Finite element analysis of radiant heating systems based on gas-fired infrared heat emitters

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Abstract. The article presents a finite element model for simulating a gas-fired IR radiation system. Simulation of gaseous combustion and discrete ordinates radiation model were used to solve a number of heat-transfer problems in ventilated rooms with radiant heating. We used Ansys Multiphysics software and Fluent CFD solver for implementing finite element analysis. To solve differential equations of heating and gas dynamics, the following boundary conditions were considered. Dry methane was used as the fuel and air with 21% of oxygen, as oxidizer. Fuel consumption was 0.5 m3/hour; the gas pressure before the nozzle was 1270 Pa. The air–fuel ratio was 9.996.

1 Formulation of the problem

Large-scale production buildings can only be effectively heated by modern radiant heating systems based on gas-fired infrared heat emitters [1, 2]. However, high operating temperatures of emitter ceramic surfaces create a number of shortcomings [3, 4].

We used Ansys Multiphysics software and Fluent CFD solver to implement finite element analysis [3]. The goal of this analysis was to establish a correlation between experimental and finite element temperatures in reference points of gas-fired infrared heat emitters. A discrete ordinates radiation model simulating gaseous combustion was used to solve a number of heat-transfer problems in ventilated rooms with radiant heating.

$$\frac{dI(\vec{r},\vec{s})}{ds}+(a+\sigma_s)I(\vec{r},\vec{s})=an^2\frac{\sigma T^4}{\pi}+\frac{\sigma_s}{4\pi}\int_0^{4\pi}I(\vec{r},\vec{s}^{\,\prime})\Phi(\vec{s}\cdot\vec{s}^{\,\prime})d\Omega^{\prime} \tag{1}$$

where ŕ = position vector; ŝ = direction vector; ŝ’ = scattering direction vector; s = path length; a = absorption coefficient; n = refractive index; σ_s = scattering coefficient; σ = Stefan-Boltzmann constant; I = radiation intensity; T = local temperature; Φ = phase function; Ω = solid angle.

To solve differential equations of heating and gas dynamics, the following boundary conditions were considered. Dry methane was used as the fuel and air with 21% oxygen, as

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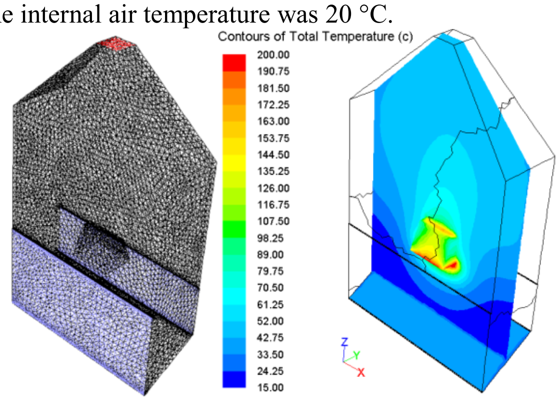
oxidizer. Gas-fired infrared heat emitters with heat output of 5, 10, 15, 20, 30, 40 kW were studied. The gas pressure before the inlet nozzle was 1270 Pa. The air-fuel ratio (AFR) was 9.996.

A gas-fired infrared heat emitter is made of steel 12Cr18Ni10Ti of 2 mm with thermal conductivity coefficient, $\lambda=0.018\cdot T+9$ W/(m·K); specific heat capacitance is $c=-2\cdot10^{-4}\cdot T^2+0.45\cdot T+324.5$ J/(kgK)

The finite element model with grid and partitions is shown on Fig. 1. Tetrahedron is adopted as a finite element with 287403 cells. The gas-fired infrared heat emitter and computational domain of the heat transfer are CFD cell-zones with double walls at the contact points. On the walls bounding computational domain the third order heat transfer conditions are set. The internal air temperature was 20 °C.



(a) (b)

Fig. 1. The finite element model with grid (a) and partitions (b) colored by temperature (°C).

2 Results of the study

Along with the standard gas-fired infrared heat emitter (Fig. 2, a) with a reflector made of polished stainless steel the following technical solutions were considered. A gas-fired infrared heat emitter with a low thermal conductivity coefficient of the reflector insulation (Fig. 2, b); a gas-fired infrared heat emitter with water cooling of the reflector (Fig. 2, c).

