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POTENTIALS FOR IMPROVEMENT OF THE THERMAL CONDITIONS IN SELF-PROPELLED AGRICULTURAL MACHINE CAB

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Abstract

Cabins of agricultural tractors and self-propelled mobile machinery are exposed to significant thermal loads in hot environment. Uncomfortable thermal conditions have an adverse effect on operator's thermal ergonomics thus on his health and performance. Characteristics of different solutions that contribute to improvement of thermal conditions inside the cab are described. Potentials for reducing the energy consumed for cab cooling by application of conventional and non-conventional measures are given and discussed.

***Key words**: self-propelled agricultural machine, cab, thermal comfort*

1 INTRODUCTION

Modern mobile agricultural machines are complex and highly efficient systems, and the general direction of the development is the reduction of the negative impact they have on the environment. There is also a tendency to improve the ergonomics of operator's workspace. The conditions inside a cab have significant impact on the performance of the operator, and in that way on the total efficiency of the operator-machine-environment system as well.
The overview of the characteristics of the agricultural tractor cabs that have direct or indirect effect on thermal ergonomics is given in work of Ružić and Časnji [4, 6]. The research included the analysis of the thermal processes that influence the human body in the cab. The result showed that cabs of modern tractors have many common features, from the materials used to the size and the design. In general, the tractor cabs have a high level of ergonomic features. However, there are still tractors and self-propelled machines of lower range whose equipment is inappropriate in terms of modern ergonomics, especially the equipment responsible for thermal comfort, as one of most expensive additional systems.
Efficient cab air-conditioning is a one of the prerequisites for reducing the additional fuel consumption. Two main actions important in decreasing the energy consumption and/or increasing the comfort in self-propelled machine cab are prevention and reduction of heat gain at the first place, and then the proper and optimal cooling of the operator [5, 7, 8]. The problem of achieving of good thermal environment in cab interior is more prominent in self-propelled farm machines than in farm tractors since the machines are sometime powered with IC engines of lower rated power than the farm tractors. In this paper, the methods for improvement of thermal conditions and in turn for improvement of energy efficiency of air-conditioning system are explained on an example of self-propelled agricultural machine.

2 THEORETICAL BACKGROUND

Microclimate conditions and hence human thermal sensation as well, are dependent on air temperature, air velocity, relative humidity and mean radiant temperature. However, individual differences regarding physiological and psychological response, clothing insulation, activity and preferences in terms of air temperature and air movement also have a strong impact on thermal sensation.
In an uncomfortable hot ambient, owing to the thermoregulation system, the human body sets off the process of vasodilatation and sweating, trying to prevent the rise of internal body temperature. Since these processes can cool down the body only to a certain degree, in order to prevent further rise in body temperature and to avoid the risk of hyperthermia, it is necessary to make the space comfortable or to enhance the process of releasing the heat from the body.
According to the requirements for thermal comfort in summer conditions, interior air temperature should be in the range of 23 to 28°C [3].
The sum of heat gain for a closed self-propelled machine cab in hot environment, under the steady-state conditions, consists of the following (Fig. 1.):

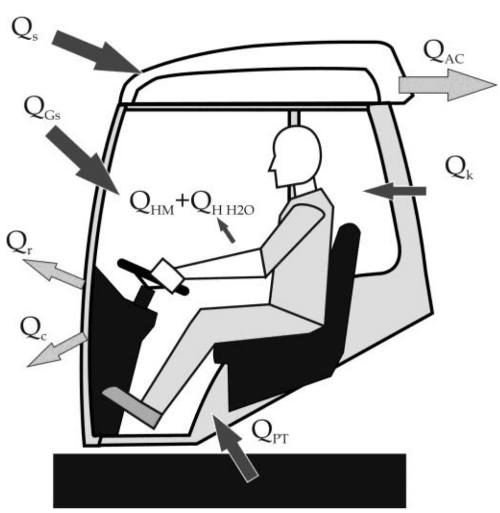

***Fig. 1** Thermal processes between a self-propelled machine cab and hot environment [6]*

- heat transfer through the cab envelope due to the temperature difference Q_k,
- heat transfer through the cab walls caused by solar radiation Q_s,
- solar radiation transmission through the cab glazing Q_{Gs},
- heat gain from the powertrain Q_{PT},
- sensible (Q_H) and latent heat ($Q_{H\ H2O}$) released by the operator.

Heat load by infiltration is assumed to be zero due to mandatory pressurisation of the cab. In theory, in order to maintain the interior temperature constant, the heat removal by the air-conditioning (Q_{AC}) should be equal to the heat gain.

