SimTerm 2019

Energy – Efficiency – Ecology

PROCEEDINGS

19th International Conference on
Thermal Science and Engineering of Serbia

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Contents

Comparison of Two Models of Human Thermal Sensation in an Agricultural Tractor Cab

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Abstract: This study investigates the influence of thermal conditions in an agricultural tractor cab on the operator's thermal sensation. The study was performed using computational fluid dynamics (CFD) software Star CCM+. To evaluate the microclimate conditions, parameter equivalent temperature (standard EN ISO 14505-2) was used and compared with the results obtained according to the procedure proposed by the standard ASABE/ISO 14269-2. The results showed that some correlations between those two assessment methods exist, but none of them include all parameters that completely describe the operator's thermal sensation.

Keywords: Agricultural tractor cab, Air conditioning, Thermal comfort, Air temperature, Equivalent temperature, Computational fluid dynamics.

1. Introduction

Sensible heat exchange between the occupants and the interior of a vehicle cabin, directly contributing to the thermal sensation, takes place by convection, conduction and thermal radiation, including the solar radiation that comes through the cabin glazing. The same applies to an agricultural tractor cab with an operator inside. An operator is directly able to influence the heat transfer using forced convection only by changing the modes of air flow over the surface of his body. The AC system is able to change the air temperature in the cab by mixing ventilation. Indirectly, the temperature of interior surfaces will be changed too, although much more slowly. The airflow around the human body is usually a combination of both natural and forced airflow. The local skin temperature and its rate of change, and thus the thermal sensation, will depend on the heat exchange between the body surface and the surroundings, making the analysis of these processes in a real system very complicated [1]. For this reason, simplified models are applied because they provide insight into the relative thermal sensation under given circumstances, based on the principle of heat exchange between the human body and its surroundings [2].

Basic parameter to describe a thermal conditions in some ambient is an air temperature. However, the air temperature alone is not enough because the other parameters that influence heat exchange must be considered. Standards ASABE/ISO 14269-2 [3] and DIN 1946-3 [4] take into account local air temperatures, relative humidity and air velocity in vicinity of operator's head. Widely used Fanger's PMV thermal comfort index (Predicted Mean Vote, standard ISO 7730 [5]) includes four environmental and two individual parameters, but it is applicable to moderate, stationary and more-less uniform conditions. For local comfort assessment according to the same standard, DR index (Draught Rate) is used. Standard ISO 14505-2 covers evaluation of thermal environments in vehicles by determination of sensible (dry) heat exchange between the driver and the surrounding [6].

For evaluation of human thermal sensation in vehicles some of mentioned indices were used in recent researches. Mišanović et al. [7] monitored and recorded the air temperature inside the passenger compartment of electric city bus in summer as well as in winter conditions. Kilic and Sevilgen used sensible heat flux together with local air velocities and air and surface temperatures [8]. Bohm et al. [9] used equivalent temperature determined by physical thermal manikin for evaluation of thermal sensation in closed cab. Ružić [10] used equivalent temperature determined by virtual thermal manikin. Oh et al. [11] used PMV index and equivalent temperature for evaluation of thermal sensation.

In this paper, local thermal sensations of agricultural tractor operator were analyzed and compared in two cases of thermal boundary conditions. The analysis was performed using a numerical simulation (CFD) on a virtual model of a tractor cab with an operator. The aim of the paper is to compare the evaluation of the microclimatic conditions the parameter equivalent temperature (EN ISO 14505-2) with the method proposed by standard ASABE/ISO 14269-2 under different air flow regimes and cooling power.

2. Human thermal sensation evaluation

In this section two methods that are chosen to be compared in this research are explained: evaluation of thermal sensation according to the standard ASABE/ISO 14269-2 and method proposed by the standard EN ISO 14505-2.

