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AGRICULTURAL TRACTOR CAB CHARACTERISTICS RELEVANT FOR MICROCLIMATIC CONDITIONS

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The basic purposes of an agricultural tractor cab are to provide comfortable environment for an operator and to protect him from vibrations, noise and other adverse influences. The microclimatic features of middle-sized tractor cabs are the focus of this paper. The microclimatic conditions are related with design features that influence heat processes between the cab and the environment, including the effects on the operator.

One of methods for improvement of the microclimatic conditions and for reducing of air-conditioning energy consumption is prevention of cab heat gain, achieving this by appropriate heat rejection and insulation. Since the cab material characteristics and cab design play the main role in the heat transfer processes between the cab and the environment, these features are analyzed on existing middle-sized tractor's cabs. The aim of the paper is to identify and evaluate most important influences, in order to create the basis for microclimatic and energy consumption reduction aspects of a tractor cab design. The results showed that the cab glazing is probably the most influencing factor, where the selection of the appropriate properties could be the way for cab and operator heat load reduction.

Key words: Tractor, Cab, Ergonomics, Microclimate, Glass

INTRODUCTION

Modern agricultural tractors are complex and highly-efficient systems, whose development is constantly directed towards reduction of negative impact on the environment (higher fuel efficiency and lower pollution, less soil compaction, to mention a few), but also towards operator's space ergonomics. Conditions inside the cab have significant impact on operator performance, therefore on total result in the man-tractor-environment system too. From the operator's point of view, cab ergonomic is a key factor in ensuring of his optimum working performance, which could easily become the weakest link in the working process. While, on the one hand, the cab offers the mechanical protection and protection from adverse ambient conditions, on the other hand, even under moderate outside conditions the closed cab act like green house and its closed interior could become unpleasant, unbearable and even dangerous.

This paper covers designing aspects of tractor cab that have direct or indirect effect on ergonomics of the thermal environment on operator's working place. Ergonomics of the thermal environment is based on the relationship among air temperature, interior surfaces radiant temperature, air velocity and relative humidity, which in combination should obtain the absence of discomfort, for given operator's activity and clothing [6], [15].

Thermal processes in cab system are almost independent from tractor's working operation, in contrast to noise and vibration, but are depending on outside thermal conditions (air temperature, air velocity, intensity of solar radiation). Therefore, the cab is here taken as a separate unit. Since decreasing the heat gain of the cab means also reduction of thermal load to the operator, relevant design parameters are analyzed in this paper. The aim of the paper is to identify most influencing factors in order to consider pos-

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sibility for improvement of the microclimatic design aspects of agricultural tractor cab.

MAIN DESIGN FEATURES OF TRACTOR CABS RELATED TO THERMAL LOAD

Brief overview of the design features related to the thermal processes and HVAC characteristics was made, based on the available documentation and by inspection of the agricultural tractors that are present on local market. The analysis involved 26 different cabs that are installed on 90 models made by 11 tractor manufacturers. Orchard and vineyard tractors (narrow track tractors) were not included into the analysis. All tractors from the sample are 4WD wheeled tractors, with power ranging from 40.5 to 155 kW, weight ranging from 2750 to 8410 kg and wheelbase ranging from 2.055 to 3.089 m.

Main outer cab dimensions are evaluated from 9 different cab data, which are installed on 29 models of tractors made by 5 tractor manufacturers. These tractors are powered by 54.5 – 118 kW rated diesel engines, weighting from 3330 to 6555 kg and with wheelbases ranging 2.316 – 2.800 m. Cab outer lengths are from 1.40 to 1.77 m, cab widths are from 1.38 to 1.70 m, and cab heights are from 1.45 to 1.80 m. The dimensions of the cabs meet relevant standards ([14], [20], [21]). Correlations between basic tractor design features and cab dimensions are given in Table 1. It can be seen that the cab length has the largest correlation coefficient with wheelbase, the cab width has the largest correlation coefficient with engine power and the cab height has no significant correlation with any of the parameters.