Cab of self-propelled machines have an air distribution system with air vents (outlets of ventilation system) usually placed on the ceiling. The operator can change the velocity, temperature and direction of the air jet. Vapour compression system is used for air-conditioning (AC), same as in automotive applications. The power that AC compressors takes from the engine can be in range 10 - 100% of the actual engine power [4]. Highest value is achieved when the engine is idling.

3 METHODS FOR REDUCING THE HEAT GAIN FOR A CLOSED SELF-PROPELLED MACHINE CAB

The total thermal load of the cab under the typical Central-European summer conditions will depend on the size of the cab and on its orientation to the sun. The maximum solar irradiation on a horizontal roof surface in the central Europe region on a summer day may exceed 900 W/m^2. In total, adding the heat released by the operator and other modes of heat transfer, the estimated thermal load of the cab could be up to 2 kW [4, 6].

1.1. Reduction of solar energy transmission through glass

In the previous researches [1, 4, 6, 10] it is concluded that the highest heat flux that enters the cab is caused by solar radiation through the glass (which is several times higher than the heat transferred by other modes). Paying attention to solar characteristics of glass is a direct way to indirectly and directly increase the operator's comfort.

The total amount of the heat transmitted through the glass caused by solar radiation is related to the normal projection of the machine cab in the direction of radiation. The maximum solar transmissivity of glass is in the region of incident angles that are less than 30°, being the most inconvenient case both in terms of solar radiation transmittance to the cab interior as well as the direct effect on the operator.

Total heat flux caused by the solar radiation through the tinted glass (green, with 75% transmittance of visible light) will be around 70% of the total heat flux through the clear glass [4, 6, 17]. The drawback of the tinted glass is its solar radiation absorptivity, which causes the rise in the temperature of glass, increasing the mean radiant temperature. In fast moving road vehicles, like cars and buses, outer air flow velocity removes heat from the glass by forced convection. This is not a case in slow moving working machines as well as farm tractors. A method for reducing glass inner surface temperature would be cooling the glass using the airflow from the AC, in steady state thermal conditions when direct cooling of the operator is not necessary nor pleasant any more.

In comparison to solar absorbing glass, a better but also a more expensive solution is the infra-red reflective glass that rejects almost a half of the solar radiation energy with less obstruction of visible light transmission and less heating due to absorption [1, 17]. This kind of glass is used in automotive applications.

Further improvement in the reduction of the heat gain through glazing could be the use of roof overhangs and/or adjustable sun visors. In contrast to the typical farm tractor cab, whose glazing is inclined with the upper part towards inside (inclination angle in the range of 8..20° [4, 6]), self-propelled machines often have opposite glass inclination (inclination angles around -10°), fig. 2. This feature together with the roof overhanges serves as a kind of more efficient shade, because of bigger roof surface than on farm tractor, for the same size of the cab base. Consequently, the protection of the operator from the solar radiation transmitted through the glass will be better [10].

Fig. 2 *Self-propelled agricultural machine made by Hidromatik, Serbia. Windshield is inclined towards outside, the roof is white. Further improvement in heat gain reduction can be achieved by longer roof overhang, adjustable sun visors and solar reflective glazing*

1.2. Measures for reduction of heat gain by solar radiation on opaque surfaces

The absorbed part of the solar irradiation heats the cab's outer opaque surfaces (the roof and walls, for example) and their temperature rises. The solar absorptivity and longwave emissivity of the wall material, as well as thermal conductivity, are very important design factors. Therefore, the outer cab surfaces should have a low solar absorptivity coefficient α_s and high emissivity ε (small α_s/ε ratio is preferable), with low thermal conductivity at the same time [2, 6, 14]. Solar absorptivity is also dependent on the colour of the surface. In terms of colour, light colours are preferable. Under the same conditions, but with a dark coloured outer surfaces (especially the roof) with solar absorptivity of 0.9, the heat transfer rate increases three times in comparison with the roof that has the solar absorptivity of 0.3 [2, 4, 6, 14]. Also, the temperature of the wall inner surfaces will be higher for more than 10 degrees, while the radiant heat flux emitted by the wall's inner surfaces would in this case rise more than 50% [4, 6]. Despite the high thermal conductivity, one of the most popular materials for the reflection of thermal radiation is aluminium), but it is not used for these purposes in cabs.