2.1. Evaluation of thermal sensation according to the standard ASABE/ISO 14269-2

The method for an evaluation of agricultural tractor air conditioner performances defined in standard ASABE/ISO 14269-2 [3] is based on the conventional approach of measuring air temperatures, relative humidity and air velocity. The locations of the temperature and velocity sampling points are defined by their distances from the seat index point (SIP), Fig. 1a. Acceptable values of air temperatures are between 24°C and 27°C, according to the comfort zone (Fig. 1b). The temperatures in the operator's environment shall be uniform within 5°C. The air velocity in vicinity of the eyes (location 7, Fig. 1a) must not exceed 0.3 m/s [3].

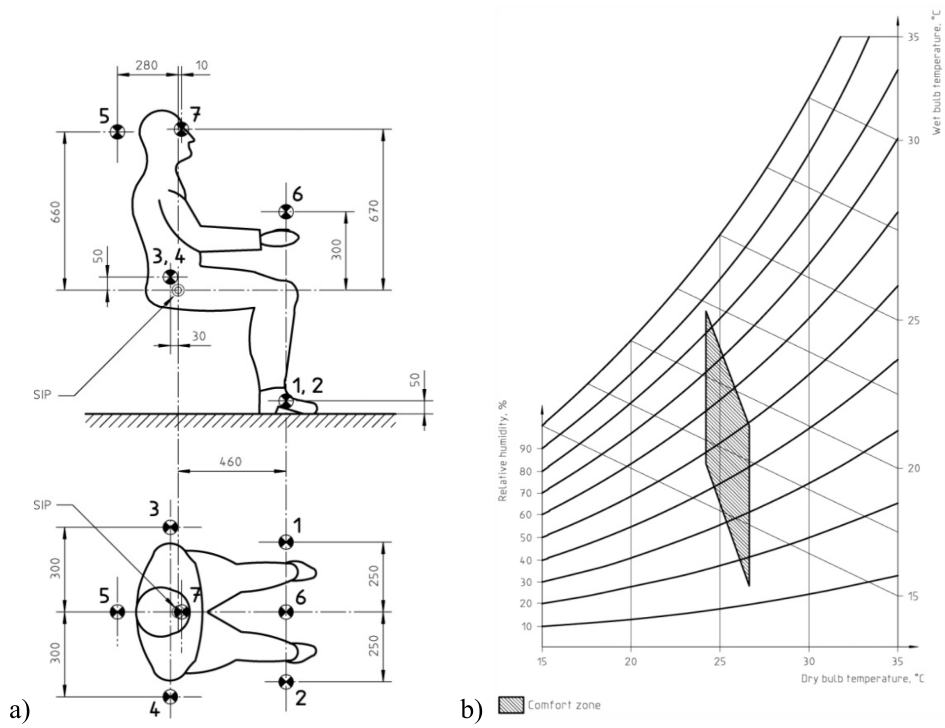


Figure 1. a) Locations for measuring air temperatures (1-6) and air velocity (7) according to standard ASABE/ISO 14269-2. b) The comfort zone proposed in the same standard [3]

2.2 Evaluation of thermal sensation using the equivalent temperature

The equivalent temperature model [6] is based on the sensible (dry) heat transfer. The equivalent temperature is defined as a uniform temperature of an imaginary enclosed space with the air velocity equal to zero where a person would have the same sensible heat transfer as in the actual, non-uniform environment. The relation between the values of equivalent temperatures and thermal sensation is defined by the standard ISO 14505-2 [6]. Thermal conditions are considered favourable if the equivalent temperature deviates less from the neutral value. The equivalent temperatures limits of cold and hot sensation for individual segments are shown in Fig. 5 and 6 (the dashed lines labelled '*too cold*', '*neutral*' and '*too hot*'). From the dry heat balance of the human body and the surroundings, by equating the total heat exchange in real and in imaginary (equivalent) surroundings in which the air temperature is equal to the mean radiant temperature (both equal to so-called equivalent temperature), it follows [6]:

$$q = C + R + R_S = C_{eq} + R_{eq} \tag{1}$$

The equivalent temperature in general form (for the whole body as well as for individual body segments) will be [6]:

