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MATHEMATICAL AND PHYSICAL MODEL OF THE MIXERS OF AIR/FUEL AND OXYGEN ENRICHED AIR/FUEL BURNER

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The effect of mixing of natural gas with air and oxygen enriched air as the oxidising agents is described in this paper. The theoretical basics of the oxy/fuel combustion and the effect of increasing of oxygen content in the oxidising agent on the flue gas composition and theoretical temperature at natural gas combustion are briefly described. The burner of 2 kW thermal power with two types of mixing devices was designed. The mixing devices were tested using the mathematical model formulated on the basis of CFD-software and monitoring the flame temperatures on the physical models. In order to achieve a better comparison of the mixing devices, only their geometry were being modified, while the input parameters such as the mass flow of natural gas and oxidants remained the same. Using CFD modelling the different mixing chambers was also designed, of which the best results were achieved at the mixers with truncated cone shape. However, it has not been confirmed experimentally on the test apparatus.
Key words: oxy/fuel combustion, oxygen enriched air, CFD mathematical model.

Matematički i fizički model miješalice kod gorionika zrak/gorivo i kisikom obogaćen zrak/gorivo. U ovom radu opisan je učinak miješanja zemnog plina sa zrakom te kisikom obogaćenim zrakom kao oksidirajućim sredstvima. Sažeto su opisane teorijske osnove izgaranja kisik/gorivo i utjecaj povećanja sadržaja kisika u oksidirajućem sredstvu na sastav i teorijsku temperaturu plinova izgaranja pri izgaranju zemnog plina. Plamenik toplinske snage od 2 kW projektiran je s dvije vrste uređaja za miješanje čija funkcionalnost je istraživana pomoću matematičkog modela formuliranog na osnovi CFD programskog paketa i praćenjem temperature plamena na fizičkom modelima. Kako bi se postigla bolja usporedba uređaja za miješanje, modificirana je samo njihova geometrija dok su ulazni parametari, kao što su maseni protok zemnog plina i oksidirajućih sredstava, ostali isti. Korištenjem CFD modeliranja također su konstruirane komore za miješanje različitih oblika, od kojih su najbolji rezultati postignuti kod miješalica oblika krnjeg stošca. Međutim, to nije eksperimentalno potvrđeno na ispitnom uređaju.
Ključne riječi: izgaranje kisik/gorivo, kisikom obogaćen zrak, CFD matematički model.

INTRODUCTION

In many industrial processes the heating processes can be enhanced by replacing the combustion air with oxygen or using the oxygen enriched air. The combustion with oxygen is called oxy-fuel combustion. The general benefits of oxygen enhanced combustion are increased productivity, higher thermal efficiencies, improved flame characteristics (in terms of higher turndown ratio, increased flame stability, better ignition characteristics), lower exhaust gas volumes, higher heat transfer efficiencies [1,2]. The detailed studies on oxy-fuel combustion were carried out by International Flame Research

Foundation (IFRF) dealing with the various measuring equipments, characterization, CFD development and validation [3,4]. The mixing of the air and air enriched by oxygen with natural gas plays an important roll in the oxy-fuel combustion.

Recently a great stress is placed on the environment and pollutant emissions. In many cases of the metallurgical production the gaseous fuels are being applied as the source of heat energy. In the past, as well as in the existing time, the gaseous fuels are combusted in majority of cases in the air/fuel burners forming in the flues gas a certain amount of CO_2 and NO_x emissions. These emissions are ranked among the GHG and therefore it is of importance to investigate the options of their reduction. One of the aspects like development of possible methods is the combustion of gaseous fuels with oxygen enriched air or even replacing all of the air with high-purity oxygen, which results in the significant reduction of pollutant emissions with flue gases.

The enrichment of the combustion air with oxygen results in reduction of nitrogen content in the combustible mixture. The increase in the oxygen proportion in the oxidant leads to:

- Furnace efficiency increase and reduction of the fuel nominal consumption,
- Increase of the flame temperature,
- Increase in heat transfer,
- Reduction in pollutant emissions.

