METALLIC PLATE HEATING BY A FLAT BURNER
Experiments and CFD Simulations

by

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Original scientific paper
https://doi.org/10.2298/TSCI210419282D

Metal plate heating by new microflare burner has been studied experimentally and by CFD simulations, additionally, concentrations of NO_x were measured to compare conventional and microflare burners. In addition, the article provides a numerical simulation of the combustion of a microflame burner. It has been demonstrated that microflare burners are more efficient and allows more uniform heating of metal plates. The comparison of NO_x concentrations of conventional and microflare burners indicate better performance of the latter.

Key words: *combustion, NO_x, burner, metal, heat conduction, CFD*

Introduction

An analysis of the main reasons for the formation of NO_x in various devices and the prospects for the development of the power industry showed that traditional methods of fuel combustion do not provide the required parameters. Improving the efficiency of fuel combustion can be obtained by using microflame combustion [1-3].

Despite the limited amount of experimental data on the use of microflame combustion in combustion chambers, various authors in [4, 5] note the following positive qualities of this method: low gas pressure losses, reduced dimensions of combustion chambers, reduced irregularities of temperatures on the outlet of combustion device, low NO_x with combustion products [6].

Currently, there are several main directions of microflame combustion, but they all have one thing in common – this is the *spreading* of the torch along the front of combustion [1]. A most common method of microflame is spreading in the burner by supplying fuel through numerous nozzles. Even thou, microflare burners are mostly used in combustion chambers, they also could be used in metallurgy. A current research paper is devoted to a particular problem – uniformity and heating speed of metal plates.

Burners for heating purposes are among the contemporary direct heating/combustion topics in [7-11]. Investigation of hole arrangement in burner in [7] showed that inline configuration for perforated plate is preferable.

The article [8] presents the result of the investigation of the influence of CH_4 mixture at different Reynolds numbers in the range of 50-600 on heat transfer for a flat plate. Ex-

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periments have shown that the most optimal location of the cells at a distance of 7 mm is the most optimal for heat transfer. Investigations of partially premixed CH_4-air and CH_4-oxygen flames stabilized over a perforated-plate burner [9] showed that premixing can significantly decrease NO and CO concentrations.

Installing a grid from a catalyst [10] can significantly reduce the concentration of NO and CO.

The micromix burner study [11] showed that such burners can maintain lox NO_x concentrations in the range of 4-14 ppm. This is due to the efficient mixing called *micromix* and the use of hydrogen as fuel. Studies of micromix burners in [12] have shown that the longer the mixing time of the fuel with the oxidizer can improve combustion efficiency.

In general, the analysis shows that there is a possibility of increasing combustion efficiency and reducing NO_x concentrations due to the preliminary mixing of fuel and air in separate channels and pipes.

Novelty of the research. Considering all of the previous, the authors have developed a novel burner device shown in fig. 1. The main novelty of which is the ability to distribute fuel. To determine the efficiency of a burner device that can be used in metallurgy, an experiment was carried out to heat two metal plates with various thicknesses.