4 OPTIMAL UTILIZATION OF THE CONDITIONED AIR

The conventional approach for the analysis of thermal processes in vehicle cabin is based on the balance between the sensible and latent thermal load of the cabin and the heat removal by supplied air. Therefore, quantity and conditions of the air supplied by the AC influences the overall thermal state in the cabin. This approach, although technically correct, is not suitable for the assessment and prediction of the operator's thermal sensation. Furthermore, an operator is treated only as a source of certain amount of sensible and latent heat. The human-based design takes into account the operator's shape, volume, and his local and overal thermal sensitivity.

The heat loss from the body surface in warm conditions relies on convective heat loss and the heat loss by sweat evaporation from the skin surface. The equation for the dry heat flux by convection can be written as [3]:

$$C = f_{cl} \cdot h_c \cdot (t_{cl} - t_a), \text{ W/m}^2 \qquad (1)$$

Factor f_{cl} is the clothing area factor, which describes the ratio between the area of the clothed body and the area of the nude body. The temperature of the clothing surface (t_{cl}) will be equal to the skin temperature (t_{sk}) on body surfaces without clothing: face, forearms, hands and neck.

The coefficient of convective heat transfer (h_c) is dependent on air velocity and the shape of a body part. The coefficient increases with the increase of air velocity [3]. Evaporative heat loss from the skin is dependent on air humidity, skin wetness and evaporative heat transfer coefficient (h_e). The evaporative heat transfer coefficient is dependent on air velocity as well.

Therefore, the ventilation system is able to influence this part of the heat transfer directly, by changing the airflow rate through the ventilation outlets (air vents). In addition, air-conditioning lowers the relative humidity of the interior air and consequently improves the latent heat loss by the evaporation of sweat.

The ventilation system drives and distributes the air inside the cab using the air distribution system. The air distribution system consists of a blower, air ducts and several adjustable air vents usually positioned on the cab ceiling. This airflow causes changes in local and overall microclimate conditions, consequently also changing the heat loss from the operator's body.

The body's overall thermal sensation is affected by the local thermal state of individual body parts, at the same level of cooling, due to different physiological properties (different sensibility for warm versus cool sensations, different sweating rate etc.) [11]:

- Back, chest, and pelvis strongly influence overall thermal sensation, which closely follows the local sensation of these parts during local cooling.
- The head region, arms and legs have an intermediate influence on the body's overall thermal sensation.
- Hands and feet have much less impact on the overall sensation.

This must be considered when when air distribution system is being designed in order to obtain proper airflow for certain parts of the operator's body.

The research of Ružić [9] deals with the comparison of three different arrangements of the air distribution system in the small farm tractor cab that could be valid for conditions inside the cab of self-propelled machine as well. The first design has three vents of 65 mm in diameter placed close to the middle part of the ceiling (labelled *V3* fig. 3). The second design has four vents placed near to the cab pillars (labelled *V4*, Fig. 3). The third design is a large rectangular perforated part of the ceiling (labelled *VD*, Fig. 3). The area of the perforated opening is 0.288 m^2

The research was done on the virtual model of the cab and the operator, using the CFD software STAR-CCM+. Virtual thermal manikin (VTM) is shaped in a form of a simplified human body in a sitting position, Fig. 3. VTM's surface temperature was constant (34°C) and it was divided into 18 segments. The assessment of the thermal sensation was done using so called equivalent temperature. The equivalent temperature is defined as the uniform temperature of an imaginary closed space with the air velocity equal to zero, in which a person would have the same sensible heat transfer as in a real environment. Thermal conditions are considered favourable if the equivalent temperature deviates less from the neutral value. Local and overall neutral values are determined by relevant standard [16]. Due to local discomfort, thermal conditions can be considered uncomfortable even when the equivalent temperature of the entire body is at the neutral value. For this reason, this study evaluates even the deviations in the segmental equivalent temperatures from their neutral values, taking into account the thermal sensitivity and size of the individual segments.

