Heating of large agricultural and industrial buildings

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Abstract. This paper presents the results of 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 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.

Calculations were performed using the CFD software ANSYS-Fluent. For comparison of variants 3D model was used, including a heat source, natural convection and heat transfer through surrounding structures. There were studied mainly the results of thermal comfort of working environment in the level of people, or growing zone of plants or storage space for goods. 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 vertical temperature profiles and the effect of surrounding walls surface temperature on the thermal state of an indoor environment.

Created model was verified according results of experiments in large buildings equipped with different heating systems. Based on the results of simulation calculations and according to results of experimental measurements, radiant heating method seems to be suitable solution of heating systems for studied types of buildings.

Key words: energy, radiation, thermal comfort, simulation

Introduction

Heating of large buildings represents together with ventilation or air conditioning very important issue, which significantly affects the operation of these facilities. This article is aimed at those buildings used in industry, agriculture or in different repair shops and service centres. These buildings are used year-round and must be maintained for 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 the overall large 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 satisfaction and functional reliability of these buildings. Energy comnsumption, indoor climate and sophisticated regulation systems take a great deal for well-constructed buildings (Rajaniemi & Ahokas, 2012; Reinvee et al., 2012).

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

The following article briefly summarizes some of the results of measurements in the practical operation of 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 was used the measurement of large-area industrial hall with a total interior height of 8 m, 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 two different concepts 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 and as well as in one section heated by radiant panels.

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

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

From the measured values (measured ten values of each parameter in level 1,1 m above the floor, regularly distributed in the area roughly 25 m^2 in each measured section of the hall) were calculated the average globe temperature T_g (°C) and air temperature T_a (°C) which were used according to 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} ($W.m^{-2}.K^{-1}$) was calculated according to the equation (3). From the measured cooling time τ (s) of Kata-thermometer and calibration constant Q ($J.m^{-2}$) were calculated according to the equation (4) average values of so called cooling rates Kata-values K ($W.m^{-2}$).

$$T_r = \left\{\sqrt[4]{\left[(T_g + 273)^4\right] + \left[1{,}855.10^7.h_{kg}.(T_g - T_a)\right]}\right\} - 273, \quad (1)$$

$$T_o = 0.5.T_a + 0.5.T_r, \quad (2)$$

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

$$K = \frac{Q}{\tau}, \quad (4)$$

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 ($W.m^{-2}$)
Q – calibration constant ($J.m^{-2}$)
τ – cooling time (s).

Simulation of conditions in the hall was carried out using the CFD (computational fluid dynamics) program Ansys Fluent. Fig. 1 shows the geometrical model. 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 15 m and it has a dimension 2x14 m. Four input/output openings of hot air heating system are located at a distance of 2 m from the front/back walls and 1.2 m from side walls. Classic hot water radiators, each with dimension 15x0.8x0.2 m, are located on the both long sides of the hall at the height 1 m above the floor. The computational domain consists of about 1 million tetrahedral cells with characteristic dimension about 15 cm.