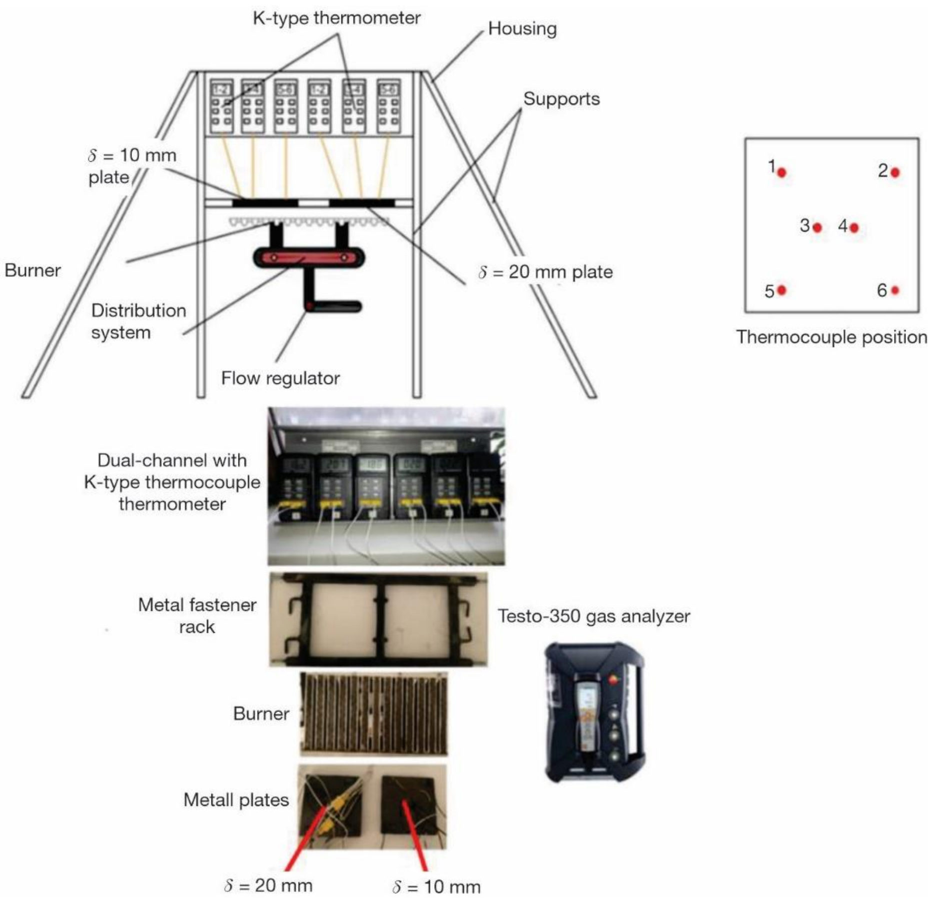

Figure 1. Experimental installation

This forms a suitable background to continue an investigation on microflare combustion and especially plate heating and this paper presents the experimental and CFD results of the research.

Methodology

The experimental installation designed for the studies is shown schematically in fig. 1. It consists of a microflare burners, connected to the fuel (natural gas) supply system (by a flow controller at 0.1 kg/h). Two types of burners were studied: microflare burner and conventional burner, fig. 2. The excess fuel ratio was $\varphi = 0.7$ taking into account the results of the experiments presented in [12]. Two steel plates with thicknesses of 10 mm and 20 mm, see tab. 1 for the physical parameters, were used in the experiments. Some elements of the experimental system used are shown in fig. 2.

Table 1. Thermophysical properties of steel used in modelling

Name of device	Model	Error margin
Gas analyzer	Testo-350 XL	±5%
Flowmeter	Porter Model 201	±1% full scale

Measurement and data acquisition

Six double-channel thermometers DM6802 B with a temperature range of 50-1300 °C (with nominal errors of 0.6% ±2 °C) were used, fig. 1, connected to thermocouples (located at different position in the plane of the heated plates – see the inset in fig. 1). To eliminate the effects of the uprights, the holes are drilled in the plates for positioning the thermocouples. The of nitrogen oxides concentration was measured by a universal gas analyzer Testo-350 XL. The error of the gas analyzer and flow meter are presented in tab. 1. Gas consumption data obtained from the flow meter were converted to [kgs^{-1}] using:

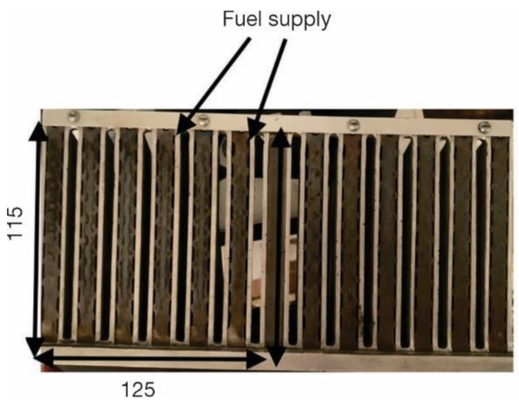

Figure 2. View of the burner

$$G_{\text{kg/h}} = \frac{Q_{\text{flowmeter}}}{\rho_{\text{gas,st}}} 60\,\text{minutes} \tag{1}$$

During the experiment, the two tested plates were adjusted to the metal stand and with thermocouples preliminarily located at different position over the plate surfaces. After opening the fuel supply valve, the flow controller was set to a fuel flow rate of 1.5 kg/h. The fuel consumption in the experiment was constant. Then the surface temperatures of the metal plates were measured every 60 seconds. The thermophysical properties of metal plate is presented in tab. 2.

