Modelling of thermal comfort in spaces with radiant heating

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ABSTRACT
The paper discusses hygiene problems of infrared radiant heating of large enclosed spaces (i.e. industrial halls) with non-uniform requirements for space and time distribution. Further, it explores computer-modelling methods for infrared radiant heating (IRRH), selection of the simulation tool, the level of the simulation detail and criterion for design optimization. The example summarizes the results of the application of this method to the industrial hall, with different requirements on indoor environment in parts of the hall. The evaluation is focused on optimization of energy consumption for heating and indoor environment, represented by the operative temperature.

INDEX TERMS
Infrared radiant heating; Industrial heating; Thermal comfort; Energy consumption; Computer modelling and simulation

INTRODUCTION
Infrared radiant heating (IRRH) is usually used for space heating of large halls. It is very common to see building designs based on the air temperature as a basic reference parameter. However, it cannot be used for infrared radiant heating systems, where we need to know the simultaneous effect of radiation and convective heat transfer modes. Operative temperature is a parameter that is usually used for evaluation of thermal comfort (Kabele and Krtková, 2000). The traditional approach to design of IRRH is based on evaluation of thermal comfort in one reference point in steady state. This method enables us to make safe design, but not optimal, because in the design phase we know nothing about the operative temperature distribution and thermal comfort in the entire hall. A new method, based on the integrated computer simulation of radiant and convective heat transfer and indoor environment evaluation, permits to optimize the heating system design according to optimization criterions.

HYGIENE OF ENVIRONMENT OF BULDINGS WITH IRRH
Temperatures, moisture and air velocity are parameters characterizing the eventual heat-moisture quality of internal environment of buildings. These parameters are possible to apprehend as an influential determinative area of subjective viewing of strain or stress and in extreme cases even as harmful pollutants with a negative impact on body health. These extreme cases are inherent especially in working places where main pollutant is heat (besides air contamination by technological causes) and it can be demonstrated by symptoms of acute disorders ensuing from heat (indisposition, headache, inadequate behaviour—hysteria, aggressiveness, apathy, etc.) in extreme cases. IRRH is healthier then warm-air heating (regarding hygiene), which has to work with indispensable air velocity. The air flux also has its hygienic criteria, but dust and other pollutants from a workplace that are stirred up by air and can get into lungs easily represent a more serious hazard. Varying noisiness is also impossible to avoid. Small fans of dark radiators have a lower level of noise.

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Czech Hygienic Rules and Recommendation for IRRH

There is no independent rule governing IRRH in the Czech Republic. The situation in the area of hygiene of workplaces with IRRH is more positive. There was a hygienic regulation of Department of Health No. 46/1978 on hygienic requirements for workplaces a short time ago. This regulation was amended on 18.4.2001 in the form of a decree of the government to a new act on health care (original act No. 20/1996). This decree of the government defines conditions of health protection during work. The amendment was compiled pursuant to the assumed European standard and rules, namely ČSN ISO 7726/93: 'Thermal Incidence of Environments, Instruments and Measuring of Physical Authority' and ČSN EN ISO 7730/99: 'Moderate Thermal Environments—Determination of the PMV and PPD Indices Specification of the Conditions for Thermal Comfort'. These regulations have brought in a new factor previously unexploited in the Czech Republic. For evaluation of thermal comfort on the basis of the amended hygienic regulation it is necessary to define the following parameters: operative temperature t_0 (°C), temperature radiant asymmetry Δt_r (°C), difference of operative temperatures between head and ankle Δt_0 (°C), air speed v_a (m/s), eventual turbulence intensity T_u (%), intensity of radiation I (W/m^2) and relative humidity rh (%). These parameters should be completed by thermal resistance of clothing R (clo) and energy expenditure M (W/m^2) if we want to evaluate hygienic requirements for thermal comfort for a certain class of the work. The energy expenditure comes up to a particular class of work (*I* to *V*) that is divided according to the demand factor of class of the work.

TOOLS FOR MODELLING OF THERMAL COMFORT IN SPACES HEATED BY IRRH

The problem of simulation of infrared radiant heating systems is the simultaneous effect of relative intensive radiation and convection heat transfer modes. The simulation tool should include not only one direction radiation from the primary heat source (usually the dark infrared radiant tube heater), but also radiation from secondary sources, like the surrounding walls and floor. Another problem is air flow modelling.

