SIMULATION IN CONTROL SYSTEM SENSOR LOCATION DESIGN

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ABSTRACT

This paper focuses on the study of the office room, investigating the influence of temperature sensor placement on the heating energy consumption and thermal comfort in the central European climate conditions. Temperature simulation of the zone focused on different boundary conditions at points on the location of the sensor compared to the centre of the room. A new approach in the use of ESP-r for evaluation of resultant temperature for different locations in the room, using MRT (mean radiant sensor) function and air temperature was tested. Temperature related results are discussed and evaluated herein.

INTRODUCTION

Requirements for higher energy performance and nearly zero-energy buildings in conjunction with the increasing demands on the quality of the indoor environment leads to higher requirements on the control of heating, cooling and ventilation system, that will be able to respond to variable requirements, given by differences in heating/cooling/ventilation loads in individual zones. Each of these control systems is thus equipped with sensors that provide information about the current state of the controlled environmental variable in the zone. Based on the feedback from practice we know many cases when non-proper placement of the control system sensor caused uncertain behaviour of the system resulting either in discomfort and/or to increased energy use. This paper focuses on the study of the office room, investigating the non-uniformity of air, mean radiant and operative (resulting) temperature distribution in different possible locations of the sensor. Questions which this paper aimed to answer were: What is the impact of the temperature sensor placement to the comfort and energy performance of the room? Is it necessary in modern office rooms with convection heating/cooling to distinguish between resulting and air temperature?

PROBLEM ANALYSYS

To answer the above-mentioned questions, requirements on modelling and simulation tools have been formed, which should enable the model and provide dynamic simulation of:

- room internal surfaces temperatures,
- room air temperature,
- operative or mean radiant temperature in different position of the room,
- energy performance of the building,
- sensor type and actuator for heating and cooling.

CFD modelling is the standard approach for temperature distribution and non-uniformity in room investigation. The problem with this method is that to get reasonable values from CFD we need an accurate model of the room with all details of interior, furniture, and air inlets and outlets. Of course, it is not a problem to create the model, but to miss information about the details. In addition, the sensitivity of the CFD model to changes of interior layout (and movement of persons) is high and so this method is suitable mainly for places with fixed geometry and boundary conditions (i.e. cars, technology buildings, fixed working places). Even though the capacity of modern computers in recent years has grown, most of CFD analysis is based on steady-state model of given static boundary conditions and that is the next problem in solution of above-mentioned questions. The third problem of CFD is the missing link of CFD results to energy performance simulation.

After deeper analysis of different tools (DesignBuilder, Flovent) we decided to use ESP-r, as a tool for investigation of this problem, which fulfils most of the requirements, especially the possibility to simulate mean radiant temperature in different points of the room.

The model in ESP-r has been validated by measurements on an actual room.

MODELLING AND SIMULATION

The case solves the influence of location of the sensor for measuring the command variable of regulation heating and in two adequate size offices, which differ from each other in thermal insulation of external walls. The computer simulation evaluates variants of various locations of indoor temperature sensors for the building control system. For purposes of the analysis, two office rooms, which adjoin one another, was chosen as the example.

Software ESP-r

Dynamic simulation software ESP-r has been used for analysis of location of the sensor . Computer programme ESP-r (Environmental Systems Performance - research) is environment of dynamic simulation for analysis of mass flows and heat flows in buildings. In the course of the simulation the evolution of mass flows and energy flows during changes in regulatory intervention and limiting conditions (outdoor microclimate and operating indoor conditions) is monitored. At every time step of simulation a problem is limited to steady flows (ESP-r manual, 1998).

Model

For purposes of analysis of the influence of the sensor location (for measuring indoor temperature) onto the heating system control and energy performance of offices, two reference rooms, which differ from each other in isolation of external walls were selected. The office "A225" was additionally insulated by VIP panels (λ = 0,017 W/m.K) from inside the external wall, according to reality. The room "A226" is kept in original condition without insulation. These offices are situated in an existing building of the Faculty of Civil Engineering CTU in Prague. The rooms are located in a sixteen-storey three-tract building with active heating and ventilation without air conditioning.