Figure 2 shows the scheme of the experimental burner. The burner consists of a fuel-spreading manifold with a length of 115 mm and longitudinal openings.

Table 2. Thermophysical properties of steel plate used in modelling

Parameter	Value
Carbon mass fraction, [%]	0.05-0.12
Normalizing temperature, [°C]	900
Thermal conduction, [$Wm^{-1}K^{-1}$]	60.5

Modeling approach

The metallic plate heating was simulated by the CFD using the code ANSYS steady-state thermal utilizing the physical data of the steel used in the experiments, tab. 3. The turbulence model of *k-ε realizable* was used to implement the turbulent flow. No radiant heat transfer model was assumed because of relatively low temperatures. The initial modelling conditions are summarized in tab. 2.

Table 3. Initialmodelling conditions [12]

Parameter	Unit of measurement	Value
Thermal conductivity, ANSYS steady state thermal		
Ambient temperature	[°C]	25
Metal surface temperature	[°C]	Taken from tab. 5
Combustion, ANSYS Fluent		
Ambient temperature	[°C]	22
Natural gas temperature	[°C]	15
Air velocity	[ms^{-1}]	0.5
Gas flow rate	[kgh^{-1}]	1

Schematically the geometrical models used in the simulations, fig. 3(a), correspond to the physically studied samples, fig. 3(b). The heat conduction was simulated upon the assumption that the entire plate surface is uniformly heated when a microflare burner is used while in the case of the conventional burner the hottest spot (position where the flame is impinging the plate) was assumed as a circle with 12 mm in diameter.

The combustion chamber geometry is shown schematically in fig. 4. It is mainly oriented to simulation of the nitrogen oxides generation rather than the thermal field distributions over the heated plates. The air-flow was accounted for by artificial assumption that the lower surface of the pate is just above the flares.

Comparing the experiments with simulation results, tab. 4, it was estimated that the cell size assuring the best outcomes in the generated grid was 5 mm, on the basis of stationary temperature profiles

Table 4. Comparison of experimental and simulation results

Value	Simulations	Experiments
NO_x (at 15%O_2) ppm	21.5	23
Temperature [K]	514	527

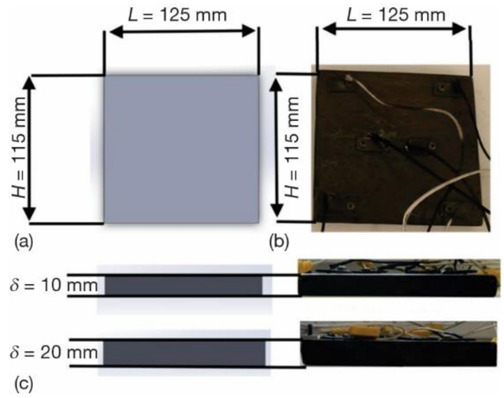

Figure 3. Plates used in the experiments (simulations and physical); geometrical (a), physical (b) models, and views correspondingly (c)

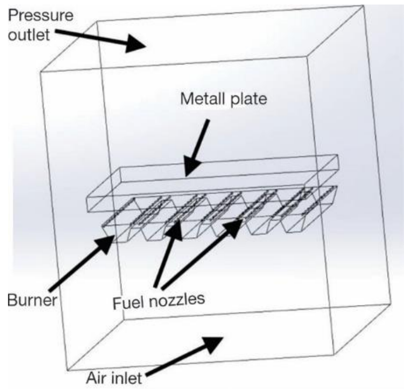

Figure 4. Schematic presentation of the simulated combustion chamber

Results

Surface temperature distribution

The temperature profile measured over the surface plate is shown in fig. 5 when a plate of 10 mm thickness was heated by two different types of burners. The profiles presented reveal that when a microflare heated is used, the plate surface points can attain for a about 60 seconds temperatures within the range of 80-105 °C and therefore it could be assumed, to some extent, as almost homogeneously heated. However, when a conventional gas burner is used, the temperature distributions exhibit maxima around the point where the flame is impinging the plate (center of the plate), *i.e.* bell-shaped profiles, while template edges remained relatively colder. With a microflare burner the temperature maximum was measured about 420 °C while the conventional gas burner heating the maximum attained was only 303 °C.

