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Numerical modelling of high-temperature radiant panel heating system for an industrial hall

Ioan Sarbu *, Adriana Tokar

Department of Building Services Engineering, Polytechnic University of Timisoara, Piata Victoriei 2A, 300006 Timisoara, Romania

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ABSTRACT

This paper shows how the use of the numerical modelling method of the radiant heat flux depending on the absorption and reflection coefficients and the energy transmission degree can optimise a ceramic radiant panel heating system for an industrial hall with geometrical dimensions of 80×30×8 m and heat demand of 277.3 kW using Systema software. The optimal location of the 14 ceramic panels obtained through modelling is selected so that by controlled conducting of the heat flux of 1.03 W/m^2 emitted by the radiant panels towards the working area can ensure adequate comfort. The heating system configuration flexibility enables both changing the location of radiant panels and the heat flux orientation. Thus, the operative temperature to the outdoor walls resulted in the range 19.2–19.7 °C, and the uniform operative temperature in the working area is equal to 22.6 °C in accordance with the international standards ISO 7730 and ASHRAE 55. Additionally, the expected mark (EM) value of 0.04 calculated as the ratio between the predicted mean vote (PMV) and the predicted percent dissatisfied (PPD) indexes indicates the assurance of adequate thermal comfort conditions, according to the same standards. The estimated energy consumption and operating costs show that liquefied petroleum gas utilisation is clearly the best solution with respect to methane and diesel for fuel supply of the modelled radiant heating system.

1. Introduction

Interest and growth in radiant panel heating and cooling systems have increased in recent years because they have been demonstrated to be energy efficient in comparison to all-air distribution systems (Bojic et al., 2012). The radiant panel systems are characterised by better thermal comfort levels than those of other heating systems, simplified structural systems, and few parts, which simplify the maintenance and operation and thus eliminate noise.

The ceiling panels are able to provide higher performances than those of the floor during both heating and cooling. Several studies were carried-out on this topic. Kilkis et al. (1995) developed the so-called stationary composite model for modelling of radiant systems for heating and cooling. Miriel et al. (2002) experimentally and numerically investigated performance, thermal comfort and energy consumption of low-temperature radiant ceiling panel heating/cooling systems. Okamoto et al. (2010) developed a computational model for estimating heat fluxes from radiant ceiling panels. Causone et al. (2009) investigated the assessment of heat transfer coefficients between radiant ceiling and rooms in typical conditions of occupancy of an office or residential building. Additionally, numerous studies on modelling radiant heating/cooling systems linked to thermal comfort indexes in buildings were presented by Strand and Baumgartner (2005).

Heating of large buildings together with ventilation or air conditioning represents a very important issue, which significantly affects the operation of these facilities.

The buildings used in industry are characterised 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. There is different information in the literature concerning the heating and ventilation of these buildings. Recommendations of several authors are focused on radiant heating systems by different types of radiant panels (Vio,

* Corresponding Author.
Email Address: ioan.sarbu@upt.ro (I. Sarbu)
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2011). Furthermore, by using a radiant system, it is possible to obtain similar comfort levels with less energy than the conventional system (Takeda et al., 2000). Industrial heating solutions, highly recommended for areas with large dimensions, mainly heights, are those with radiant ceiling panels (ACRE, 2000; Zajicek and Kic, 2014).

Numerous studies on radiant heating systems have followed, mostly evaluating the advantages and disadvantages of this type of heating system and comparing them with traditional convective heating systems. In general, these studies proved that radiant heating systems offer the potential of (1) reduced heating unit sizes (due to reduced heat load and peak load), (2) reduced energy consumption (DeWerth and Loria, 1989; Howell and Suryanarayana, 1990; Imanari et al., 1999; Petras and Kalus, 2000; Feng et al., 2006) and (3) favourable tie-in capabilities with low-temperature and low-intensity energy sources such as solar systems and heat pumps (Kilkis et al., 1995) (4) while maintaining acceptable thermal comfort (Imanari et al., 1999).

Some international standards as ISO (2012) and EN (2008) can be used for design, dimensioning and installation of embedded radiant heating systems (ISO, 2012). Additionally, a variety of approaches can be used to determine the sizing of a radiant panel system (DeWerth and Loria, 1989). However, there is not yet a specific standard for design and positioning of ceramic radiant panel heating systems. In general, designers often rely on the calculation techniques provided by the manufacturers of radiant panels on how to estimate the number of units that one can install in a given space. There are, however, several studies that give recommendations on how to design (e.g., dimensions and number of units) heating systems (Howell and Suryanarayana, 1990) and how to position the radiant panels (e.g., installation height, inclination angle, etc.) to produce thermal comfort conditions (Dudkiewicz and Jeżowiecki, 2009).