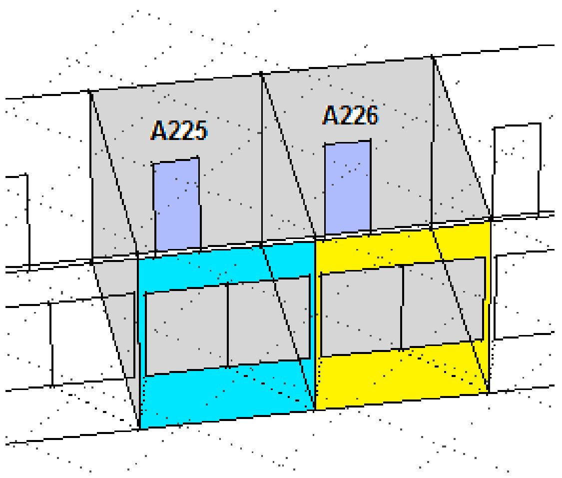

Figure 1. Model of part the office building with marking the reference rooms - the programme ESP-r

The evaluated office rooms are 5 m x 3 m in size and the ceiling height is 3.3 m. Both rooms have one external wall with a window a size 3 m x 1.6 m, floor, ceiling, interior wall separating the room from the corridor, the partitions between the offices and the hall door. Because the offices are on the second floor, heat losses by transmission are expected to occur only through the perimeter wall. The facade is oriented toward the southwest.

Proposed working hours in the office building are in the working days from 8:00 a.m. to 5:00 p.m.

For heating to a temperature of 21 °C, the performance of the heating elements available are in the range of 0 - 4000 W. This performance is designed to cover the heat needs and to ensure the requirements of the indoor environment in the extreme cases in the Czech climatic conditions. Heat energy is distributed by 25 % radiation and 75% convection. Heating is controlled according to indoor temperature. The heating system is working permanently (it was established on the basis of previous measurements) also during not-working hours and on weekends and holidays. Humidity is not controlled in either of the rooms "A225" and "A226" (Kabrhel et al., 2011).

Table 1
Heat transfer coefficient of different constructions.

BUILDING STRUCTURE	U_{VALUE} [W/m^2.K]
Perimeter wall without insulation A226	0,68
Perimeter wall with insulation A225	0,15
Window	4,10 **!**
Floor	0,85
Ceiling	0,85
Indoor wall	2,56
Partition wall	2,00
Door	3,50

Ventilation is forced, with a fixed fresh air change rate. Supposed the intensity of air exchange during a working time differs according to nominal occupancy of the room. In the office "A225" the intensity of air exchange is set at 100 m^3/h (2 persons in a room) and in office "A226" the intensity of air exchange is 50 m^3/h. The intensity of air exchange decreases outside the normal working hours to 20 m^3/h (in all offices). Infiltration of old windows results in considerable proportion of the ventilation, it provides 1,5 times the air exchange.

To determine the indoor gains should be considered during model building operation. The model reckons with the presence of one or two people in the office during working hours. Office facilities (computers, printers, etc.) should also be reckoned with. Computers and printers are the biggest producers of indoor heat gains. Lighting operates during working hours throughout the year (illumination intensity is 500 lux) (Bartoňová,Kabele,2011).

Table 2
Determination of indoor heat gain

SOURCE OF HEAT GAIN	VALUE
Person	150 W/person
Computer set (PC and printer)	250 W
Lighting	35W/m^2

Verification of the model

To verify the model functionality, it was necessary to perform the verification model on the basis of the measurements. Measurements were carried out in the winter 2010 as a part of student assignment.. This measurement consisted of outdoor air temperature, humidity, solar radiation intensity, speed and wind direction and indoor air temperature in the reference room (office "A226"). Unfortunately, it was not possible to measure operative temperature at that time due to technical and operational circumstances (the room was occupied and cooperation with user was not the best). It was necessary to accept assumption that in case that the simulated results of indoor air temperature will match the measured values, it is possible to expect that there is no major mistake in the model.