$$t_{eq} = t_{sk} - \frac{q}{h_{cal}} \tag{2}$$

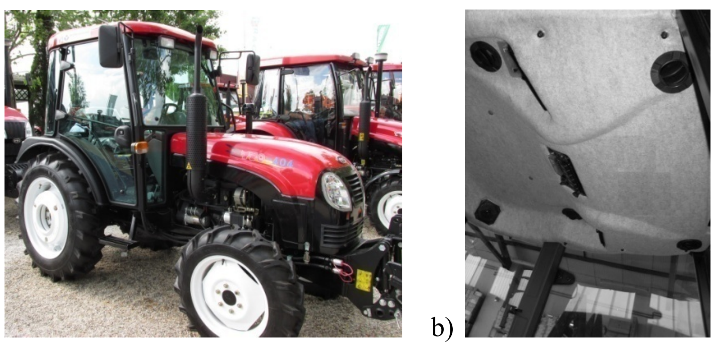
The dry heat transfer coefficients of the individual body segments ($h_{cal,\ seg}$) necessary for the calculation of equivalent temperature are determined by so-called calibration of the thermal manikin. Calibration should be performed in a chamber with homogeneous microclimate conditions without forced airflow in which the mean radiant temperature is equal to the air temperature, that is the equivalent temperature: $t_a = t_{mr} = t_{eq}$. Based on the heat loss by segments under calibration conditions, calibration heat transfer coefficients for surface temperature of certain body segments are calculated according to [6]:

$$h_{cal,seg} = \frac{q_{cal,seg}}{t_{sk} - t_{eq}} \tag{3}$$

3. The model description

3.1 Model of a tractor cab

The interior of the tractor cab is modelled on the basis of the existing cab, installed on the farm tractor YTO (Fig. 2 a). The air is introduced into the cab through four vents in the ceiling (Fig. 2b). The AC system consists of compressor Sanden SD5H14 and evaporator with blower Konvekta B54-000.079. Maximal refrigeration capacity is 5 kW and maximal rated volumetric air flow is 600 m^3/h.



a) b)

Figure 2. a) Tractor YTO with the air-conditioned cab. b) Position of the vents in the ceiling

In those virtual experiments the domain of CFD simulations is a simplified geometric form of the tractor cab interior space. The inlets in the domain are vent openings of air-conditioning system. The settings of CFD model were done by implementing of the available experimental data and the features of similar numerical models of the vehicle cabin [12], [13], [14], [15].

3.2 Model of a tractor driver: Virtual thermal manikin

The tractor driver was modelled as a virtual thermal manikin (VTM) using the STAR-CCM+ software (Fig. 3) [16]. Changes in the air mass flow and/or air flow direction reflects on the heat loss from the VTM's body. The VTM reacts with changes of boundary heat flux while the surface ("skin") temperature is kept constant (t_{sk} = 34°C). In order to monitor the heat exchange on individual segments, the VTM's body is divided into 18 body segments (head, neck, chest, back, etc.). Standing body height is 1.7 m, sitting height is 1.27 m and the body surface area is 1.8 m^2. The virtual thermal manikin, meshed in surface elements of 35 mm in nominal size (around 13,600 surface elements) with six layers of prismatic cells on the body surface had generally good agreement with experimental data in both forced and natural flow conditions [16], [17], [18], [19]. The turbulence model is two-layer RANS Realizable k-ε turbulence model. For more complex flow situations that can be encountered in a vehicle cabin, the number of the surface elements of the VTM was increased.