This paper shows how the use of the numerical modelling method of the radiant heat flux depending on the absorption and reflection coefficients and the energy transmission degree can optimise the ceramic radiant panel heating system for an industrial hall using software Systema (2012). The optimal location of the ceramic panels is selected so that by controlled conducting of heat flux emitted by the radiant panels towards the working area to ensure the adequate comfort. The heating system configuration flexibility enables both to change the location of radiant panels and the heat flux orientation. The zone control of radiant temperature allows obtaining a specified temperature on the heated surfaces. To obtain the optimal system, on the simulated thermal maps, the surfaces and isothermal lines that correspond to mean radiant and operative temperatures will be highlighted. These temperatures should be according to International Standards ISO (2005) or ASHRAE (2010). Additionally, an expected mark (EM) ratio between the predicted mean vote (PMV) and the predicted percent dissatisfied (PPD) is calculated to assess the fulfilment of thermal comfort conditions, according to the same standards. Finally, the energy consumption and operating costs are estimated for three fuel types used by the modelled radiant heating system.

2. Description of high-temperature radiant heating system

Radiant heating application is classified as panel heating equipment if the panel surface temperature is below 150 °C (ASHRAE, 1996). Panel heating equipment provides a comfortable environment by controlling surface temperatures and minimising air motion within a space. Sensible heating panels transfer heat through temperature-controlled (active) surface(s) to or from an indoor space and its enclosure surfaces by thermal radiation and natural convection. A radiant system is a sensible heating system that provides more than 50% of the total heat flux by thermal radiation. In thermal radiation, heat is transferred by electromagnetic waves that travel in straight lines and can be reflected.

Radiant panels have lower thermal mass, which means they cannot store the same amount of heating energy, but they can respond to rapid fluctuations that occur due to changes in the internal and external heat load. Therefore, radiant panels are more suitable for buildings with spaces that have a greater variance in heating and cooling loads.

The main purpose of heating industrial spaces is to provide an indoor environment that is generally acceptable and does not impair the health and productivity of the occupants. Given the large variety of radiant heating systems, the selection of the optimum heating solution is very important depending on the specifics of technological process and environmental comfort. Currently, considerable research is being devoted to finding the most energy-efficient method for space heating while maintaining acceptable thermal comfort conditions. One system that has recently been given attention is the use of ceramic radiant panels or infrared radiant (IR) heaters that can be powered by natural gas, liquefied petroleum gas (LPG), diesel or electricity. If correctly designed with consideration for all the standard parameters, radiant panel heating systems can provide optimal microclimatic conditions within the entire heated space.

Radiative transfer between the occupant and surrounding surfaces benefits from the difference in the fourth power of the temperatures compared to the heat exchange by convection between the occupant and the adjacent air, which varies linearly with temperature difference (Ardehali et al., 2004).

In general, the required area for heating with panels is reduced as panel heating surface temperature increases, e.g., 49% of the ceiling area was covered with radiant panels with a surface temperature of approximately 49 °C, while 20% was covered with radiant panels with a surface temperature of 82 °C (Howell and Suryanarayana, 1990).

There are several methods to evaluate the performance of a radiant panel. One method is the computation of total heat flux from radiative and convective heat transfers, which can be computed both numerically and with the use of empirical relations that account for the radiative and convective heat transfer from a panel with a homogeneous surface temperature (Ardehali et al., 2004). With radiant ceiling panels, both radiation and convection constitute the major mode of heat transfer from the surface of the panels to the air space being heated. A higher panel surface temperature results in a lower combined flux (radiative and conductive) from the panel for a given ambient temperature. Moreover, this combined flux for the panel increases with increasing ambient temperature (Ardehali et al., 2004).

The constructive and operational conditions of the industrial spaces determine the selection of radiant heating systems from among the following types:

(1) Low-temperature radiant panels are recommended for space heating with low height and intermittent utilisation mode;
(2) High-temperature radiant panels are recommended for large space heating with medium heights and intermittent utilisation modes;
(3) High-temperature ceramic panels are recommended for large space heating with medium to high heights and intermittent utilisation mode.

The particularity of ceramic radiant panel heating systems is that local heating can be achieved specific to technological needs and can be used with maximum efficiency for local heating in open spaces. Because of the low thermal inertia, these systems are recommended for production space heating with intermittent occupancy.