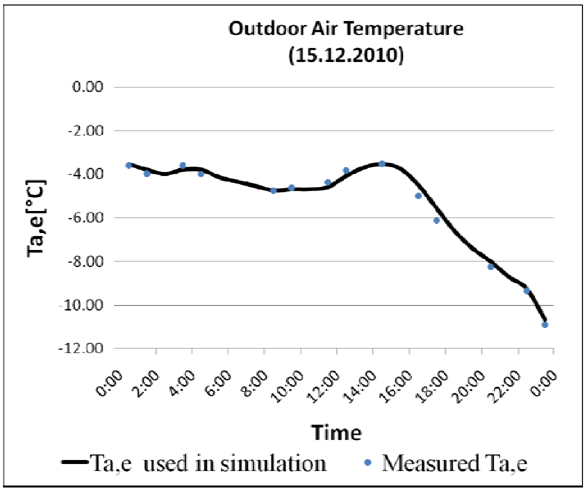

Figure 2 Comparison of the measured and in the model used outdoor air temperature

Measured outdoor temperatures were used as input to the model. Due to differences between measurement time steps and that required by the model, interpolation was required. The comparison is shown in Figure 2.

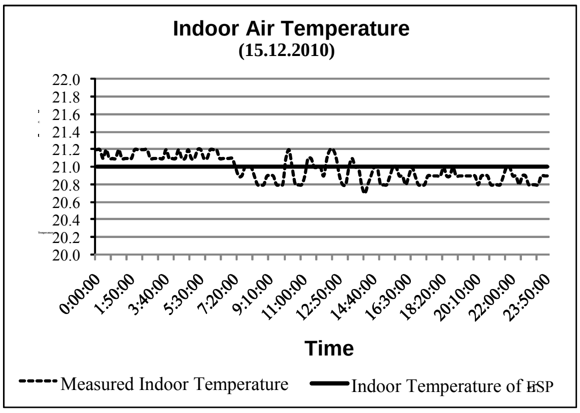

Figure 3 Comparison of the indoor air temperature with measured values

Figure 3 shows that the program ESP-r expected to maintain the desired indoor temperature, but in fact there was a decrease or increase in temperature. Actually, the measured temperature rose and fell in the range of ±0.2 °C around the temperature selected in simulation programme. This difference was evaluated as acceptable and model in the air temperature domain has been considered as satisfactory.

Simulation

In the next step, the work continued with the simulation. The question to be solved at this point was how to deal with the limited possibilities of ESP-r in terms of operative temperature calculation and requirement for more detailed view on the temperature distribution in the room to get data for the next experiments and decisions related to optimal sensor placement.

ESP-r enables to calculate operative (in the program called resulting) temperature t_o in one point, which is located in the ideal centre of the room. This value is sufficient for building energy performance calculations, but not for our task, where we wanted to investigate non-uniformity of the operative temperature within the room. To simulate this, we used the MRT (mean radiant temperature, t_{MRT}) module of ESP-r (Kabele, Krtková, 2001). This module enables to simulate MRT in selected and by coordinates specified positions of the room. The problem is that MRT gives information only about surface temperatures “visible” from a given point and no information about operative temperature, which is defined as “*a uniform temperature of a radiantly black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform air temperature*” . To get operative temperature in different points of the room, we used the basic definition of operative temperature expressed by equation (1):

$$t_o = \frac{(h_c \cdot t_a + h_r \cdot t_{MRT})}{h_c + h_r} \quad [°C] \tag{1}$$

According to (Government regulation 523, 2002) for air movement velocities in the room up to 0.2 m/s it is possible to simplify the equation (1) into equation (2), based on assumption, that within low air velocities, convective and radiant heat transfer coefficients are equal:

$$t_o = \frac{(t_a + t_{MRT})}{2} \quad [°C] \tag{2}$$

We focused simulation on a typical winter week, when the differences were expected to be significant. The simulation was based on the following boundary conditions and simulation set-up:

- Actual Prague climate data from December 2010;
- Integrated simulation with time step of 0.5 hour;
- Initial start-up period of 3 days.

For investigation of non-uniformity focused on possible sensor placement and workplace location, we selected 8 different reference points in both offices located according to Figure 4 at the height 1.1 m above the floor.

