Thermal analysis of the car windscreen

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Abstract. The task of the ventilation and heating/cooling system in cars is to maintain the thermal comfort conditions in the passenger compartment to ensure safe driving. Designing such systems requires knowledge of many physical parameters, which often have to be specified individually. Such factors include heat transfer coefficients. The paper presents the results concerning the determination of the local heat transfer coefficients at the interface between the car windscreen and the cooling air from the inner side of the passenger compartment. The temperature of the outer side of the vehicle windscreen was measured using infrared thermography. The 2D mathematical approach describing the steady state heat transfer on a car windscreen was proposed. The temperature distribution was determined by the Trefftz method, and the heat transfer coefficient at the airï vehicle windscreen interface was calculated using the third type boundary condition. Graphs were used to represent thermographic images of the vehicle windshield, its temperature distribution, and corresponding values of local heat transfer coefficients as a function the length of the windshield. Results are presented and discussed.

1 Introduction

The restrictions imposed systematically on consumption of non-renewable fuels induces search for innovative technologies. To a high extent, it affects the transport sector, which belong to the three largest energy consumers. The research carried out pertain to the quest for blends containing ecologically friendly fuels [1], adaptation of the existing devices to burn them [2], and studies on systems affecting the safety and comfort of the journey [3]. It pertains not only to thermal & humidity conditions referred by human, but also to providing a proper visibility through the window panes and an appropriate air purity what was shown by Benterki *et al.* in [4]. Moreover, these systems should provide a possibility to adjust the air temperature, mass flow and its distribution to proper zones of the vehicle. It requires a complex system of ventilation channels, through which the required amount of fresh air is being pumped, considering the fact that additionally, under winter conditions, the air must be heated to a proper temperature, and cooled in summer. Requirements connected with the individual human condition because of drowsiness, fatigue and concentration, favouring a reduction of traffic collisions [5], are imposed separately. For the evaluation of the thermal & humidity comfort, results from studies of answers from adequately large human populations concerning given thermal conditions are used. Qualitative values are reported by two quantities proposed by Fanger more than 30 years ago. These are as follows: Predicted Mean Value (PMV) and Predicted Percentage of Dissatisfied (PPD) [6]. In paper [7], studies on a group of fifty persons were carried out, having attributed them randomly to journey under three different climatic conditions: the first group ï under cold conditions at 5°C, the second group ï under neutral conditions at 20°C, and the third group ï at a temperature of 35°C. In all cases, uniform conditions of relative humidity equal to 50% were maintained. The highest efficiency in vehicle driving was ascertained under neutral conditions. No influence of the ambient temperature on the body temperature or the heartbeat rate during 30-minute measurements carried out was found. On the other hand, the quality of driving is affected hugely by the driverȏs focus, clearly lowered with manual control of the parameters of the air being pumped. The effect of changes in relative humidity in the cabin on the thermal comfort sensation of the passengers was considered by Alahmer *et al.* in [8]. The results of the thermodynamic and psychrometric analyses indicate that a change in relative humidity may facilitate the air preparation process and reduce energy losses. The analysis results are reported in a plot of the PPD indicator vs. PMV. In paper [9], the influence of air inlet channel settings on thermal comfort, air quality and energy consumption during cooling was studied. It was proved that in the case of two or more persons present in a cabin of a five-person car, where the ventilation system was not turned on, the CO_2 level increases, exceeding the admissible value. Based on the carbon dioxide balance equation, it was shown that even 50 s are needed to remove used air and bring the vehicleȏs interior to a composition close to that of atmospheric air. On the other hand, cooling or heating the vehicle interior to the

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thermal comfort conditions after a prolonged halt requires even several minutes [10]. A proper location and orientation of the ventilation channels to the head area reduces this time, resulting in a lower energy consumption. The observed strong dependencies between the thermal comfort, air quality and energy consumption require advanced control systems for the carôs ventilation, heating and air-conditioning systems.