Table 1. Correlation coefficients between basic tractor design parameters and cab dimensions

Correlation coefficients	Cab length	Cab width	Cab height
Engine rated power	0.234	0.503	0.197
Tractor weight	0.366	0.741	-0.032
Tractor wheelbase	0.498	0.420	0.041

The weights of the cabs are determined as a difference of the tractor weights with and without cab. The data were available for 6 cabs of 3 tractor manufacturers and cab weight is ranging from 150 to 250 kg.

Basic materials for cab frame are steel profiles, taking in account demands for mechanical protection of an operator. Cab frames mostly have six pillars, although there are designs with four pillars [14]. In order to provide the best visibility from the operator seat (according to [23]), vision obstructing elements need to be minimized, which is in contrast to the requirement for high mechanical strength of the cab structure. For that reason, main and the thickest pillars are usually placed in the rear part of the cab, behind of main field of the vision. Cab roof is made of polymers and contains the ventilation air distribution system, as well as evaporator and blower of air-conditioner.

The cab glazing (excluding the roof window) in modern tractors are approximately 60% of total cab surface area. Glass is generally tempered and tinted.

All cabs have air distribution system with outlets placed on the ceiling (top air distribution system). Cabs of larger tractors from the sample have also outlets on the instrument panel (front air distribution systems). Additional air distribution system placed laterally can be seen rarely, only in top-class tractors. The air outlets (nozzles) on the ceiling can have symmetrical or asymmetrical layout, while the nozzles on the instrument panel always have symmetrical layout. Nozzles have mostly circular cross-section and air jet direction could be changed by the operator.

Automotive vapour compression closed systems are used for air-conditioning (AC). Installed compressors could take around 4 – 6 kW from the tractor engine, which presents 2.5 - 15% of the rated power in this tractor category.

DESIGN PARAMETERS RELATED TO THE HEAT EXCHANGE BETWEEN THE CAB AND THE ENVIRONMENT

The analysis of thermal characteristics of the cabs was done for adverse environmental conditions that can be encountered in the local region [7], [18]:

- maximum outdoor air temperature greater than 30°C,
- total solar irradiation on outer surfaces up to 1000 W/m2,
- prolonged periods of unchanged tractor po-

sition related to the sun, over the flat landscape without shade,

- closed cab because of protection from noise and air pollution,
- low tractor velocity that limits the natural cab ventilation.
- Sum of cab heat gain in hot environment under the steady-state conditions, without sensible QH and latent heat QHw released by the operator, is consisted of (Fig. 1.):
- heat transfer through the cab envelope due to temperature difference Qk,
- heat transfer through the cab roof caused by the solar radiation Qsun,
- solar radiation transmission through the glazing QGsun,
- heat gain from the powertrain QPT.

In order to maintain interior temperature constant, heat release by the air-conditioning QAC should be equal to the heat gain. According to the requirements for thermal comfort in summer conditions, interior air temperature should be in range of 23 to 28°C, combined with adequate local air velocities [16], [17].

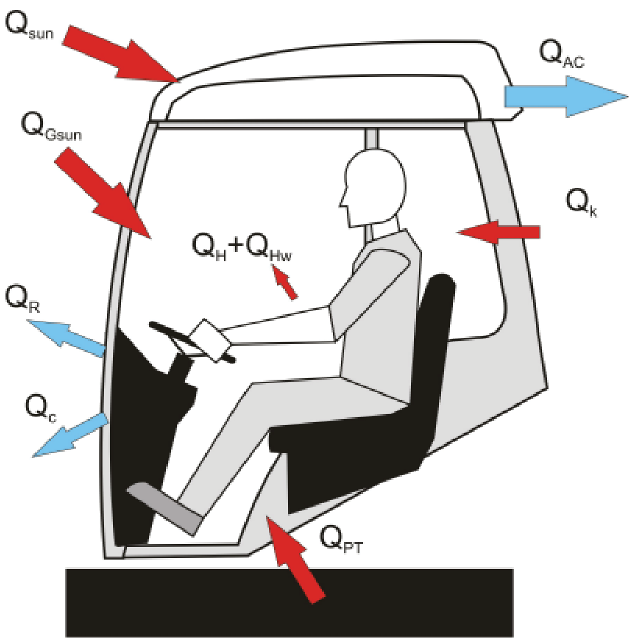

Figure 1. Thermal processes between a tractor cab and hot environment.

