EVALUATION OF HEATING EFFICIENCY AND THERMAL COMFORT IN SPECIAL PURPOSE VEHICLE CABINS

by

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The paper presents the integrated application of two methods during testing HVAC system efficiency in the cabins of HUMMER M1151A1 and OAR 1RL-128D off-road vehicles. Spatial measurements of change in air temperature per time have been performed at three vertical levels (head, knees, and feet) of the driver and passengers, which totals to 15 measuring points per vehicle. The main goal of testing was to evaluate accurately the efficiency of heating and cooling in relation time interval required to attain a designed temperature of comfort in the vehicle cabin, on condition that the difference in ambient temperature levels does not exceed 10 °C. With a view to more efficient evaluation of thermal comfort in vehicle cabins, the testing was performed also of predicted mean vote and predicted percentage of dissatisfied indices. Standard thermal comfort surveys ask subjects about their thermal sensation on a seven-point scale from cold (–3) to hot (+3). This research is carried out according to the methods based on ISO 7730, ASHRAE 55, and SORS 8419 standards.

Key words: *vehicle, thermal comfort, predicted percentage of dissatisfied, measuring, predicted mean vote, AC*

Introduction

The development of motor vehicle industry and rapid increase of competition in the vehicle market dictate the increasing obligation manufacturers to meet complex users' requirements in terms of comfort when using vehicles. In addition the level of internal noise and vibrations, thermal comfort as a subjective feeling and ventilation represent the most important characteristics of comfort insider motor vehicle cabin [1]. It is a long-known fact in literature that disturbed microclimatic conditions as well as harmful effects of noise and vibrations have negative impact on people during the working process, in terms of fatigue, the lack of concentration, and they can even result in professional diseases [2-5].

The most of researches related to the problems of thermal comfort testing refer to savings that can be achieved during the operation of AC system, in order to reduce fuel and electric energy consumption, *i.e.*, to achieve more autonomy in vehicle movement [6-10]. The use of air conditioning system not only considerably improves the comfort during driving, but it also reduces the internal noise and the need for additional opening of the window. The AC compressor

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at maximum operation can additionally reduce the motor vehicle engine power for 5-6 kW [11]. The influence of AC system operation on technical characteristics of modern vehicles with electric, hybrid or fuel cell drives is even more significant. A National renewable energy laboratory – Toron, Canada (NREL) study showed that in the USA seven billion gallons (26.4 billion liters) of fuel is spent on air conditioning annually in light passenger cars, which is the equivalent of 5.5% of the total fuel consumption at the national level for light passenger cars and 9.5% of the quantity of imported crude-oil [11, 12]. The significant part of research deals with the study of dominant influence of sun radiation through glass surfaces in the public transportation vehicles, agricultural mechanization, as well as the air quality inside them [13-15].

Comprehensive research related to the issues of quality of heating and cooling inside the motor vehicle cabin have been done by the experts of Korean car manufacturer Hyundai Motor Company in cooperation with the American researchers of the National Renewable Energy Laboratory – Colorado. The testing was conducted in road exploitation conditions with Hyundai Sonata PHEV (plug-in hybrid electric vehicle) car driven along the testing track in Fairbanks, Alaska, at the environmental temperatures ranging from –14 °C to –1 °C. The vehicle was also tested in the cold chamber – Superior Township, Michigan, at the ambient temperature of –7 °C (cold engine start and cabin heating). The testing inside the hot chamber was conducted at the ambient temperature of 35 °C [16]. As in the previously mentioned research, the main goal of this one was to reduce the energy influence of climate control system on the autonomy of electric-drive vehicle range.

A part of previous research deals also with the influence of thermal comfort on safety, fuel consumption, as well as environmental pollution, by using software simulations, *i.e.*, 3-D model of vehicle cabin [17]. Some other studies are based on comparative analyses of comfort parameters and improvement of measuring methods, as well as the use of thermal manikins, in order to achieve optimal results in vehicle cabins [18-20]. Improvement of microclimate in the cabins of agricultural mechanization and passenger cars using localised air distribution is an important subject of research presented in papers [21, 22].

