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NUMERICAL MODELING OF OXY-FUEL AND AIR-FUEL BURNERS FOR ALUMINIUM MELTING

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Abstract

In recent years oxy-fuel combustion has become an increasingly attractive alternative as a heating source when melting aluminium. A newly developed Low Temperature Oxy-fuel burner from Linde Gas was investigated and compared to a conventional cold air-fuel burner in an instrumented pilot scale furnace. Measurements and heating trials of aluminium samples were done for four different case studies. 3-dimensional CFD models using the commercial software package ANSYS Fluent were developed to attain additional knowledge and to demonstrate CFD as a viable tool to model aluminium melting furnaces. Good agreement was found between the numerical models and the measurements where the difference in heat transfer between the two burner technologies was clearly demonstrated.

Introduction

Oxy-fuel combustion is nothing new in aluminium furnaces but the early experiences resulting in high dross formation and furnace wear due to hot spots have made the industry conservative towards this type of burners. A newly developed low temperature oxy-fuel burner claim to have solved some of these problems while still retaining the advantages of oxy-fuel combustion [1, 2, 3, 4]. The temperature of the burner flame is reduced by so-called flameless combustion resulting in a spread out flame with a more uniform temperature.

This paper presents numerical models which were developed based on measurements and experiments performed in a pilot scale furnace. The focus of the models was being able to reproduce the burner characteristics measured in the furnace and to determine the heat transfer mechanisms created by the burners in the furnace. Heating experiments of aluminium samples up to 600°C were performed in the furnace to study differences in the heat transfer into metal. Transient CFD models were developed to simulate these experiments.

Numerical model

3-dimensional CFD models were developed for the cold air-fuel burner and the low temperature oxy-fuel burner in the furnace. The commercial software ANSYS FLUENT 13.0 was used for the simulations. The following physical models were applied in the simulations of the furnace cases.

Fluid flow

Turbulent fluid flow was modeled using Reynolds-Averaged momentum equations and a k-ϵ turbulence model based on the Realizable formulation. Compressible flow equations were applied to capture effects of the high velocities in burner outlets.

Heat transfer

The energy equation was solved for heat conduction in materials and convection in gas-solid interfaces. Radiation heat exchange in the furnace was calculated using the The Discrete Ordinates radiation model.

Chemical reactions

The Eddy Dissipation Model was applied for the modeling of combustion using a 2-step reaction for propane and air. For the oxy-fuel case the air was replaced with pure oxygen. The Eddy Dissipation model assumes fast chemistry where the reactions are controlled by the turbulent mixing. The reaction steps are

$$C_3H_8 + 3.5O_2 \Rightarrow 3CO + 4H_2O \quad (1)$$
$$CO + 0.5O_2 \Rightarrow CO_2. \quad (2)$$

A pressure-based solver using the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) algorithm was used to solve the equations.

Furnace geometry

The pilot scale furnace used for the experiments and the numerical models is cylindrical with a diameter of 1.4 m and a length of 4.5 m before the flue gas channel. Three water-cooled tubes were used in the bottom of the furnace to control the temperature in the furnace during the experiments. These were modeled as solid cylinders with heat sinks in the numerical model. The shape of the furnace was used to create a symmetry in the model where only half the furnace was modeled using a vertical symmetry plane through the middle of the furnace as seen in Figure 1.

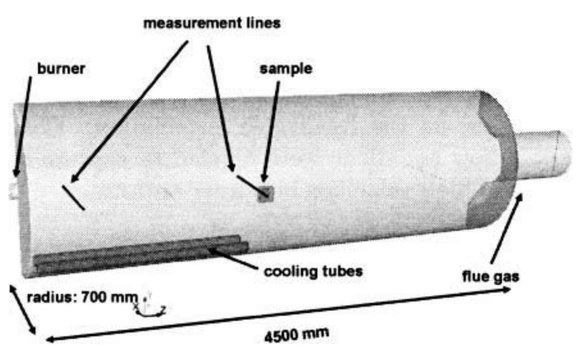


Figure 1: Pilot scale furnace geometry in CFD model with symmetry line and aluminium sample placement in heating experiments.