The simplest modelling tools describe this reality in two-dimensional models only, the more complex ones include a third dimension and most complex tools are based on four-dimensional reality description (space + time)—CFD. The thermal comfort approach, which not only requires the quantities and types of building materials but also the installation locations, provides a philosophy derived from delivering thermal comfort to the built environment rather than simply establishing a design air temperature (ASHRAE, 1992). The thermal comfort approach, however, is rarely applied by the design engineer; it generally requires the use of sophisticated computer algorithms. The procedure is complex because of the need to predict the radiation field in the built environment. The radiation field, which translates into thermal comfort parameters such as the mean radiant and operative temperatures, is primarily a function of the room surfaces temperatures and locations and types of windows and heating system. Consequently, the problem evolves from the typical envelope calculation to a sophisticated energy distribution calculation (Hensen, 1991).

Many techniques and standards exist to accurately size heating systems to provide a design air temperature. Little information is available for sizing and placing radiant heating system.

ESP-r

ESP-r (Clarke 1985) is the outcome of model development projects funded over the years by the UK Science and Engineering Research Council (now ESPRC) and the European Commission's DGXII. ESP-r is a transient energy simulation system that is capable of modelling the energy and fluid flows within combined building and plant systems when constrained to conform to control action. The package comprises a number of interrelating programme modules; for instance, the Climate Database Management Module, the Event Profiles Databases Management Module, the Plant Components Databases Management Module, the Simulator, the Results Analysis Module, etc. One of these modules is the View Factors Module (Sars *et al.*, 1988). This module offers the possibility to calculate view factors between each zone surface, the mean radiant temperature as a function of position in space and the vector radiant temperature, which is a vector quantity and gives information about the radiation asymmetry in a room. The calculation method used here involves a small cube at the test point. Furthermore, it is assumed that the surrounding surfaces are black and that the intervening medium does not scatter or absorb radiation (Sars *et al.*, 1988).

The Results Analysis Module enables a visual and numeric interpretation of the results. The graphical representation of an isomap of the mean radiant temperature in a room cannot be obtained. The only possible output is a graphic chart of the time history of the MRT in a certain position (ESRU, 1996). This design methodology is based on a powerful unsteady algorithm used to evaluate thermal comfort conditions under various indoor, outdoor and time design conditions (Hensen, 1991).

Hefaistos

The computer-modelling SW Hefaistos (Kabele *et al.*, 2000) can calculate three-dimensional distribution of operative temperature and intensity of radiation in spaces heated by IRRH. With this SW it is possible to optimize number, outputs and lay-out of the IR heaters so as to satisfy hygienic requirements for certain space. The physical model used in the software is fitted to describe the steady state in an enclosed hall with IRRH. The input data needed for simulation include operative temperature, geometry of the hall, thermo-technical characteristics of the envelope, the operation schedule, the thermal district, where the hall is situated, demands on ventilation, destination of the work area in the hall and description of the body's work. The output is graphical illustration of the intensity of radiation and operative temperature in a certain level above the floor including hygienic appreciation if a certain design complies or disagrees with hygienic requirements. The hygienic appreciation is illustrated in the ground projection at a certain height above the floor, where there are illustrated areas in which the requirements are executed (orange colour) or dishonoured (tints of blue colour). Each ground projection has a legend with values describing the tints of colours.

APPLICATION OF SIMULATION IN THE DESIGN OF THE INDUSTRIAL HALL IRRH

The aim was to investigate the indoor climate and optimize the start-up period of intermittent heating of the industrial hall with infrared gas dark radiant heating system (IRRH). The size of the hall was 10 × 20 × 8 m. The hall was located in the industrial zone in the climatic conditions of the Czech Republic. There was a requirement for local heating of the working places located in the centre of the hall, with the working time on weekdays 3 a.m. to 4 p.m. The required minimal operative temperature in the working area was 18°C, the radiation was not supposed to exceed 200 W/m^2.