Based on the review of literature, it can be stated that the number of studies of thermal comfort in vehicle cabins are limited, primarily due to high costs of experimental research, as well as inexistence of adequate climate chambers of the corresponding volume that would fit the vehicle external dimensions. This research is particularly significant for adapting the vehicles for military purposes, taking into account that they are intensively used in peace time conditions as well. Passenger space is mainly used as a working space to perform complex operations such as: communication, reconnaissance and intelligence, artillery guidance*, etc.* This is why it is necessary to provide adequate microclimatic conditions for uninterrupted crew performance [23]. The research results, related to the military purpose vehicles, are mostly not available to a wider academic community.

Unlike measuring thermal comfort in offices and buildings [24], measuring in vehicles requires a different approach, mainly due to limited space, installation of numerous equipment, as well as non-stationary external and internal parameters during the measuring. However, testing in real conditions offers the most reliable data, providing the possibility to repeat measuring, as well as to compare the results for various solutions of installation of AC units and their integral components in motor vehicle cabins. This paper presents the results of the achieved level of thermal comfort in the cabin of HUMMER M1151A1 special purpose off-road vehicle, with the original (factory) system of heating and air conditioning, as well as the comfort inside the modified and adapted cabin of OAR 1RL-128D vehicle through installation of KONVEKTA air conditioning unit and Eberspacher air heater.

Theoretical framework

Methods of thermal comfort testing in vehicle cabins are determined in more detail by ISO 7730, ASHRAE 55, SORS 8419 and SORS 0114 standards. Comfort conditions, as a part of the method described in SORS 0114 [25] military standard, refers to the state of air with internal design temperature of +16 °C. The standard allows testing both inside the cold chamber and in the natural environment, without the request for the measurements to be conducted exclusively in the set conditions of the external temperature of –16 °C. In non-stationary conditions this is difficult to provide but, even in arbitrary environmental conditions, it is possible to get a graphic presentation of dependence of time when the design comfort temperature is achieved.

The coefficient of efficiency is the rate of attaining comfortable temperature conditions in the cabin and usable space in a vehicle. This criterion applies only for the part of the function with linear dependence – the system is efficient only up to that external environmental temperature to which linear dependence between the time of heater operation and the external ambient temperature is maintained. This procedure of determining the heating efficiency estimates the heating power of the installed heater together with heat-insulating properties of the usable space in a vehicle. The efficiency coefficient K_{ef} (°C per minute) is defined:

$$K_{ef} = \frac{|t_a| + t_{kom}}{\tau_{kom}} \tag{1}$$

where τ_{kom} [minute] is the time required to attain the temperature of comfort according to the criterion of this method t_{kom} = 16 °C, by continuous air heating in the cabin of a vehicle usable space from a starting temperature, $t_{a.}$ The referent standard defines the air velocity at the height of the crew members' heads in winter conditions when all ventilation and observation openings are closed and it cannot exceed 0.15 m/s. It is considered that an efficient heating system is the system which in the measuring conditions defined by this standard has achieved the coefficient of efficiency:

– $K_{ef} \geq 0.5$ is the for armoured combat vehicles, whereas the temperature difference Δt_{max} must not exceed 10 °C.
– $K_{ef} \geq 0.7$ is the driver cabins and special superstructures of non-combat vehicles, whereas the difference in temperature distribution Δt_{max} must not exceed 10 °C.
– $K_{ef} \geq 1$ is the for vehicles whose working space is subject to special requirements for heating, whereas the temperature difference Δt_{max} must not exceed 5 °C.