The furnace and burner geometries were meshed using a combination of tetrahedral and hexahedral volume elements. The oxy-fuel burner cases were meshed using a tetrahedral mesh which was converted to polyhedral volume elements with a total size of 306 thousand cells. The air-fuel cases were meshed using a hybrid mesh of tetrahedral elements with a hexahedral core and a total size of 435 thousand cells.

Furnace set-up

The furnace was run at two matching temperature levels for each of the two burners where the water cooled tubes were used to control the temperature. Table I shows the four cases considered in the experiments and in the corresponding CFD models.

Table I: Overview of the burner cases considered. The furnace temperature is defined as the average of 16 thermocouples placed inside the wall of the furnace.

Case	Burner type	Burner power (kW)	Cooling (kW)	Furnace temp. (°C)
Case 1	Air-fuel	311	23	1131
Case 2	Air-fuel	308	64	1016
Case 3	LTOF	257	66	1142
Case 4	LTOF	257	133	1008

Comparison of burner properties

A comparison of the temperatures in the furnace between the numerical model and the measurements for case 1 and case 3 can be seen in Figure 2 and Figure 3.

We notice a slight underestimation of temperatures away from the center of the furnace for the air-fuel burner at borh distances from the burner. A slight overestimation of the temperature away from the center closest to the burner is found in the oxy-fuel case. There is also a shift away from the furnace center line in the measurements and this was due to a disalignment in the furnace fitting for the burners, particularly in the air-fuel case. The temperatures are otherwise comparable between the two burner cases with a more uniform temperature in the LTOF burner case. Temperature comparisons at the back of the furnace (not shown here) revealed a higher temperature for the LTOF burner cases. A temperature distribution in a horizontal plane of the furnace is showed for the four cases in Figure 4 and Figure 5. The figures reveal a more uniform temperature in the furnace for the LTOF burner cases with lower maximum flame temperatures.

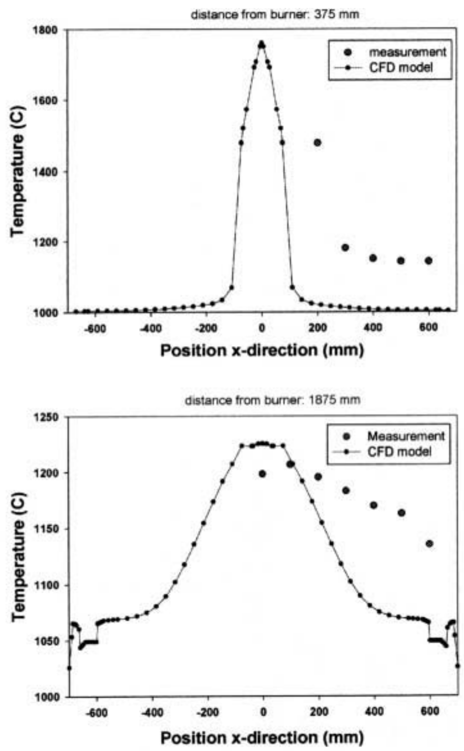


Figure 2: Comparison of temperatures in numerical model with experimental measurements for Case 1.