Methodology and Modelling

To evaluate the required parameters of the energy and environmental behaviour of the designed solution of the heating system in the industrial hall, it was necessary to use more sw products. To describe the indoor climate, represented by the operative temperature and radiant flux, we used the static model Hefaistos to describe energy consumption; for time-dependent variation of the mean radiant temperature during intermittent heating we used ESP-r (Clarke, 1985; ESRU, 1996). The indoor climate was represented by the operative temperature, time-dependent variation of the mean radiant temperature and operative temperature during intermittent heating. The energy consumption was described by daily, monthly and annual energy used for heating. For the specific hall mentioned above, the infrared gas radiant heater had an output of 36 kW and was located in the centre of the hall at a height of 8 m above the floor.

Using Hefaistos, we received radiation and the operative temperature distribution chart over the floor plan hall to specify critical areas given the extreme conditions. Figure 1 shows this distribution chart at a level of 1 m above the floor of the hall. There are significant critical areas around the entrance gate and below the radiant heater. Figure 2 shows dynamic behaviour of the hall within 1 day, when the start-up period of the heating is not optimized based on results from the dynamic simulation in ESP-r.

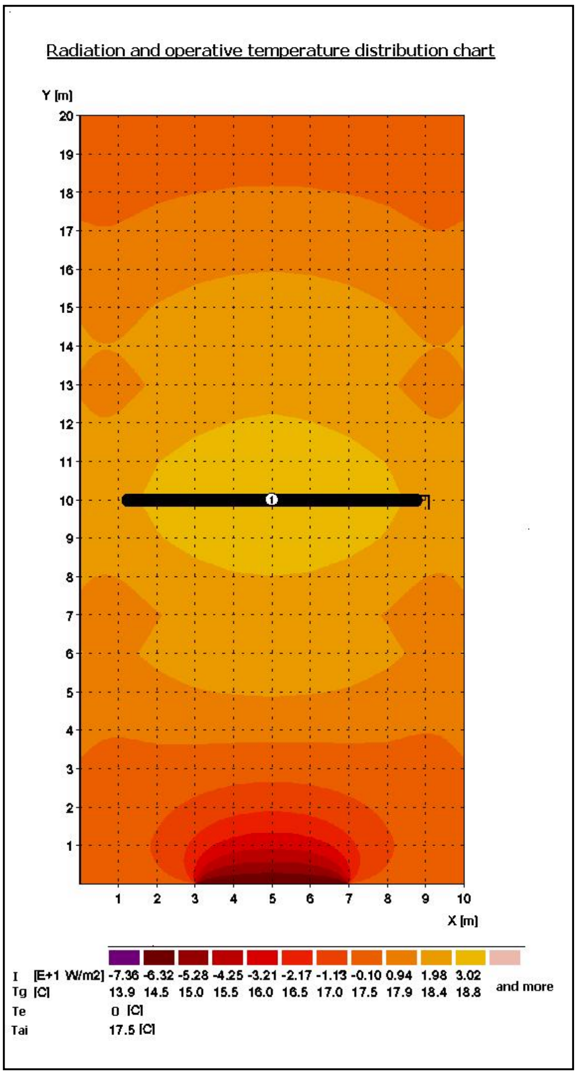


Figure 1 Distribution chart of the operative temperature (T_g) and intensity of radiation (I) on the floor plan of the hall.

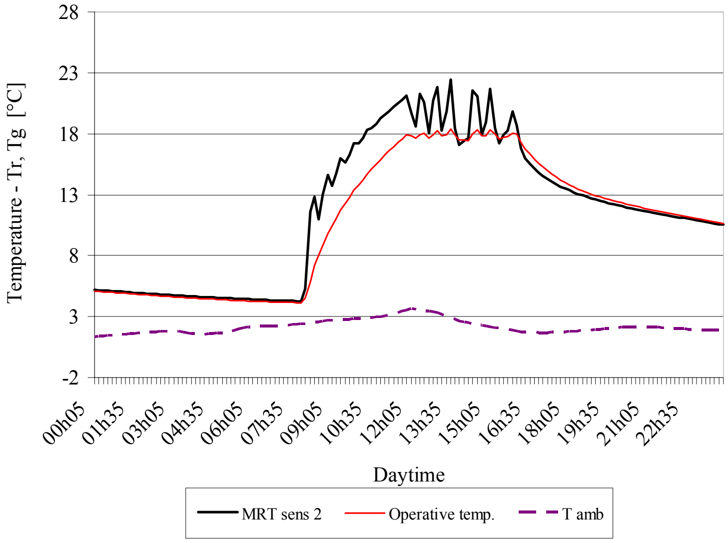
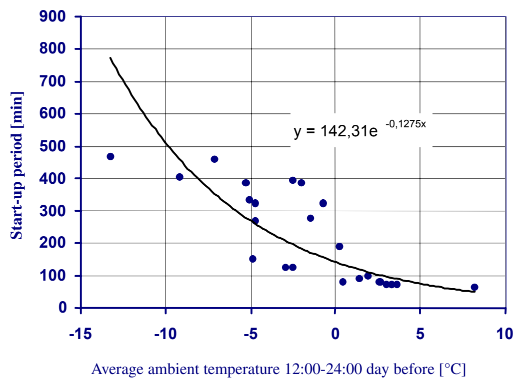