Heated air provided to the cabin has a higher-than-average temperature and accumulates in the upper part of the cabin, at the head height. When cool air is pumped, it is deposited in the vicinity of the lower limbs. Both phenomena affect the driverôs motoric functions adversely. A desirable temperature distribution may be obtained by an increase in the velocity of the air pumped to the upper area of the cabin. This velocity should be selected so as to cause avoid a feeling of breathlessness or overheating or cold. It is assumed that under any conditions, the air temperature at the head height should be by several degrees lower than that at the leg level. It favours concentration and speed of response while driving. The temperature of ventilation with warm or cold air is usually improper to be pumped directly to the area near a personôs head. In general, the airflow is directed onto the windscreen or side windows. Such an orientation favours a faster defrosting and pane fogging on colder days [11]. Physical characteristics of the air and locations of air outlets are of key importance for the rapidity of obtaining the desirable state of thermal comfort. While designing such systems or verifying correctness of their operation, proper heat transfer coefficients should be determined.

Development of a measurement procedure, and selection of an effective method for calculation of local values of the discharged heat flux based on it, is the goal of this paper. The proposed set of equations led to a solution of the two-dimensional inverse heat conduction problem (IHCP) in a vehicleôs windscreen. For determination of the temperature distribution in vehicleôs windscreen, the Trefftz method was used [12].

2 Experiment

Balancing of the need for power necessary for heating or cooling a carôs cabin requires a conceivably precise estimation of losses on external partitions. In any case, it requires knowledge of corresponding heat transfer coefficients, having values are subject to measurement carried out individually. On this basis, one can determine the power necessary for driving a ventilation-air conditioning system, define its operational parameters and time required for stabilisation of desirable thermal conditions. Partitions, having the direct flow of heated or cooled air directed onto, are of particular importance. Most of all, it pertains to glazed openings. The direction of the airflow onto them may be, as in the case of, for instance, the windscreen, given or set by adjusting the guides.

In this paper, studies using a thermal imaging camera were carried out, which was used to measure the thermal field on the external surface of the windscreen of a Suzuki SX4 passenger car equipped with an air conditioning system controlled manually. The camera was fixed on a support stand so as to the tested windscreen was oriented perpendicularly to the lens axis as shown in Fig. 1

Fig. 1. Tested windscreen with a thermal camera.

The experiments were performed using a *VIGO System* V50 camera, operating in the long-wave infrared range (8-11 µm), equipped with a 384 x 288 microbolometer FPA (Focal Plane Array), whose sensitivity at a temperature of 30 ^{o}C is less than 0.08 K. Example thermograms are shown in Fig. 2.

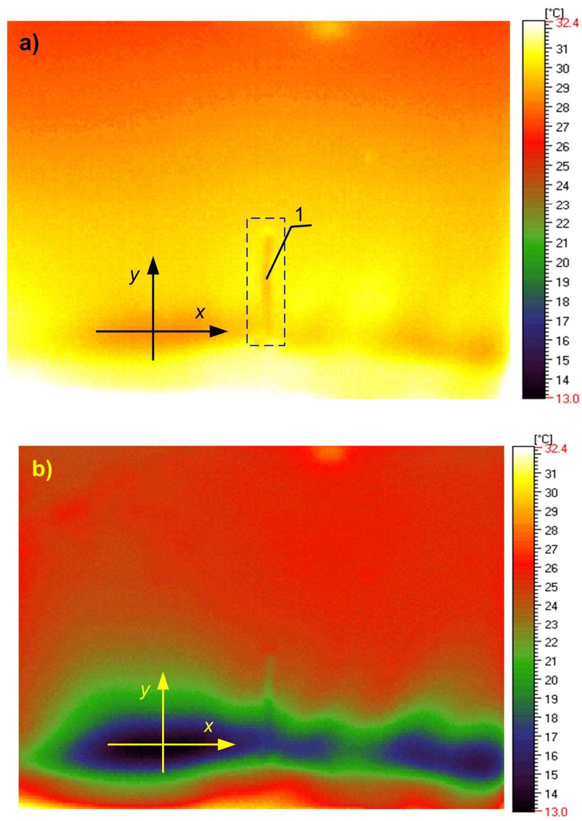

Fig.2. Thermograms of a windscreen respectively 4 and 18 minutes after switching on the cooling system, 1- calibration line.