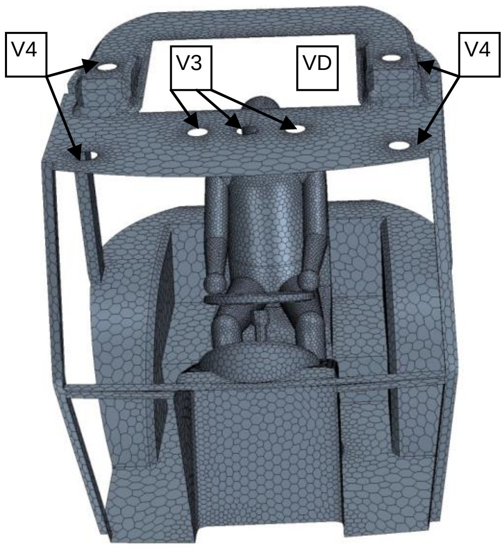

Fig. 3 *Arrangements of all three air distribution designs on meshed model of the cab [9]*

The boundary conditions in the virtual experiments were as follows [9, 12, 13, 15]:

- the initial air temperature in the cabin 32°C;
- constant temperature of the interior surfaces, 32°C;
- emissivity of the cabin interior surfaces $\varepsilon = 0.95$,
- virtual thermal manikin with constant and uniform surface temperature of $t_{sk} = 34$°C, emissivity $\varepsilon_{sk} = 0.95$
- The cooling power at the evaporator of the air-conditioner was the same in all three cases, equal to 2,7 kW

Under the conditions without solar radiation, regarding the heat loss from the operator's body, the most efficient appeared to be the system with three vents, labelled V3. In order to achieve neutral equivalent temperature for the body it would be necessary to reduce the cooling power in this type of system. However, the extremely low equivalent temperatures on the hands, lower arms and legs make the conditions far from comfort limits.

It must be taken into account, that due to inter- and intra-individual differences among people in the mobile machine cab and because of non-uniformity of boundary thermal conditions the operator must have possibility to precisely adjust temperature and direction of air flow adjustments. Settings of the operating parameters of air conditioning systems must be wide enough and the use of it suitable and understandable to the exposed person. This includes asymmetric setting of the system for the compensation of asymmetric boundary conditions, mainly caused by the solar radiation. Regarding this issue, design with more smaller vents offers better performances than the design with one large vent.

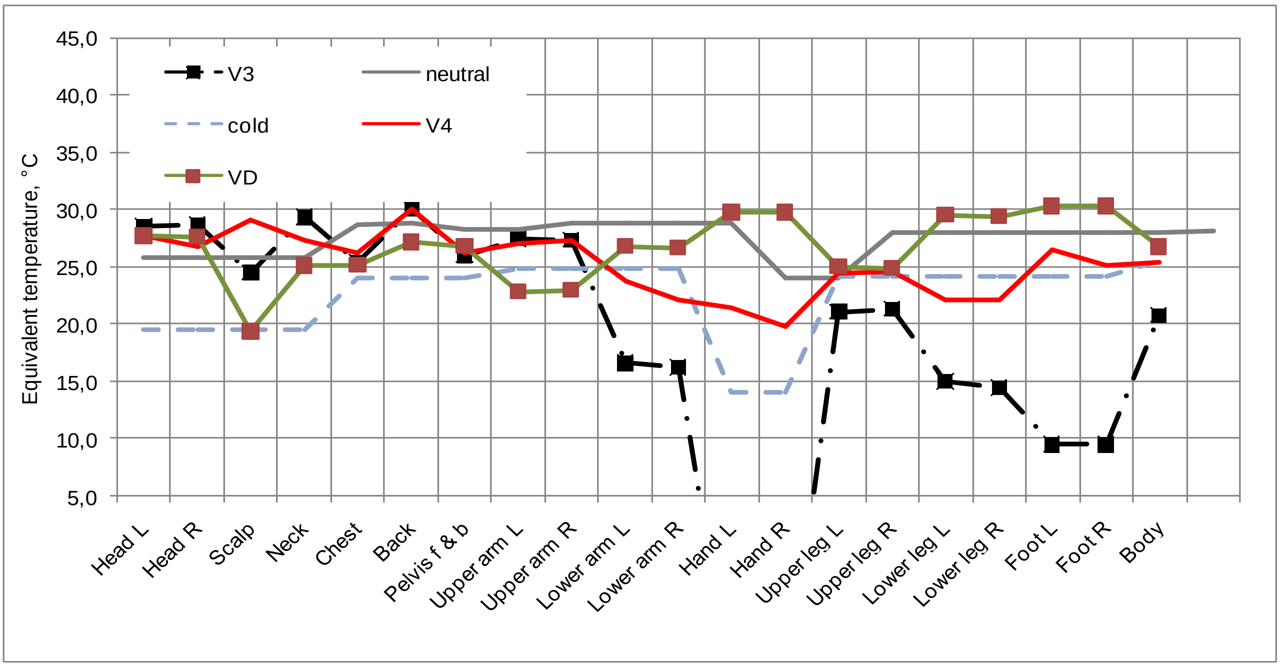

***Fig 4** Comparison of equivalent temperatures in tractor cab for three different designs of air distribution system*

5 CONCLUSIONS

Several methods for reducing the heat gain for a closed self-propelled machine cab are presented in this paper. The highest heat flux that enters the cab is caused by solar radiation through the glass (which is several times higher than the heat transferred by other modes). Paying attention to solar characteristics of glass as well as opaque surfaces is a direct way to reduce the operator’s thermal load. Further improvements in the reduction of the thermal load are the use of roof overhangs and adjustable sun visors which must not restrict the operator's field of vision.