For the analytical investigation of influencing parameters, it was assumed that the heat flow is one-dimensional steady flow through a plane wall with natural convection on both sides. Radiant heat exchanges among inner surfaces are neglected, because of complexity and relatively small surface temperature difference.

Heat transfer through the cab walls due to temperature difference

Assuming that temperature in vicinity of the walls are uniform on inner as well as outer side, one-dimensional heat flow through this part of cab walls is (Fig 2):

$$Q_k = A_k \cdot q_k = A_k \cdot U \cdot (t_{ao} - t_{ai})$$

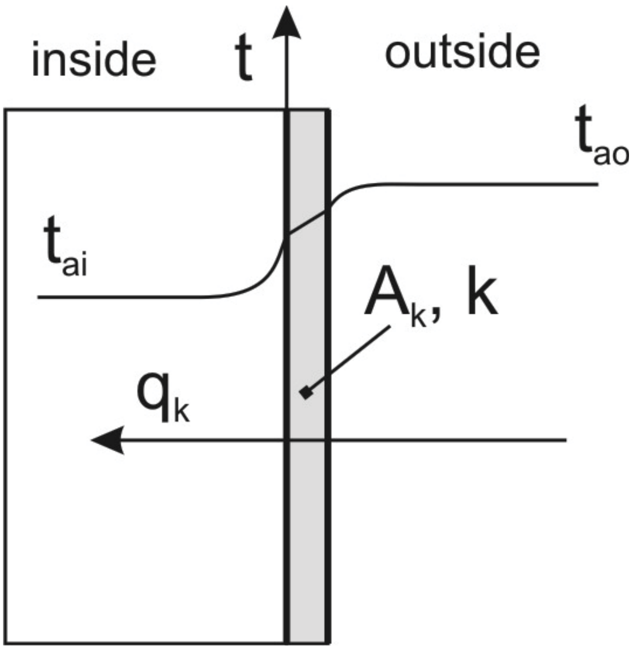

Figure 2. Heat transfer through the cab wall due to air temperature difference.

Parameter U is total heat transfer coefficient which combines convections from each side of the wall and conduction. General equation for a wall of area Aj with number of layers equal to m is:

$$U_j = \frac{1}{\frac{1}{h_{ci}} + \sum \frac{\delta_m}{k_m} + \frac{1}{h_{co}}}$$

For all surfaces with the heat transfer due to air temperature difference, the total value of U is:

$$U = \frac{1}{A_k} \sum U_j A_j$$

This value is dependent on wall layer material thermal characteristics (thermal conductivity k, W/mK), layer thickness and their areas. The surfaces where this mode of heat transfer takes place are surfaces that are not exposed to the solar radiation neither radiation from the powertrain. For example, these surfaces are windows on the shaded side of the cab. Therefore, main factors for this mode of heat transfer are dependent on glass thermal characteristics, the glass area and thickness.

Based on very limited sources, it is assumed that for cab of standing vehicle U = 3 ÷ 8 W/m2K [1], [11], [22]. For chosen outside-inside air temperature difference equal to 36° – 23° = 13°C, heat flux through the cab wall qk would be in the range of 40 – 100 W/m2.

Heat transfer through the cab roof caused by the solar radiation

Caused by absorbed part of the solar irradiation, cab outer surface is heated and its temperature is increased. Maximum solar irradiation on horizontal surface (roof) on a summer day in the central region of Vojvodina may exceed 900 W/m2 [7]. After the certain time of exposure to the sun radiation, the heat gain by the radiation and heat release reach the thermal equilibrium. From the outer surface heat is released by longwave radiation to the environment (mostly to the sky) and by convection to the colder surrounding air. Part of the heat passes through the wall, heats the material up and being released to the colder interior air by convection and emitted by the longwave radiation. Cab surfaces involved in this part of heat process are roof, pillars and glasses exposed to the sun (Fig. 3.). Cab glazing will be analyzed in the part of the paper that deals with transmission of thermal radiation through the glass.

