UNIVERSITY OF NIS FACULTY OF MECHANICAL ENGINEERING

THE EIGHTH INTERNATIONAL CONFERENCE
TRANSPORT AND LOGISTICS

til 2021

EXPERIMENTAL ASSESSMENT OF THERMAL ENVIRONMENT IN MOBILE MACHINERY CAB

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Abstract

An overview of experimental procedures for assessment of thermal environment in a mobile machinery and farm tractor cab is given in this paper. The thermal comfort experimental investigation is characterized by measurement of various physical parameters necessary for an assessment of the human thermal sensation. In order to demonstrate practical application of the procedures, the setups of some examples of the experiments carried out on farm tractors are presented and discussed. It is concluded that the field of experimental research of thermal comfort in operator's cabs is not developed enough compared to the researches in other types of vehicles. The field experiments indicate on potential problems which could influence the results of thermal sensation evaluation under given boundary conditions.

***Key words**: mobile machinery, farm tractor, operator's cab, thermal comfort, experiment.*

1 INTRODUCTION

Working in a mobile machinery and farm tractor cab during hot or cold weather beside of lack of comfort, can result in an increased risk of heat stress (when the body's means of controlling its internal temperature starts to fail) and influence operator's performance: reduced concentration and alertness, as well as work rate, etc. In addition of the heat release from a powertrain, the highest heat flux that enters the tractor or machinery cab in hot environment is caused by solar radiation through the glass. This heat flux can be several times higher than other modes of the heat transfer [1]. Because of this and having the powertrain waste heat for the heating, the cab cooling is more critical than the cab heating in cold environment.

The typical objectives of experimental researches of operator's thermal ergonomics are directed towards an overall system efficiency and performance [1]:

- to identify and evaluate the most important influences on heat transfer processes between the operator and the cab, and between the cab and the surroundings, under the given conditions, or
- to explain the effects of the air distribution system design and settings on the operator's heat exchange and thermal sensation.

The motivation for physical experiments is also acquisition of data that are to be used for setting and validation of a numerical model in CFD simulations.
Despite of the importance of the thermal environment inside a machinery cab on operator's performance and health, it can be notice that modern literature sources mostly deal with researches performed on passengers' cars. Obviously, there is a need for further research that should improve ergonomics and energy efficiency of machinery and farm tractor cabs.
The aim of this paper is to give an overview of experimental procedures and measuring techniques for determining thermal conditions inside the farm tractor cab based on relevant standards and several experimental setup examples. Discussion covers practical aspects of the experiments carried out in field and laboratory environment.

2 THERMAL COMFORT STANDARDS

Traditionally, a 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 ambient parameters influences heat exchange between the human body and the surroundings. From that reason, standards that specify conditions and performances of HVAC (heating, ventilation and air-conditioning) systems used in mobile machinery and farm tractor cabs uses additional environmental parameters to evaluate thermal conditions inside the cab.
The standard ASABE/ISO 14269-2 "Tractors and self-propelled machines for agriculture and forestry - Operator enclosure environment - Part 2: Heating, ventilation and air-conditioning test method and performance" specify a test method for measuring the contribution to operator environmental temperature and humidity provided by HVAC system operating in a specific ambient environment [2]. The standard uses effective temperature, i.e. a combination of relative humidity and temperature as an indicator of operator's comfort level. The air temperatures in the operator's environment shall be uniform within 5°C [2], but there is no typical requirement that the temperature in the head level should be lower than in feet level. In addition to the recommended values of the effective temperature, a limit value of air velocity in vicinity of operator's head is given. The requirements on minimum cab pressurization and ventilation levels are included in the standard. Surface temperatures or radiant temperatures are not taken into account in the standard. The standard ASABE/ISO 14269-2 is derived from the SAE J1503 standard, "Performance test for air-conditioned, heated, and ventilated off-road self-propelled work machines". Similar requirements and performance tests are proposed in the standard SAE J3078/4 "Off-Road Self-Propelled Work Machines Operator enclosure environment - Part 4: Heating, ventilating and air conditioning (HVAC) test method and performance". The

conditions for examination of the cab cooling under the solar radiation are defined in the standards ASABE/ISO 14269-3 and SAE J3708/6 [3].

