STUDY OF THE EFFECT OF TEMPERATURE CHANGES ON THE BEHAVIOUR OF SUPERSONIC GAS JET IN AN LD CONVERTER – PART I

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ABSTRACT

The jet of gas passing through a D-type Laval nozzle was investigated using simulation in fluid mechanics, which aims to get a better understanding of the behaviour of employees in a gas jet LD oxygen converter. Gas flow was simulated using the FLUENT CFD code. The results were validated with experimental results, which appeared in a previous work. The numerical simulation allows simultaneous evaluation of the gas flow field and changes in temperature behaviour, and gives an useful overview of the most complex phenomena occurring in a LD oxygen converter.

Keywords: numerical simulation, gas jet, oxygen converter, steelmaking.

INTRODUCTION

In the steel industry, and more precisely in the BOF, an outgoing gas (typically oxygen) jet passing through a nozzle at supersonic speed is used to reduce the carbon content in the molten iron by oxidation reactions and to ensure the conversion of the latter into liquid steel. The use of supersonic jets is for the purpose of having a good impact on the surface of the liquid metal; the creation of a large reaction area (impact area) and to ensure the homogeneity of the mixture. In contrast, blowing or the successive increase in jet velocity can cause a splash contributing to damage of the refractory wall of the converter and affecting the nozzles. So, it is important to study and understand the behaviour of the jet in the converter at different temperatures, in order to ensure a better performance. Various numerical and experimental studies have been done on the behavior of the jet as it leaves the nozzle De-Laval nozzle [1 - 4].

In this article, we have investigated the influence of temperature changes inside the converter on the behavior of the supersonic gas jet. The temperatures, studied using the Fluent CFD code range from ambient to the high temperatures encountered inside an LD BOF. The model of the selected nozzle [5] is shown in Fig. 1.

THEORY OF SUPERSONIC GAS JETS

A gas jet is a fluid flow that comes from a nozzle towards an open environment. Depending on the speed of the fluid stream, a gas stream may be divided into three categories [8]:

Subsonic flow: The fluid flow velocity is lower than the speed of sound in that particular state.

Sonic flow: in this case the fluid flow velocity is equal to the speed of sound.

Supersonic flow: The fluid flow velocity is higher than the speed of sound.

Laval type nozzles are used to accelerate the gas jet and reach supersonic speeds [6]. The Laval nozzle is a pinched tube used to accelerate the gas to pass through and thus reach supersonic speeds by converting the kinetic energy in the pressurized gas, as shown in Fig. 2 [7].

The flow through the nozzle can be described as follows:

$$m = \rho A U = \text{constant} \quad (1)$$

where ρ is the density of the gas (kg/m^3); A - the section of the nozzle (m); U - the velocity of the gas (m/s).

The Mach number, denoted M*a*, is a dimensionless number, which represents the ratio of the local fluid velocity at the speed of sound in the same fluid.

$$\frac{dA}{A} = \frac{dU}{U}(Ma^2 - 1) \quad (2)$$

From equation (2) we can conclude that:

- For subsonic flows ($Ma < 1$), a reduction of the section will lead to an increase in speed.

- For supersonic flows ($Ma > 1$), an increase in distance will result in an increase in speed.

- For sonic flow ($Ma = 1$), da = 0, the speed of sound is reached when the rate of variation of the section equals to zero.

The Laval nozzle must be designed and used so, that the static pressure at the outlet of the nozzle, is equal to the ambient pressure. Otherwise shock waves will be generated at the output of the nozzle [7]. However, in the steel industry the output pressure should be slightly higher than the ambient pressure so that the dust-laden gas from the environment is not drawn into the nozzle, which may cause wear of the surface of the nozzle or blocking the hole [6].

When an outgoing supersonic gas jet of a Laval nozzle interacts with the environment (air), it produces a turbulent mixing zone as shown in Fig. 2. This process leads to an increase in the jet diameter and a decrease in its speed.

A supersonic jet from a Laval nozzle can be divided into three distinct regions [1]

1) ***Potential core region***: In this region, the axial velocity of the gas is constant and is equal to the nozzle exit velocity. The length of this region is proportional to the pressure and temperature of the ambient medium.

2) ***Transition region***: This region begins when the turbulent mixing layer reaches the axis of the flow.

3) ***Fully Developed flow***: In this region, the fluid becomes turbulent; the jet begins to spread at a higher rate than that of region 1.