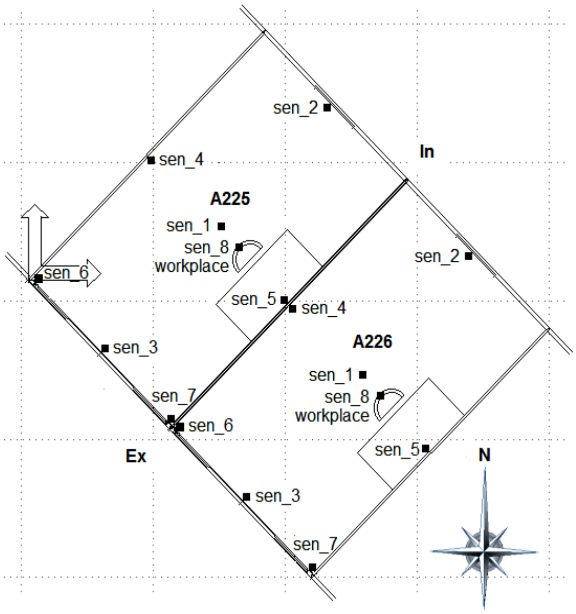

Figure 4 Position sensors for measuring the mean radiant temperature

Results analysis

ESP-r results of air temperature t_a and MRT t_{MRT} were used to calculate the operative temperature according to equation (2). The summary of the results is presented in figures 5,6,7,8 and tables 3 and 4.

The charts indicate that the largest temperature differences are, as was predicted, between sensors placed near window (sensors number 3, 6 and 7) and sensors in the middle of the room „A225“ (sensors number 1,2,4,5 and 8). The absolutely largest difference is between sensor number 2 (placed near a door leading to a corridor) and sensor number 3, placed near the window.

Similarly to room A225, the largest difference in the room A226 is between sensor number 2 (placed near a door leading to a corridor) and sensor number 3, placed in the middle of window.

The temperature curves in both rooms are similar in terms of their shapes. Hence, additional insulation has no effect on sensor placement. The insulation has, however, a direct effect on energy performance. Insulation of perimeter wall contributes to lower heating dissipation to outdoor environment

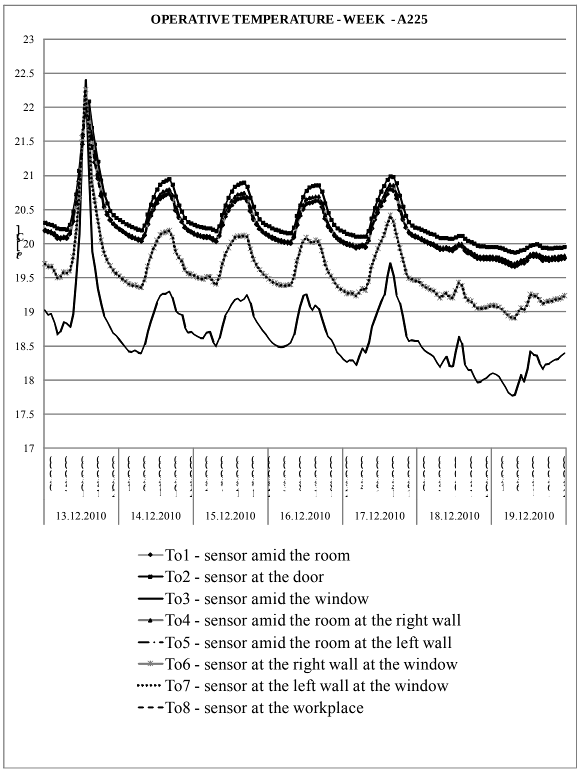

Figure 5 Operative temperature in selected sensor positions in the room "A225"

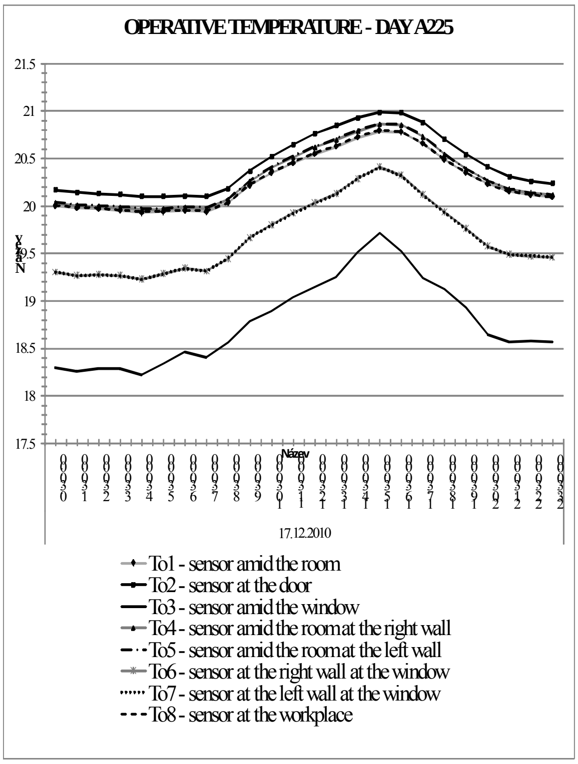

Figure 6 Operative temperature in selected sensor positions in the room "A225"