Another measuring method, which is far more used today, is based on the theory by Fanger [1], which dates back to 1970's and which is the foundation of the current ISO 7730 standard. The standard has been adopted as European Standard, but it is applied in a large number of countries as national. The model of thermal comfort calculation is based on processing of four environmental parameters (air temperature, air velocity, relative humidity and mean radiant temperature) and two individual characteristics (type of testers' activity, as well as insulation properties of their clothes). It is important to mention that unlike the previous

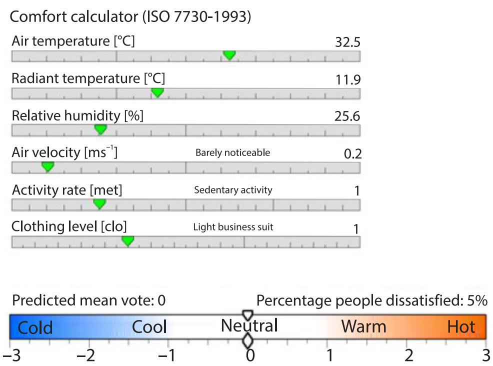

Figure 1. The PMV and thermal sensation [26]

method, predicted mean vote (PMV) index evaluation method treats the entire body as one object. The PMV index predicts the mean response of a larger group of people about the thermal comfort in a given environment [27, 28]. The PMV scale presented in fig. 1 has seven levels of thermal sensation, from –3 (cold) do +3 (hot), whereas 0 determines thermal neutrality. However, even when PMV index is 0, there will always be some individuals who are not satisfied with thermal environment, regardless of the fact that they are all dressed similarly or that they all perform similar level of activity – the evaluation of thermal comfort is subjective. It is important to mention that inadequately determined parameters of thermal insulation of clothes and metabolic rates can considerably reduce the accuracy of PMV index.

In order to estimate how many people are not satisfied in a given thermal environment, predicted percentage of dissatisfied (PPD) index has been introduced. The ISO 7730 prescribes three levels of quality, A, B, and C. Level A corresponds to PPD index of 6%, level B to the index of 10%, and level C to the index of 15%. SORS 8419 military standard [29] recommends that PPD index should be maintained below 10%. The USA adopted ASHRAE Standard 55 in 2004, which was updated in the meantime and today it is based on PMV/PPD indices concept.

Measuring concept

When selecting the concept and measuring parameters, it was taken into account that it corresponds to the real conditions of vehicle exploitation. The measurements presented in this paper were conducted in both cold and hot chamber of the Technical Test Centre in Nikinci, Serbia. The capacities of cold and hot chamber are identical – the volume is about 170 m^3, with the possibility to use the antechambers of 30 m^3 (the total of about 200 m^3). The cooling system of cold chamber works on a principle of two-stage compression. In the course of the cooling cycle, the chamber can attain the temperature of up to –40 °C at the engine wet sump of a vehicle with the approximate mass of 50000 kg within the interval of maximum 24 hours. Shorter time is required to attain ambient temperature, but the practical experience has shown that attaining a desired temperature at engine sump provides with great certainty that the desired temperature is also attained at all other parts of the vehicle. Hot chamber provides ambient conditions to conduct testing with the maximum temperature of up to +60 °C without the presence of humidity. In order to achieve the desired temperature up to four hours are needed in case of testing vehicles with maximum dimensions and mass. Air heating is provided by 120 kW rod electric heaters. Both cabins have three ventilators installed which can simulate the air circulation velocity of up to 60 km/h.

The three thermal sensors were installed vertically inside the cabin, for each working place, as well as temperature sensors at each of ventilation openings of the cabin heating system. In addition, there is also an external temperature sensor (ambient temperature inside climate chamber). Thermocouple extension cables connect sensors inside the vehicle and the data acquisition measuring equipment through special openings in the chamber wall (for cables, lighting and such). The data acquisition equipment, as well as the persons who is conducting the testing, are in an observation room with a visual contact with the chamber through a special glass. Climatic conditions in this room are more favourable for people and measuring equipment there. Also, great attention is paid to insulation of the premises, and all openings between these two areas are well closed with special cork and/or asbestos cloths after the measuring equipment is installed.

In order to obtain the reliable results before the testing begins, the vehicle is previously held for at least six hours at the testing temperature, and all doors and ventilation openings at the vehicle are open. After this time period, it is necessary to determine that internal temperature at all measuring points inside the vehicle cabin does not differ for more than 3 °C. In case these conditions are fulfilled, all doors and ventilation openings are closed. The difference between the external temperature at the beginning and the end of testing must not exceed ±1 °C.