Effect of the combustion with oxygen enriched air, known as oxygen-enhanced combustion or OEC, on the combustion process parameters at natural gas combustion are given in the Figures 1-3.

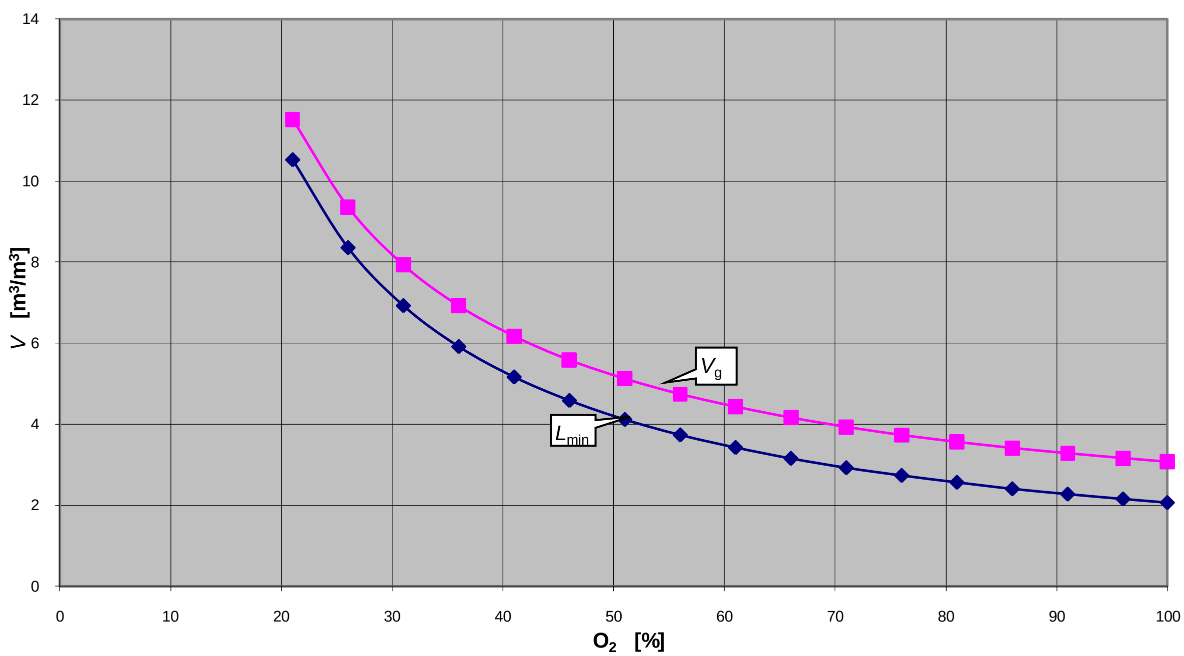


Figure 1. Effect of oxygen content in the oxidant (%) on the amount of oxidant (L_{min}) and combustion gases (V_g)
Slika 1. Utjecaj sadržaj kisika u oksidirajućem sredstvu (%) na količine oksidirajućeg sredstva (L_{min}) i plinova izgaranja (V_g)