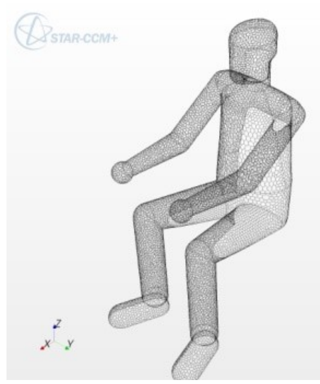


Figure 3. The model of a tractor driver presented by meshed surface

3.3 Calibration of the VTM

Values of calibration heat transfer coefficients on the VTM obtained by the simulations inside calibration chamber are given in Table 1. A nominal size of surface elements on VTM was 20 mm and six layers of boundary prismatic cells had thickness of 20 mm. The VTM surface was discretized into around 24,000 surfaces, while the entire domain was discretized in around 320,000 finite volumes. The VTM surface temperature was set on 34°C and the equivalent temperature was 24°C.

Obtained values of calibration coefficients are compared with available experimental values in Table 1. In the experiment described in [20] the manikin had summer clothing and hair, which increase insulation of certain body segments. In benchmark experiments [17] a nude manikin was used. Due to difference in size and shape between the VTM and physical manikins, values of calibration coefficients can be accepted as values for further calculations of equivalent temperatures.

Table 1. Calibration heat transfer coefficients $h_{cal\ seg}$ [W/m^{2}K] obtained by CFD simulations of the virtual thermal manikin inside the calibration chamber (t_{eq} = 24°C)

Body segment	CFD	Experiment [20], summer clothing	Experiment [17], nude
Head	9.33	8.25	8.00
Scalp	8.31	3.49	8.00
Neck	7.63	8.25	8.00
Chest	8.40	3.89	6.71
Back	8.25	5.79	6.90
Pelvis	9.75	3.85	6.90
Upper arm	8.70	4.48	8.20
Lower arm	9.42	5.18	8.20
Hand	10.84	8.55	8.55
Upper leg	9.05	4.89	7.81
Lower leg	8.98	4.97	7.81
Foot	10.52	3.73	7.81
Whole body	9.05	-	7.46

3.4 The numerical model of the cab with the operator

The interior of the tractor cab was discretized into around 700,000 polyhedral finite volumes (Figure 4). The mesh was finer around the VTM and the vents. A nominal size of surface elements on the VTM was 20 mm, while boundary prismatic cells have thickness of 20 mm in six layers. Body surface of the VTM was discretized into around 24,000 surfaces. A nominal size of surface elements on roof, ceiling, seat and glazing was in range of 40 to 60 mm. The problem was treated as a steady-state, with segregated flow and fluid energy solver. The VTM body and all internal surfaces were modelled as solid no-slip surfaces with constant temperature. The same other settings were applied as in the cab validation model.

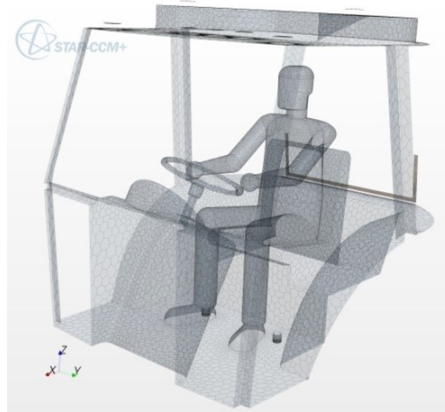


Figure 4. Meshed model of the tractor cab with a virtual thermal manikin

3.5 Boundary conditions

The guideline for determining the boundary conditions was the fact that the first minutes after the operator enters the cab which was heated-up in the sun is more important than those in steady state situation. The ambient conditions were set according to the standards for tractors and self-propelled machines for agriculture ASABE/ISO 14269-2 and 14269-3 [3], [21]. The ambient air temperature of 32°C and relative humidity of 54% were kept constant in all virtual experiments. Although only the dry heat transfer is relevant in this research, the relative humidity influences the cooling power. In the case when the sun is above the cab, as is proposed by ASABE/ISO 14269-3, the cab roof prevents direct solar irradiation on the operator's body surface. Therefore, the solar radiation is used only for determining the cab interior surface temperature.