Correct and exact temperature reading using a thermal imaging camera requires a recalculation of a so-called

radiation temperature to a real one. To this end, correction factors are introduced for the ambient radiation and signal dampening, and a real emission factor of the observed object is defined. In case of bodies for which the transmission coefficient is different than zero, an additional signal component having object located at the opposite side as a source should be taken into account. In the investigated case, it is an additional thermal radiation signal from the vehicleὂs interior.
The thermal imaging camera used for the studies works in the long-wave range. Emissivity of the internal and external surfaces for this range amounts to 0.88, and the reflection factor is 0.05. Consequently, only about 7% of the heat flux emitted from the carὂs interior is recorded by the cameraὂs detector. This amount was confirmed during calibration measurements. To this end, a broad line was painted on the surface of the pane being measured using a paint with known emission properties in the cameraὂs spectral range (line 1 in Fig. 2a). A comparison of the paneὂs temperature with that of the paint-coated surface allows for determining a proper correction, thus improving the measurement accuracy.
The result of the tests carried out is a temperature distribution on the front surface of the pane. Two mutually perpendicular lines were selected for the analysis. One of the lines ran in the horizontal direction, and the other one ï in the vertical direction (see Fig. 2). Their locations were selected so they were running through a point being the minimum-temperature-location during cooling the vehicleὂs interior. Corresponding temperature distributions for various moments in time measured from the beginning of the cool air blow are shown in Fig. 3 for the horizontal line and in Fig. 4 for the vertical line.
From the temperature distribution along both lines, it results that in every moment a minimum in the same point occurs. An analysis of the measured thermal field confirms that the location of such a minimum is constant in time and it occurs in a point located in the intersection of both lines, marked in Fig. 2.
The condition of occurrence of the minimum consists in zeroing of the first derivative with respect to a corresponding coordinate, which ï as mentioned earlier ï occurs correspondingly along both selected lines. Such a condition is tantamount with a reduction of the heat transfer state to a two-dimensional problem, and also stationary after an adequately long time. The studies showed that such an almost stationary state may be considered present already after about 9 minutes from starting the cold air blow.
Cooling of the carὂs interior was carried out at a given rotational speed of the blowing fan, defined by setting the control knob to position 2. The temperature of the air being pumped was measured by a thermocouple using a measuring instrument having an indication resolution of 0.1 K and precision ±0.5 K. The temperature recording was carried out for several minutes, and the measured values were averaged. The measured temperature of the pumped air was almost constant and amounted to about 12°C.

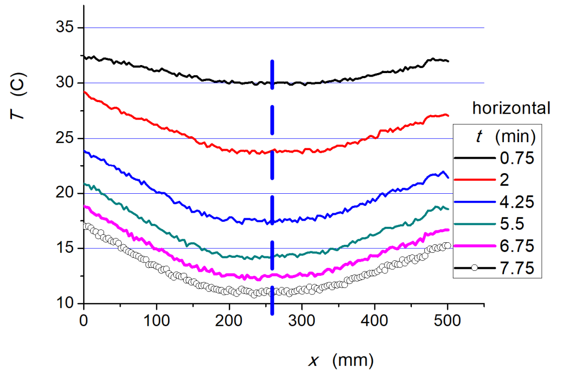

Fig. 3. Temperature distribution along horizontal *x* coordinate (see Fig. 2).

