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Heating of large agricultural and industrial buildings

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Abstract. This paper presents the results of the simulation calculations used in the selection and design of an appropriate method of heating of large buildings for agricultural or industrial purposes. These halls are characterized by a large built-up area, large room height and high consumption of energy for heating. The aim of the simulation calculation was to find a way of heating, which leads to a reduction in energy consumption while maintaining the required thermal comfort of indoor environment.
The calculations were performed using the CFD software ANSYS-Fluent. For comparison of variants, a 3D model was used, including a heat source, natural convection and heat transfer through surrounding structures. The results of the thermal comfort of the working environment in the level of people or the growing zone of plants or the storage space for goods were mainly studied. The second area of interior space, especially important in terms of heat losses, is the level of the ceiling.
The results of the calculations provide a detailed analysis of the vertical temperature profiles and the effect of the surrounding walls surface temperature on the thermal state of an indoor environment.
The created model was verified according to the results of experiments in large buildings equipped with different heating systems. Based on the results of the simulation calculations and according to the results of experimental measurements, radiant heating method seems to be the suitable heating system solution for studied types of buildings.

Key words: energy, radiation, thermal comfort, simulation.

INTRODUCTION

Heating of large buildings together with ventilation or air conditioning represents a very important issue, which significantly affects the operation of these facilities. This article is aimed at the buildings used in industry, agriculture or as different repair shops and service centres. These buildings are used year-round and must be kept at the required air temperature, corresponding to the requirements of workers or technological processes. These buildings are characterized by a large surface area, high height, and large overall volume. This creates a need for substantial inputs for heating, which together with the high cost of energy can manifest itself quite significantly in the efficiency of production, or in the satisfaction and functional reliability of these buildings. Energy consumption, indoor climate and sophisticated regulation systems take a great deal for well-constructed buildings (Rajaniemi & Ahokas, 2012; Reinvee et al., 2012).

There is different information in literature concerning the heating and ventilation of these buildings. Recommendations of several authors are focused on radiant heating by different types of heating panels (Cihelka, 1961; Kotrbaty & Kovarova, 2002; Basta, 2010; Vio, 2011.)

The following article briefly summarizes some of the results of the measurements in the practical operation of an industrial open-plan hall and at the same time it is shown how they can use modern simulation methods to verify the assumptions in the pre-design phase.

MATERIALS AND METHODS

For the research work presented in this paper, the measurement of a large-area industrial hall of the total interior height of 8 m was used, which was equipped with several different types of heating. This building was selected for this research as there are not so many large halls, where is possible to study two completely different heating systems of indoor sections in one single-storey building (200 x 150 m) with the same thermal properties of the surrounding walls.

The greater part of the hall was heated by hot air; few sections were heated by hot-water radiant panels mounted below the ceiling. It was possible to examine and compare the two different concepts of heating under actual operating conditions. The thermal state of the environment was measured in the working zone in three different sections of the hall heated by hot air and in one section heated by radiant heating panels. The height temperature profile was measured both in the hall section heated by hot air as well as in one section heated by radiant panels.

As the studied large industrial building was equipped with very sophisticated technological equipment operating in three work shifts under extremely hard control of all activities, it was necessary to choose representative places suitable both for studying different heating systems and as regards the placement of measurement instruments between the installed machinery with operators very carefully. It was also very important from the perspective of measurement to choose a place, which is not influence by the other heating system, only by the studied one.

For measurements of the thermal environment, a sensor measuring the global spherical thermometer of diameter D = 150 mm FPA805GTS was used with centrally-located Pt100 sensor for measuring the globe temperature T_g (°C), with a measuring range of -50 to +200°C, the temperature of the surrounding air T_a (°C) was measured by the sensor FH A646-2 including the temperature sensor NTC type N with and operative range from -30 to +100°C, with accuracy ± 0.1 K, and the relative air humidity Rh (%) by a capacitive sensor with an operative range from 5 to 98%, with accuracy ± 2%. For an indicative control of the thermal comfort of the indoor environment in the hall, Kata-thermometer 24/66, F 567 was used. The sensors were connected to the instrument ALMEMO 2590-9. The temperature profiles inside the hall were measured using an ALMEMO 2690-8 instrument with a thermocouple Ni-NiCr. All measured data were subsequently recorded.