Tested vehicles

The paper presents the test results of two off-road vehicles which are essentially different in their intended purpose, external dimensions and time of manufacturing. The HUMMER is newly manufactured vehicle with factory installed air conditioning and ventilation system, while after many years of service (OAR) 1RL-128D vehicle has been upgraded with the new system of cabin air conditioning. The cabins in both off-road vehicles are also the working space for crew members.

The HUMMER off-road motor vehicle is intended for reconnaissance and observation, control of terrain in off-road conditions, transport and protection of people, as well as transport of the cargo. It is classified as high mobility multi-purpose wheeled vehicle (HMMWV), and it is presented in fig. 2.

Microclimatic conditions inside the cabin of the tested vehicle are provided by the heater and AC unit, designated as AC for HMMWV M998A2 series of vehicles, driven by the vehicle engine. Figure 3 presents a scheme of installation for air conditioning inside the vehicle cabin and the main components of the system.

Figure 2. Vehicle HUMMER, type M1151A1

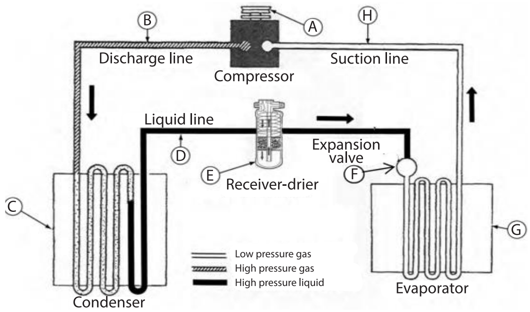

Figure 3. Scheme of AC installation:
A – compressor, B – discharge line, C – condeser, D – liquid line, E – receiver-drier, F – expansion valve, G – evaporator, and H – suction line

The other tested vehicle is surveillance and acquisition radar (OAR) 1RL-128D, an upgraded vehicle used as a part of air defence, and it is presented in fig. 4. The KLIMA-128 air conditioning system has been installed in the cabin, which consists of a redesigned KONVEKTA-KL20KDE air cooling unit with cooling capacity of 4300 W, presented in fig. 5 and the Eberspacher D8 LC-24V heating unit with the heating capacity of 8 kW.

Figure 4. The OAR 1RL-128D

According to the request of the client (the Serbian Armed Forces), the systems which provide thermal comfort in both tested vehicles have been subjected to the same testing conditions. The efficiency of air conditioning system in cooling mode was tested in hot chamber at the am-

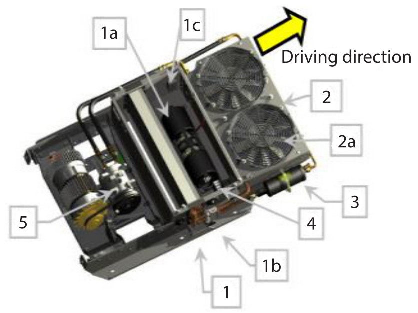

Figure 5. The KONVEKTA-KL20 KDE: *1 – evaporator coil, 1a – duble fan, 1b – expansion valve, 1c – thermostat, 2 – condeser coil, 2a – axial blower (condeser blower), 3 – dryer-colector-sight glass unit with combined pressure switch, 4 – electric, and 5 – driving unit compllete with compressor SD5H09 → not to apply with KL20*

bient temperature of 40 °C. The efficiency of heating was tested in cold chamber at the ambient temperature of –16 °C.