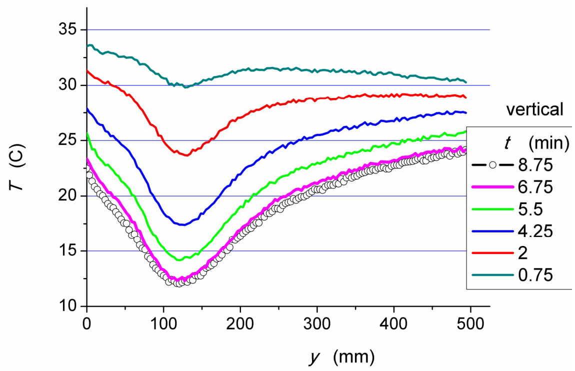

Fig. 4. Temperature distribution along *y* coordinate (see Fig. 2).

3 Mathematical model

As has been proved earlier (Fig. 4), the heat transfer in a car windscreen along the line running through the minimum temperature points may be considered a stationary process after an adequately long time.
In the presented mathematical approach, two dimensions: dimension *y* referring to the length of line 1 with a length of *L* (see Fig. 2a), and dimension *z*, perpendicular to the former, referring to the thickness δ of the vehicleὂs windscreen were taken into account. It was assumed that in the domain $\Omega = \{(y,z) \in R^2 : 0 < y < L, 0 < z < \delta\}$, the windscreen temperature *T* satisfy the Laplaceὂs equation in the form

$$\frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = 0 \qquad (1)$$

For the equation (1), the following boundary conditions (2), (3) were adopted at the contact of the vehicleὂs windscreen with the external air

$$T(y,0) = T_{approx}(y) \text{ for } 0 \le y \le L \qquad (2)$$

$$-\lambda \frac{\partial T}{\partial z} = \alpha_{air}(T - T_{air}) \text{ for } 0 \le y \le L \text{ and } z = 0 \qquad (3)$$

where λ ï thermal conductivity of the windscreen, T_{air} ï ambient temperature, T_{approx} ï polynomial approximating the windscreen temperature measurement, α_{air} ï heat transfer coefficient at the outer side of the investigated windscreen.

In case of free convection on the inclined surface the following correlation is recommended by Bayazitoĵlu, and ŕzisik in [13]

$$Nu = 0.56\left(Gr_H Pr \cos\theta\right)^{1/4} \tag{4}$$

where θ - the angle the plate makes with vertical, Nu and Pr - Nusselt and Prandtl numbers. Grashof number is determined by formula

$$Gr = \frac{g\beta\left(T_{air} - T_w\right)H^3}{\nu^2} \tag{5}$$

In (5), the designations are used: g=9.81 m/s^2, β - the coefficient of thermal expansion, ν - kinematic viscosity of the fluid, H - characteristic length, T_w- according to measurement.
In (4), all the physical properties and coefficient of thermal expansion β are evaluated at T_{air}+0.25(T_w-T_{air}). In such a case equation (4) is applicable for θ <88^o, and Ra_H=$Gr_H Pr$ < 10^{11}.

In the thermal balance of the carŝ cabin, thus the amount of power for providing a desirable thermal comfort for the driver and passengers, the amount of energy being dissipated by all partitions should be taken into account, particularly by the partitions having the airflow directed onto. In the considered case, it may be determined based on the boundary condition of the third kind

$$\alpha(y) = \frac{-\lambda\dfrac{\partial T}{\partial z}(y,\delta)}{T(y,\delta) - T_{car}} \tag{6}$$

where T_{car} ï the air temperature in the cabin of the vehicle. For its determination, knowledge of the temperature distribution $T(y,z)$ is necessary, which may be found by solving the set of equations (1)-(3), leading to solving of the IHCP.