From the measured values (ten values of each parameter were measured at the level of 1.1 m above the floor, regularly distributed in the area of roughly 25 m^2 in each measured section of the hall), the average globe temperature T_g (°C) and air temperature T_a (°C) were calculated, which were used according to the equation (1) for calculation of the mean radiant temperature T_r (°C) and according to the relation (2) for the operative temperature T_o (°C), an important parameter for evaluation of thermal environment, particularly in terms of the influence of radiation. The heat transfer coefficient h_{kg} ($W \cdot m^{-2} \cdot K^{-1}$) was calculated according to the equation (3). From the measured cooling time τ (s) of Kata-thermometer and the calibration constant Q ($J\ m^{-2}$), the average values of the so-called cooling rates Kata-values K ($W\ m^{-2}$) were calculated according to the equation (4).

$$T_r = \left\{ \sqrt[4]{\left[(T_g + 273)^4\right] + \left[1{,}855 \cdot 10^7 \cdot h_{kg} \cdot (T_g - T_a)\right]} \right\} - 273, \tag{1}$$

$$T_o = 0.5 \cdot T_a + 0.5 \cdot T_r, \tag{2}$$

$$h_{kg} = 1.4 \cdot \left(\frac{|T_a - T_g|}{D} \right)^{0.25}, \tag{3}$$

$$K = \frac{Q}{\tau}, \tag{4}$$

where: T_r – mean radiant temperature (°C); T_g – globe temperature (°C); h_{kg} – heat transfer coefficient ($W\ m^{-2}\ K^{-1}$); T_a – air temperature (°C); T_o – operative temperature (°C); K – cooling rate Kata-value ($W \cdot m^{-2}$); Q – calibration constant ($J\ m^{-2}$); τ – cooling time (s).

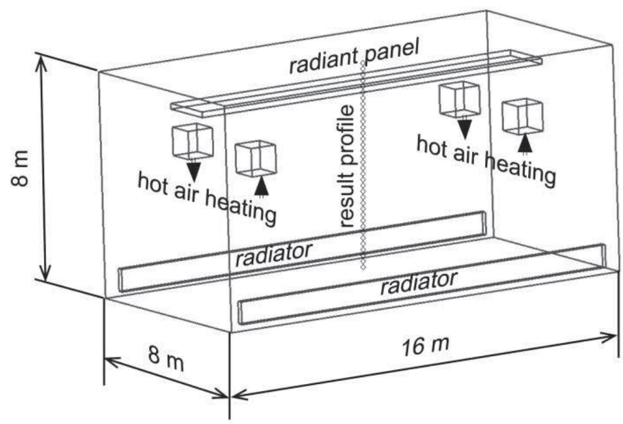


Figure 1. The geometrical model of the computational domain with zones used for simulation of different heating system concepts.

The simulation of conditions in the hall was carried out using the CFD (computational fluid dynamics) program Ansys Fluent. Fig. 1 shows the geometrical model. The computational domain is a rectangular block of width 8 m, height 8 m, and length of 16 m. The ceiling radiant panel is located at the height of 15 m and the dimensions of the panel are 2 x 14 m. Four input/output openings of the hot air heating system are located at a distance of 2 m from the front/back walls and 1.2 m from the side walls. Classic hot water radiators, each with dimension 15 x 0.8 x 0.2 m, are located on both long sides of the hall at the height of 1 m above the floor. The computational domain consists of about 1 million tetrahedral cells with the characteristic dimension of about 15 cm.

RESULTS AND DISCUSSION

The results of the measurements in the hall

The results of the measurement of the thermal environment in the hall are summarized in Table 1. The results are obtained by measurement of the thermal environmental state. Monitoring points HA 1, HA 2 and HA 3 were measured in sections with hot air heating. Measuring point RP was in a section with radiant heating.

Table 1. Average values of the thermal state of the environment in 3 sections of the hall with hot air heating and in one section with radiant heating panels (HA 1, HA 2, HA 3 – measuring points in sections with hot air heating; RP – measuring point in a section with radiant heating panels)

Section	T_a	T_g	Rh	v	K	T_r	T_o
	°C	°C	%	m s^{-1}	W m^{-2}	°C	°C
HA 1	21.97	22.62	25.2	0.21	279.3	22.9	22.4
HA 2	24.65	25.22	22.2	0.09	171.7	25.4	25.0
HA 3	25.05	25.66	20.8	0.10	166.5	25.9	25.5
RP	24.45	25.67	21.0	0.10	183.6	26.2	25.3

The measurement results in Table 1 indicate that there are considerable differences in air temperature between the sections with hot air heating. The lowest air temperature was measured in section HA 1, farther away from the inlet of warm air. Contrarily, the air temperature in section HA 3 was too high. In terms of comfort, there is a recommended optimum environment for working activity in a hall where people are working on machine tools or in light assembly (Act No. 262/2006 Coll., labour class II b) with average body energy production, M = 106–130 W m^{-2}, the recommended air temperature of 14–32°C, relative humidity of 30–70%, and air velocity from 0.05 to 0.3 ms^{-1}. Generally, the inside air T_a temperature was too high and the relative humidity Rh of the whole building too low, as there are no sufficient sources of vapour inside. In the section with radiant panels, the globe temperature T_g is higher than the average air temperature T_a. The air-speed was at an acceptable level.