A radiant panel type radiant ceramic system (SCR) operating with gas (Fig. 1) has a porous ceramic emitter designed to operate in the 800 to 900 °C temperature range.

Fig. 1: A radiant panel SCR

The pre-mixing chamber of the panel burner has a high efficiency and offers the possibility to adjust the thermal power. This fact leads to the increase of radiative heat transfer efficiency. Radiant efficiency of gas radiant heating is 83%. Inside the pre-mixing chamber of the burner, an air filter or tubing can be mounted to exhaust the air-gas mixture. The air-gas combustion system has a fan with rotational speed and a gas solenoid valve that ensures the gas pressure stabilisation. The thermal efficiency of this system increases due to the presence of grid resistance to high temperatures. Ceramic plates and grids at high temperature emit infrared radiations that are directed by the reflectors towards the receiver surfaces to be heated. With the reflector options available, they may be mounted at a variety of mounting heights and angles for a wide selection of heating applications, including control options that allow for heater installation where no power supply is available. Automatic control of this heating system self-adjusts thermal power of the burner depending on environment thermal balance and keeps indoor air temperature constant.

The radiation can be directed to the heated area by the geometric orientation of the radiant panel. When the panels are mounted, a slope of 30° to the horizontal for small panels and of 15° for large panels must be ensured. The safety area establishment is achieved by computing the temperature field around the panel.

Radiant heat flux q, in W/m^2, from panel on a receiver surface is expressed in equation (ASHRAE, 1996; Sarbu and Sebarchievici, 2015):

$$q = \sigma a\left(T_p^4 - T_r^4\right) \quad (1)$$

where $\sigma = 5.67\times10^{-8}$ W/(m^2·K^4) is the Stefan-Boltzmann constant; a is the radiation exchange factor (dimensionless) with the assumed value of 0.8; T_p is the absolute temperature of the radiant panel, in K; and T_r is the absolute temperature of the receiver surface, in K.

Providing a uniform radiant heat flux is one of the radiant heating issues. Uniformity of radiant heat flux depends on the radiant panel surface temperature uniformity because the heat flux transmitted by radiation is an exponential function of 4th order of the panel temperature. The radiation intensity is mostly influenced by the radiant panel temperature, but it is also influenced by the angles of heat flux vector and the distance between the receiver and emitter surfaces.

To select and to design the heating system, the heat demand that provides thermal comfort parameters in heated space must be determined. The heat flux exchanged through the building elements with the neighbouring environments can be determined by combining conductive, convective and radiative fluxes (Kusuda, 1977; Bradshaw, 2006) due to the envelope structure.

The heat demand Q_{req}, in W, for a space represents the sum between the total heat lost through the building envelope (Q_t) and the required heat for heating the outdoor air (Q_a), and it is determined with the following equation (SR, 1997):

$$Q_{req} = Q_t\left(1 + \frac{A_c + A_o}{100}\right) + Q_a\left(1 + \frac{A_c}{100}\right) \quad (2)$$

where A_c is the addition for compensation of cold surfaces with the assumed value of 4, and A_o is the addition for orientation with the assumed values of –5, 0, and +5 depending on orientation South, East or West, and North, respectively of the external walls.

The main purpose of most buildings and installed heating and air-conditioning systems is to provide an environment that is acceptable and does not impair health and performance of the occupants. Criteria for an acceptable thermal climate are specified as requirements for general thermal comfort (PMV-PPD index or operative temperature) and for local thermal discomfort. Such requirements have been found in standards such as ISO (2005) and ASHRAE (2010). The optimal operation of a heating system requires proper design of each system component, reflected in thermal comfort and economical operation (Negoitescu and Tokar, 2010).

Technological developments in sensors and microprocessors make a higher standard of comfort control possible using radiant heating systems. Sensors have recently become more reliable and relatively inexpensive as they become mass-produced. The same is true with microprocessors, which allow more sophisticated decision-making and can use expert system methods for selecting and operating the most appropriate system at its optimum performance (Scheatzle, 1996). Studies in this field had been performed to incorporate thermal comfort parameters in the control loop to ensure an acceptable and stable indoor environment with the lowest energy consumption possible. Two major concepts of control have come from these studies: PMV control and operative control.

