EXPERIMENTAL AND SIMULATION TEMPERATURE EVALUATION WHICH DETERMINE THERMAL COMFORT

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ABSTRACT

The paper deals with the evaluation of operative temperature and indoor air temperature by computer simulation method and their comparison with measured temperatures in real air-conditioned room. Also calculation of the extreme thermal states in winter and summer time by the program created in Excel software is shown. Difference between operative temperature and indoor air temperature is given by mean radiant temperature in the room, which is affected by indoor and outdoor radiant sources.

INTRODUCTION

Thermal comfort in the spaces with human occupancy in hygienic requirements is determine by operative temperature t_o (°C), or globe temperature t_g (°C). But designers of the air-conditioning and heating systems, are not able to count those two temperatures with common design methods using. This is because operative temperature t_o and globe temperature t_g depends on the surface temperatures of the walls. Surface temperature of the wall is possible to calculate by simulation methods.

Czech legislative act [1] defines operative temperature t_o (°C) and globe temperature t_g (°C) as a criteria for microclimate definition. Temperature t_o is quite easy to solve on the basis of measurement of the indoor air temperature t_a (°C), globe temperature t_g (°C) and air velocity w (m/s).

Air-conditioning and heating design calculation methods mostly determine heat load and heat loss by convective heat transfer from the wall surface. For this kind of calculation the indoor air temperature determines the indoor environment. When designers use common calculation methods, they don't know wall surface temperatures (mean radiant temperature) and they are not able to determine operative temperature in the space as well.

In the hygienic regulations from 1978 was listed equation, which express relationship between indoor air temperature t_a and globe temperature t_g for winter and summer time

$$t_a = t_g + B \tag{1}$$

where coefficient B is defined for *summer* (if the shading is used properly)

$$B = 0 \tag{2}$$

and for *winter* (if the heating system compensate influence of the negative radiation by the windows)

$$B = \frac{4.720w^{1/2} - 1.710}{44.500w^{1/2} + 122.965w}\left(0.913q_m - 19.14\right) \tag{3}$$

where

w (m/s) is air velocity (at intervals from 0 to 0.5 m/s)
q_m (W/m^2) is specific heat production of the human body

Equations mentioned above is evidence, that also in the past was ambition to give background to the designers, which would respect influence of the radiation and air velocity for thermal comfort.

The assumed (required) operative temperature t_o in the space is possible to define with using present calculation methods (dynamic simulation of the building energetic balances and environmental engineering systems). Matter of those methods is calculation of the mean radiant temperature t_r (°C) under stationary or dynamic conditions.

Important thing is that operative temperature is changing in every point of the space. Also in case when we assume air temperature to be constant. Changes of operative temperature are affected by mean radiant temperature, which depends on location in the space. Operative temperature changes are useful in the room to follow in horizontal direction and vertical direction as well. There is influence of the window surfaces (summer and winter) in horizontal direction and influence of the cooling or heating ceilings (summer and winter) in vertical direction. Operative temperature analysis in vertical direction is also important for consideration of the conditions given in [1] for height 0.1 m (height of ankles), 1.1 m (height of head of the sitting person) and 1.7 m (height of head of the standing person).

In this paper theoretical and experimental results are presented, which deals with specification of the mean radiant temperature, globe temperature and operative temperature:

a) mean radiant temperature calculation in general point of the room – software Excel (VBA)
b) operative temperature calculation in the room for stationary thermal balance – software Excel
c) mean radiant temperature and operative temperature calculation for dynamic thermal balance – ESP-r simulation program
d) experimental determination of the mean radiant temperature and operative temperature in the air-conditioned room in summer time

MEAN RADIANT TEMPERATURE CALCULATION IN GENERAL POINT OF THE ROOM – SOFTWARE EXCEL

Mean radiant temperature calculation mentioned in [1], consist of determination of the view factors in random point on the basis of the geometric position ratio between radiant and irradiated surface (person). In the fact mean radiant temperature should be detached to the human body surface (S_t = 1.8 m^2), but such a calculation is not very easy. For simplification, the mean radiant temperature is detached to the globe surface; let us say to the point, which is located in the human centre of gravity. The view factor for radiant point defined according to figure 1 can be calculated as

$$\varphi_{1-2} = \frac{1}{8} - \frac{1}{4\pi} arctg \frac{c\sqrt{a^2+b^2+c^2}}{ab} \qquad (4)$$

On the basis of the mentioned calculation method the program for monitoring of mean radiant temperature distribution in the space – *MRT Analysis* was created. By using of this program it is possible to evaluate mean radiant temperature in the isomap form in