Data collection

The measurements at both vehicles were conducted with OMEGA 199 digital thermometer and B and K Thermal comfort meter type 1212, with MM0023 sensor. The MM0023 measuring probe was placed behind the driver's seat at the height of 0.6 m above the floor between the driver and the co-driver. Vertical distance of sensor-thermocouple, *K*-type, above the vehicle floor for the feet was at 0.1 m, for the knees at 0.6 m and for the head at 1.1 m. Inside the HUMMER's cabin, there were 16 sensors installed according to the following arrangement: 1 – driver's feet, 2 – driver's knees, 3 – driver's head, 4 – co-driver's feet, 5 – co-driver's knees, 6 – co-driver's head, 7 – feet of the operator in the second row left, 8 – knees of the operator in the second row left, 9 – head of the operator in the second row left, 10 – feet of the operator in the second row right, 11 – knees of the operator in the second row right, 12 – head of the operator in the second row right, 13 – at hot/cold air inlet into the driver's cabin, in front of the driver, 14 – at hot/cold air inlet into the driver's cabin, in front of the co-driver, 15 – at hot/cold air inlet into the driver's cabin at the back platform on the left, and 16 – external temperature in climate chamber (at 1.5 m above the floor).

The testing results at respective external temperatures are shown in tabs. 1-4.

Table 1. Values of thermal comfort measured with B&K 1212 meter at the temperature of –16 °C

HUMMER –16 °C											
t [minute]	5	10	15	20	25	30	35	40	45	50	55
PMV	–2.6	–2.1	–1.7	–1.5	–1.2	–1	–0.97	–0.85	–0.74	–0.63	–0.54
PPD [%]	86	84	67	56	40	30	25	20	16	13	11
t [minute]	60	65	70	75	80	85	90	100	110	120	
PMV	–0.5	–0.39	–0.35	–0.30	–0.29	– 0.25	–0.17	–0.13	–0.09	–0.09	
PPD [%]	10	8.4	7.9	7.3	7.2	6.7	6.1	5.8	5.4	5.5	

Table 2. Values of thermal comfort measured with B&K 1212 meter at the temperature of 40 °C

HUMMER +40 °C									
t [minute]	5	10	15	20	25	30	35	40	45
PMV	–	–	–	0.19	0.05	0.03	0.03	0.01	0.01
PPD [%]	–	–	–	5.63	5.3	5.2	5.2	5.1	5.1

Table 3. Values measured with OMEGA 199 thermometer at the temperature of -16 °C

	HUMMER M1151A1 –16 °C*															
	$T_{ambient}$	Driver			Co-driver			Second row operator left			Second row operator right			Hot air inlet		
Time		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
[minute]	°C	F	K	H	F	K	H	F	K	H	F	K	H	Driver	co-driver	Second row
0	–17	–17	–17	–17	–17	–17	–17	–16	–17	–17	–17	–17	–17	–17	–17	–16
5	–14-17 °C	–12	–6	7	1	5	6	–11	-4	5	–13	–10	3	32	13	–8
10		–12	–4	13	5	10	10	–11	–2	10	–12	–6	7	36	16	–6
15		–12	–2	15	7	12	12	–11	–1	13	–11	–4	9	38	19	–4
20		–11	0	17	9	14	14	–10	0	15	–11	–2	11	39	19	–4
25		–11	1	19	10	15	15	–9	0	17	–10	0	12	41	21	–2
30		–10	3	21	11	16	16	–9	1	18	–9	0	13	42	22	–1
35		–9	3	21	12	17	16	–9	1	19	–7	2	14	42	22	–1
40		–8	4	22	13	17	17	–8	2	19	–6	2	15	43	23	0
45		–8	5	23	14	18	17	–7	3	20	–5	4	15	44	24	1
50		–7	6	24	14	18	18	–7	3	21	–4	4	16	44	24	2
55		–7	6	24	15	19	19	–7	4	22	–3	5	17	45	25	2
60		–6	6	24	15	19	18	–6	4	22	–2	5	17	45	25	2
65		–6	7	24	16	20	19	–6	5	23	–1	6	18	46	26	3
70		–5	7	25	16	20	19	–5	5	23	–1	6	18	46	26	4
75		–5	7	25	16	20	19	–5	6	23	0	6	18	46	26	4
80		–5	8	26	16	20	19	–4	6	23	0	6	18	46	26	5
85		–4	8	26	16	20	20	–4	6	23	0	6	18	46	26	5
90		–4	9	26	17	21	20	–4	7	24	0	7	19	47	27	6
100		–3	10	26	17	21	20	–3	7	24	2	7	19	47	27	6
110		–3	9	27	17	21	20	–3	7	24	2	7	19	47	27	7
120		–3	10	27	17	21	20	–3	7	24	3	7	19	47	27	7