The predictive mathematical model, which was based on the PMV index, developed by Sarbu and Sebarchievici (2013) can be used to design a device for controlling comfort, hence referred to as a comfortstat. Similar to a thermostat, a comfortstat would maintain conditions within a range of acceptable values. Both the air temperature and the mean radiant temperature of a space should be taken into account when assessing occupant thermal comfort. The combined influence of these two temperatures is expressed as the operative temperature. A control system can also be designed based on operative temperature alone.

3. Numerical modelling of ceramic radiant ceiling panel heating system using Systema software

3.1. Description of the modelled industrial hall

For the research presented in this paper, the ceramic radiant panels 25M SCR under consideration are used to heat an industrial hall with geometrical dimensions of 80×30×8 m (Fig. 2) built with sandwich panels and with a floor made of concrete, located in Timisoara, Romania. The latitude and longitude of the city are 45°47' N and 21°17" E, respectively.

The radiant ceiling is equipped with several ceramic plates. The following data are known: the thermal transmittances (U-values): walls (10 cm sandwich panel) 0.175 W/(m^{2}K), ceiling (25 cm sandwich panel) 0.071 W/(m^{2}K), floor (20 cm concrete) 0.145 W/(m^{2}K), windows 1.1 W/(m^{2}K), and doors 0.175 W/(m^{2}K); glass wall surface, 143.2 m^2; indoor air temperature, 16 °C; outdoor air temperature, –15 °C; air exchange rate, 0.5 h^{-1}; and heat demand, 277.3 kW. The heating system operation period is equal to 10 h/day. The workstations are located at 1 m from the floor level.

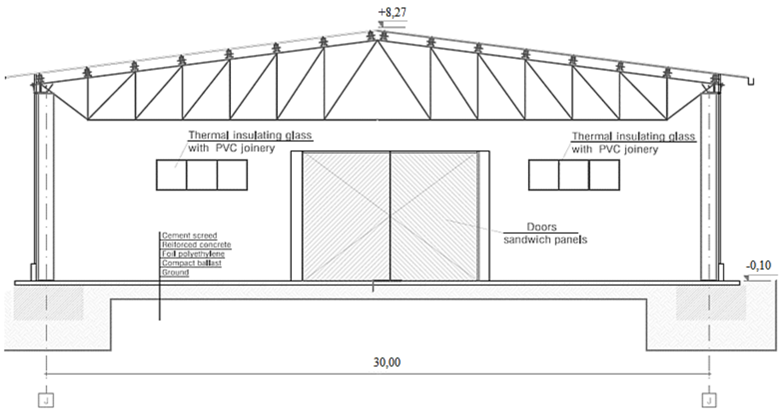


Fig. 2: Heated industrial hall

The activities of polyester filler/fibreglass putty application, sanding with abrasive paper, and technical quality control occur in the industrial hall. The polyester filler application operation is executed manually, and the sanding operation is performed mechanically with electric or pneumatic orbital sanders. Therefore, a discontinuous activity is performed inside the industrial hall with workstations changing. This fact requires a local heating system for the workstation areas (e.g., an automotive service). To obtain the optimal constructive solution for heating systems of the industrial hall the heat flux of ceramic panels is modelled using a specialised programme Systema (2012) for designing of radiative panels, by change of the radiant panels' location. The simulation of the radiant heating systems was carried out to choose the optimum system as to avoid the air stratification phenomenon, both horizontally and vertically.

3.2. Numerical simulation results

Based on the input data, the constructive solution of SCR 25M heating systems was generated by the computer programme Systema, as illustrated in Fig. 3. The design is obtained from a formal optimisation approach.

It is noted that to cover the heat demand, the computer programme generated 14 ceramic radiant panels, each having a maximum thermal power of 24 kW and minimum thermal power of 12 kW, to be placed so that the cones of temperature provide a uniform temperature at the ground level. To avoid heat losses caused by the direct radiation reaching the wall, it is necessary that the radiant panels be placed towards the central area of the modelled space at a height of 7 m.