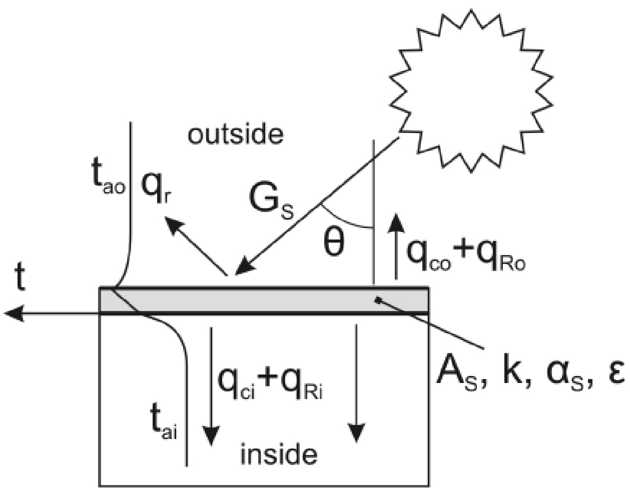

Figure 3. Heat transfer through the cab roof caused by the solar radiation.

Cab roof is generally hollow and contains ventilation and AC components, so heat transfer from hot outer surface is not direct, but through the air space. For that reason, such roof is not very critical from the solar radiation problems, as single wall roof (or such part of the roof) is. Inside the hollow roof, heated outer layer transmits energy to the air and radiate to the inner layer. Inner layer receive the thermal energy and transmits it to the cab interior. Similar situation is valid for pillars too, since the pillars are made from hollow steel profiles. In contrast to the roof, steel pillars present a thermal bridge to the cab interior due to higher thermal conductivity of the steel, unless some kind of upholstery is used on the inner side of the pillar.

Thermal balance equation for outer surface of the roof can be written as:

$$G_{S(time)} \cdot \cos\theta \cdot \alpha_{S(\theta)} - \varepsilon \cdot \sigma \left(T^4_{roof,o} - T^4_{sky} \right) - $$
$$- h_{c,o} (t_{roof,o} - t_{a,o}) - \frac{k_{roof}}{\delta_{roof}} (t_{roof,o} - t_{roof,i}) = 0$$

while the thermal balance on the inner roof surface is:

$$\frac{k_{roof}}{\delta_{roof}} (t_{roof,o} - t_{roof,i}) - h_{c,i} (t_{roof,i} - t_{a,i}) - q_{R,i} = 0$$

Heat radiation of warm wall has direct influence on an operator, and it is depending on wall surface temperature and wall's emissivity, which is generally high for non-metallic surfaces (larger than 0.9 [8]). Using an example of heat flux assessment for the opaque roof, treating the roof as a single layer wall, design parameters will be discussed. Hence, equation of heat flux that flows through the roof, caused by solar radiation, is:

$$q_{sun} = \cos\theta \cdot \alpha_{S(\theta)} \cdot G_{S(time)} - \varepsilon \cdot \sigma \left(T^4_{roof,o} - T^4_{sky} \right) - $$
$$- h_{c,o} (t_{roof,o} - t_{a,o}) = \frac{k_{roof}}{\delta_{roof}} (t_{roof,o} - t_{roof,i}) = h_{c,i} (t_{roof,i} - t_{a,i})$$

For selected thermal properties of the roof material, its thickness and for 900 W/m2 of solar irradiation on horizontal surface with solar absorption coefficient of 0.3 (Table 2.), calculated heat flux through the roof was greater than 40 W/m2. This presents at least 15% of total radiation on the surface, assuming that the AC keeps interior air temperature on level of 23°C. Using the iterative method for outside and inside roof surface temperatures calculation, interior surface temperature was estimated on more than 50°C. Large uncertainty for analytical determination of the heat flux was caused by calculation of the convection coefficients, which could differ according to the various sources [2], [4], [8].