The optimum cooling rate Kata-value K should be between 170 and 250 W m^{-2}. If it is less than 170 W m^{-2}, people feel warm, if it is more than 250 W m^{-2}, people feel cold. The thermal comfort from this point of view was too cold in the measuring point HA 1 and too warm in the place of measurement HA 3.

The comparison of the vertical profiles in the hall shown in Fig. 2, where the mean values of the set of 20 measurements are presented, is very interesting. The vertical temperature profiles measured in the section heated by hot air and in the section heated by radiant panels are completely different. It is obvious that hot air heating causes lower air temperature in the zone near the floor where people move and significantly higher temperature near the ceiling. This increases heat losses through the top of the walls and the ceiling. Contrarily, radiant heating panels heat the floor and the floor environment where people work by radiation; the upper part of the hall is cooler. This is very beneficial in terms of reduction of energy consumption for heating.

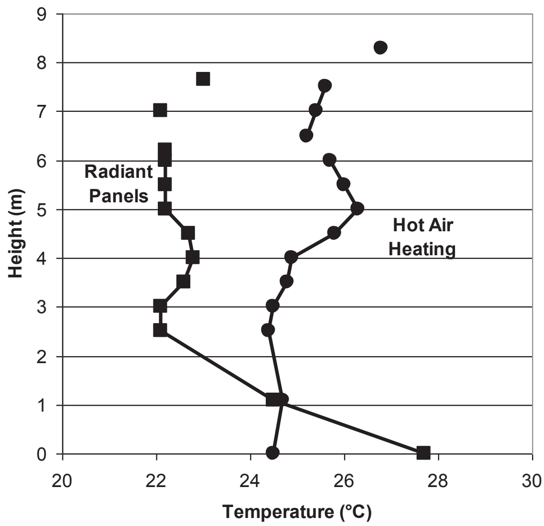
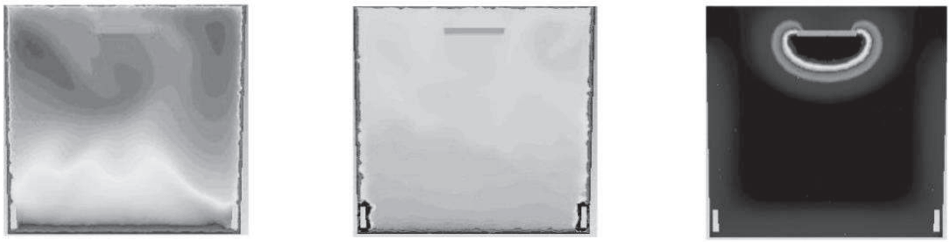


Figure 2. Comparison of the mean values of the vertical temperature profiles measured in the section heated by hot air and in the section heated by radiant panels.

The results of the simulations of heating in the hall

All solved cases assume the same initial conditions, namely, the initial temperature inside and outside of the building is 7°C, the total heat transfer coefficient through the side walls is 12 W m^{-2} K^{-1}, through the ceiling 18 W m^{-2} K^{-1}, and through the floor 10 W m^{-2} K^{-1}. The surface-to-surface Fluent's radiation model can be used to account for the radiation exchange in an enclosure of grey-diffuse surfaces. The energy exchange between two surfaces depends on their size, separation distance, and orientation. These parameters are accounted for by a geometric function called a view factor, which is the prescription of the fact of how the total radiation flux is distributed to surfaces other than the source surfaces.

Three basic variants are solved as shown in Fig. 3 − hot air heating with classical warm water radiators (A), using a forced ventilation system, which brings pre-heated air into the domain (B), and radiant panels located under the ceiling (C). All these cases consider the same input thermal power of 35 kW supplied into the building. Fig. 3 shows the typical contours of the temperature profile shapes for the solved variants. The difference between the whirl shape of forced air movement (A) and the stratification of radiator heating (B) can be seen nicely. The main advantage of forced convection is the fast heating of the whole space. While the time needed to heat the whole indoor space by radiant panel heating or hot water radiator heating is about 2 hours for the presented boundary conditions, hot air heating can achieve the similar effect in about 20–30 minutes.



A B C

Figure 3. The character of the temperature profiles during (A) - hot air heating, (B) - hot water radiator heating and (C) - radiant panel heating.

