integration of optical measurements	Review of Up-to-data Optical measurements in HVAC systems
(Bencs, 2023)	✓	×	×
(Adkin and Lamb, 2014)	×	✓	×
(Gena et al., 2020)	×	✓	×
(Bencs et al., 2014)	×	✓	×
Current review	✓	✓	✓

Table 2 Various BTMS types for cooling (Bencs, 2023)

BTMS type	Notes
Air-cooled	Cost-effective, Simple, Safe, Lightweight, Easy to maintain, etc.
Liquid-cooled	Higher thermal performance, and Better efficiency
PCM-based	A high amount of heat absorption is due to the latent heat of the PCM.
Heat-pipe (HP) based	Used widely in recent years, HPs are heat transfer pipes filled with slight amounts of liquid.
Hybrid	Combines the advantages of two or more BTMS types and Eliminates the disadvantages of this combination.
Other more recent types	For example, hydrogels, thermos-electric, and cold hydrogen.

3 Optical measurements in HVAC systems for future vehicle applications

In the past, the Schlieren measurement technique was considered a qualitative measurement system compared with laser Doppler anemometry (LDA), particle image velocimetry PIV, and laser holography. Nevertheless, with the advances in digital imaging and its processing, Schlieren measurement became a more quantitative measuring tool, providing high-quality flow imaging that was obtained at a fast rate. Moreover, it can be applied in many areas, including indoor air quality, thermal comfort, and HVAC (Gena et al., 2020). Background Schlieren measurement BOS is the most significant and recent development in the Schlieren system. It has several benefits, including its portability and the ability to utilize natural backgrounds. It also provides a significantly wide field of view, at least half the size of its background (Settles and Hargather, 2017).

BOS utilizes light deflection caused by density gradients in the flow field to visualize the background pattern. Consequently, the background impacts flow visualization and the obtained temperature data. An experiment was held to check the effect of the background on the BOS system results by visualizing the temperature field of the vortex street past a heated rod in a closed wind tunnel. After repeating the measurement on 28 different backgrounds, different results were obtained. Then, comparing the 28 temperature curves with the ambient and cylinder surrounding environment, one background was selected as the best, providing realistic results (Bencs et al., 2012).

Three setups of the same engine were examined to examine the effect of integrating optical measurements in the conventional engine and monitor its influence on combustion behavior. They were an all-metal engine, a full-load optical engine, and a modified full-optical engine, Fig. 1. The all-metal engine was examined with thermodynamic experimentation. The full-load optical engine was fitted with a LaVision water-cooled ultraviolet endoscope ring inserted between the cylinder liner and the cylinder head. In this setup, both the combustion chamber and clearance length are slightly altered due to the modification. The full optical engine layout was the same as the second one; however, a fisheye endoscope replaced one of the exhaust valves, further altering the compression ratio. The fisheye endoscope had a 180-degree angle with a mirror of 45-degree ability to defect (Karmann et al., 2022).

The comparison between the first and second setups revealed that both could reach the nominal load while exhibiting marginally different combustion characteristics, which is because of the decreased temperature of the water-cooled endoscope ring. Even with this slight difference in combustion behavior, the difference in the engines' total hydrocarbon emissions is approximately 50% different. Comparing the first setup with the third one, they are comparable, especially if the offset in geometrical values and the temperature change are considered despite a considerable deviation in the temperature of the cylinder wall, which is attributed to the declined coolant temperature and the adaptation of the skip fire operation. Besides, further modification in the second setup was recommended for enhanced comparability on engine emissions by reducing the dead volume. Therefore, the full optical engine setup manifested comparable combustion behavior. (Karmann et al., 2022).