Optimal utilization of the conditioned air is the other requisite and important way for improvenment of thermal conditions inside the mobile machine cab. The arrangement of the vents is very significant factor influencing the local distribution of heat fluxes over the operator's body. It follows that by increasing the number of vents the non-uniformity of thermal conditions inside the cab would be reduced. The direction of the air jet is one of the most crucial factors regarding heat losses from the body. On the other hand, the system design must be such that allows setting of asymmetric thermal conditions, in order to compensate asymmetric boundary condition that could be caused by solar radiation radiation and to adapt to different individual preferences regarding thermal conditions.

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REFERENCES

1. Bohm M., Holmer I., Nilsson H., Noren, O., 2002, *Thermal effects of glazing in driver's cabs*, JTI-rapport 305, JTI – Institutet for jordbruks, ISSN 1401-4963, Upsala, Sweden,.
2. Incropera, F. P., DeWitt, D. P., 1981, *Fundamentals of heat and mass transfer*, John Wiley & Sons, 980 p.
3. Parsons, K., 2003, *Human Thermal Environments: The Effects of Hot, Moderate and Cold Environments on Human Health, Comfort and Performance*, 2nd ed. Taylor & Francis, London, UK, 538 p.
4. Ružić, D., Časnji, F., 2011, *Agricultural tractor cab characteristics relevant for microclimatic conditions*, Journal of Applied Engineering Science 9(2), pp. 323-330.
5. Ružić, D., Časnji, F., 2011, *Efficiency assessment of different cab air distribution system layouts*, Proc. 15th Symposium on Thermal Science and Engineering of Serbia, Niš, pp. 819-828.
6. Ružić, D., Časnji, F., 2012, *Thermal Interaction Between a Human Body and a Vehicle Cabin*, Heat Transfer Phenomena and Applications, InTech, Rijeka, Croatia, pp. 295-318,
7. Ružić, D., Časnji, F., 2012, *Design of Vehicle Cabin Air Distribution System Based on Human Thermal Sensation*, Proc. 7th International Symposium "KOD 2012", Balatonfüred, Hungary, pp. 255-260.
8. Ružić, D., 2012, *Analysis of airflow direction on heat loss from operator's body in an agricultural tractor cab*, Proc. 40th International Symposium "Actual Tasks on Agricultural Engineering", Opatija, Croatia, pp. 161-169.
9. Ružić, D., 2014, *Comparison of different air vents arrangements in a tractor cab using the CFD techniques*, Proc. 8th International Symposium "KOD 2014", Balatonfüred, Hungary KOD pp. 97-104.
10. Ružić, D., Poznanović, N., 2013, *Virtual investigation of the tractor operator heat loads caused by solar radiation*, Tractors and power machines, 18(3), pp. 49-57.
11. Zhang, H., 2003, *Human Thermal Sensation and Comfort in Transient and Non-Uniform Thermal Environments*, PhD thesis, University of California, Berkeley, USA, 415 p.
12. Anon., 1997, ASABE/ISO 14269-2: 1997, Tractors and self-propelled machines for agriculture and forestry - Operator enclosure environment - Part 2: Heating, ventilation and air-conditioning test method and performance
13. Anon., 1997, ASABE/ISO 14269-3: 1997, Tractors and self-propelled machines for agriculture and forestry - Operator enclosure environment - Part 3: Determination of effect of solar heating
14. Anon., 1999, ASHRAE Book of Applications, Chapter 32: Solar Energy Use, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, USA, 1999.
15. Anon. 1983, ISO 6097: 1983, Agricultural tractors and selfpropelled machines - Performance of heating and ventilation systems in closed cabs - method of test
16. Anon. 2008, SRPS EN ISO 14505-2: 2008, Ergonomics of the thermal environment - Evaluation of the thermal environment in vehicles. Part 2: Determination of equivalent temperature
17. http://www.sekurit.com, Glazing Manual, Saint-Gobain Sekurit, accessed in July of 2013

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