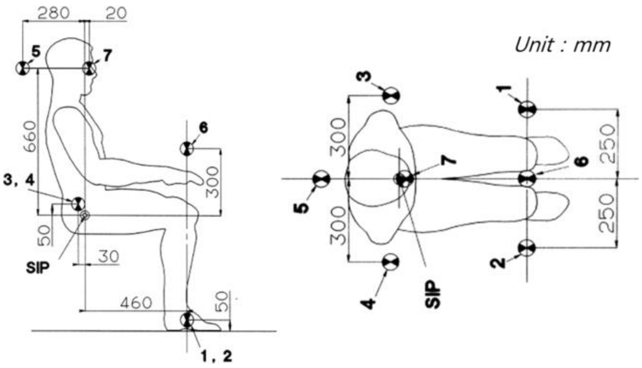

Fig. 1. *Temperature and air velocity measurement locations (The standard ASABE/ISO 14269-2, [2])*

Widely used Fanger's PMV (Predicted Mean Vote) thermal comfort index, standard ISO 7730 [4], includes four environmental and two individual parameters. This method is applicable to moderate, stationary and more-less uniform conditions. However, it is very often used in researches where more spatially and temporally deviations of parameters can be encountered, such as in motor vehicle cabin [5], [6], [7], [8], [9]. For passenger cars, the standard ISO 14505-2 can be used for evaluation of thermal environments by determination of sensible (dry) heat exchange between the driver and the surrounding [10]. In the standard, the thermal sensation is expressed by equivalent temperature, for overall body as well as for individual body parts. The boundary conditions are specified for transient and steady-state conditions (cool down or heat up). A bus driver thermal environment, according to the standard ISO 16121-4 [11] is described by the recommended values of air temperature and air velocity around the body under the steady state conditions. Additional requirements are the values of the surrounding surface temperatures.

3 EXPERIMENTAL INVESTIGATION OF THERMAL CONDITIONS

The experimental research of thermal conditions inside the operator's cab can be done in a laboratory or in a field. In the laboratory experiments only a cab can be used instead of the entire tractor. In any case, an environmental chamber in the laboratory must obtain a precise setting and control of the climate. Air temperature, relative humidity, air velocity and artificial solar radiation are the parameters that are to be controlled, making the experimental facility very expensive. The standards ASABE/ISO 14269 and SAE J3708 consider an option of laboratory experiment, with or without a solar radiation. Since HVAC system is powered by tractor's engine, exhaust gases must be taken out efficiently from the chamber. Figure 2.

Uncontrolled environmental conditions are typical problem regarding field experiments. According to the standard ASABE/ISO 14269, the measurement is to be carried out on a stationary tractor, with or without the operator. However, in the case of experiments under real conditions of non-stationary tractor, the measuring equipment should be portable and powered independently from the main grid. In addition, an operator must be present in the cab and to drive the tractor, influencing the measurement by both the body heat and moisture release. This factor decreases repeatability of the experiment.

Fig. 2. *Farm tractor in environmental chamber during the experiments carried out by Oh et al. [12]*

The characteristics of the measurement instruments for measuring of dry and wet bulb thermometer and air velocity required in the standard ASABE/ISO 14269-2 are according to the characteristics of instruments specified for thermal stress conditions in the standard ISO 7726 [13]. The standard ASABE/ISO 14269-2 also requires that the temperature recording intervals are not greater than 5 min. This indicates that the observed processes are relatively slow and it is not a problem to achieve this condition using the conventional measuring equipment.

3.1. Examples of experimental setup

The experiment done by Ružić and Simikić [14] and by Ružić et al. [15] presents quantification of thermal conditions inside the cab of farm tractors Belarus and New Holland. The experiments were carried out in hot ambient condition and the tractors were exposed to the solar radiation. The tractors were stationary, and the engines were idling during the cool-down processes (Fig. 3). The measurement included interior air temperatures, interior surfaces temperatures, radiant temperature, air velocity, relative humidity and barometric pressure. The results can be used for research in field of improvement of thermal conditions in cabs and as a basis for boundary conditions for analytical or numerical models (CFD).