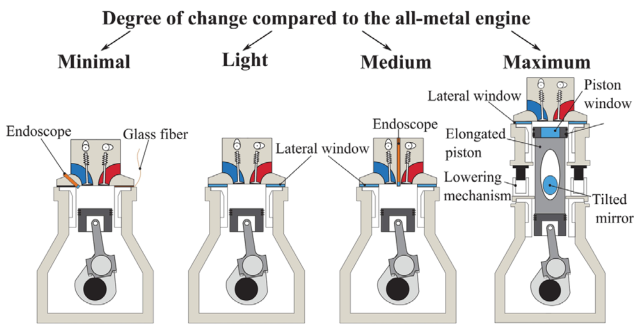

Fig. 1 Accessibility degree of optical measurements (Karmann et al., 2022)

In addition to the conclusion of Bencs et al. (2012), the maximum length sequence (MLS) background image was used to enhance the BOS measurement of the hot air flow of fan heaters. MLS is a pseudo-random set of numbers between 0 and 1 with a length of $L = 2n - 1$, where n is an integer. At zero lag, the normalized autocorrelation of unipolar MLS functions is 1, which equals $4/(L - 3)$ at the other lags. This sequence is robust to external noise and affects the sequences' entire lengths. Then, the Chinese remainder theorem, a technique to transform all 1D sequences into a 2D image matrix, is applied with the ideal autocorrelation preservation and noise rejection characteristics. Finally, the sequence is diagonally wrapped into an image matrix. This method of background improvement produced a high-quality and smooth image without the need for introducing more devices for the BOS setup, such as the interrogation windows (Adkin and Lamb, 2014).

Moving to air conditioning and human comfort, the thermal plume of human-generated heat was investigated. A heated manikin analogous to humans was made. A new single-mirror, large-field, high-sensitivity Schlieren optical setup was installed, and the image of the manikin's thermal plume, together with qualitative data of the flow velocity, was obtained and compared with the data obtained from the thermistor and hotwire anemometer. The Schlieren setup shown in Fig. 2 consists of:

1. Mirror of spherical shape.
2. Light source (LED).
3. Schlieren cutoff of knife-edge type.
4. Digital camera.
5. Wheels of the four-caster type.
6. Three leveling bubbles.
7. Large handwheel for mirror height control.
8. Ruler for the height of mirror center control.

The principle of measurement operation is as follows:

1. The light source is placed at the radius of curvature on the mirror's axis.

Fig. 2 Schlieren imaging layout (Gena et al., 2020)

2. The mirror reflects the light diverging from its source, causing it to collide with the thermal plume above the manikin and return along the same path. An identical light beam traverses every point in the Schlieren object.
3. The thermal plume causes the rays to be refracted, resulting in a shadow when refracted downwards by the Schlieren cutoff. Conversely, the rays appear bright when they are refracted upward. As a result, the flow feature becomes visible.

The manikin's surface temperature was 34 °C, simulating human body heat release. After obtaining the Schlieren images, PIVlab was used for image processing. Comparing the Schlieren images' extracted data and the anemometer data, they both produced same-shape Gaussian profiles; nevertheless, for turbulent plumes, the centerline (CL) velocity values of the Schlieren measurement were one-half of those of the anemometer. Therefore, it can be concluded that the PIV and anemometer arrays' CL velocity values are double Schlieren values. The authors of this paper recommended this Schlieren setup for HVAC, indoor air quality, and thermal comfort analysis (Gena et al., 2020).

4 Recent advances in measurement devices for vehicles HVAC

In this section, the newly developed optical measurement devices in vehicle HVAC systems are presented so that they can be integrated into these systems. LaVision is one of the pioneering companies in this field. Hence, their devices are discussed. At the end of this section, a recently implemented experiment at the University of Miskolc, Hungary, is detailed, which utilizes a combined optical measurement.

In-cylinder optical engine indication (ICOS), Fig. 3, is a device for measuring the concentration of exhaust gas and gas temperature. It offers data rates in a fast manner (in the kHz range). Endoscopic in-cylinder imaging

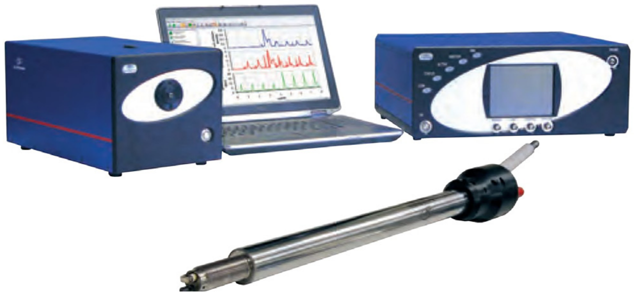

Fig. 3 ICOS system (LaVision, 2020)

is appropriate for measuring the flame propagation speed, soot temperature, concentration, etc.; Fig. 4. This device produces the illumination and carries out the imaging at high resolution and high-speed recording. Furthermore, it is versatile and adapted to the engine, including the sealing sleeves (LaVision, 2020).