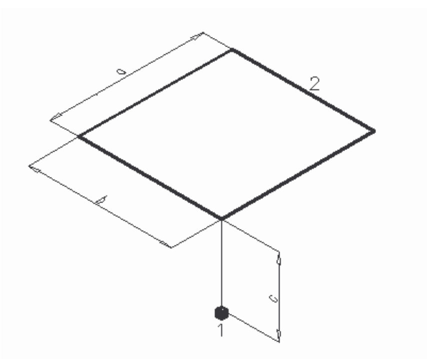

Figure 1 Parameters for view factor calculation

random plane of the space. Program allows calculation in the simply rectangle enclosure with perpendicular walls. It is possible to insert additional surface to the each wall (e.g. window, ceiling) with corresponding surface temperature. It is possible to evaluate mean radiant temperature t_r or operative temperature t_o as well.

Graphical example of the evaluation is visible in the figure 3. Example represents the room with a cooled ceiling (18 °C) and warmed surface of the window (35 °C). Mean radiant temperature calculation was carried out with mesh 50 x 32 points in the vertical plane located in the middle of the room. From the figure it is visible, that mean radiant temperature is not identical in the space. Influence of thermal boundary conditions and space geometry is present. Program is able to evaluate operative temperature (for defined air velocity) in random vertical and horizontal planes, i.e. also in the vertical points mentioned in [1] and [8].

OPERATIVE TEMPERATURE CALCULATION IN THE ROOM FOR STATIONARY THERMAL BALANCE – SOFTWARE EXCEL

Calculation target was to determine the difference between indoor air temperature t_a and operative temperature t_o in the extreme climatic conditions under which the air-conditioned unit was designed. Calculation was carried out separately for summer and for winter [3], [4]. Basis of calculation were heat load calculation (summer) according to ČSN 730548 [5] and heat loss calculation (winter) according to ČSN 060210 [6].

For set indoor air temperature, climatic conditions, thermal conditions in surrounding rooms, heat transfer coefficient, overall heat transfer coefficient and position of the mean radiant temperature the program calculate surface temperatures of the walls and windows t_{pi}. Next calculation allows to determine mean radiant temperature t_r in random point of the space. According to set value of indoor air temperature t_a and air velocity w it is possible to define operative temperature t_o in chosen point.

The model of the room with dimensions 7.3 x 4.6 x 3.1 m (l x w x h) was analysed. Building in which is room located, is made of iron-concrete skeleton (ceiling and floor is made of concrete with thermal insulation), indoor walls are made from hollow bricks, outdoor walls are also made from hollow bricks with thermal insulation. For this model the whole outdoor wall was made from glass U = 1.5 W/m^2 K.

Monitoring cases:

Winter

- Room is heated by ceiling radiant heating system with surface temperature 40 °C and 50 °C, indoor air temperature 20 °C.

Summer (shading coefficient of the blinds is 0.6)

- Air-conditioned room, indoor air temperature 25 °C.

<u>Room is heated by ceiling radiant heating system with surface temperature 40 °C, 50 °C, indoor air temperature 20 °C</u>

Mean radiant temperature t_r and operative temperature t_o was calculated in the middle of the room along its height (indoor air temperature t_a = 20 °C is assumed homogenous in the whole space).

Results are visible in figure 4. According to [1] the microclimate was evaluated in three elevations: 0.1 m; 1.1 m; 1.7 m above the floor. Results of calculation for those elevations are visible in the table 1.

Table 1 Operative temperature t_o in vertical direction

Elevations above the floor (m)	Operative temperature t_o (°C)	
	Ceiling temperature t_p = 40 °C	Ceiling temperature t_p = 50 °C
0.1 m (ankles)	21.3	22.3
1.1 m (the head of the sitting person)	22.,0	23.4
1.7 m (head of the standing person)	22.7	24.4

<u>Air-conditioned room, indoor air temperature 25°C</u>

Surface temperature of the inside blinds was defined on the basis of experiment [3] under extreme summer conditions at south-east side of the room and was set to 46 °C.

Operative temperature was defined along vertical line to the outside glass wall, in the middle of the room in the height of 1.1 m above the floor. Results are visible in the figure 5.

<u>MEAN RADIANT TEMPERATURE AND OPERATIVE TEMPERATURE CALCULATION FOR DYNAMIC THERMAL BALANCE – ESP-R SIMULATION PROGRAM</u>

Dynamic simulation model was created by ESP-r simulation program. For computation room described in previous article was chosen; outside wall was simulated like in a real room in which experiments described in next article was carried out (3 windows in outside wall at size of 2,2 x 2,0 m). Model of the room is in the figure 2.