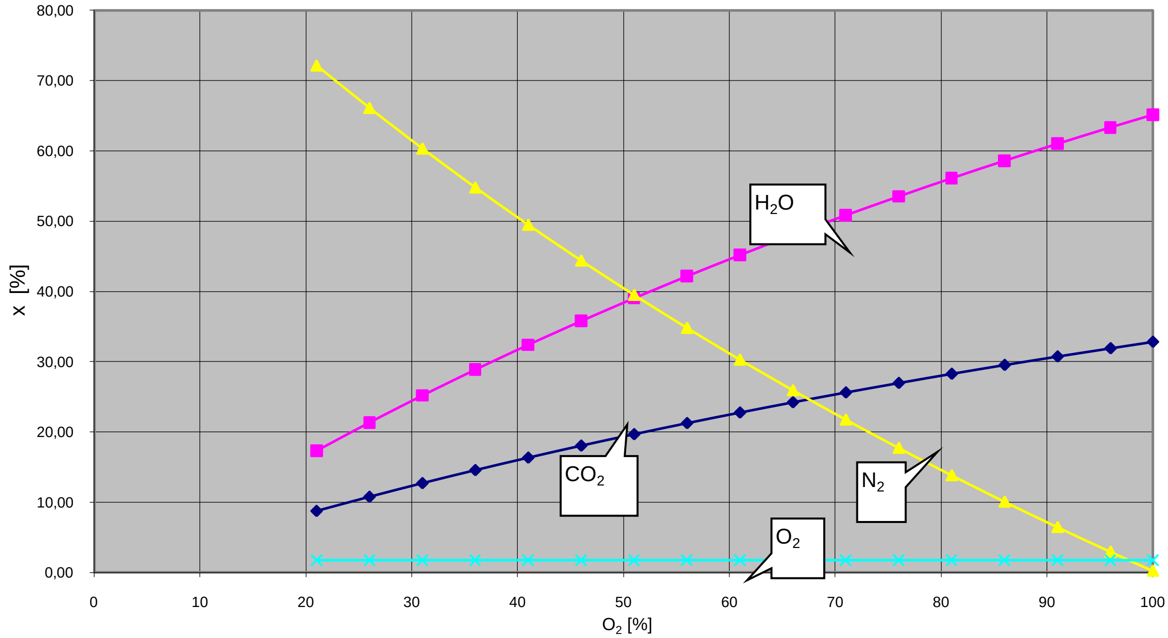


Figure 2. Effect of oxygen content in the oxidant (%) on the composition of combustion gases
Slika 2. Utjecaj sadržaja kisika u oksidirajućem sredstvu (%) na sastav plinova izgaranja