Moving to PIV techniques, an in-cylinder laser imaging device is mainly used for in-cylinder flow fields, NOx formation, and imaging of mixture formation (Fig. 5). Its principle is based on the PIV. Crank angle-resolved

Fig. 4 Endoscopic in-cylinder imaging system (LaVision, 2020)

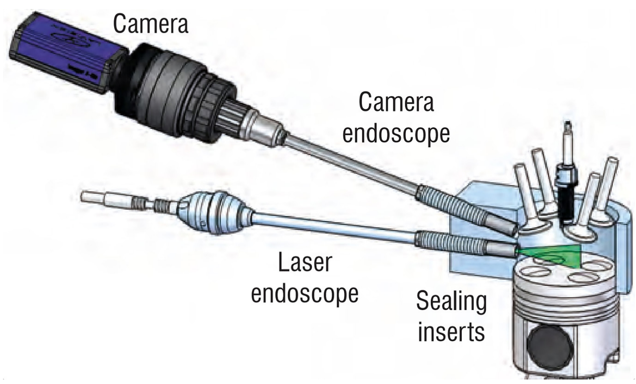

Fig. 5 In-cylinder laser imaging system (LaVision, 2020)

in-cylinder laser imaging uses pulsed laser light sheets in transparent engines or keyhole imaging using minimally invasive endoscopes. Crank angle readings are integrated with engine encoder signals to accurately track engine operation modes such as skip fired, cold start, and acceleration modes. It is characterized by minimal optical access thanks to the endoscopic PIV, high-speed videos of the in-cylinder particle motion, and endoscopic access for imaging and sheet illumination. Another PIV measuring tool, but now combined with particle tracking velocimetry (PTV), is the FlowMaster PIV system, which visualizes the accurate and real-time field of the flow. It allows remote control, and its data can be synchronized with the test parameters of another wind tunnel. This precise and self-calibrated measuring device can measure pressure fields from velocity data. Furthermore, it cancover large view fields thanks to the helium bubble seeder and the 3D camera robot for scanning 3D flow fields, Fig. 6. Furthermore, Fig. 7 shows the layout of this setup (LaVision, 2020).

For vehicle indoor flow visualization, FluidMaster BOS, which is based on the Schlieren principle, is a cost-effective and straightforward alternative compared to methods of laser imaging, Fig. 8. It is a highly sensitive device to the gradient of air temperature without seeding. It is a simple setup and can be used flexibly inside the vehicle without special modifications or preparations.

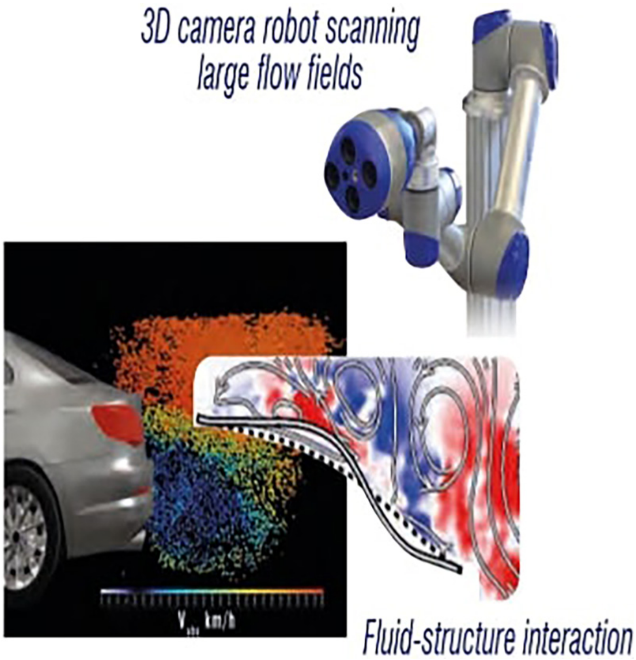

Fig. 6 3D camera of FlowMaster PIV & PTV system layout (LaVision, 2020)