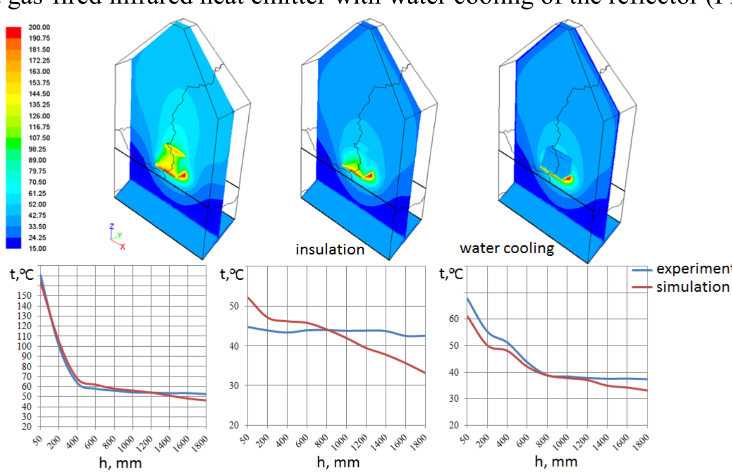


Fig. 2. Temperature contours (°C) of a standard, insulated and water-cooled gas-fired infrared heat emitter with thermal power of 5 kW and its comparison with the experimental data (charts).

The results of the mathematical modeling of heat and mass transfer in a turbulent reaction medium with a combustion reproduce the experimental data produced by a measurement in real operating conditions of the gas-fired infrared heat emitter (see Fig. 2). According to the model, the temperature of the radiating ceramic tiles for all investigated emitters did not depend on the performance of the reflector and was 900 °C (Fig. 3). This leads to the conclusion that the performance of the reflector does not affect chemical processes and combustion.

Detailed temperature contours of the ceramic tiles (Fig. 3) enable estimation of the diffusion and reaction zone dimensions. The diffusion of the fuel jet into the air stream occurs in a special mixing chamber over the ceramic tiles of the gas-fired infrared heat emitter. Therefore, fuel is mixed with air before entering the holes in the ceramic tile. Air-fuel mixture moves in these cylindrical holes, heats and ignites forming the narrow laminar combustion front. The maximal combustion rate is observed at the outlet of the cylindrical holes.

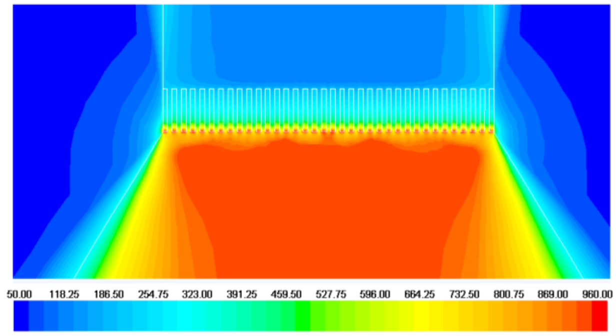


Fig. 3. Temperature contours (°C) in the longitudinal section of the ceramic tiles of the gas-fired infrared heat emitter.

To verify the fulfillment of thermal comfort conditions, the distribution of the intensity of thermal irradiation of the working area was calculated. The maximum local heat fluxes of infrared irradiation in the working area should not exceed 150 W/m^2. For the parameters studied, this condition corresponds to the following heights: for 5 kW height is 4 m (119.3 W/m^2); for 10 kW height is 6 m (106.1 W/m^2); for 15 kW height is 7 m (116.9 W/m^2); for 20 kW height is 8 m (119.3 W/m^2); for 30 kW height is 9 m (114.6 W/m^2); for 40 kW - 10 m (148.2 W/m^2). The most uniform intensity of irradiation of the working area is ensured by installing a number of gas-fired infrared heat emitters with an equal thermal power at the distance mentioned above. The value of heat flux for such a radiant heating system is 25% higher than a single gas-fired infrared heat emitter (Fig. 4). It has been established that the higher gas-fired infrared heat emitter location causes the more uniformly distribution of local heat fluxes in the working zone and its lesser magnitude in the epicenter of irradiation.

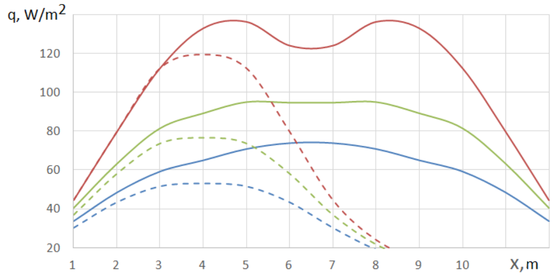


Figure 4. Local heat fluxes q (W/m^2) of thermal irradiation in the working area.

4. Conclusion

The results of studies based on bench tests and mathematical modeling:
- discrete ordinates radiation and gaseous combustion mathematical simulation are suitable for description of high-temperature gas-fired infrared heat emitters elements interaction;
- the temperature of the radiating ceramic tiles for all investigated emitters was 900 °C and did not depend on the performance because the reflector does not affect chemical processes and combustion;
- the most energy efficient way to heat large-scale production buildings is to use modern radiant heating systems based on gas-fired infrared heat emitters with an equal thermal power at the distances 4, 5, 7,.8, 9, 10 for 5, 10, 15, 20, 30, 40 kW of heat output respectively;
- virtual prototypes of high-temperature gas-fired infrared heat emitters based on discrete ordinates radiation model enable assessment of its efficiency; the value of heat flux for proposed radiant heating system is 25% higher than a single gas-fired infrared heat emitter.

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