This fact is shown in Fig. 4. It compares the vertical temperature profile in the central vertical axis of the domain for radiant heating panels on the left side and heating with conventional hot water radiators on the right. It is evident that after two hours from turning the heating system on, the central area of the domain achieved the temperature of about 24°C, but in the case of radiant heating panels significantly higher gradients towards higher temperatures can be seen, caused by direct heat transfer onto the heated surface. The classical hot water radiator heating, however, leaves the bottom of the domain cooler, because of the heat transfer through the floor. Those numerical results correspond well with the dependence obtained from the measurements shown in Fig. 2.

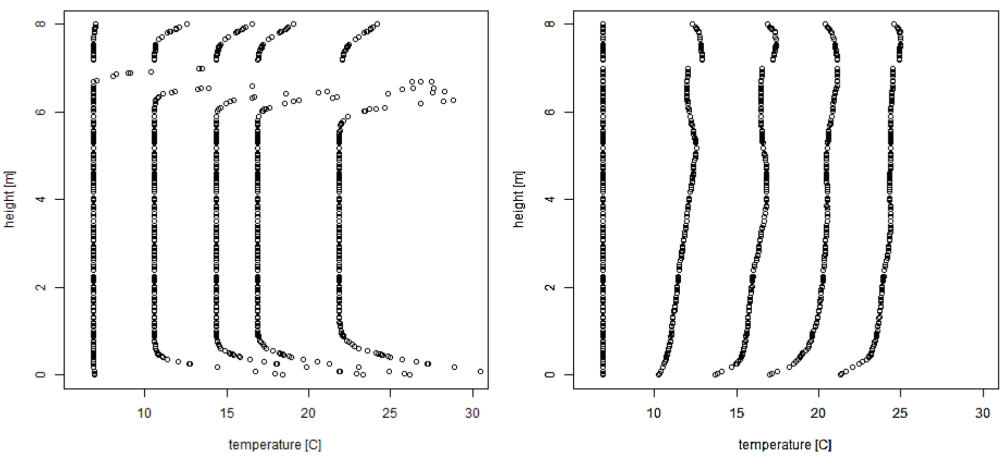


Figure 4. Temperature profile development for radiant panel and hot water radiator heating, the time step is 30 minutes.

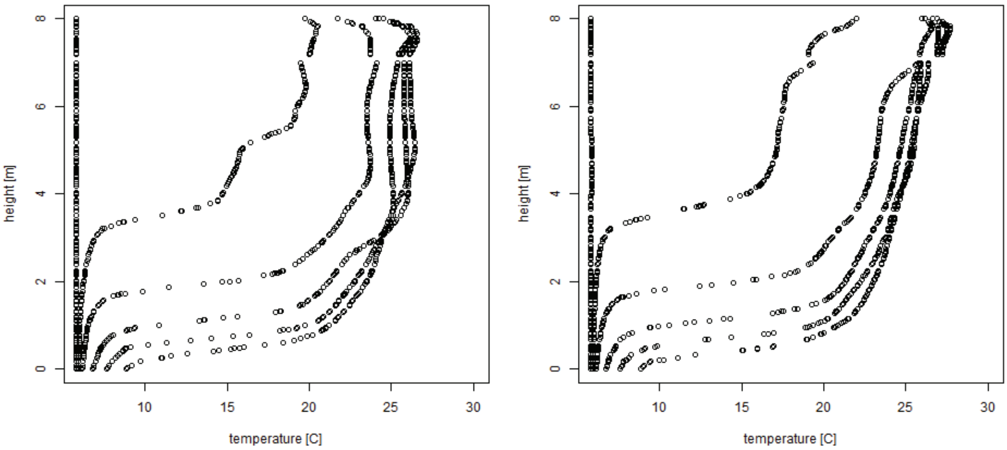


Figure 5. Temperature profile for hot air heating in the plane of ventilators and in the central plane of the hall, the time step is 5 minutes.

The situation during hot air heating is illustrated in Fig. 5, where the time step between the curves is shorter. The two graphs show the profiles in the central vertical axis and in the middle between the inlet and outlet opening. It is clearly seen that the effect of natural convection together with ventilation make the upper part of the domain heated very quickly, but forced ventilation leads to quick mixing of cold and hot air.

CONCLUSIONS

Heating the large industrial and agricultural buildings with radiant heating panels looks advantageous. The thermal comfort of the people who are moving in such areas is guaranteed by the increase in the surface temperature due to the radiation heat transfer and the results of measurements and simulations confirm that the temperature on heated surface can be up to six times greater than in the surrounding environment. Hot air heating is mainly usable mainly when there is a need for quick compensation of temperature fluctuations caused by operational needs. Conventional hot water radiators are shown as particularly disadvantageous because of the long heating time which goes together with temperature stratification and therefore increases the heating costs due to the need to overheat the upper parts of the building space to achieve the required conditions just above the floor.

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