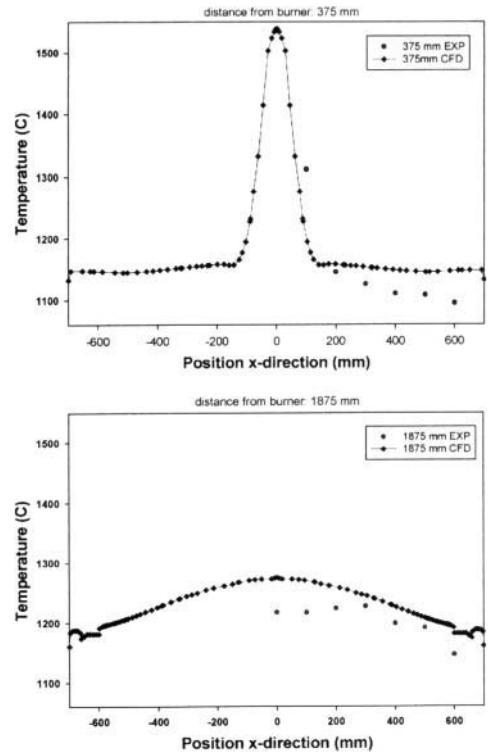
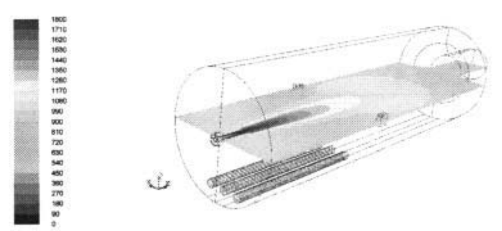


Figure 3: Comparison of temperatures in numerical model with experimental measurements for Case 3.

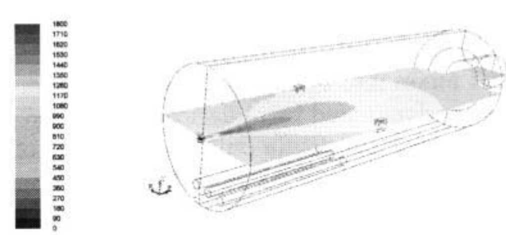
Heating of aluminium samples

Heating of aluminium samples were done for each of the four furnace cases. Four equal samples were prepared using 99.9% aluminium material with dimensions 85x85x40 mm (LxWxD). They were equipped with three thermocouples as seen in Figure 6 and placed in the furnace 1875 mm downstream from the burner, 100 mm from the furnace wall (600 mm from the centre). A specially designed ladle construction was used to insert the samples inside the furnace through a hatch on the side. They were heated from room temperature up to 600°C. The samples were insulated with a fiber material to limit heat transfer to the front side of the sample.

The results for the various cases are found in Table II, where heating times from 100°C to 600°C are compared to avoid possible differences in the start phase from the insertion of the sample into the furnace.

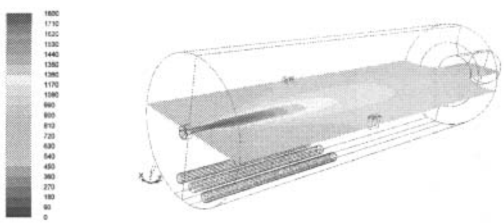


(a)

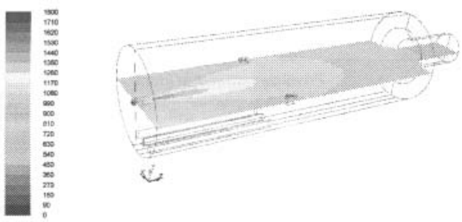


(b)

Figure 4: Temperature contours in the horizontal middle plane with (a) air-fuel burner (Case 1) and (b) low temperature oxy-fuel burner (Case 3).



(a)



(b)

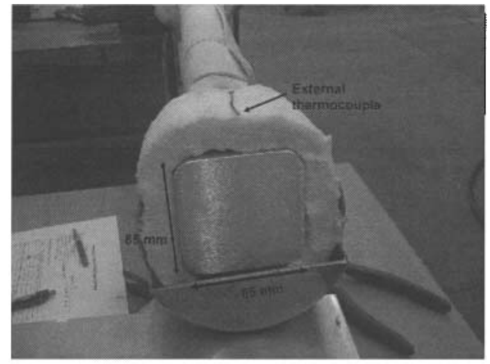
Figure 5: Temperature contours in the horizontal middle plane with (a) air-fuel burner (Case 2) and (b) low temperature oxy-fuel burner (Case 4).