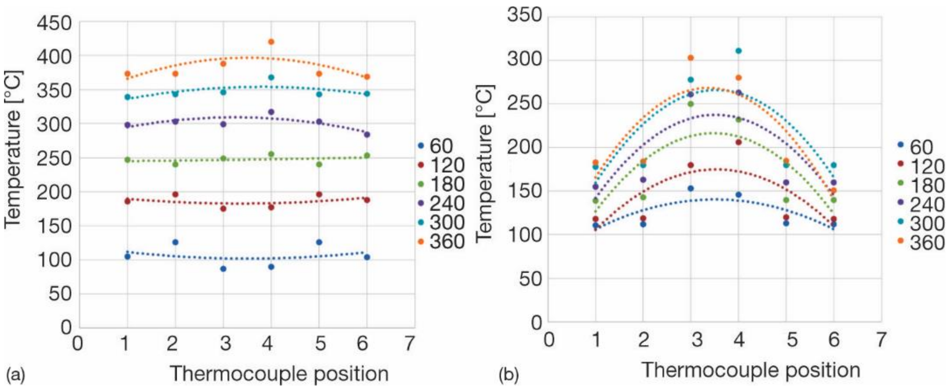

Figure 5. Temperature profile over the plate surface (case with δ = 10 mm thickness); effect of the burner type; (a) heating by the microflare burner and (b) heated by the conventional gas burner

The results obtained with the plate of 20 mm thickness shown in fig. 6 demonstrate similar behavior. For the first 60 seconds the microflare heater allows temperatures within the range 80-99 °C to be attained, while for 360 seconds the temperatures level grows up to 260-270 °C, thanking into account the warming process is slower due the doubled plate thickness. With conventional gas burner, the heating also results in bell-shaped profiles similar to the ones obtained with the plate of 10 mm thickness. The temperature maximum attained with the microflare burner was about 275 °C, while in case of conventional burner the maximum attained is higher and about 310 °C.

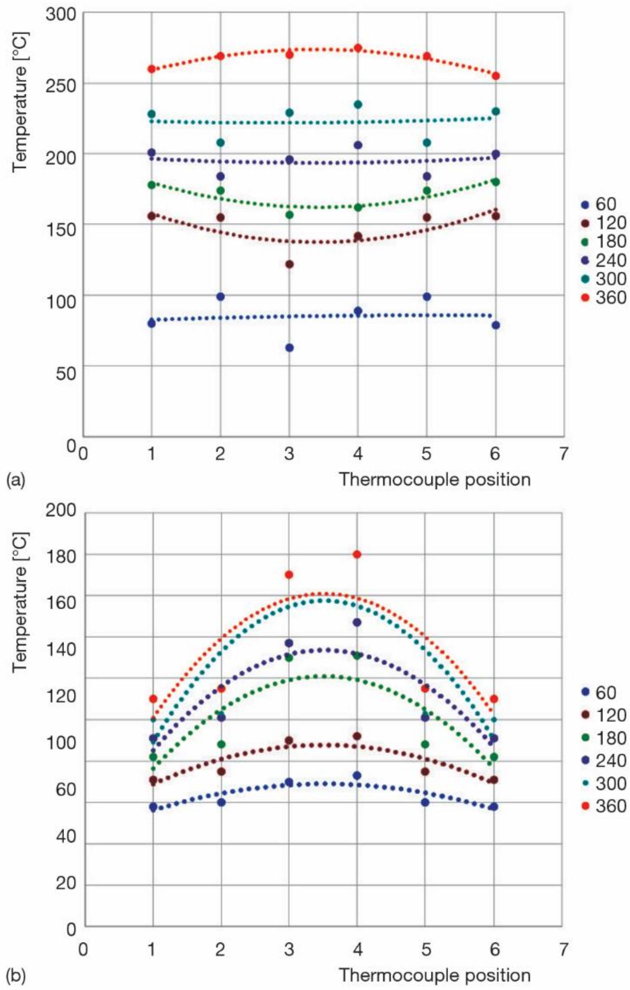

Figure 6. Temperature profile over the plate surface (case with δ = 20 mm thickness); effect of the burner type; (a) heating by a microflare burner and (b) heated by the conventional gas burner