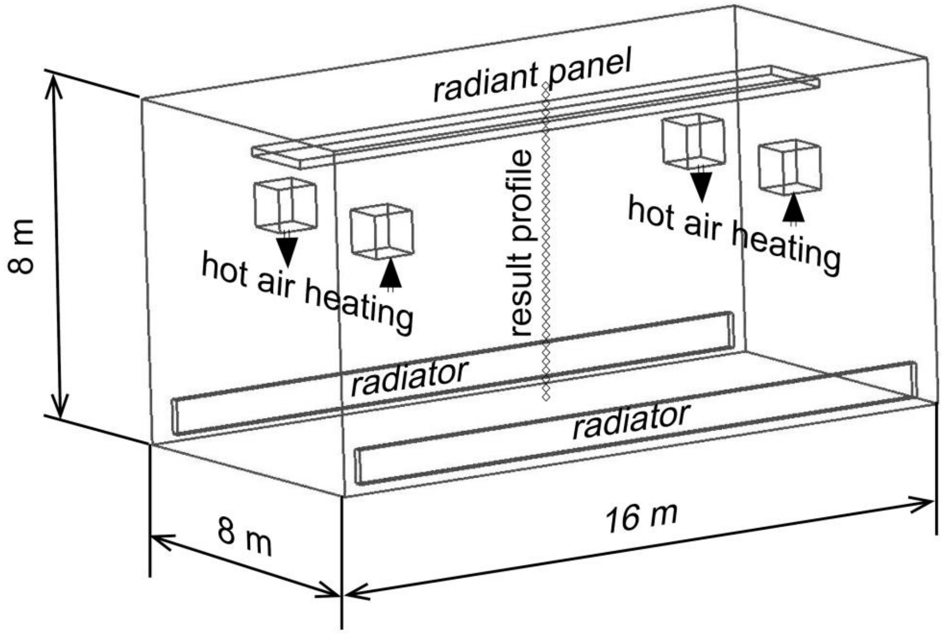

Figure 1: The geometrical model of the computational domain with zones used for simulation of different heating system concept.

Results and discussion

The results of measurements in the hall

Results of measurement of thermal environment in the hall are summarized in Table 1. There are the results obtained by measurement of 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 thermal state of the environment in 3 sections of the hall with warm 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 points in sections 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

Measurement results in Tab. 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. On the contrary air temperature in the section HA 3 was too high. In terms of comfort there is recommended as optimum environment for the working activity in the hall, where people are working on machine tools or they work in light assembly (Act No. 262/2006 Coll.), the labour class II b) with the average body energy production, M = 106-130 $W.m^{-2}$ recommended air temperature to 14-32°C, relative humidity 30-70% and air velocity from 0.05 to 0.3 ms^{-1}. Generally it is the inside air T_a temperature too high and relative humidity Rh is the whole building too low, as there are inside not sufficient sources of vapour. In the section with radiant panels is globe temperature T_g rather higher than average air temperature T_a. Air-speed was in acceptable level.

The optimum of cooling rate Kata-value K should be from 170 to 250 $W.m^{-2}$. If it is less than 170 $W.m^{-2}$ people feel the warm, if it is more than 250 $W.m^{-2}$ people feel the 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.

Very interesting is comparison of vertical profiles in the hall shown in Fig. 2, where the mean values from the set of 20 measurements are presented. 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 the hot air heating causes a lower air temperature in the zone of movement of people near the floor and significantly higher temperature near the ceiling. This increases heat losses through the top of the walls and ceiling. In opposite, radiant heating panels by radiation heat the floor and floor environment where people work; an upper part of the hall is cooler. This is very beneficial in terms of reduction of energy consumption for heating.

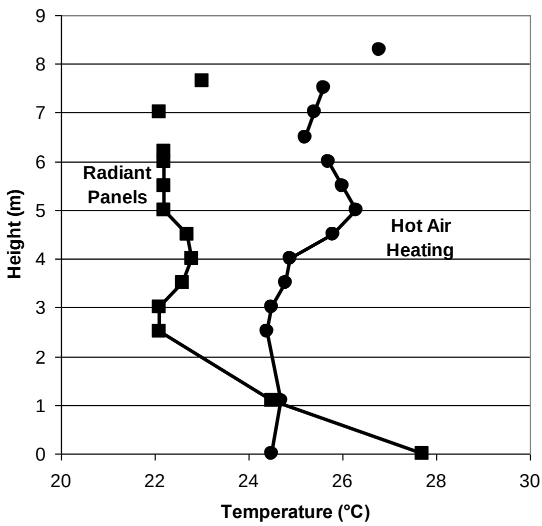

Figure 2. Comparison of mean values of vertical temperature profiles measured in the section heated by hot air and in the section heated by radiant panels.

The results of simulations of heating in the hall

All solved cases assume the same initial conditions, namely the initial temperature inside and outside of the building 7°C, total heat transfer coefficient through side walls 12 W.m^{-2}.K^{-1}, through the ceiling 18 W.m^{-2}.K^{-1} and through 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 gray-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, how the total radiation flux is distributed to other, than source surfaces.

A B C

Figure 3. Character of temperature profile during (A) - hot air heating, (B) - hot water radiator heating and (C) - radiant panel heating.