Consequently, the most influencing factors are solar absorptivity and longwave emissivity of the roof material, then its thickness and conductivity. Therefore, outer roof surface should have low solar absorptivity coefficient and high emissivity (small αs / ε ratio is preferable [8]), with low thermal conductivity in the same time. Although, in order to reduce thermal radiation towards operator's body surface, interior roof surface should have low thermal emissivity.

Thermal properties of materials are given in Table 2. Solar absorptivity is depending also on surface colour [1], [8]. From this point of view, more preferable are light colours, which are widely used for tractor roofs. Despite the high thermal conductivity, one of most popular material for reflection of thermal radiation is aluminium (αs = 0.09 – 0.15 [8]), but it is not utilized for these purposes in tractor cab design.

Table 2. Thermal characteristics of cab materials

	solar absorptivity, αs	surface emissivity, ε	thermal conductivity, k (W/mK)	normal solar transmissivity, τ
plastic, white	0.23 – 0.49 [2],	0.90 – 0.97 [2], [8], [11]	0.12 /11/	-
tempered single glass, clear	0.08 [19]	0.8 – 0.95 [1], [2], [8], [11]	0.8 [19]	0.84 – 0.90 [1], [19]
tempered single glass, green tinted	0.45 [19]	0.8 – 0.95 [1], [2], [8], [11]	0.8 [19]	0.49 [19]
metal, painted white	0.21 – 0.25 [1], [8], [11]	0.85 -0.96 [1], [8], [11]	40 – 45 [11], [12]	-
metal, painted black	0.80 [11]	0.97 [1], [8], [11]	40 – 45 [11], [12]	-

Cab glazing is semitransparent medium where solar irradiation can be partially reflected, absorbed and transmitted, Fig. 4.

Solar irradiation on a cab surface is variable because of sun position as well as orientation of the cab surfaces. Maximum ("clear sky") intensity of normal irradiation and its variations in time and due to various positioning of the cab surfaces are showed on Fig. 5 and Fig. 6, for vertical surface and for 20° inclined surface, respectively.

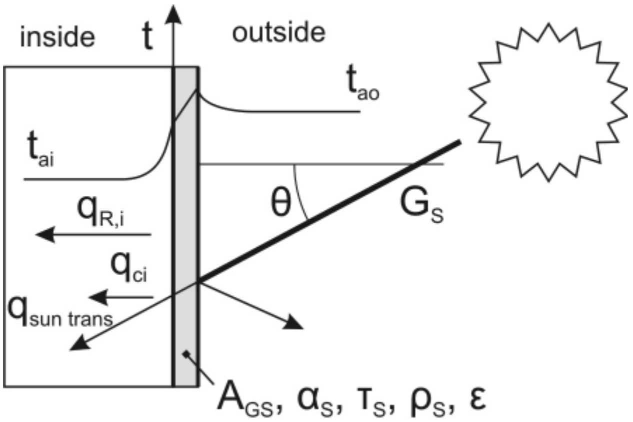

Figure 4. Solar energy transmission through the glass

Heat transmitted through the glass exposed to the solar radiation is:

$$Q_{sun} = A_{Gs} \cdot \left(G_s \cdot \tau_s \cdot cos\theta + h_c \cdot \left(t_{G,i} - t_{a,i}\right) + q_{GR,i}\right)$$

As can be seen, absorbed part of the solar energy will be emitted to the cab interior by both convection and longwave radiation. Using available values of glass properties (Table 2) with solar irradiation on inclined glass equal to 876 W/m2 (west-faced glass, afternoon, Fig. 2), estimated total heat flux will be around 760 W/m2 for clear, and less than 500 W/m2 for tinted glass (green, with 75% transmittance of visible light /19/).

Within the sample of tractors, windshield inclination is in range of 8 – 20° and side windows inclination is in range of 7 – 10°. According to the Fig. 5 and Fig. 6, the vertically positioned glass receives around 16% less solar irradiation than the glass inclined at an angle 20°.

Total amount of heat transmitted through the glass caused by solar radiation is related with cab surface projection normal to the radiation direction. Since maximum solar transmissivity of the glass is in region of incident angles less than 30°, areas that are directed within this angle to the radiation direction are critical, for two reasons. First, because of maximum solar radiation transmittance to the cab interior, and second because of direct effect on the operator, increasing his skin temperature and hence producing the discomfort.