To determine the efficiency of heating, the surface temperatures of the plates were measured by thermocouples. Table 5 shows the calculations of the average temperatures on the surface of metal plates. As can be seen from tab. 5, for a 10 mm plate, the plate surface temperatures for microflame plates are lower compared to a conventional burner. In the case of 20 mm thick plates, the situation is vice versa. This happens due to the fact that microflame burner heats evenly due to more efficiency fuel distribution.

Table 5. The average temperatures on the surface of metal plates

Time, [s]	Average temperature on surface of metal plate [°C]			
	δ = 10 mm, microflame burner	δ = 10 mm, conventional burner	δ = 20 mm, microflame burner	δ = 20 mm, conventional burner
0	25	25	25	25
60	106.3	124.5	84.8	63.2
120	186.3	143.5	147.7	79.0
180	247.3	174.0	170.8	100.2
240	300.7	193.7	195.2	111.3
300	347.2	217.8	223.0	126.0
360	382.7	214.3	266.3	133.3

To calculate the heating, the average surface temperature was taken for all values of thermocouples presented in tab. 5.

$$\text{Temperature increase} = \frac{\Delta t_n - t_{n-1}}{\tau} \tag{2}$$

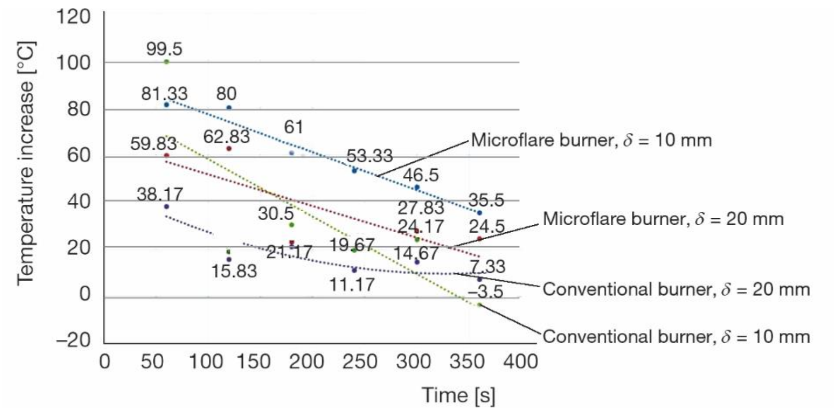

Figure 7. Average plate temperature evolution in time; (a) heating by a microflare burner and (b) heated by a conventional gas burner

Figure 7 shows the temperature change as a function of time. As can be seen from the figure, it with an increase in the temperature of the plates, *i.e.* over time, the level of temperature rise decreases. Moreover, for conventional burners, the overall gain is noticeably lower compared to microflame burner. The average growth rate for plates 10 mm and 20 mm thickness, with microflare burner, are 59.6 °C per minute and 40.6 °C per minute, respectively. With the conventional burner these rates are 31.5 °C per minute and 18 °C per minute, correspondingly.

The main reason for this is a more uniform heating of the plate due to a distributed fuel supply and more efficient mixing of gases with an oxidizer.

The photos in fig. 8 clearly show that the microflare burner has small torches distributed over the entire area of the metallic plate. With this approach a high level of the combustion completeness can be achieved as well as almost uniform temperature profile across heated plate.