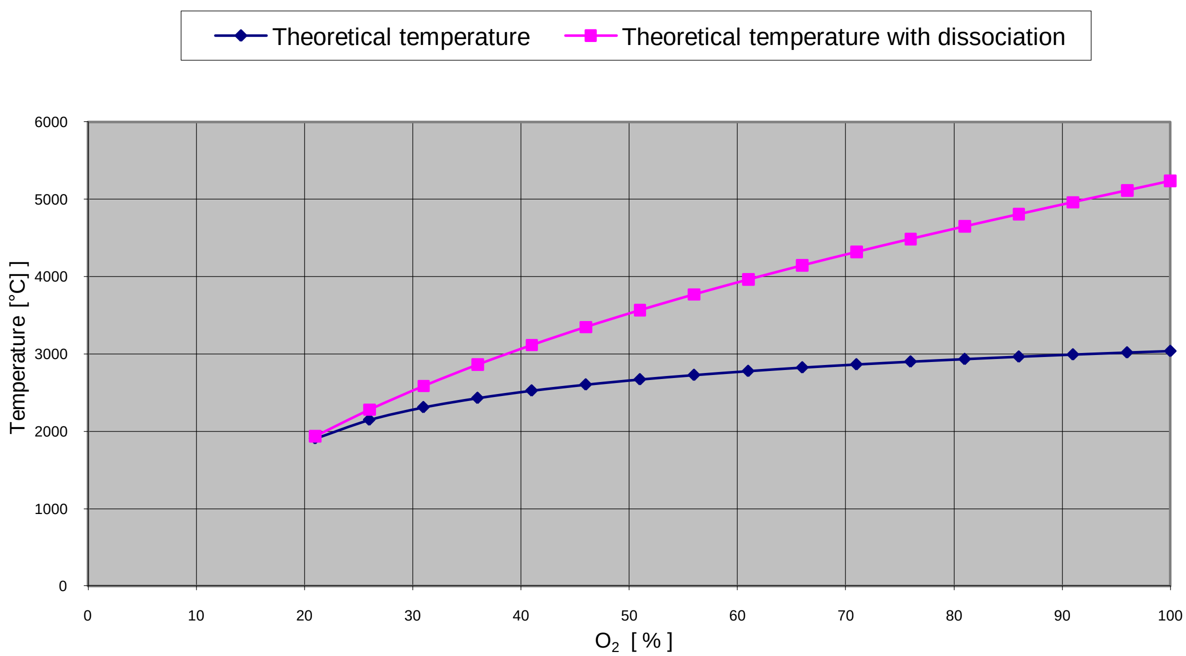


Figure 3. Effect of oxygen content in the oxidant (%) on the theoretical temperature of combustion gases (°C)
Slika 3. Utjecaj kisika u oksidirajućem sredstvu (%) na teorijsku temperaturu plinova izgaranja (°C)

Enrichment of the combustion air with oxygen affects the heat transfer process by convection and radiation between flue gases and charger.

For the oxygen content in combustion air is characteristic:

- Rise in temperature, level of which depends on the oxygen content and the amount of excess oxidant,
- Reduction in flues gas volume in a combustion chamber,
- Increase in the flame heat release rate (kW/m^3),
- Reduction in NO_x emissions,
- Drop in heat transfer by convection due to the drop in flues gas amount,
- Significant increase of the radiation from the flame to the charge due to the flame temperature increase,
- Change in flue gas composition.

In order to make judgments in relation to the above mentioned facts, the mathematical and physical modelling was implemented to qualify the process of the oxidant mixing with the fuel at the burner of 2 kW power and to study the process of the combustion carried out with this burner under the laboratory conditions.

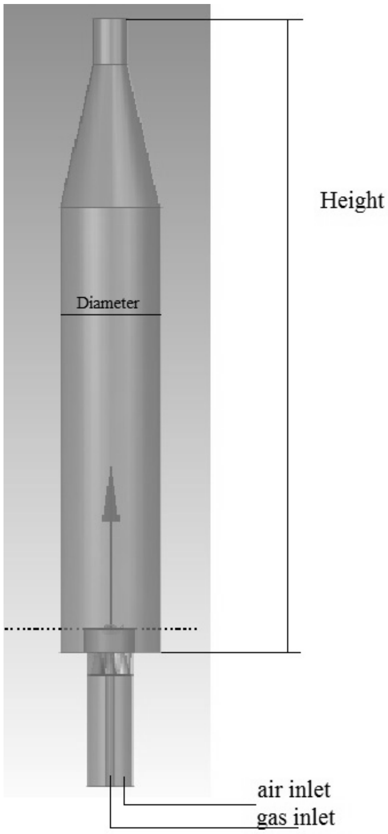
MATHEMATICAL MODEL OF THE COMBUSTIBLE MIXTURE MIXING

To simulate the combustible mixture mixing the CFD software was used to formulate the mathematical model giving emphasis to the process of mixing of natural gas and oxidant. The standard k-ε model was used for turbulence. To simplify the process of the description of natural gas and air mixing, the model of methane/air mixing was applied.

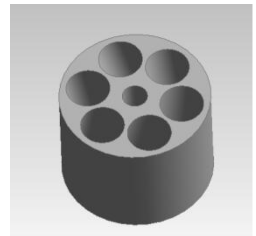
To compare the individual mixing devices, the similar procedure as in the physical model was applied in both cases of designed mixers. In the third case, it was simulated the mixing process of natural gas and air enriched with the 35% oxygen in the mixing camber of truncated cone shape with the diameter of 15 mm and height of 20 mm.

Pilot scale apparatus

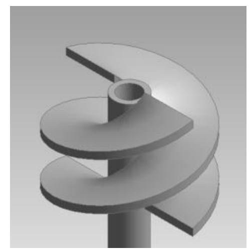
Burner with power of 2 kW was placed in the combustion chamber of the height of 600 mm and diameter of 60 mm (Fig 4a). The inlet diameter for natural gas is 4.5 mm and for air is 27 mm. Two types of mixing devices were designed. One of them is in the form of spiral (Fig 4b) and the second has 7 holes in its body. The hole in the centre, with diameter of 4,5 mm, is for natural gas supply and other holes, with diameter of 6 mm and inclined at an angle of 30°, for air (Fig 4c).