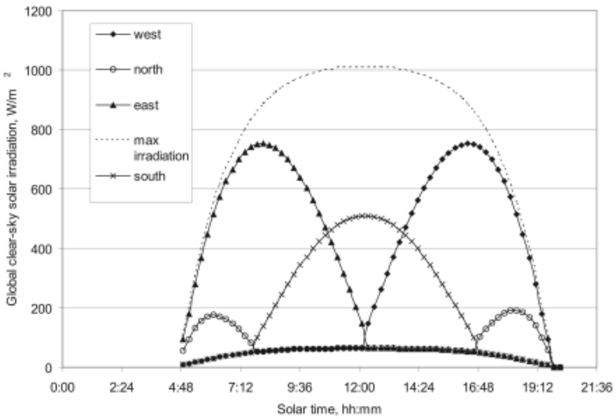

Figure 5. Global solar clear-sky irradiation Gs on a vertical plane for different orientation, in a central part of Vojvodina on a day in July [7]

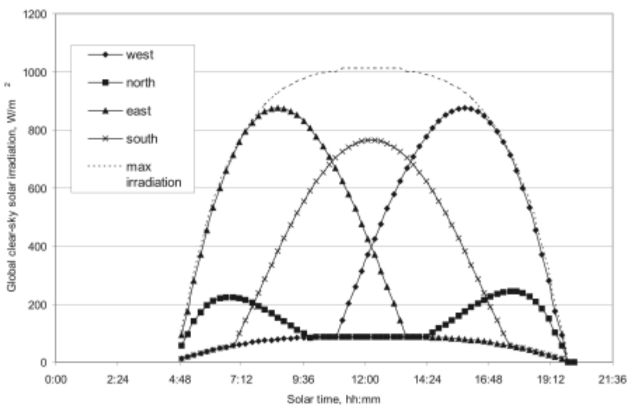

Figure 6. Global solar clear-sky irradiation Gs on a plane inclined at an angle 20° from vertical, for different orientation, in a central part of Vojvodina on a day in July [7]

Heat gain from the powertrain

Powertrain (transmission) is situated beneath the cab of typical tractors. Powertrain of smaller tractors partly "protrude" in the cab space, while larger tractors have a flat floor. For the purposes of sound and heat insulation, floor is generally multi-layer (rubber or polymer as interior flooring, steel sheet floor and in some designs, with a foam insulation material or composite heat shield on the powertrain side of the floor).

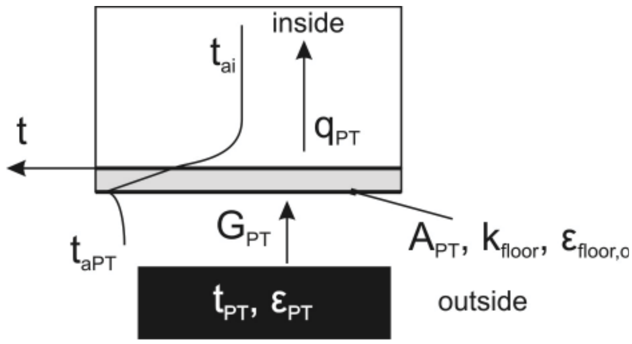

Figure 7. Heat gain from the powertrain

In this case, heat transfer through the floor is modelled as a combination of radiation from hot powertrain surfaces and natural convection from hot surrounding air on the bottom side of the floor, Fig. 7. It was assumed that the air between the powertrain and the floor has a temperature of 80°C as well as powertrain outer surfaces (taken from service manual as maximal recommended transmission oil temperature). In addition to radiative properties and temperatures of the surfaces, geometry has also influence on heat exchange, which is included through a view factor. Because of parallelism and small distance between the powertrain and the floor, it is assumed that view factor is equal to unity [8], [12]. Heat flux that floor absorbs from hot powertrain surface and surrounding air can be written as:

$$q_{PT} = \varepsilon_{red} \cdot \sigma \left(T_{PT,o}^4 - T_{floor,o}^4 \right) + h_{c,o} (t_{a,o} - t_{floor,o})$$

where /12/:

$$\varepsilon_{red} = \frac{1}{\dfrac{1}{\varepsilon_{PT}} + \dfrac{1}{\varepsilon_{floor,o}} - 1}$$