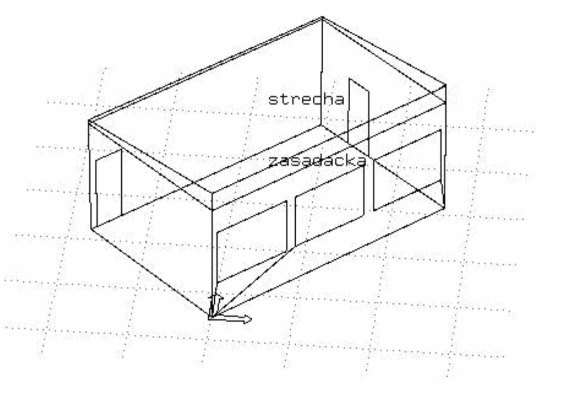

Figure 2 Model of the room in the ESP-r

In ESP-r software it is possible to calculate the operative temperature in random point by *MRT* sensor (Mean Radiant Temperature). Sensor represents standing person has a block shape with dimensions of 0,3 x 0,3 x 1,1 m (l x w x h), located 0,7 m above the floor.

Simulation was carried out using climatic database measured in Department of Environmental Engineering, Faculty of Mechanical Engineering, CTU in Praque.

Results of the simulation are visible in the figure 6 and 7. In both pictures there are also thermal comfort measured values. Simulation and measurement was carried out under the same climatic conditions. Graph in the figure 6 shows quite good agreement of operative temperature t_a gained by simulation and by measurement as well. It is necessary to mention that set indoor air temperature (22.5 °C) was in the simulation evaluated (in term of thermal comfort in the summer) as a low value. In the figure 6 it is visible high percentage of dissatisfied people in the space (*PPD*) – up to 24 %. When operative temperature is higher (23.5 °C) *PPD* index decreases to 5 %. Graph in the figure 7 shows simulating values of the indoor air temperature. At noon (extreme heat load) indoor air temperature is changing from maintained value of 22.5 °C to 23.5 °C. This happened because of the low cooling output of the air-conditioned unit, which was not enough for maintain temperature of 22.5 °C.

Massive drop of the mean radiant temperature in the night and in the morning is affected by over-estimating of the long wave radiation cooling in ESP-r.

EXPERIMENTAL DETERMINATION OF THE MEAN RADIANT TEMPERATURE AND OPERATIVE TEMPERATURE IN THE AIR-CONDITIONED ROOM IN SUMMER TIME

Measurement of the inside environment parameters was carried out from 8/6 to 11/6/ 2004. Thermostat of the air-conditioned unit (split system) was set to 22.5 °C. Continuously were measured: indoor air temperature t_a, globe temperature t_g, surface temperature of selected subjects t_{pi} and outdoor air temperature t_e. At the same time the intensity of sun radiation was measured in the department solar laboratory.

Indoor air temperature in the room was measured with shaded thermometer in two points, on the window and near the internal wall at the height of 1.7 m above the floor. This height complies with the CSN EN ISO 7726 standard and represents the height of head of standing person. Equal conditions were used for measurement of the globe temperature t_g by globe thermometer (diameter of 100 mm). Surface temperature t_{pi} was scanned on selected superficies, i.e. window, floor, cabinet, ceiling.

Measured temperatures were recorded with EfLab central (15 minutes recording interval). Air velocity in the room (measured by heating string) was recorded with programmable central Almemo 3290. During the measurement it was investigated that air velocity was not higher than 0.2 m/s. This simplified interpretation of the operative temperature.

In the figures 6 and 7 it is visible oscillation of the temperatures (about 0.3 °C). Oscillation is affected by accuracy of the sensors and accuracy of the measurement central. There is also visible stronger temperature oscillation at noon, which is affected by short-time variability of the sun radiation.