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

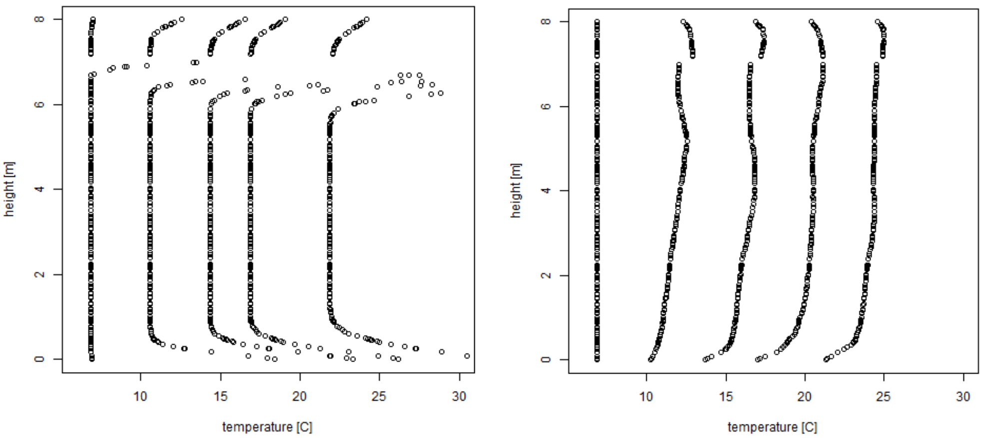

Figure 4. Temperature profile development for radiant panel and hot water radiator heating, time step is 30 minutes.

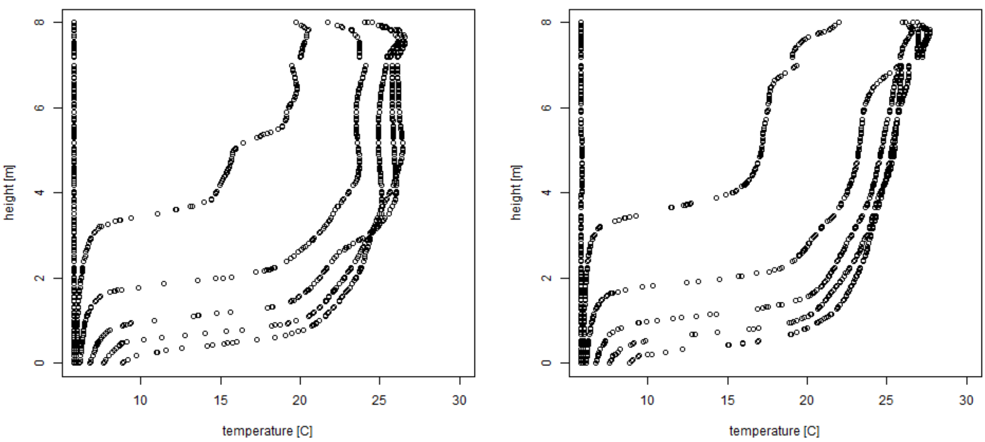

Figure 5. Temperature profile for hot air heating in the plane of ventilators and in the central plane of the hall, time step is 5 minutes.

This fact is shown in Fig. 4. It compares the vertical temperature profile in central vertical axis of domain for radiant heating panel on the left side and heating with conventional hot water radiators on the right. It is evident, that after two hours from the turning the heating system on the central area of domain achieved the temperature about 24°C, but in the case of radiant heating panel there can be seen a significantly higher gradients towards higher temperatures caused by direct heat transfer onto heated surface. Against it the classical hot water radiator heating leaves the bottom of domain cooler because of the heat transfer through the floor. Those numerical results correspond well with the dependence obtained from the measurement shown in Fig. 2. The situation during the hot air heating is illustrated in Fig. 5, where the time step between curves is shorter. Two graphs show profiles in central vertical axis and in the middle between inlet and outlet opening. It is clearly seen, that the effect of the natural convection together with ventilation make the upper part of domain heated very quickly, but due to forced ventilation leads to mixing the cold and hot air quickly.

Conclusions

Heating the large industrial and agricultural buildings using the radiant heating panels looks advantageous. Thermal comfort of people who are moving in such areas is guaranteed by increase of the surface temperature due to radiation heat transfer and results of measurements and simulations confirm that the temperature on heated surface can be up to six times greater, than surrounding environment. . Hot air heating is usable mainly, when there is a need of 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 increasing the heating costs due to need of overheating upper parts of building space to achieve requested conditions just above the floor.

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