Since the thermal radiation is included in the sensible heat transfer, surface-to-surface grey thermal radiation model was activated in the simulations. Emissivity of all surfaces was set to 0.95. Constant boundary temperature means that the convective heat transfer can be analyzed independently (Eq. 1). Temperatures of the floor, the glass and the ceiling surfaces were set based on empirical values, in two levels: low and high thermal radiation. The floor and the ceiling temperature was set to be 32°C or 50°C in low or high thermal radiation case, respectively. The temperature of the glass was set to be 32°C (low thermal radiation case) or at value of 40°C (high thermal radiation case) [1], [12]. In a real situation, a while after the air conditioning has been turned on the temperature of the interior surfaces will start to decrease, leading to the decrease of the mean radiant temperature too. The radiant heat loss from the body will be higher, and a comfort should be achieved with less cooling power. Independent simulations were used to determine radiative heat fluxes under those two different boundary conditions (labelled "low R" and "high R"). The values are given in Table 2. The minus sign here indicates the heat gain by thermal radiation.

Table 2. Radiative heat fluxes [W/m^2] obtained by CFD simulations of the virtual thermal manikin inside the tractor cab.

Body segment	low R: $t_{s\ int}$ = 32°C	high R: $t_{s\ int}$ = 40..50°C
Head	10.7	-48.1
Scalp	12.3	-82.8
Neck	10.6	-41.1
Chest	9.5	-44.3
Back	11.6	-43.0
Pelvis	10.3	-37.2
Upper arm	9.7	-44.0
Lower arm	10.0	-47.4
Hand	11.1	-50.0
Upper leg	9.3	-38.3
Lower leg	11.1	-57.2
Foot	10.9	-63.2
Whole body	10.4	-48.4

3.6 Factors of the virtual experiments

The parameters of the AC system that were varied in the virtual experiments were the air temperature and the total air mass flow through the vents. The values of air temperature at the vents (t_{aVO}), air mass flow and air volume flow ($\dot{m}_a$, $\dot{V}_a$) are given in Table 3. The cooling power and the air flow rate of the AC system are limited by the system design. The heat removed from the outer hot and moist air passing through the evaporator can be calculated using eq. (4):

$$Q_{evap} = \dot{m}_a[(i_1 - i_2) - i_{w2}(x_1 - x_2)] \quad (4)$$

In those simulations, it is assumed that the air state at the inlet of the evaporator corresponds to the ambient conditions. The air temperature at the vents will be higher than the air temperature immediately after the evaporator because of the heat exchange in hot air ducts. It is assumed that there is a temperature increase of five degrees.

Table 3. The values of the vent air temperature, the air mass flow and the cooling power in the virtual experiments

Case	t_{aVO} [°C]	$\dot{m}_a$ [kg/s]	$\dot{V}_a$ [m^3/h]	Q_{evap} [kW]
t5v43	5	0.0137	43	0.90
t13v43	13	0.0137	43	0.69
t5v244	5	0.0763	244	5.00
t13v320	13	0.1000	320	5.00

The simulations are coded according to the values of air temperature and volumetric air flow rate: for example, "t5v43" denotes that the factors are t_{aVO} = 5°C and $\dot{V}_a$ = 43 m^3/h. The lowest value of the air flow is chosen according to the minimum value proposed by the standard ASABE/ISO 14269-2. The higher values are corresponding to the maximum cooling power for discharge air temperatures 5°C and 13°C, respectively. The vents were directed vertically downwards and the air comes out in the direction normal to the vent.

4. Results and discussion

4.1 The assessment of thermal sensation

The segmental equivalent temperatures were calculated using the resulting heat fluxes on the individual body segments (Eq. 2). The equivalent temperatures are shown on Fig. 5 and 6, for the values of air temperature and air mass flow given in Table 3. As a neutral value of the equivalent temperature for the entire body, the value of 28.1°C was used [6], [20].