4a.



4c.



4b.

Figure 4. The pilot scale apparatus and the type of mixers
Slika 4. Ispitni uređaj i vrste miješalica

To compare the performances of two types of mixing devices, two testing procedures have been implemented. In the first, the mixture of natural gas and air tests was burnt. In the second, the air was enriched by oxygen up to level of 35% inside the mixing chamber of cylinder shape with the outlet diameter of 15 mm and the height of 20 mm.

The input parameters for the simulations on the pilot scale apparatus were as follows: the mass flows of natural gas was 7,58E-04kg.s^{-1}, the mass flows of air enriched by 21% and 35% oxygen was 7,58E-04kg.s^{-1}, input temperatures of media in all cases were 20°C.

During the experiments the mass flows of input media were not changed.

The scheme of pilot scale apparatus with specified position of thermocouples is given in Fig. 5.

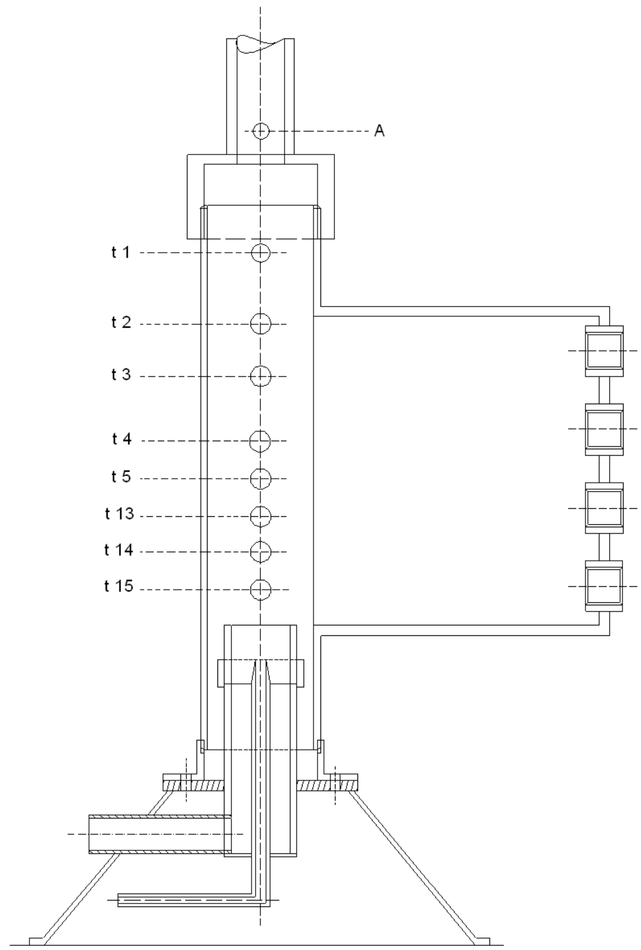


Figure 5. Scheme of experimental equipment
Slika 5. Shema eksperimentalne opreme

RESULTS AND DISCUSSION

The results obtained from the simulation processes in two mixing devices at the air-fuel combustion are given in Fig.6. As it can be seen, the improved mixing can be attained in the mixer with holes inclined by the angle of 30°. The temperatures measured on the thermocouple placed in the combustion chamber during the preliminary tests of these two mixing devices are given in Tab 1. The reason for the better achieved mixing in the case of mixer with holes is probably in the fact that the natural gas flow is better mixed by the separately injected air streams into the combustion chamber from the individual holes.