Figure 2 Dynamic behaviour of the mean radiant, operative and ambient temperatures.

For energy evaluation we used ESP-r running on Czech TRY (test reference year) climate data. A reference, basic alternative heating system operation schedule was given by the fixed start-up time and switch-off time during the whole year operation. In this alternative the dark gas heater was switched on according to the practical experience at 3 a.m. (5 h before the start time of the working period) and switched off at 4 p.m. on every weekday. The required operative temperature during the weekdays was set to 18°C, during the rest of the time (including weekends) the heating was set to the off mode. To find the annual energy consumption during the whole heating period and also during the spring and autumn time, we run the simulation during the whole year period. The heating period, used for the energy calculation in the Czech Republic, is about 220 days/annum with the average temperature +4°C. In terms of the resultant operative temperatures, we made adaptive searches for the optimal start-up period of the dark radiant



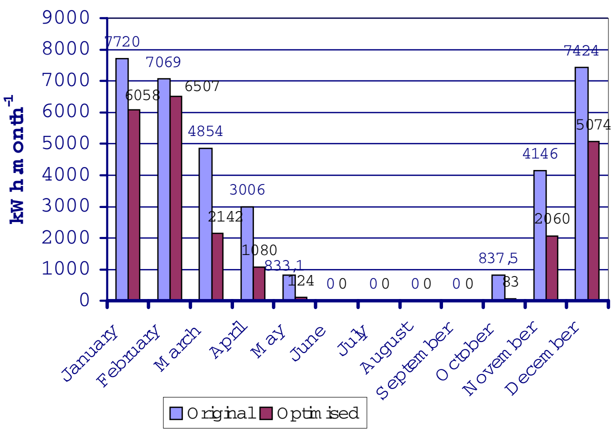


Figure 3 Start-up period after night break versus average ambient temperature 12:00–24:00 day before.

Figure 4 Heating energy consumption in the month distribution for original start-up period and for optimal start-up

heater to optimize energy consumption. This means the varying start-up period of the dark gas heater. To optimize the start-up period of the gas radiant heater, we found a relation between the time which is necessary for reaching the required operative temperature after the heating system night break and the average ambient temperature during the last 12 h. This relation was based on the simulation results, where for each day we calculated the time between the start of the heating and the time when the required operative temperature was reached. These functionalities enabled us to optimize the start-up period depending on ambient average temperature during the last 12 h (night break or weekend break) (Figure 3). For this varying behaviour of the dark heater we calculated the monthly energy consumption for the whole year period with the results as shown in Figure 4.

CONCLUSIONS

The computer simulation of infrared radiant heating systems is a tool that can help to find critical nodes of the heating system and prevent problems with indoor environment in large spaces heated with IRRH. This tool can also be used for optimization of temperature distribution in halls and for appreciation of thermal comfort for the hall's occupants. The use of the complex simulation provides the overall overview of the heated space. In terms of energy the design can be optimized to help reduce energy consumption to a minimum. Existing computer tools are aimed to span the gap between research and practical application for daily use by designers and consulting engineers.

The presented case study shows possible uses of the method to decrease energy consumption in the industrial hall, heated with dark infrared gas radiant heating, typical of this type of halls. The method of the optimized start-up period of the intermittent heating system, based on evaluation of the ambient temperature in the last 12 h, can be simply implemented into existing control devices of heating system and bring the required energy savings. In the presented case study, the expected energy savings were about 31% of the energy consumed in the base alternative. The development of application of the methods of computer simulation opens up a large space for future research in the field of optimization of the building energy performance. New control mechanisms can be embedded in the algorithms of Smart houses like in traditional heating systems.

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