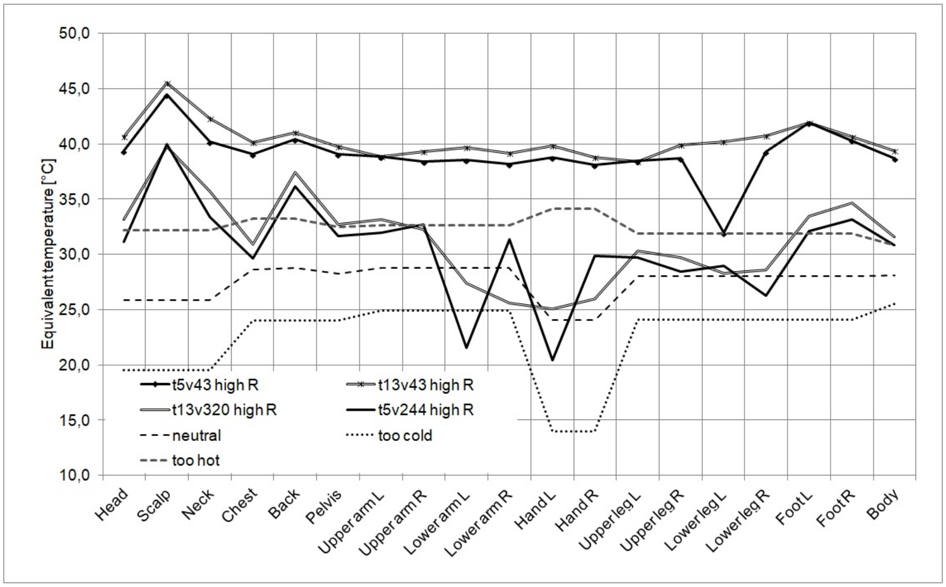


Figure 5. Equivalent temperatures in the cases with high thermal radiation

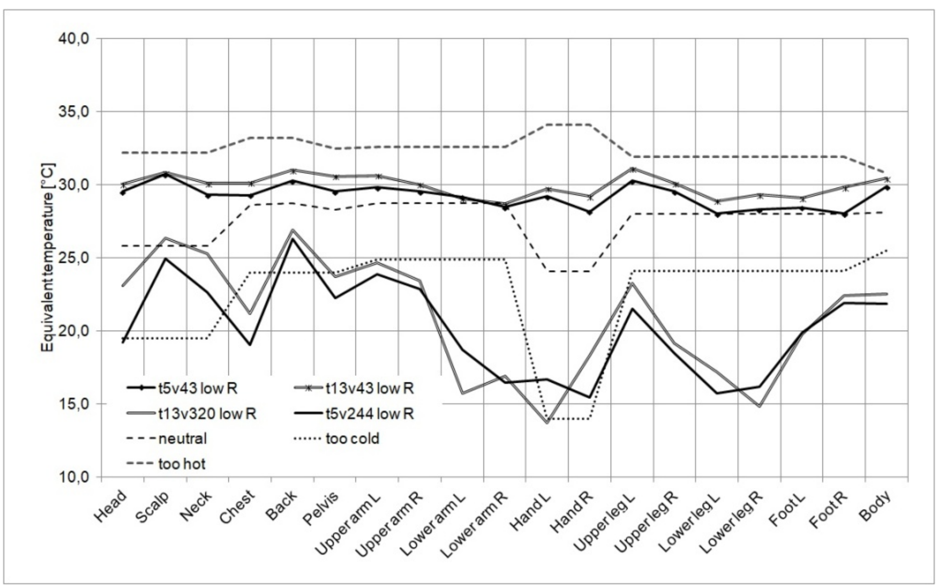


Figure 6. Equivalent temperatures in the cases with low thermal radiation

The variations of cooling power acquired by the changes in temperature and/or air flow are reflected in the adequate change of the equivalent temperature in a logical way.

The cab surface temperature has high influence on heat loss from the operator's body, thus on power required to achieve thermal comfort. Difference in the surface temperature of order of 10 degrees makes the difference in the equivalent temperature of the same order. The cooling power is around five times higher in the high thermal radiation case than in low thermal radiation case for the similar thermal sensation.