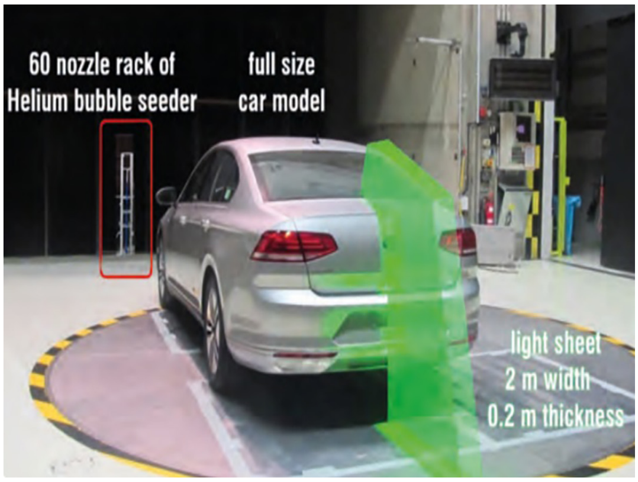

Fig. 7 FlowMaster PIV & PTV system layout (LaVision, 2020)

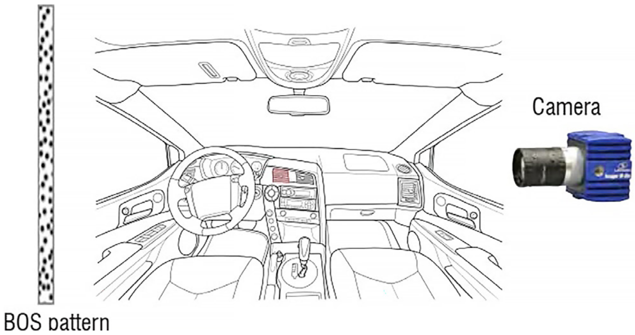

Fig. 8 FluidMaster BOS system arrangement (LaVision, 2020)

Moreover, it provides a real-time capability for image processing (LaVision, 2020).

A related experiment was implemented at the University of Miskolc. This experiment can be applied to measure the heat flow and vortices in the heat exchanger, a vital component in vehicle HVAC systems. Using PIV and Schlieren measurement systems, two optical measurements were combined to measure the temperature field and flow velocity simultaneously. A circular cylinder was subjected to a parallel flow inside a wind tunnel heated up to different temperatures. Referring to Fig. 9, the measurement system is a coupled Z-type Schlieren and 2D-PIV system with a triggering system to synchronize the output of the PIV camera, the Schlieren camera, and the PIV laser. The PIV system comprises an objective, a double-frame CCD camera, a double-pulse Nd-YAG laser, PIV software (TSI Incorporated, 2014), a grabber card, and a trigger box. The Schlieren system consists of an objective, a CCD camera, a Schlieren light source, a PC with software and a firewire card, and Schlieren mirrors. The measurement section is lit using an LED as a light source. The PIV system measures the velocity field, and its accuracy mainly depends on the particle image's density, shift, and diameter; and

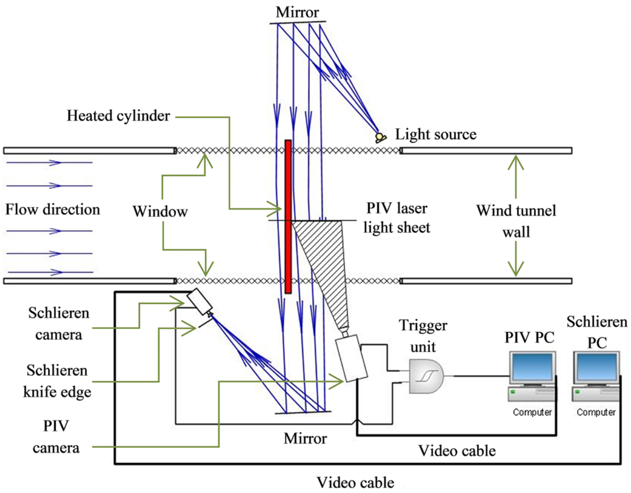

Fig. 9 Schematic of experiment layout (Bencs et al., 2014)