Table II: Results from heating of aluminium samples in the furnace.

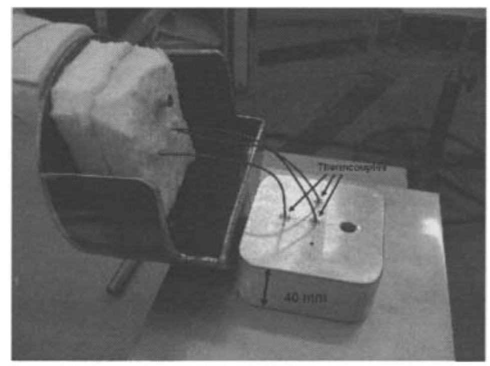
Case	Heating time 100-600°C (s)	Average heat flux (kW/m^2)
Case 1	688	79
Case 2	766	71
Case 3	497	109
Case 4	675	84

The significant difference in the heating times between the LTOF burner and the air-fuel burner at the same temperature level in the furnace can be explained from the heat fluxes in the numerical models shown in Figure 7 and Figure 8.

The heat fluxes into the front side of the aluminium samples are dominated by radiation. The convection heat flux, which constitute only a minor part of the heat transfer is on a similar level for the two burner types. The difference between the low temperature oxy-fuel burner and the air-fuel burner is the level of radiation heat flux which is considerably higher for the former. Since the burners are compared at similar temperatures in the furnace the difference in radiation heat flux must be due to the gas species composition. Using the air-fuel burner there is a considerable amount of nitrogen in the furnace com-



(a)



(b)

Figure 6: One of the samples used for the heating experiments with (a) front side heating area of aluminium sample and (b) thermocouple placements in aluminum sample.

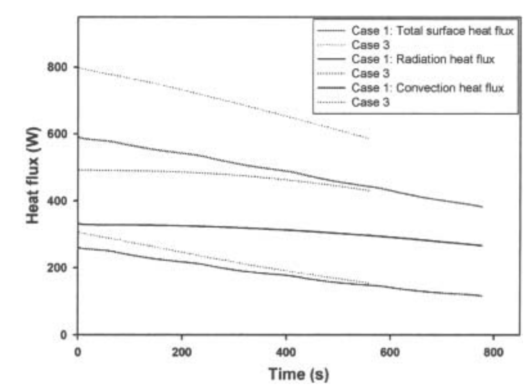


Figure 7: Comparison of heat fluxes through front side of aluminum sample in the numerical model for air-fuel (case 1) and low temperature oxy-fuel (case 3).

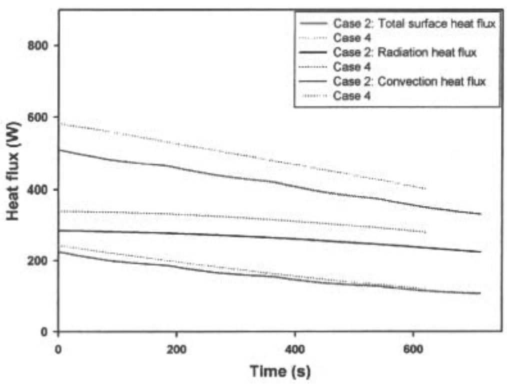


Figure 8: Comparison of heat fluxes through front side of aluminum sample in the numerical model for air-fuel (case 2) and low temperature oxy-fuel (case 4).

pared as seen in Figure 9. The only nitrogen present using a oxy-fuel burner come from possible air-leaks into the furnace. Nitrogen is a non-radiating gas except for under extreme temperatures [5] and does not contribute to radiation heat transfer to the metal.