* *F* – feet, *K* – knees, *H* – head

Table 4. Values measured with OMEGA 199 thermometer at the temperature of 40 °C

	HUMMER M1151A1 +40 °C *															
	$T_{ambient}$	Driver			Co-driver			Second row operator left			Second row operator right			Hot air inlet		
Time		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
[minute]	[°C]	F	K	H	F	K	H	F	K	H	F	K	H	Driver	Co-driver	Second row
0	42	39	42	42	38	41	43	36	35	41	35	39	41	40	41	40
5	41-43 °C	31	29	27	26	26	28	28	29	25	29	27	30	14	13	17
10		28	26	24	24	24	26	25	27	23	26	25	28	11	12	16
15		27	25	23	23	23	25	24	25	22	25	24	28	11	12	14
20		26	25	23	22	23	25	24	24	22	24	23	27	11	11	14
25		26	24	22	22	22	23	23	23	21	24	22	27	10	11	13
30		26	24	22	22	22	24	23	23	21	24	22	27	10	11	13
35		26	24	22	22	22	24	23	23	21	24	22	27	10	11	13
40		26	24	22	22	22	24	22	23	21	24	22	27	10	12	13
45		26	24	22	22	22	24	22	23	21	24	22	28	10	11	13
50		26	24	22	22	22	24	22	23	21	24	22	28	11	11	13
55		26	24	22	22	22	24	22	23	21	24	22	28	11	12	14
60		26	24	22	22	22	24	23	23	21	24	22	28	11	12	14
65		27	25	23	23	23	25	23	23	22	23	22	29	11	13	14
70		27	25	22	23	23	24	22	23	21	24	23	30	11	13	13
75		27	25	22	23	23	25	23	23	21	24	23	28	11	14	14
80		27	25	22	22	23	25	23	23	21	24	23	28	11	13	13
85		27	25	22	23	23	25	22	23	21	24	23	29	11	13	13
90		27	25	22	23	23	25	23	23	21	24	23	29	11	13	13

* *F* – feet, *K* – knees, *H* – head

Data analysis yields the characteristics of the heating and air conditioning system. At the ambient temperature of –16 °C, the prescribed comfort parameters according to SORS 0114 ($K_{ef} \geq 0.5$, $\Delta t \leq 10$ °C) and SORS 8419 ($-0.5 \leq$ PMV ≤ 0.5, PPD $\leq 10\%$, and $\Delta t \leq 5$ °C) have not been attained for the period of 60 minutes. The PMV and PPD comfort parameters were attained in 60 minutes, but with the difference in temperature (Δt_{max}) of 30 °C (allowed Δt_{max} of 5 °C). At the ambient temperature of 40 °C the prescribed comfort parameters in the cabin, ($-0.5 \leq$ PMV ≤ 0.5, PPD $\leq 10\%$, and $\Delta t \leq 5$ °C), were achieved in 20 minutes. The mean air temperature attained the value of +24 °C in that time period, whereas the difference in temperature values, Δt, was the allowed 5 °C. The measured velocity of air circulation at all testing points was 0.1 m/s.

When testing thermal comfort inside the OAR 1RL-128D vehicle cabin, the vertical distance at which the sensors-thermocouples of *K*-type were set was the same as for measuring inside the HUMMER vehicle. The space distribution of sensors at the ambient temperature of +40 °C, if observed in the direction of vehicle movement was: 1 – feet of the operator on the right, 2 – knees of the operator on the right, 3 – head of the operator on the right, 4 – feet of the operator in the centre, 5 – knees of the operator in the centre, 6 – head of the operator in the centre, 7 – feet of the operator on the left, 8 – knees of the operator on the left, 9 – head of the operator on the left, and 10 – hot/cold air inlet into the radar cabin.