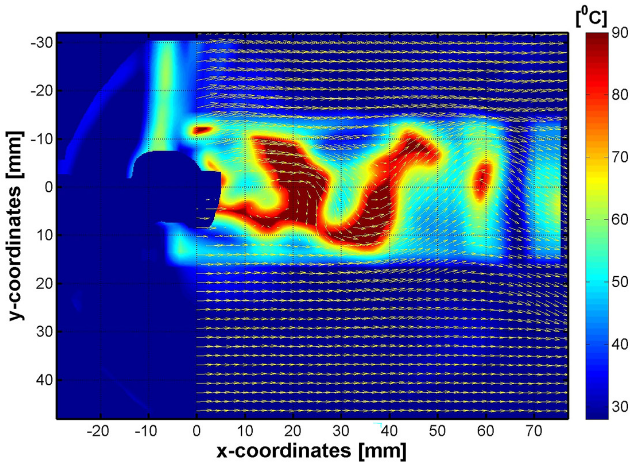

Fig. 11 Temperature field and velocity vector field distribution of the same sample after image processing (Bencs et al., 2014)

background noise. All these parameters were optimized, and a high-pass filter was used to eliminate the noise. Moreover, a minimum correlation filter was applied to the PIV images for postprocessing. The Schlieren system measures the temperature flow, and its accuracy depends on the light noise in the background. Therefore, Schlieren measurements were implemented in a dark room. In addition, before the measurement, a one-point temperature measurement was recorded behind the cylinder for the sake of validation of Schlieren images' postprocessing (Bencs et al., 2014).

A sample of the resulting raw images for the PIV system (left) and the Schlieren system (right) is shown in Fig. 10. From this figure, the vortex shedding is noticeable from both images, and the light diffraction due to the air density difference is visible on the Schlieren raw image. PIV images underwent a de-warping process to extract the velocity vector field images, whereas Schlieren images were processed using masking, and the temperature field images were obtained. The result of the sample image processing in Fig. 10 is shown in Fig. 11, in which both the temperature field and velocity vector field were obtained. This experiment showed that Schlieren images still need further improvement for better accuracy, which will be implemented in the future (Bencs et al., 2014).

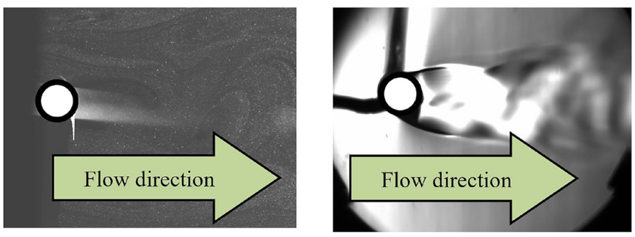

Fig. 10 PIV (left) and Schlieren (right) sample raw images (Bencs et al., 2014)

5 Summary

In this study, the thermal air flow and heat loss issues regarding EVs are presented. From the literature, BTMSs are suggested to control the temperature to be within a specific range around the battery. Furthermore, the utilization of advanced optical measurements and their integration into conventional and electric vehicles' HVAC systems has proved to be feasible since such measurements have become less invasive and more compact.

Moreover, to keep pace with the development of the available optical measuring devices specialized for vehicles, newly developed optical devices are reviewed so that they can be integrated into the HVAC systems of various vehicles as discussed in Section 3.

A newly implemented experiment at the University of Miskolc that combined two optical tools for flow measurements is illustrated. This experiment gave better flow field results with PIV; however, the Schlieren measurement results indicate that this tool needs further improvements. This experiment has a high potential to be integrated into the vehicles' HVAC systems after improvement to measure multiple parameters simultaneously.

6 Recommendations and future work

Based on the literature review of the development in the technologies of vehicles' HVAC systems, the following two recommendations are proposed for the future:

1. Modern optical measurements discussed in Section 4 should be utilized in experiments related to vehicles' HVAC systems since they become noninvasive, which will give better flow field visualization with high accuracy and resolution.

2. Combining two or more optical measurement tools is strongly recommended to measure various parameters in vehicles' HVAC systems simultaneously to make the measurement process time-effective. This recommendation has been initiated at the University of Miskolc; however, unlike the PIV measurement, the Schlieren measurement needs to be improved, which will be a proposed future work in the university.

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