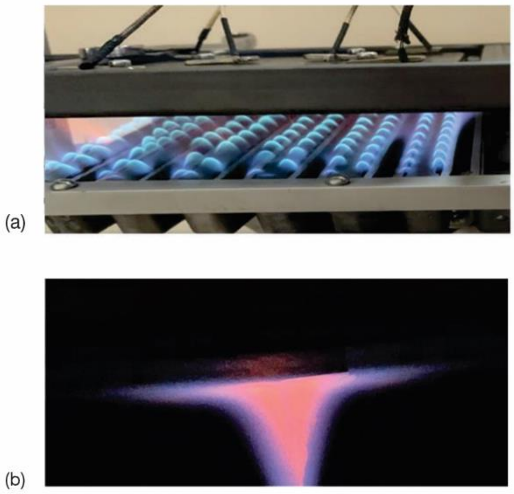

Figure 8. Photos of the burner used; (a) a microflare burner and (b) a conventional gas burner

Nitrogen oxides

The rate of NO_x generation in time, fig. 9, is almost constant since the dotted plots can be piecewise approximated by linear plots. However, the averaging of the data obtained (the solid lines) reveals no changes in time: about 23 ppm for the microflare burner and about 30 ppm for the conventional burner. The main reason for higher NO_x generation is that the flame of a conventional burner is concentrated in the middle of the plate, which leads to a significant increase in temperature. As it is known, the generation of NO_x depends on following factors: high temperature and residence time of gases in high temperature zone. In this case, high temperatures lead to increased formation of NO_x. In case of a microflame burner, the flame is distributed over the burner, which allows more efficient mixing of fuel and air, which allows maintaining the temperature at sufficiently low values and reducing the concentration of NO_x.

Results of modeling

The results from gaseous fuel combustion simulation shown in fig. 10 reveal that with the conventional burner the emissions of NO_x are about 30% higher than the emissions from the microflare counterpart. The result may be attributed to more efficient distribution of the air supply in the case of microflare burner in contrast to the conventional burner where the extremely hot zone at the flame impinging point allows NO_x to be generated.

Figure 11 shows the contours of temperatures, O_2, N_2, O, and NO_x using a microflame burner. As can be seen from the figure, combustion of CH_4 occurs under the metal plate,