Under the thermal equilibrium, the same amount of heat is transferred through the floor and transmitted to the interior air:

$$q_{PT} = \frac{k_{floof}}{\delta_{floor}} (t_{floor,o} - t_{floor,i}) = h_{c,i} (t_{floor,i} - t_{a,i})$$

The calculated value of heat flux through the cab floor caused by powertrain heat is greater than 120 W/m2, while interior floor surface temperatures would reach 50°C. With the outer insulation or heat shield, the heat flux would be halved, with the lower floor temperature.

Total thermal load of the tractor cab

Total thermal load of the cab under chosen moderate summer conditions will be depending on the size of the cab and on its orientation in relation to the sun. Worst case from the heat gain and direct influence of the solar radiation on the operator could be the case when largest side of the cab is faced to the sun. Roughly, this could be approximately 1/4 of glazed area, e. g. around 1.5 m2, which gives solar heat load of order of 1100 W. Rest of area faced to the environment (app. 7 m2) would transfer up to 700 W of heat, and estimated heat gain from the powertrain would be 200 W. In total, without the heat released from the operator, estimated heat load of the cab is around 2 kW.

CONCLUSIONS

The cabs of the modern tractors have many common features, from the material to design, and can be stated that cabs have high level ergonomic characteristics. However, the possibility for implementation of solutions for further improvement of microclimatic conditions exists, especially within the lower range of analysed tractor category. Based on presented simplified calculations, the principal conclusions may be summarized as follows:

- General cab design tendency is towards larger cabs, in addition to fact that larger tractors have larger cab too. Larger cab means more volume and mass to cool, but obviously the spacious and comfortable working space for an operator has priority. Therefore, increasing in the cab size does not mean such considerable increase in the cab thermal load.
- Most intensive heat flux that enters the cab is caused by solar radiation through the glass (5 to 10 times more than by other analysed modes of heat transfer). Less inclined glasses and solar radiation selective glasses offers possibilities for solar load reduction. In comparison to solar absorbing glasses (such tinted glasses are), better but more expensive solution would be infra-red reflective glass that rejects almost half of solar radiation energy with less obstruction of visible light transmission. Also, overhangs of the roof could help in reduction of glass area exposed to the strong solar radiation around the noon time.
- Heat shield made from reflective material placed on the bottom side of the cab could minimize the powertrain radiant heat effect on the cab floor.
- Due to significant variations among many coefficients, experimentally validated numerical methods are recommended for calculation of thermal loads, optimization of cab shape, choice of the materials and design of the air distribution system.

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NOMENCLATURE

A_{Gs} – area of glass exposed to the solar radiation, (m2)

A_k – area of cab outer surface with conductive heat transfer, (m2)

A_s – area of cab outer surface exposed to the solar radiation, (m2)

G_s – total solar irradiation, (W/m2)

hc – convection heat transfer coefficient, (W/m2K)

k – thermal conductivity, (W/mK)

Q_c – heat transfer by convection, (W)

qsun – heat flux caused by solar radiation, (W/m2)

Q_k – heat transfer through the wall, (W)

q_{PT} – heat flux gained form powertrain, (W/m2)

ta, Ta – air temperature, (°C, K)

T_{sky} – apparent sky temperature, (K) /1/

α – surface absorptivity, (-)

α_s – surface solar absorptivity, (-)

δ – layer thickness, (m)

ε – surface emissivity, (-)

σ – Stefan-Boltzmann constant (5.670•10-8 W/m2K4)

θ – incident angle of solar radiation,

τ – normal solar transmittance, (-)

Indexes

floor – cab floor material or surface

G – cab glazing

i – internal, inside the cab

o – outer

roof –cab roof material or surface

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