3.1. Trefftz method

Solving the set of equations (1)-(3) leads to the IHCP, which requires application of a stable and effective computational method. The Trefftz method, used successfully for solving even double stationary IHCPs [14], is such a method. According to the idea of the Trefftz method of [12], an unknown solution of equation (1) is approximated by a linear combination of harmonic functions $u_n(y,z)$ (also called Trefftz functions)

$$T(y,z) \approx \sum_{n=0}^{N} a_n u_n(y,z) \tag{7}$$

Unknown coefficients of the linear combination a_n are determined by minimisation of the error functional ε describing the mean squared error, with which the function (7) satisfies the boundary conditions (2) and (3), *i.e.*

$$\begin{aligned}\varepsilon = &\int_0^L\left(\sum_{n=0}^{N} a_n u_n(y,0) - T_{approx}(y)\right)^2 dy + \\ &+\int_0^L\left[\lambda\sum_{n=0}^{N} a_n\frac{\partial u_n}{\partial z} + \alpha_{air}\left(\sum_{n=0}^{N} a_n u_n(y,0) - T_{air}\right)\right]^2 dy \to \min\end{aligned} \tag{8}$$

The definition of the harmonic functions $u_n(y,z)$ and the method for determination of the linear combination coefficients a_n are described in detail in [15,16].

4 Results

The calculations were performed for experimental data concerning the temperature distribution in a Suzuki SX4 passenger car windscreen, the cooling process of its internal surface, and the heat transfer at the contact point of the windscreen with the air of the carŝ cabin. Measurements of the external surface temperature of the car windscreen obtained by a thermal imaging camera were used. The set of equations reported in section 3. leads to a solutions of IHCP. IHCPs are usually ill-posed problems and thus very difficult to solve. An additional difficulty results from inadequately accurate measurement results, utilised here in one of the boundary conditions. On this account, the distribution of the measured temperature on the external surface of the windscreen along the vertical line shown in Fig. 5 was approximated by a polynomial of 6th degree in the calculations.

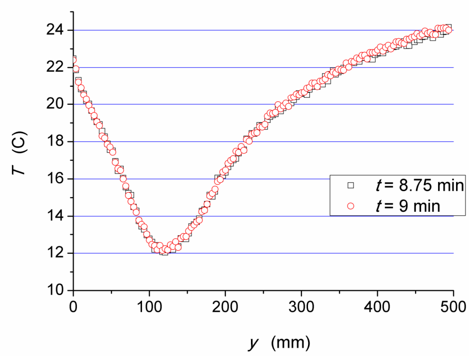

Fig. 5. Temperature distribution along the vertical line in a stationary state (after 8.75 and 9 minutes).

In formulas (4) and (5) the following experimental data were adopted: Pr =0.7323, ν =1.47·10^{-5} m^2/s, θ=π/4, H =0.9 m is length of the car windscreen, T_{air} =30°C, T_{car}=12°C. Two dimensional temperature distribution in the car windscreen was determined using the Trefftz method with nine Trefftz functions. Figure 6 presents two-dimensional windscreen temperature determined in domain Ω.

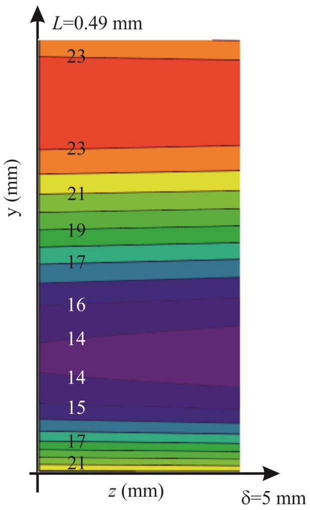

Fig.6. Two dimensional temperature distributions of the vehicleôs windscreen determined by the Trefftz method.

The known vehicle's windscreen temperature distributions allowed for determining the heat flux $q(y)$ transmitted to the vehicleôs cabin *via* its windscreen, Fig. 7, and the heat transfer coefficient. Figure 8 shows the heat transfer coefficients (as the function of the distance from the length of the windscreen) computed on the basis of condition (6).