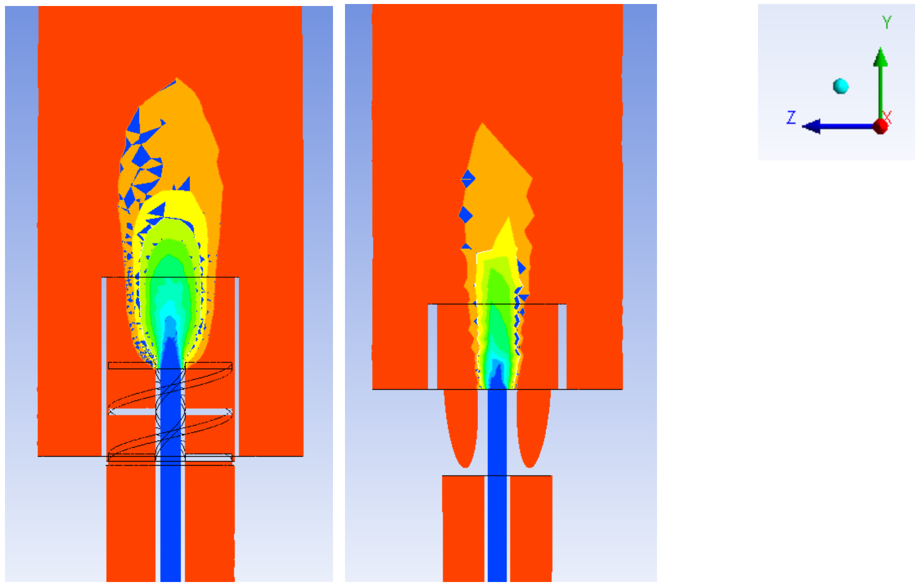


Figure 6. Contours of air and natural gas density for the mixers with spiral and holes
Slika 6. Obrisi gustoća zraka i prirodnog plina za miješalice sa spiralom i provrtima

Table 1. Measured values of temperatures at the oxy-fuel combustion
Tablica 1. Izmjerene vrijednosti temperatura kod izgaranja kisik/gorivo

	Spiral	Holes
T15 [°C]	660	731
T14 [°C]	657	834
T13 [°C]	666	866
T6 [°C]	16	17,9
T5 [°C]	682	832
T4 [°C]	652	823
T3 [°C]	646	922
T2 [°C]	662	800
T1 [°C]	367	250

Performance of the same mixing devices was also simulated at the oxygen-enhanced combustion with the level O_2 enrichment of 35%. However, in this case, the better mixing was achieved at the spiral mixer.

Obviously, at the smaller mass flow of oxidant the swirl greatly enhances the mixing of oxidant and fuel streams (Fig. 7). The values of temperatures measured during the testing of mixing devices on the physical model are presented in Tab. 2.

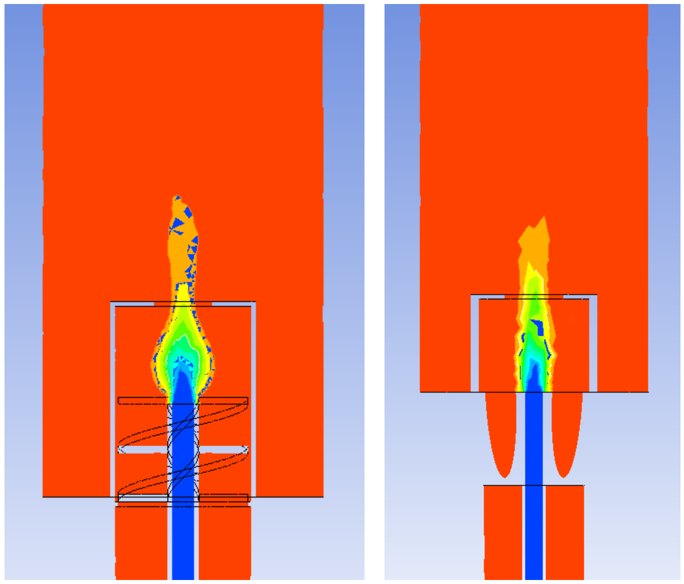


Figure 7. Contours of oxygen enriched air and natural gas density for the mixers with spiral and holes
Slika 7. Obrisi gustoća kisikom obogaćenog zraka i zemnog plina za mješalice sa spiralom i provrtima