For this study, we used the Laval nozzle type, shown in Fig. 2 [5], which is used in the LD oxygen converters for refining of molten iron.

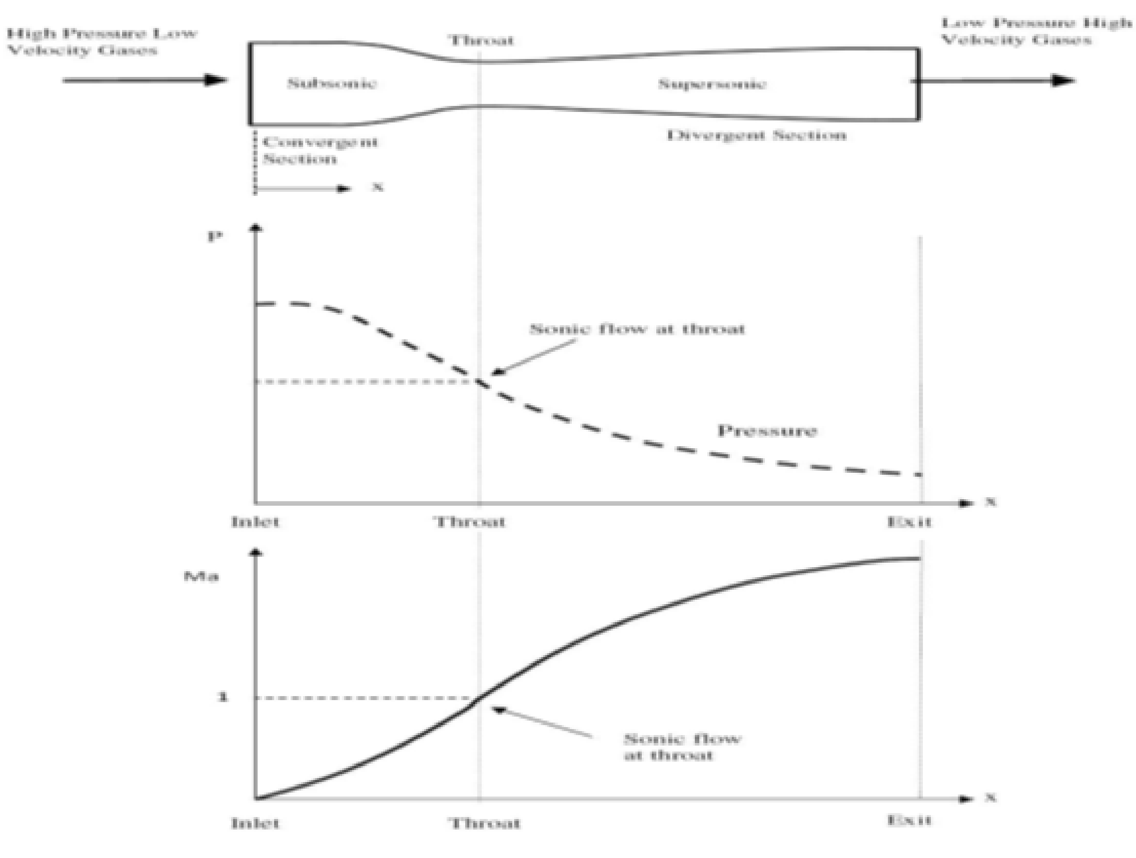

Fig. 1. Schematic of a Laval nozzle with the pressure profile and the Mach number [7].