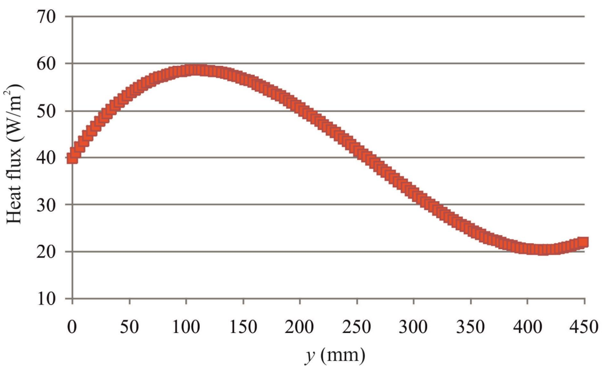

Fig.7. The heat flux transferred to cabin of the vehicle.

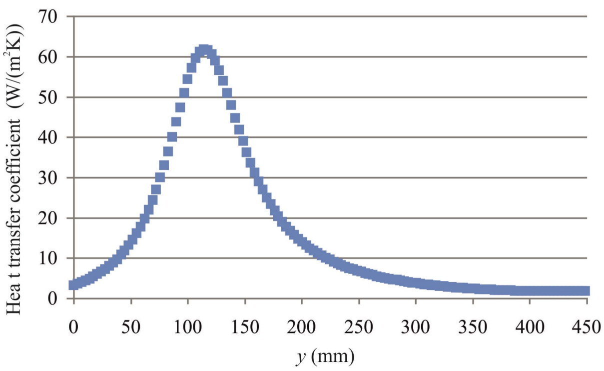

Fig.8. The heat transfer coefficient at the vehicle's windscreen ï vehicle cabinôs air contact.

The profile of the heat transfer coefficient depends strictly on the distribution of the external surface temperature of the windscreen, see Fig. 5. An increase in the values of the heat transfer coefficient occurs in the first measurement section at a length of approx. 120 mm, where it reaches the highest value of 62 W/(m^{2}K). On the farther length of the windscreen, a decrease in the value of the heat transfer coefficient is evident, which is connected with an increase in the distance between the internal surface of the windscreen and the outlet of the air-conditioning system. In the end section of the windscreen (from approx. 300 mm), the heat transfer coefficient reaches an almost constant value.

5. Conclusions

Ventilation and air-conditioning systems in cars are quite energy-intensive. A reduction in the power uptake is being sought for in their optimal control and maintaining their proper technical condition. To this end, various types of tests are carried out during their design stage, final acceptance, as well as during the operation of the vehicles. Therefore, fast diagnostic methods are being sought for. Thermal analysis using a thermal imaging camera is one of them. Other one is preparing and developing mathematical models describing the mentioned phenomena allows for obtaining more and more accurate analyses results.

Thermal imaging camera is a device recording the superficial temperature field, which usually results from processes occurring from the side which is invisible. In the considered case, this is the process of cooling the inner surface of the pane, and its result is the measured thermal field. Its analysis allowed the assessment of the correctness and quality of the air flow. For the sake of the non-invasiveness of the method, such a way of execution of the tests is fast and convenient for the user, although it requires developing effective procedures for interpretation of the results and calculations of quantities necessary for further analysis of operation of the whole system.

In the paper, a simple mathematical model, which allows for determining a two-dimensional temperature distribution of a car windscreen was presented. An assumption of stationary heat transfer in the pane simplified the model significantly and facilitated its solving. Application of the Trefftz method allowed for determining a two-dimensional temperature distribution of a carôs window pane, its gradient, and the heat transfer coefficient in the contact point of the internal surface of the carôs pane and the air in the carôs cabin.

In the future, it is planned to take account a time variable in the model and to make the physical parameters of the pane *(e.g.* thermal conductivity) temperature- and/ or time-dependant. It is also planned to apply the Trefftz functions to solve a non-linear inverse heat transfer problem arising in this case.

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