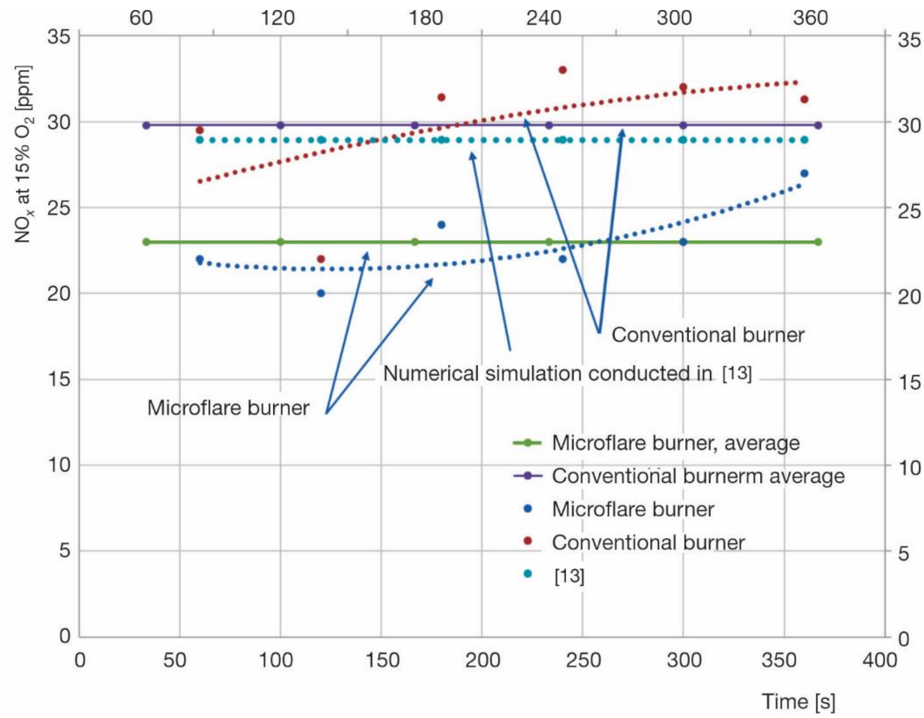

Figure 9. The NO_x concentrations *vs.* the time

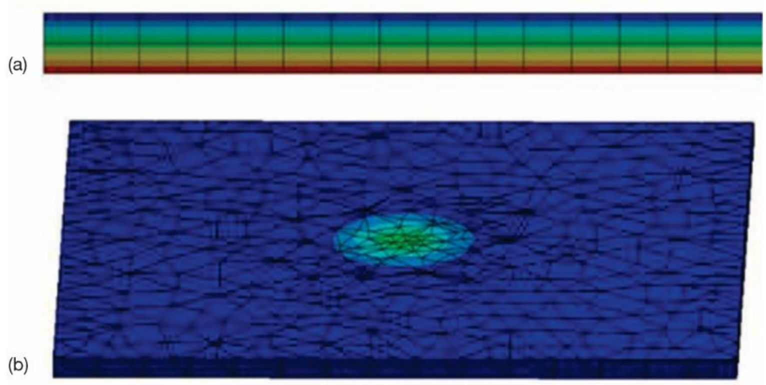

Figure 10. Temperature filed of the heated metallic plates; (a) microflame burner and (b) conventional burner

but NO_x is formed above plate. It can be seen that the elements involved in the formation of nitrogen oxides, in particular O_2, N_2, enter the high temperature zone above the plate.

From O_2 contours it can be seen that part of the O_2 supplied by convection participates in the combustion reaction, and then part of the oxygen participates in the NO_x reaction that occurs at high temperatures. The N_2 coming from the air also enters the reaction zone on the top of the plate.

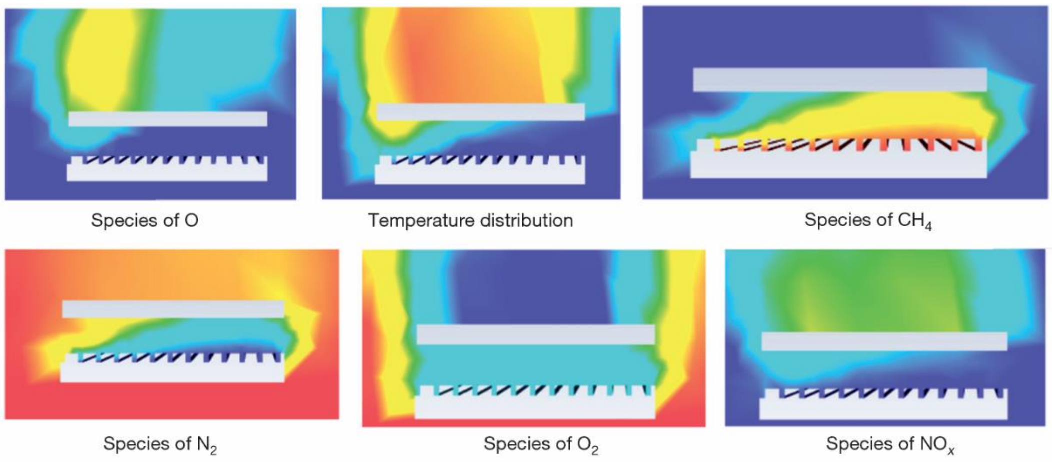

Figure 11. Distribution of temperature and species for microflame burner

Conclusion

The article presents the results of an experimental and numerical study of a microflame burner by heating a metal plates. The results of measurements showed that when using a microflame burner, a more uniform heating occurs. A 20 mm plate heats up rapidly by means of microflame burner. Additionally, measurements NO_x concentrations were carried out. Measurements showed that the microflame burner has lower concentrations of NO_x compared to conventional burner.

In addition, numerical modeling of heat transfer and combustion is carried out in the article. An analysis of the formation of NO_x above the surface of the plate is presented.

Nomenclature

$G_{\mathrm{kg/h}}$ – gas flow rate, [kgh^{-1}]
ppm – parts per million, [–]
$Q_{\mathrm{flowmeter}}$ – gas flow rate in flow meter, [m^{3}min^{-1}]

Greek symbol

δ – thickness, [mm]

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Paper submitted: April 19, 2020
Paper revised: August 18, 2021
Paper accepted: August 22, 2021