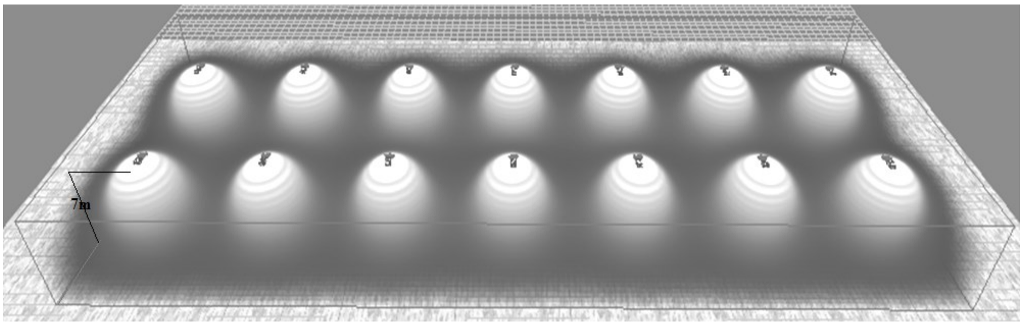


Fig. 3: Location of ceramic radiant panels for the considered model

The optimal location of the radiant panels provides acceptable uniformity of heat flux density maintaining a nearly constant temperature. Thus, the entire model surface contains no records of major and sudden temperature variations.

The software integrates the heat flux of the radiant panels on all radiant and receiving surfaces by taking into account the radiation angles and distances between the two surfaces.

To obtain the optimal constructive solution from the heat flux uniformity point of view, this was modelled by changing the radiant panels' position.

In Fig. 4, it can be observed that within the burner-panel system area where the temperature is very high, the radiant power (radiant flux) is also high, and the temperature decreases as the area is far from the burner-panel system area. This reduction is recorded based on an exponential function of the 4th order of the heat flux according to Eq. 1. The levelling of the heat flux transmitted by radiation can be accomplished by changing the radiant flux vector orientation so that the area characterised by the most intense radiation overlaps the weaker radiation area. Thus, an average intensity will be obtained.

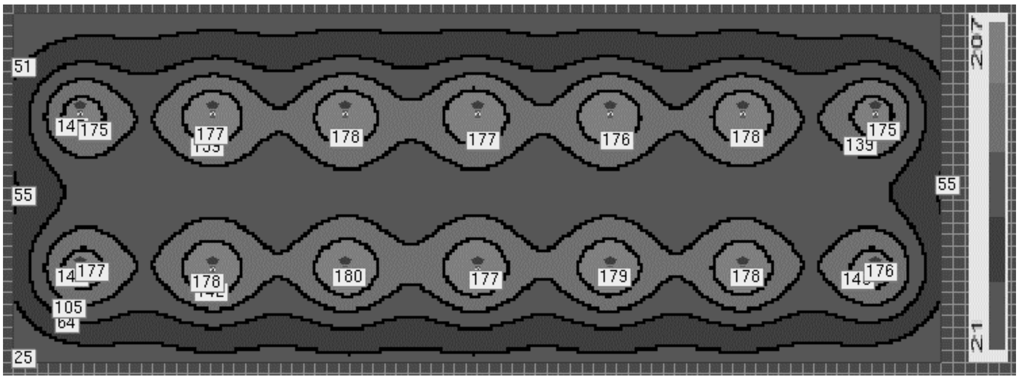
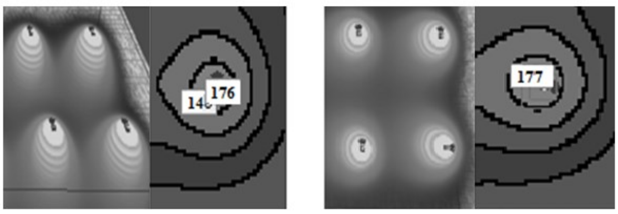


Fig. 4: The radiant power at a height of 7 m, in W

Fig. 5 illustrates the radiant power modelling by changing the heat flux vector orientation. One can notice a change in the radiant power distribution and its increase by 1 W as a result of changing the radiant panel position from north (Fig. 5a) to east (Fig. 5b). If it is necessary to establish higher intensity of radiation within the flux low intensity area, another possibility to change the radiant power can be achieved by the intercalation of some radiant panels in order to ensure the radiant flux difference.



a) b)

Fig. 5: Radiant power modelling by changing the radiant flux vector orientation: a) radiant panel North orientation; and b) radiant panel East orientation

For an area of 2,400 m² of the modelled space, establishing a number of 14 radiant panels presumes that each of these panels covers an area of approximately 172 m². Fig. 4 shows that each burner radiant power is approximately 177 W, so that the heat flux on the ground is 1.03 W/m².

The temperature distribution is obtained by simulating the thermal field inside the modelled space. The discretisation was performed with finite plane elements. To obtain the optimal system on the simulated thermal maps, the surfaces and isothermal lines that correspond to operative and mean radiant temperatures (Figs. 6 and 7) were highlighted. The included domains in Figs. 6 and 7 are the work plane and radiant panel plane at a height of 7 m, respectively.