Higher airflow rates results in more deviation of segmental equivalent temperatures. However, with the lower air flow rate it was not possible to achieve thermal comfort at the beginning of the cooling down process (high thermal radiation case). On the other hand, utilizing of the maximum cooling power lead to uncomfortably cool sensation in the case with low thermal radiation (Fig. 6).

4.3 Visualization of results

Visualisation of the results confirms uniformity of air temperature field. However, strong non-uniformity of air velocity field could cause discomfort (Fig. 7). The cab surface temperature (thermal radiation) has higher influence on air velocity field in cases with low air flow rate due to effects of natural convection. The visualization of convective heat fluxes on the operator's body could indicate potential zones of discomfort due to too much cooling or high thermal radiation.

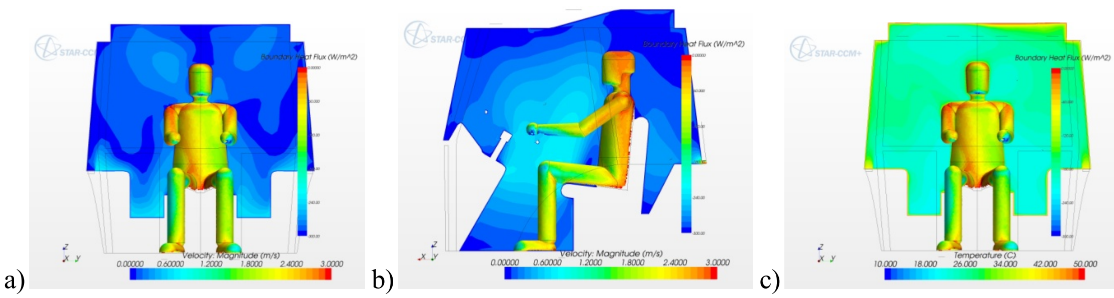


Figure 7. Visualization of results in the t5v244/high R case: a, b) The air velocity and convective heat transfer fluxes on the operator's body. c)The air temperature field) and convective heat transfer fluxes on the operator's body

4.4. Comparison of two methods for human thermal sensation assessment

The air temperatures obtained according to the standard ASABE/ISO 14269-2 are given in Tables 4 and 5. The corresponding equivalent temperatures of the segments are compared to the local air temperatures. The Table 6 shows the values of the air velocities in eyes zone.

Table 4. The resulting air temperatures in locations 1 to 6 (Fig. 1) compared to the equivalent temperatures for corresponding segment (high thermal radiation)

	Air temperatures [°C]				Equivalent temperatures [°C]					
loc.	t5v43	t13v43	t5v244	t13v320		t5v43	t13v43	t5v244	t13v320	$t_{eq\ neut}$
1	33.6	34.1	23.0	25.8	L foot	41.9	41.9	32.1	33.5	28.0
2	32.1	34.0	20.2	23.7	R foot	40.3	40.7	33.2	34.7	28.0
3	37.5	35.0	22.2	26.1	Pelvis	39.0	39.8	31.7	32.7	28.3
4	34.6	35.3	21.9	25.1	Pelvis	39.0	39.8	31.7	32.7	28.3
5	34.6	37.1	26.1	29.1	Head	41.9	43.1	35.6	36.5	25.8
6	32.1	34.5	20.8	24.7	Hands	38.4	39.3	25.1	25.5	24.1

Table 5. The resulting air temperatures in locations 1 to 6 (Fig. 1) compared to the equivalent temperatures for corresponding segments (low thermal radiation)