The air temperatures were measured using K-type thermocouples, multifunctional instrument Kimo 310, indoor analyzer Bruel&Kjaer 1213. The thermocouples were placed around the operator's working place. The acquisition was done by module Expert 9520/9018P/9017F connected to a laptop. The air velocity and plane radiant temperature in two directions were measured in the operator's head zone, using the sensors connected to the indoor analyzer Bruel&Kjaer 1213. Barometric pressure and relative humidity was recorded by multifunctional instrument Kimo 310. Internal surfaces temperatures were measured using infrared (IR) thermometer All Sun EM520A. Additionally, black globe thermometer was used for determination of radiant temperature. Air velocities in the vicinity of air vents were measured with the vane anemometer Kimo. Instead of an operator, a dummy (torso) was placed in the driver seat. Figure 4.

Fig. 3. *Farm tractor Belarus during the preparation for field experiment*

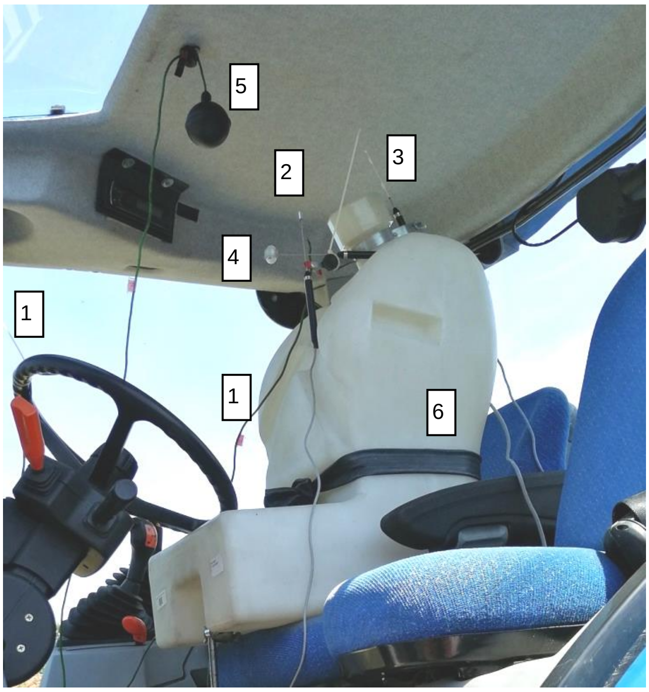

Fig. 4. *Measurement equipment arranged in the operator's seat of farm tractor New Holland. 1 - Thermocouples, 2 - air temperature sensor, 3 - air velocity sensor (constant temperature difference anemometer) 4 - sensor of plane radiant temperature, 5 - black globe thermometer, 6 - dummy torso*

An example of laboratory experiments is described in the project report by Bohm et al. [16]. In the experiment, the generic cab model was used inside the climatic chamber equipped with a sun simulator. Using the thermal manikin AIMAN, the effects of different kinds of glass and design of the windows, as well as the effects of sun protection and insulation glazing on thermal comfort was studied. Figure 5.