On the thermal maps, the grey shades represent the temperature variation. The darkest shades correspond to lower temperature values and the light shades to the highest temperature values. Thus, there can be observed five isothermal surfaces, separated by isothermal curves. The spectral bands that represent the temperature range in which the system provides the required temperature are also shown.

The location of heating panels was simulated to avoid the occurrence of the asymmetric thermal radiation. From Figs. 6 and 7, it can be observed that the air temperature variation between the workstation level (operative temperature) and radiant panel plane (radiant temperature) are not vertical temperature differences higher than 10 °C. The maximum floor-to-ceiling temperature stratification is approximately 0.7 ºC/m. The surface temperature of the floor shall normally be between 19 ºC and 26 ºC.

The operative temperatures in all points of the isothermal surfaces are within the range specified by international standard ISO (2005). Thus, the operative temperature to the outdoor walls range is 19.2-19.7 °C, and the uniform operative temperature in the working area is equal to 22.6 °C.

It can be noted that some shape differences of the thermal fields occur at the hall marginal points as a result of the non-uniform radiant thermal transfer.

3.3. Validation of simulation model

The used simulation model performance was evaluated using three statistical indices: the coefficient of multiple determinations (R^2), the root mean square error (RMSE) and the coefficient of variation (CV), as defined below (Bechthler et al., 2001; Dawson et al., 2007). There indices were used to compare simulated and measured (actual) values of the air temperature.

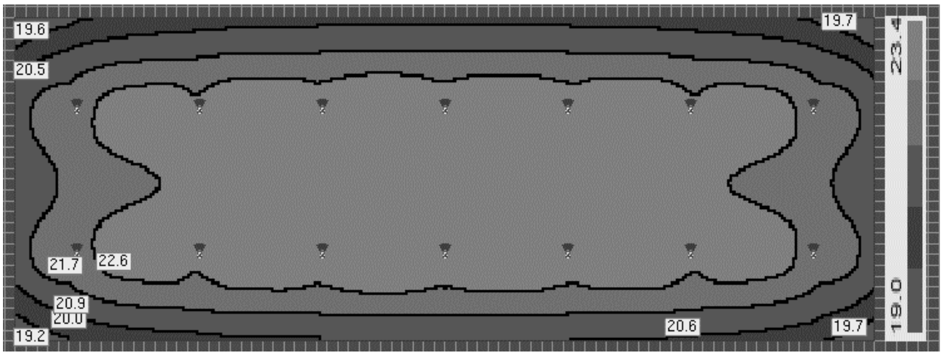


Fig. 6: Operative temperature distribution, in °C

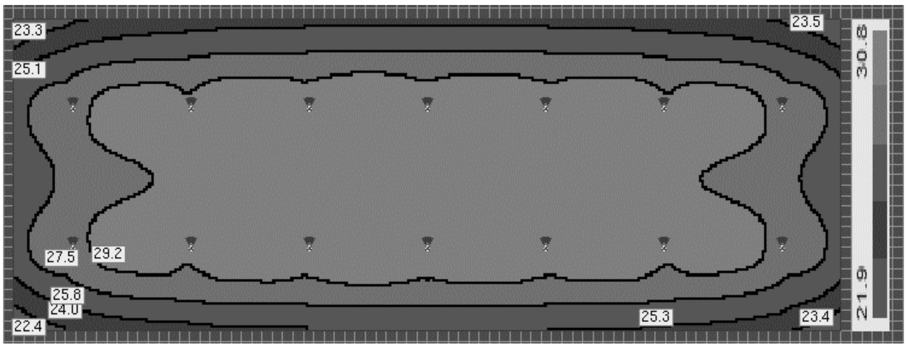


Fig. 7: Mean radiant temperature distribution, in °C

The coefficient R^2 presents the overall agreement between measured and simulated time series and varies from 0 for a poor model to 1 for a perfect model.

The coefficient of multiple determinations R^2 is expressed as:

$$R^2 = 1 - \frac{\sum_{j=1}^{n}\left(y_{sim,j} - y_{mea,j}\right)^2}{\sum_{j=1}^{n} y_{mea,j}^2} \tag{3}$$

where n is the number of measured data in the independent data set; $y_{mea,j}$ is the measured value of one data point j; and $y_{sim,j}$ represents the simulated value.

The RMSE is a measure of overall performance across the entire range of the data set. It is expressed as:

$$RMSE = \sqrt{\frac{\sum_{j=1}^{n}\left(y_{sim,j} - y_{mea,j}\right)^2}{n}} \quad (4)$$

greater or equal to 0, the RMSE shows a perfect model fit when it equals 0.