Air temperatures [°C]					Equivalent temperatures [°C]				
loc.	t5v43	t13v43	t5v244	t13v320		t5v43	t13v43	t5v244	t13v320	$t_{eq\ neut}$
1	24.6	25.7	15.7	20.4	L foot	28.4	29.1	19.9	19.8	28.0
2	24.1	26.1	17.3	21.4	R foot	28.0	29.8	21.9	22.4	28.0
3	24.9	27.0	17.5	22.1	Pelvis	29.6	30.6	22.3	23.7	28.3
4	25.6	26.4	17.3	22.4	Pelvis	29.6	30.6	22.3	23.7	28.3
5	26.5	27.8	20.9	24.1	Head	30.1	30.5	22.1	24.7	25.8
6	25.4	26.4	16.4	20.8	Hands	28.7	29.5	16.1	16.0	24.1

Table 6. The local air velocity v_{a7} in location 7 (Fig. 1)

	t5v43	t13v43	t5v244	t13v320
v_{a7} [m/s] high R	0.11	0.02	0.39	0.47
v_{a7} [m/s] low R	0.08	0.07	0.47	0.37

By comparison of the local air temperatures and the local equivalent temperatures, it can be noted that correlation exists, but the values of the equivalent temperatures are higher than the air temperatures, especially in the cases with higher thermal radiation. High air flow rate makes the local air temperature less related to the thermal radiation. The difference is slightly smaller when there are higher air flow rates. The local air temperatures are within the comfort zone in the cases of high cooling power with high thermal radiation, as well as in the cases of low cooling power with low thermal radiation. Local equivalent temperatures are closer to the neutral, i.e. comfort values only in case of low cooling power with low thermal radiation.

High air velocity in the face zone cannot be detected directly by the equivalent temperature. For example, although in the settings with high air flow rates the air velocity is above the limit of 0.3 m/s, a head equivalent temperature can be still within the comfort limits (the case t13v320 low R).

5. Conclusions

This paper presents two methods for evaluation of tractor operator's thermal sensation, using the CFD simulations. The thermal sensation was evaluated by the equivalent temperature (as defined by standard ISO 14505-2) and by the standard ASABE/ISO 14269-2. The heat fluxes on the individual operator's body segments as well as a spatial distribution of the air temperatures and the local air velocities are the main quantitative results obtained by post-processing. In this research, relative humidity was not taken into account and therefore the results should be used for comparative purposes only.

The main conclusions are summarized as follows:

- The values of equivalent temperatures are higher than the values of local air temperatures.
- High local air velocity cannot be detected directly by the equivalent temperature.
- High air flow rate makes the local air temperature less related to the thermal radiation.
- The thermal radiation has strong impact on thermal sensation and power required to obtain thermal comfort, but it is not directly detectable by measuring the air temperatures.
- The distribution of the heat fluxes over the body is better with lower air flow rates, having less deviation of heat loss from comfortable zone.

Due to inter- and intra-individual differences among people and because of non-uniformity of boundary thermal conditions in the cabin there needs to be the possibility for precise temperature air flow and direction adjustments of each vent. Change of the air flow direction from the individual air vents could produce considerable differences in local thermal conditions. From this reason, the direction of the vents is a factor that should be investigated more closely in further research.

Nomenclature

Latin symbols

C	–	Convective heat flux, in [W/m^2]
h	–	Heat transfer coefficient, in [W/m^{2}K]
i	–	Specific enthalpy of moist air, in [J/kg],
$\dot{m}$	–	Mass flow, in [kg/s],
q	–	Sensible heat flux, in [W/m^2]
Q	–	Heat, cooling power, in [W]
R	–	Radiative heat flux, in [W/m^2]
t	–	Temperature, in [°C]
$\dot{V}$	–	Volumetric flow, in [m^3/h],
v	–	Velocity, in [m/s]
x	–	Mass ratio of water and dry air in moist air, in [kg/kg]

Subscripts

a	–	Air
cal	–	Calibration
eq	–	Equivalent
evap	–	Evaporator
mr	–	Mean radiant
S	–	Solar
seg	–	Segmental
s int	–	Internal surface
sk	–	Skin
VO	–	Vent
w	–	Water
1	–	Inlet of an evaporator
2	–	Outlet of an evaporator

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