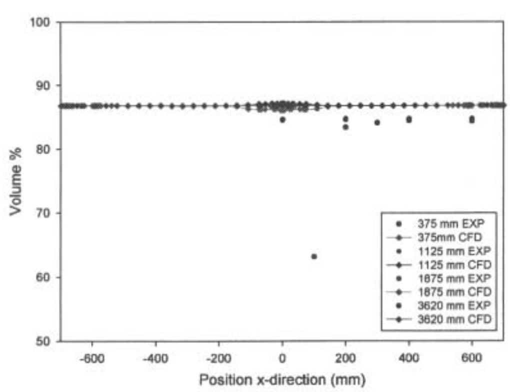


Figure 9: N_2 concentration on a dry basis in numerical model and experimental measurements for the air-fuel burner (Case 2).

The combustion gases CO_2 and H_2O-vapor do however absorb and emit radiation heat and contribute to the absorption of radiation heat into the metal. The concentration of CO_2 is presented in Figure 10 for the air-fuel burner (Case 2) and in Figure 11 for the LTOF burner (Case 4). The discrepancy between the CFD model and measured concentration is believed to be due to a small amount of air being purged into the furnace at the front near the burner during the measurements. The results clearly show a much higher level of CO_2 in the furnace for the LTOF burner.

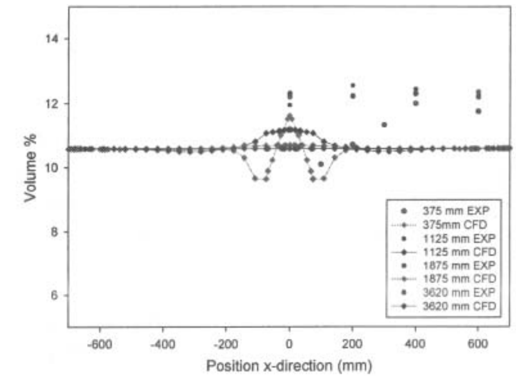


Figure 10: CO_2 concentration on a dry basis in numerical model and experimental measurements the air-fuel burner (Case 2).

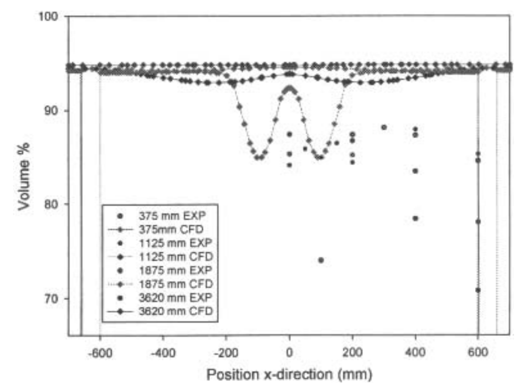


Figure 11: CO_2 concentration in numerical model and experimental measurements for the low temperature oxy-fuel burner (Case 4).

Conclusions

A comparison between a cold air-fuel burner and a newly developed low temperature oxy-fuel (LTOF) burner for aluminium melting has been done using a combination of experimental work and numerical modeling. The numerical models were able to reproduce the measured furnace conditions for both burners.

- The LTOF burner needed less power input to create the same furnace temperature.

- The flame created by the LTOF burner was more spread out and gave a more uniform temperature throughout the furnace.
- The maximum flame temperature (not measured) was higher in the CFD model for the air-fuel burner cases.
- Heating of aluminium samples revealed a 18% and 38% higher heat flux using the LTOF burner compared to the air-fuel burner at the same furnace temperature for two different temperature levels.
- The heat fluxes into the aluminium samples were dominated by radiation which constituted between 60-70% of the total heat flux.
- The convection heat flux into the aluminium samples was on the same level for the two burners, whereas the radiation heat flux was higher for the LTOF burner cases compared to the air-fuel burner cases.
- The higher radiation heat flux into the metal for the LTOF burner could be explained by differences in gas species composition due to the absence of nitrogen when using oxygen and not air as the oxidizer for the fuel.

Acknowledgment

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