The CV (in %) can be interpreted as an order of magnitude of the repeatability relative standard uncertainty. It is expressed as:

$$CV = \frac{RMSE}{|\bar{y}_{mea,j}|}100 \quad (5)$$

where $\bar{y}_{mea,j}$ is the mean value of all measured data points.

The vertical air temperature values computed with the simulation model are compared with in situ measured values on a SCR 25M radiant heating system for an industrial hall with the structure and equipment characteristics from the previous calculation example.

Experimental data were acquired in the winter of 2015. Experimental measurements were performed under real conditions, during working hours in the industrial hall, and for a continuous operation time of 10 h/day. The air temperatures measured in the same time on different high (from 0.5 to 0.5 m between the floor and ceiling) using a meter rule and a TESTO 454 instrument with an accuracy of 0.1 °C are represented by the average of three measurements. The maximum deviation between the extreme measured values was 0.15 °C.

The reported results are plotted in Fig. 8 and they show a good agreement between the experimental temperature measurements and the simulated values. Statistical values such as R^2, RMSE, and CV are 0.99998, 0.100, and 0.42%, respectively, which can be considered as very satisfactory. Additionally, the CV value is lower than 1% and this repeatability under stable experimental conditions is excellent. Thus, the simulation model was validated by the experimental data.

3.4. Thermal comfort assessment

Assessment of thermal comfort in the industrial hall is performed using the PMV–PPD model (Sarbu and Sebarchievici, 2013). The PMV index is a multi-condition parameter, where the air temperature, air velocity, globe temperature, metabolic rate, clothing and relative humidity are taken into consideration and through a determined mathematical equation quantifies the thermal comfort to a scale from –3 (cold) to +3 (warm) (Fanger, 1970). The following data are known: indoor air temperature, 16 °C; mean radiant temperature, 29.2 °C; operative temperature, 22.6 °C; air velocity, 0.1 m/s; relative humidity of air, 60%; metabolic rate, 125 W/m² (standing, medium activity); and clothing thermal resistance 1.0 clo (normal clothes).

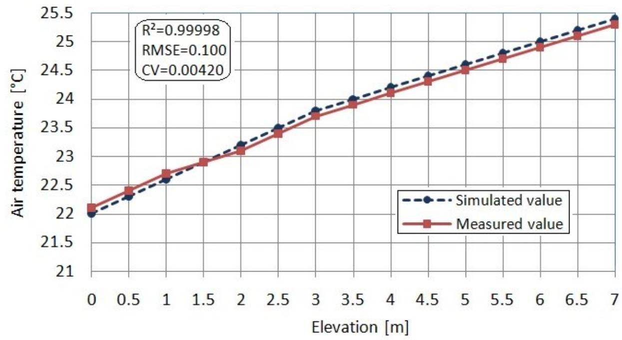


Fig. 8: Vertical air temperature variation

Systemas software provides the PMV variation for the modelled space. A PMV value of 0.94 is obtained in the working area, to which a PPD value equal to 22.2% corresponds on the thermal comfort curve.

It can be found that the EM ratio between the PMV and the PPD is equal to 0.04. This value provides general thermal comfort conditions in accordance with the standard ISO (2005). In terms of heat balance, on the thermal sensation scale with seven levels (ASHRAE, 2005), the PMV is within the neutral–slightly warm range. The PPD variation for the modelled area is illustrated in Fig. 9.

3.5. Energy and economic analysis

The energy-economic analysis was performed by considering three types of fuels, namely: methane, LPG, and diesel. To establish the optimal solution, the computer programme Systemas estimated the fuel annual consumption (Fig. 10) and operating costs (Fig. 11).

From this analysis, it can be observed that for providing the heat demand, the highest consumption is recorded for methane (10,210 m³) with an annual cost of 9699 € and the smallest for LPG (7495 m³), with an annual cost of 5247 €. On the other hand, the price of LPG is lower than the other fuels. Additionally, during the first two years of operation, the economic efficiency of the systems is similar with any fuel. The differences appear in long-term utilisation of the systems.

Although all the above-mentioned fuels provide the radiant flux required for the heating of modelled industrial hall, however, LPG utilisation is more advantageous because the pollutant emissions are much lower as a result of its combustion.