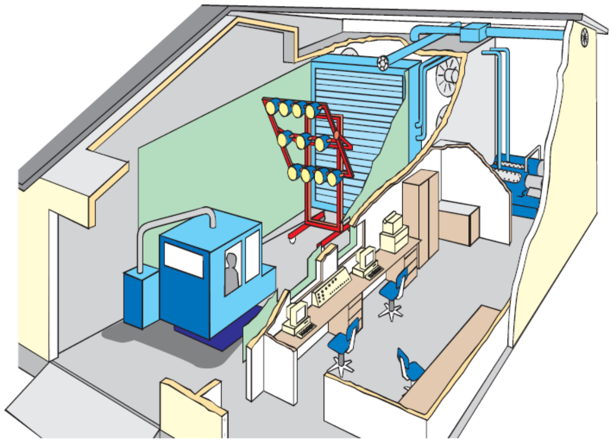

Fig. 5. *Drawing of the climatic chamber with the model of machinery cab [16]*

In the experiment carried out by Oh et al. [12], procedure according the standard SAE J1503 was carried out on the farm tractor TYM TX1500 in the environmental chamber. The chamber has a temperature and humidity control as well as solar radiation simulation (Fig. 2.). The manikin was installed in the cabin to introduce the effect of the human body on flow. The air temperatures were measured using the thermocouples in seven locations shown in figure 1. The tractor cab interior surface temperatures were monitored using 35 thermocouples glued to the glazing. The airflow rate from the air conditioner vents was measured using the vane anemometer Testo. During the test, the temperatures in AC vents were acquisited too. The results were used for validation of numerical model intended for analysis of the vent arrangement on the operator's thermal comfort.

4 DISCUSSION

By comparing the standards for vehicle cabin thermal environment in different types of vehicles, it can be noted that different parameters, boundary conditions as well as criterions are used. However, the common feature is that the air temperature only does not provide sufficient insight in the thermal conditions and thermal sensation of the person in the cabin.

A monitoring of several physical quantities in the same time (air temperature, radiant temperature, air velocity) demands use of different sensors placed approximately in the same place. A use of thermal comfort meters, i.e. sensors that are based on heat exchange instead on measurement of the physical quantities enables better organisation of measurement inside the cab due to limited space. In addition, a post-processing and complex calculation of thermal sensation could be avoided in this way.

A measurement of the physical quantities in several positions around operator's body demands use of a suitable bracket in order to hold the sensor. The bracket should prevent negative influence of the tractor vibrations on the sensors, especially on the anemometer. This as well as use of thermal manikin or the other human shaped object makes

impossible for the operator to be inside the cab and the experiment can be carried out only in stationary state. If there was a structure which allow presence of the operator, his proximity can influence the results and his moves could be limited due to sensor positions.
When the cab is exposed to the solar radiation, because of high glazing surfaces a suitable radiation shields for air temperature sensors are recommended, for both thermocouples and resistance type sensors.
The cab cooling-down is relatively slow process, which takes at least 20-30 minutes until steady-state thermal conditions are achieved. Despite this, the black globe thermometer has too high thermal inertia to closely follow the change of radiant temperature.
Taking into account the nature of the radiant/surface temperature change, one method is contactless measuring of surface temperatures at the beginning and the end of cool-down period using the infrared thermometer. In this way the surface temperatures are averaged over larger surface. A better solution would be use of an IR camera, especially if the aim of the research is analysis of the glazing demisting/defrosting.

While the vents position inside the cab is defined by the manufacturer, the direction setting is of more importance on local heat exchange between an operator and a tractor cab and local heat transfer over the operator's body differs significantly for different direction settings [17], [18].
This raise a question: how to set direction from four or more vents during the experiment? Possible setting combinations would result in too many experiments. In the case of the field experiments, the outside conditions can not be controlled, influencing the experiment repeatability. Furthermore, in order to get a real picture of an air flow field in the cab, a human body must be present as a part of the cab interior geometry, influencing the air flow field. Typical method for air velocity field mapping is measuring of air velocity by using omnidirectional anemometer in discrete points. This can not be done during the cool-down or heat-up regime, unless sufficient number of sensors is available.

5 CONCLUSION

An overview of the standards and some examples of experiments carried out for assessment of thermal environment in a mobile machinery and farm tractor cab are presented. The experiments are based on measurement of various physical quantities distributed over the cab space, during the exposure of the cab to the controlled environmental conditions. This makes those experiments very demanding in terms of the measurement equipment and the environmental conditions.
Measuring of several physical quantities in the same time but in discrete points over the cab space, optional presence of the operator during the field experiments and numerous combinations of the AC and vents possible settings are also identified as aggravating factors. The results presented in the paper indicate a direction of further definition of experimental procedures and development of measuring equipment and techniques.

ACKNOWLEDGMENT

This paper has been supported by the Ministry of Education, Science and Technological Development through the project no. 451-03-68/2020-14/200156: “Innovative scientific and artistic research from the Faculty of Technical Sciences activity domain”.

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