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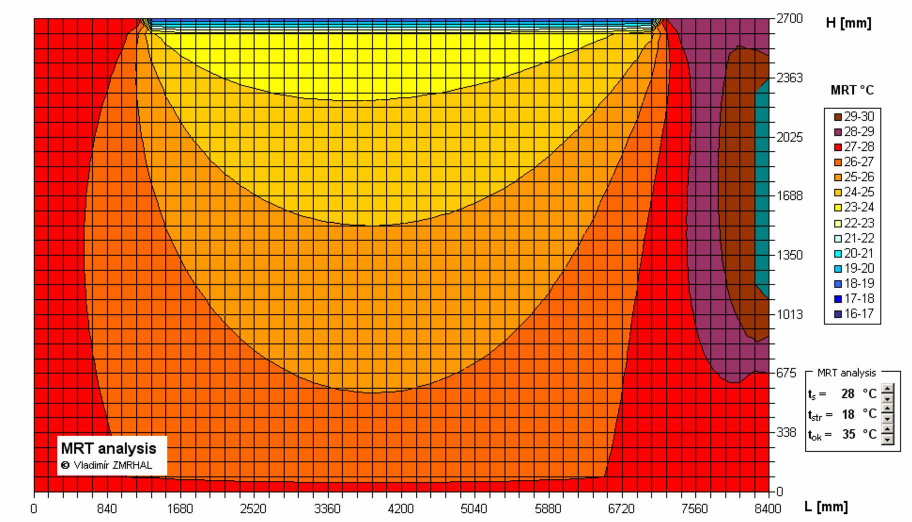

Figure 3 Evaluation of the mean radiant temperature in the "izomap" form

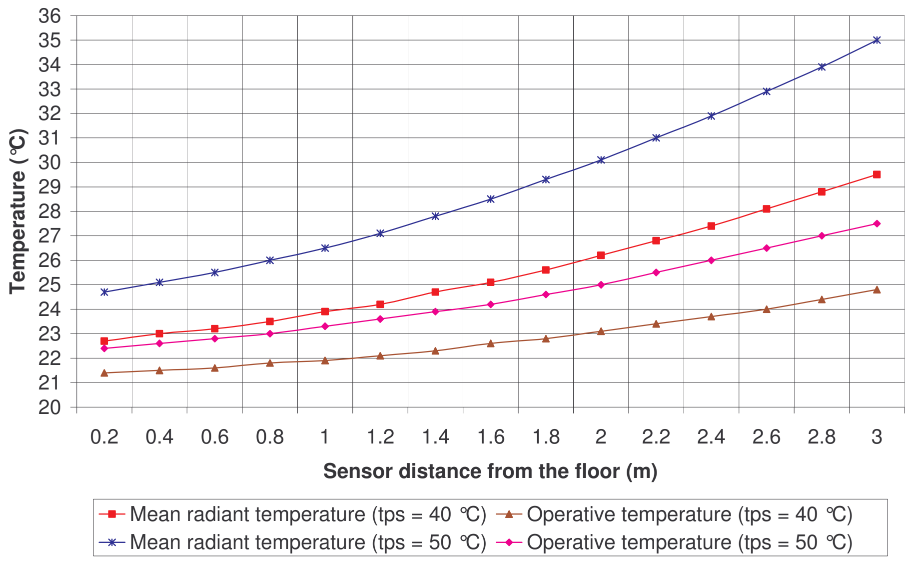

Figure 4 Vertical course of the temperatures for radiant ceiling heating (ceiling temperature 40 °C, 50 °C)

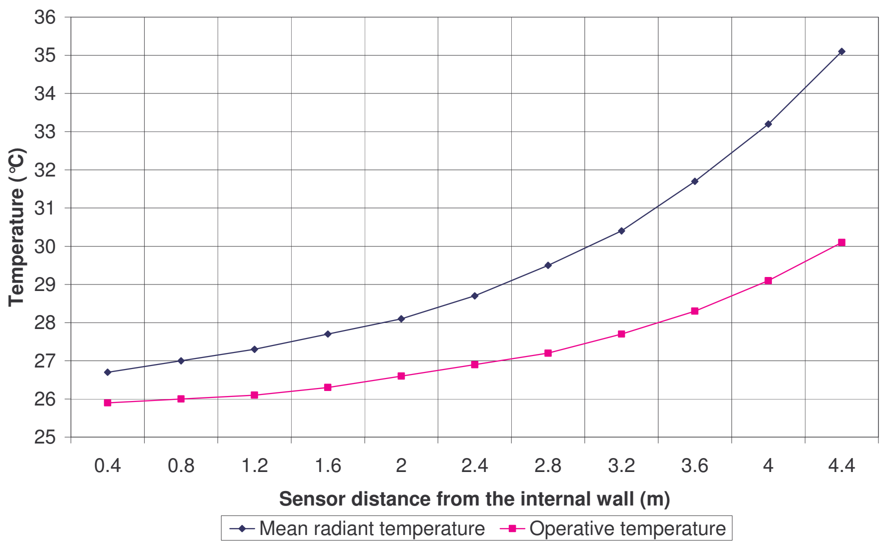

Figure 5 Horizontal course of the temperatures in the midle of the air-conditioned room in height of 1,1 m