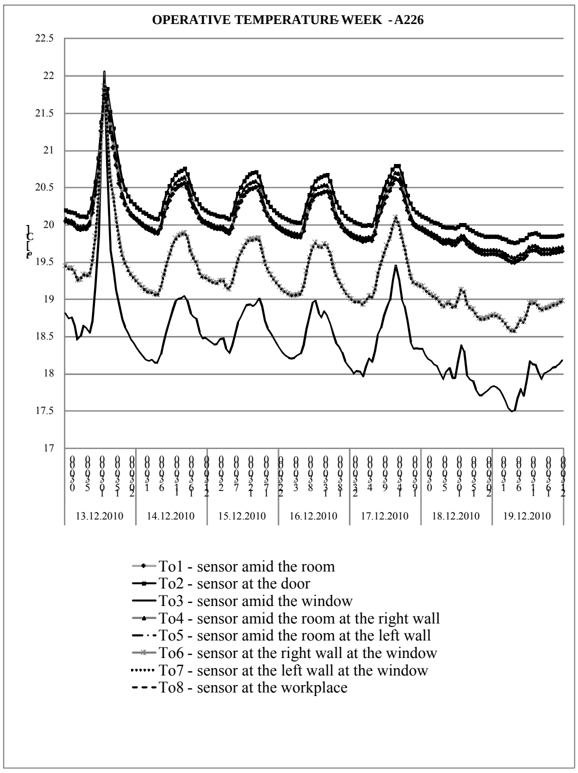

Figure 7- Operative temperature in selected sensor positions in the room "A226"

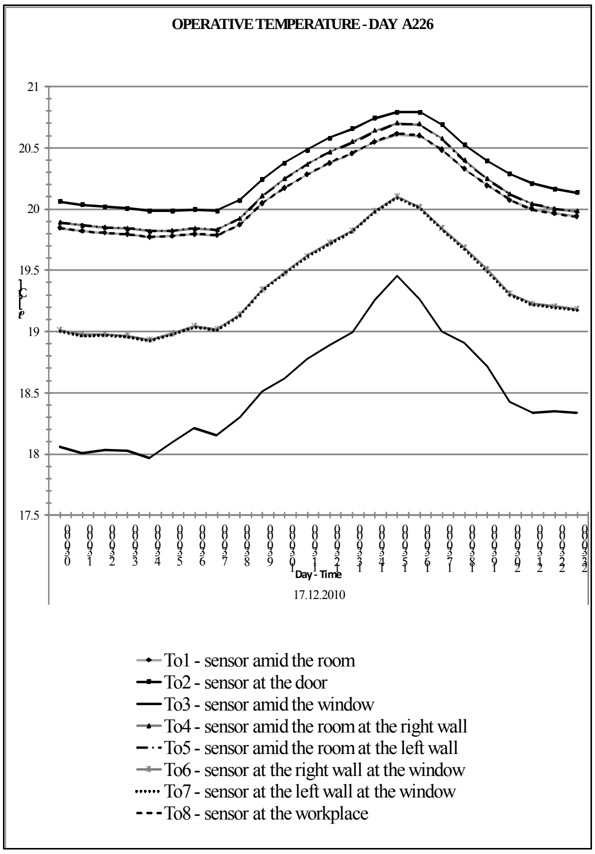

Figure 8- Operative temperature in selected sensor positions in the room "A226"

Table 3
Statistical analysis of the difference between operative temperature in different sensor positions and working place (sen_8). Avg dt_o is the average value and σ is the standard deviation of this difference.