When testing the cooling characteristics at the measuring point No. 11, the external temperature was measured in the climate chamber at 1.5 m above the floor. When testing the heating efficiency (–16 °C) at measuring point No. 11, the temperature of inlet hot air into the cabin of the driver was measured. The measuring points No. 12-14 were used to measure temperature on feet, knees and head of the driver, while the external temperature in climate chamber is shown at measuring point No. 15. The MM0023 measuring probe from the kit of B&K 1212 thermal comfort meter was set in the centre of the radar working space, between the operator in the centre and the operator on the right at the height of 0.6 m above the floor. During the testing, the redesigned KONVEKTA-KL20 KDE AC unit was operating at the maximum capacity. The test results are shown in tabs. 5-8.

Table 5. Thermal comfort values measured with B&K 1212 meter at the temperature of –16 °C

OAR 1RL-128D –16 °C										
t [minute]	5	10	15	20	25	30	35	40	45	50
PMV	–	–4.1	–2.8	–2.4	–2.2	–2	–1.8	–1.6	–1.3	–1.3
PPD [%]	–	–	–	–	–	82	70	60	42	40
t [minute]	55	60	65	70	75	80	85	90	95	100
PMV	–1.2	–1.1	–1.3	–1.4	–1.1	–0.9	–0.99	–0.69	–0.55	–0.55
PPD [%]	36	31	41	46	34	23	24	14	11	10.2

Table 6. Thermal comfort values measured with B&K 1212 meter at the temperature of 40 °C

OAR 1RL-128D +40 °C													
t [minute]	5	10	15	20	25	30	35	40	45	50	55	60	65
PMV	–	2	2.1	1.9	1.8	1.7	1.6	1.5	1.4	1.3	1.2	1.1	*
PPD [%]	–	81	86	78	73	66	60	52	47	42	37	31	*

* AC stopped working. Repeated start failed.

At the ambient temperature of –16 °C, the predetermined comfort parameters ($K_{ef} \geq 0.5$, $\Delta t \leq 10$ °C), ($-0.5 \leq \text{PMV} \leq +0.5$ PPD ≤ 10%, and $\Delta t \leq 5$ °C) have not been reached in 60 minutes, either in the working space or in the driver's cabin of the radar. The mean air temperature inside the radar working space of +16 °C was achieved in 106 minutes, while in the driver's cabin the temperature of 11.3 °C was attained after 120 minutes of operation. The PMV and PPD comfort parameters were achieved in 101 minutes with the temperature difference of $\Delta t_{max} = 17$ °C (max 5 °C allowed).

At the ambient temperature of +40 °C and the AC operating time of 60 minutes, the mean air temperature inside the vehicle (OAR working space) attained the value of +29 °C, whereas the difference in temperature values was $\Delta t = 3$ °C. The air circulation veloc-