Additionally, the radiant efficiency defined as the ratio between radiant heat flux and combined heat flux (thermal radiation and natural convection) has the highest simulated value of 83% in comparison with the situations from several European countries (e.g., UK and Germany) (Neville, 2016), which already introduced in their legislations the obligation for modern gas-fired radiant heating systems to have radiant efficiency minimum acceptable values of 60%.

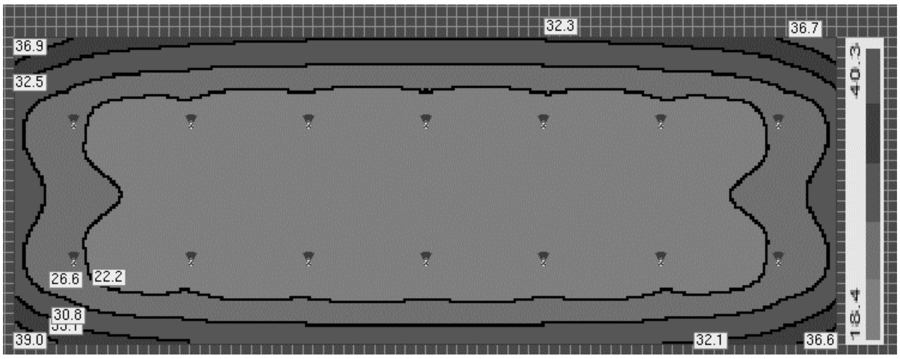


Fig. 9: Predicted percent dissatisfied variation

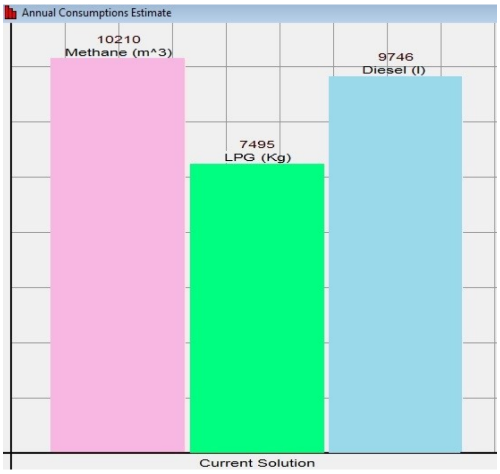


Fig. 10: Fuel annual consumption

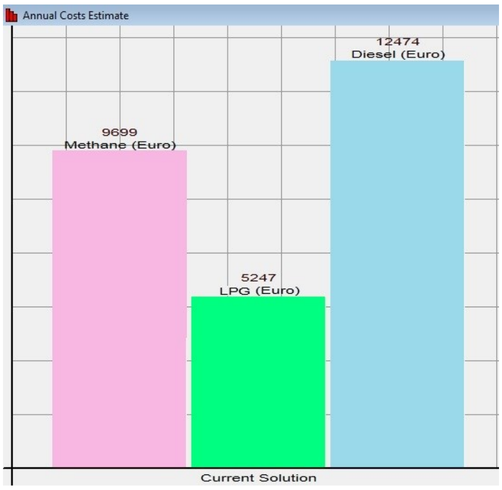


Fig. 11: Annual operating cost

4. Conclusion

Radiant ceiling panel systems are similar to other air-water HVAC systems with respect to the arrangement of its components. The important difference is that space thermal comfort is maintained primarily by radiant heat transfer instead of convective heat transfer.

After numerical modelling of the ceramic radiant panel heating system, it results in 14 radiant panels inside the modelled space. Based on the input conditions imposed to obtain a uniform radiant heat flux, the ceramic panel's layout is the optimum solution sustained also by the uniform distribution of operative temperature on the operation surfaces.

The numerical simulation results show that the considered heating system ensures the required thermal comfort parameters (e.g., PMV value is in neutral-slightly warm range on the thermal sensation scale). Although all the above-mentioned fuels provide the radiant heat flux for space heating, however, LPG utilisation is more advantageous because the pollutant emissions are much lower as a result of its combustion.

The economic analysis emphasises the advantage of using LPG due to more reduced fuel consumption and cost, and the larger reduction in concentrations of pollutant emissions.

The analysed radiant heating system is sourced with individual operation. This fact is an advantage because heat can be provided only for operational workstation areas when activities are not at full capacity. Thus, significant reductions in terms of fuel consumption and operation cost can be obtained.

A radiant heating system is a much more efficient means of heating an environment than a forced flow system. The actual amount of energy saved is dependent on many factors including how well the building is insulated, the building size, and the climate the building is located in.

Future investigations should be performed to examine other high-temperature heating systems and their combinations.

Acknowledgment

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