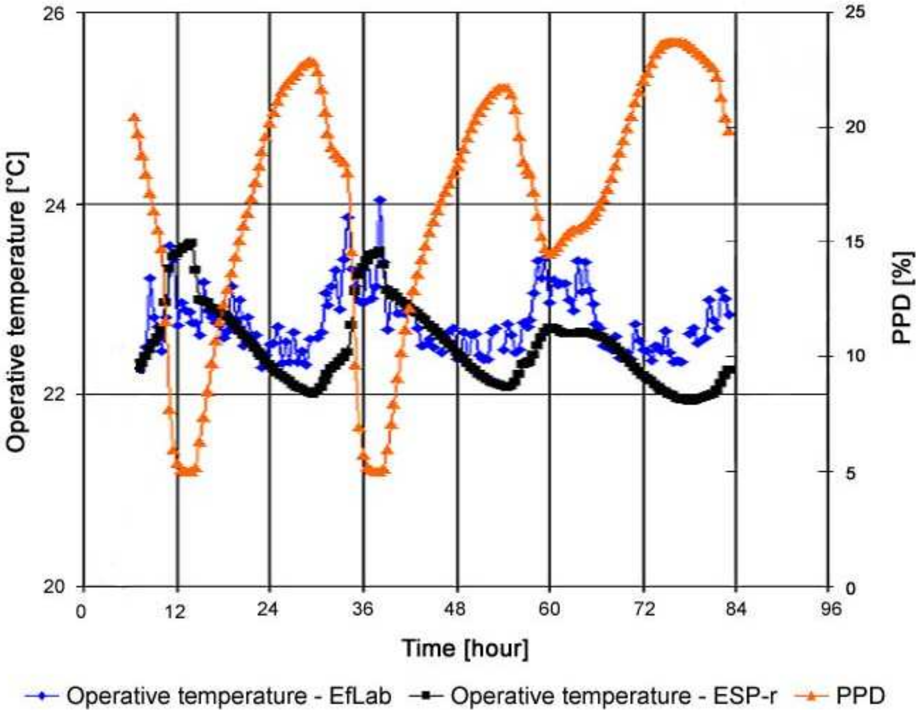

Figure 6 Results of measured and simulated values of the operative temperature and PPD

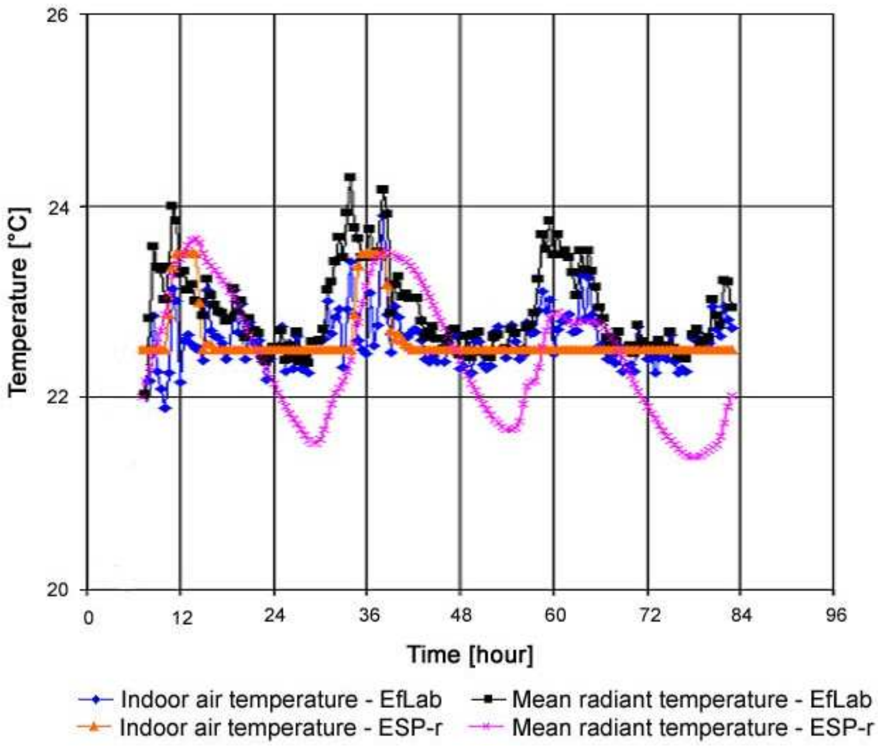

Figure 7 Results of measured and simulated values of the indoor air temperature and mean radiant temperature