Table 7. Values measured with OMEGA 199 thermometer at the temperature of –16 °C

OAR 1RL-128D -16 °C															
Measuring points	Operator right			Operator centre			Operator left			Hot air inlet		Driver			Ambient
	Feet	Knees	Head	Feet	Knees	Head	Feet	Knees	Head	Radar	Driver's cab	Feet	Knees	Head	
[minute]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	–15	–15	–15	–14	–15	–15	–15	–15	–16	–16	–15	–15	–15	–15	–16
5	–12	–7	–5	–3	0	–5	–11	–8	–5	16	–10	–13	–1	–6	–17
10	–11	–3	0	–2	5	0	–8	–4	–1	32	–7	–12	2	–3	–15
15	–10	0	3	1	8	2	–7	–2	1	40	–5	–11	2	–1	–14
20	–8	2	5	2	9	4	–5	0	3	47	–3	–10	4	1	–18
25	–7	4	6	3	11	6	–3	1	5	51	–2	–9	5	2	–16
30	–6	5	7	4	12	7	–2	3	6	55	0	–8	5	4	–16
35	–4	7	9	5	14	9	–1	4	8	56	1	–7	7	5	–16
40	–3	8	10	7	14	10	0	5	9	58	2	–6	7	6	–14
45	–2	9	12	7	16	11	2	6	10	59	3	–5	7	7	–17
50	–1	10	13	10	17	12	3	8	11	60	4	–4	9	8	–14
55	0	11	13	10	17	12	3	8	11	61	5	–3	9	9	–16
60	1	12	14	11	18	13	4	9	12	61	6	–3	10	9	–15
65	0	11	12	8	14	11	3	8	10	51	5	–3	7	8	–14
70	0	9	10	10	11	9	3	7	8	39	3	–3	7	6	–16
75	1	11	13	12	16	12	5	9	11	48	4	–2	11	8	–14
80	2	12	15	14	18	14	6	11	13	56	6	–1	12	9	–17
85	3	14	16	15	20	15	6	11	14	59	7	0	13	10	–15
90	4	15	17	14	20	17	7	12	15	61	8	0	13	11	–16
95	5	15	18	16	21	17	8	13	16	62	8	0	14	11	–14
100	5	16	19	17	22	18	9	14	17	63	9	1	14	12	–16
105	6	17	19	17	23	19	10	15	17	64	9	1	15	13	–14
110	7	17	20	19	23	19	10	15	18	64	10	2	16	13	–16
115	8	18	21	20	24	20	11	16	19	64	10	2	16	13	–14
120	8	18	21	20	24	21	11	17	19	65	11	3	17	14	–17

ity measured at the operators' points was 0.1 m/s. The prescribed comfort parameters ($-0.5 \leq \text{PMV} \leq +0.5$ PPD $\leq 10\%$) were not attained in 60 minutes. After 60 minutes of operation the AC unit shut. The attempt to restart it failed.

Conclusion

By applying the methods given in ISO 7730 and SORS 8419 standards, we cannot determine accurately the values of spatial distribution of temperature inside a vehicle cabin. This is particularly significant when designing and developing the elements of heating and air conditioning systems, especially the lay-out of elements for hot or cold air distribution. From the presented test results for HUMMER vehicle, it can be seen that after 80 minutes of opera-

Table 8. Values measured with OMEGA 199 thermometer at the temperature of 40 °C

OAR 1RL-128D +40 °C											
Measuring points	Operator right			Operator centre			Operator left			AC	Ambient
	Feet	Knees	Head	Feet	Knees	Head	Feet	Knees	Head		
[minute]	1	2	3	4	5	6	7	8	9	10	15
0	38	40	41	38	40	41	37	40	40	40	41
5	33	33	34	35	35	34	35	34	33	21	41
10	33	33	32	34	34	33	34	34	32	20	41
15	32	32	32	34	33	32	33	33	31	20	42
20	31	31	32	33	33	31	32	31	30	20	42
25	31	31	31	33	33	31	32	31	30	20	42
30	30	30	31	33	33	31	32	31	30	19	41
35	30	30	31	33	32	30	31	31	29	19	41
40	30	30	30	33	32	30	31	30	29	19	40
45	29	29	30	32	31	30	30	30	29	19	41
50	29	29	30	32	32	29	30	29	28	18	41
55	29	29	29	32	31	29	30	29	28	18	41
60	28	28	29	31	31	28	29	29	28	18	40
65	AC stopped working. Repeated start failed										

tion of the heating system the difference in the temperatures measured at vertical points of the driver's feet and head was even 30 °C.

This information suggests there is a need to redesign the points of hot air inlets.

The results of testing a cabin of OAR 1RL-128D vehicle also suggest that with the purchase and installation of AC system of the well-known producers the problems related to achieving the adequate thermal comfort do not necessarily have to be solved. The fact that the cooling unit stopped working suggests it was overloaded, *i.e.*, that there is a need to install the greater cooling capacity unit. Thanks to the fact that the measurements were conducted in strictly controlled conditions, there is a possibility to repeat the experiment and the possibility to compare the results of both tests with various placements of the thermal comfort system elements.

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