Sensor location	A225		A226	
	Avg $t_{o,x}$ - $t_{o,8}$	σ	Avg $t_{o,x}$ - $t_{o,8}$	σ
sen_1 - sensor amid the room	0.00	0.00	0.00	0.00
sen_2 - sensor at the door	0.17	0.03	0.21	0.03
sen_3 - sensor amid the window	**-1.50**	**0.25**	**-1.58**	**0.26**
sen_4 - sensor amid the room at the right wall	0.04	0.02	0.06	0.02
sen_5 - sensor amid the room at the left wall	0.04	0.02	0.06	0.02
sen_6 - sensor at the right wall at the window	**-0.60**	**0.12**	**-0.73**	**0.12**
sen_7 - sensor at the left wall at the window	**-0.60**	**0.12**	**-0.74**	**0.12**

From the statistical analysis it is interesting to see the average value of the difference between operation temperature at the working place and the different sensor positions, as well as, standard deviation. As the values of the average difference lower than 0.5 °C are negligible, higher values (0.6 – 1.58 °C, bold in Table 3) denote the possibility of energy saving measures. In the case that the sensor will be placed in the location, where operative temperature is 1,58 °C lower, than operative temperature at the working place, the building control system will receive wrong information about the actual situation in the room. Based on this information, the control system will try to achieve the required temperature in the heated room. In the case of sufficient heating output, the result will be in the correct temperature at the sensor position, but overheating at the working place.

Table 4 presents statistical evaluation of the difference between operative and air temperature in different sensor locations. This table could support the answer to the question about the type and set-up of the sensor to be used in such a building with poor quality envelope. In all positions we can see the negative difference between operative and air temperature in the range 0.63 up to 2.54 °C. That means, that in case of standard air temperature sensor, the perceived temperature in any place of the room will be lower than the displayed (or by control system set and measured) value. Unfortunately, operative temperature sensors (globe thermometers) are not frequently used due to their robustness and construction and so this issue must be solved by a temperature offset included in air temperature sensor required value set-up. This offset should not be constant, but variable according to exposed surface temperature.

Table 4

Statistical analysis of the difference between operative and air temperature in different sensor positions. Avg t_o-t_a is an average value and σ is standard deviation of this difference.

Sensor location	A225		A226	
	Avg t_o-t_a	σ	Avg t_o-t_a	σ
sen_1 - sensor amid the room	-0.81	0.38	-0.96	0.38
sen_2 - sensor at the door	-0.63	0.39	-0.76	0.37
sen_3 - sensor amid the window	**-2.30**	**0.58**	**-2.54**	**0.58**
sen_4 - sensor amid the room at the right wall	-0.77	0.39	-0.91	0.39
sen_5 - sensor amid the room at the left wall	-0.76	0.39	-0.91	0.39
sen_6 - sensor at the right wall at the window	**-1.40**	**0.47**	**-1.69**	**0.47**
sen_7 - sensor at the left wall at the window	**-1.41**	**0.47**	**-1.70**	**0.48**
sen_8 - workplace	-0.80	0.38	-0.96	0.38

The utilised method of dynamic simulation with program ESP-r enabled to quantify impact of proposed solutions. The computer model created on a level of detail described above yields a clear picture of the condition of thermal comfort in the evaluated offices.

The above charts and tables indicate that optimal sensor placement for measuring the indoor temperature (from the perspective of energy performance) is on the following places:

- On the wall between the offices and corridor (sensor number 2), or
- Middle of the room, placed on the partition wall between the offices (sensors number 1, 4 and 5).

CONCLUSION

The presented study based on computer simulation and measurements confirmed that the differences between operative temperatures in the different locations of the room are significant. It is recommended to use an operative temperature sensor for heating system control, because air temperature does not express enough accurate information about thermal comfort. Of course, due to technical problems with the globe thermometer installation, it is acceptable to use air temperature with offset setup. Placement of the temperature sensor into a location, which is colder than working place, will increase energy use and discomfort in the room as the value measured by the sensor will indicate lower/higher temperature.

This study is the partial result of an on-going project focused on an integrated view of the building, system and control searching solutions, and technologies which, with less energy, will create a better indoor environment.

ACKNOWLEDGEMENT

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NOMENCLATURE

t_o operative temperature [°C]

t_{MRT} mean radiant temperature [°C]

t_a air temperature [°C]

h_c convective heat transfer coefficient [W/m^{2}K]

h_r radiative heat transfer coefficient [W/m^{2}K]

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