Table 2. Measured values of temperatures at the oxygen-enhanced combustion with the level O_2 enrichment of 35%
Tablica 2. Izmjerene vrijednosti temperatura kod izgaranja s kisikom obogaćenim zrakom (35% O_2)

	Spiral	Holes
T15 [°C]	1305	1050
T14 [°C]	1140	1190
T13 [°C]	900	890
T6 [°C]	18,2	20,7
T5 [°C]	825	820
T4 [°C]	800	800
T3 [°C]	760	875
T2 [°C]	893	775
T1 [°C]	280	210

In order to achieve the more homogeneous mixture of natural gas and oxygen enriched air, with the oxygen enrichment of 35%, two types of mixing chamber in form of truncated cone were designed. The previous extension in form of cylinder, of height of 20mm, was replaced with the extension in form the truncated cone.

The results of simulation of mixing for this extension were obtained only on the mathematical model (Fig. 8) but so far the testing under the laboratory conditions has not conducted.

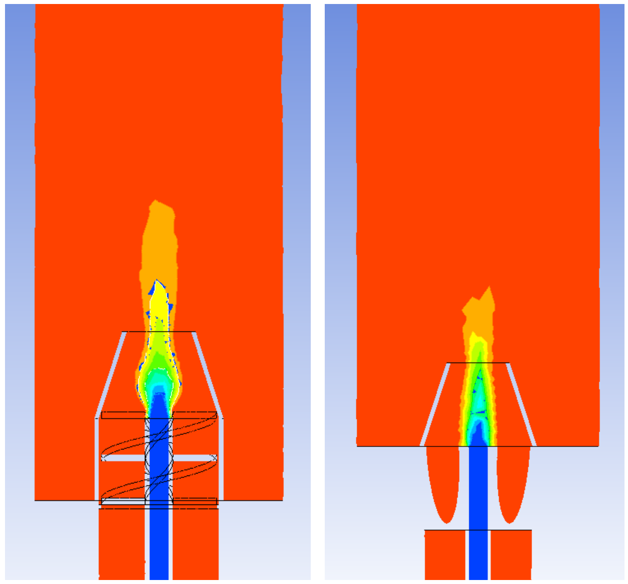


Figure 8. Contours of oxygen enhanced air and natural gas density at the truncated cone shape mixers with spiral and holes
Slika 8. Obrisi gustoća kisikom obogaćenog zraka i zemnnog plina kod mješalice oblika krnjeg stožca sa spiralom i provrtima

Based on the previous results it can be concluded that the better results were achieved by the spiral mixer with the extension in the form of truncated cone.

CONCLUSIONS

The mathematical and physical modelling was implemented to qualify the process of the oxidant mixing with the fuel and to study the process of the combustion carried out with the burner of 2 kW power under the laboratory conditions. Two types of mixing devices were designed. One of them is in the form of spiral and the second with holes in its body.

To compare the performances of two types of mixing devices, two testing procedures have been implemented. In the first, the mixture of natural gas and air was burnt. In the second, the air was enriched by oxygen up to level of 35% inside the mixing chamber of cylinder shape. The better mixing was attained in the mixer with holes. Performance of the same mixing devices was also simulated at the oxygen-enhanced combustion with the level O_2 enrichment of 35%. However, in this case, the better mixing was achieved at the spiral mixer because at the smaller mass flow of oxidant the swirl greatly enhances the mixing of oxidant and fuel streams.In order to achieve the more homogeneous mixture of natural gas and oxygen enriched air, two types of mixing chamber in form of truncated cone were designed. The previous extension in form of cylinder, of height of 20 mm, was replaced with the extension in form the truncated cone. Based on the results of simulation of mixing obtained on the mathematical model it can be concluded that the better results were achieved by the spiral mixer with the extension in the form of truncated cone. As the results of simulation of mixing for this extension were obtained only on the mathematical model, it would be necessary to implement the additional testing in laboratory conditions.

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