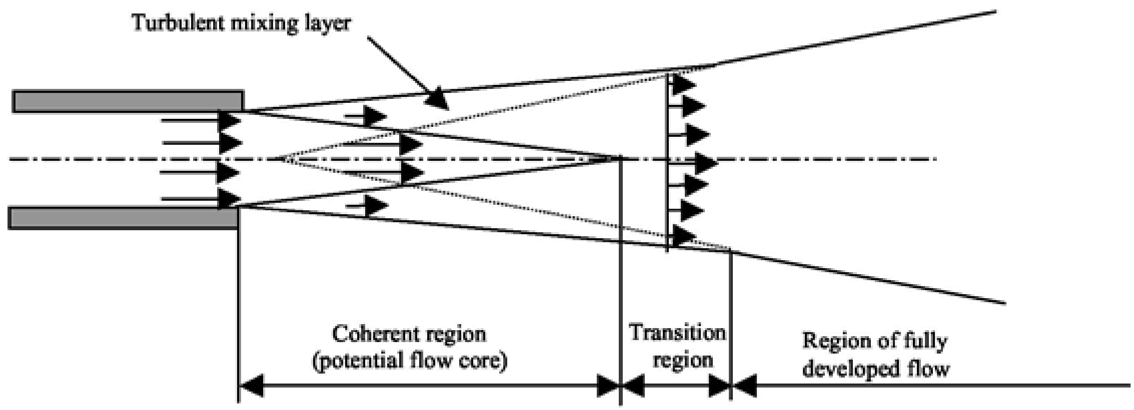

Fig. 2. Supersonic jet area at the outlet of the nozzle [1]

SIMULATION PART

A two-dimensional model of a D-Laval type nozzle has been studied It is presented in Fig. 3.

Computational domain and boundary conditions

A standard k-ε turbulence model was used to simulate the gas jet behaviour in this work. The computational domain for the Laval nozzle is shown in Fig. 3. The mesh has been created in a non-uniform manner, with a refinement near the walls of the nozzle and at the exit of the jet.

Input: A pressure of 1414 MPa was used at the inlet of the nozzle and a temperature of 273 K.

Output: Three temperatures were used (293 K, 1000 K and 1873 K).

Wall: No conditions were placed on the walls of the nozzle.

Geometry obtained with the gambit software is shown in Fig. 4.

RESULTS AND DISCUSSION

Flow Model

The contours of the Mach numbers are shown below. To see the influence of ambient pressure on the jet flow; four ambient pressures (400 mbar, 200 mbar, 100 mbar to 10 mbar) were selected. The temperature of 1873 K

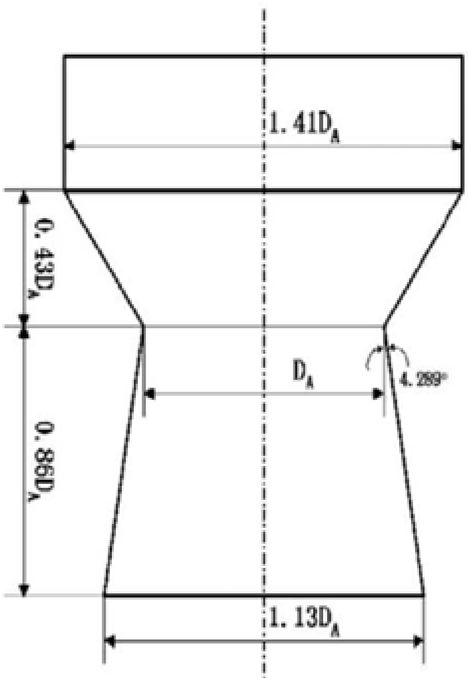

Fig. 3. Geometry of the nozzle [5]

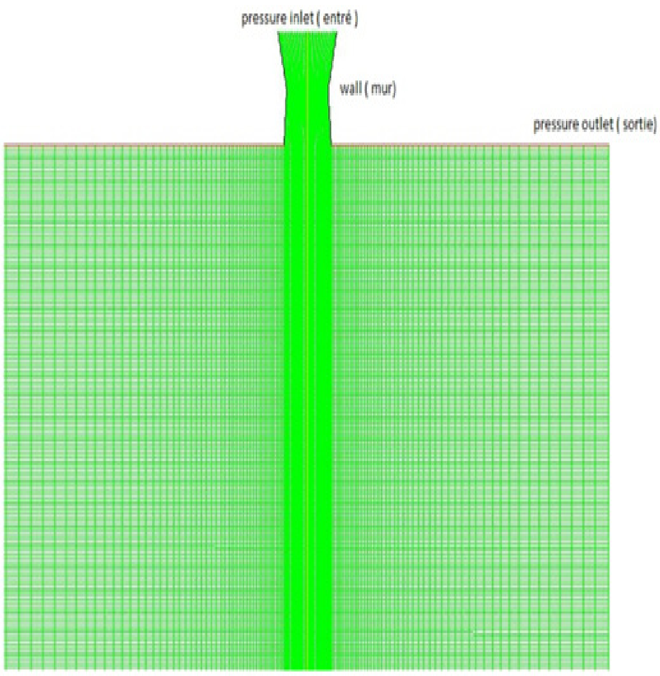

Fig. 4. Areas calculating the Laval nozzle

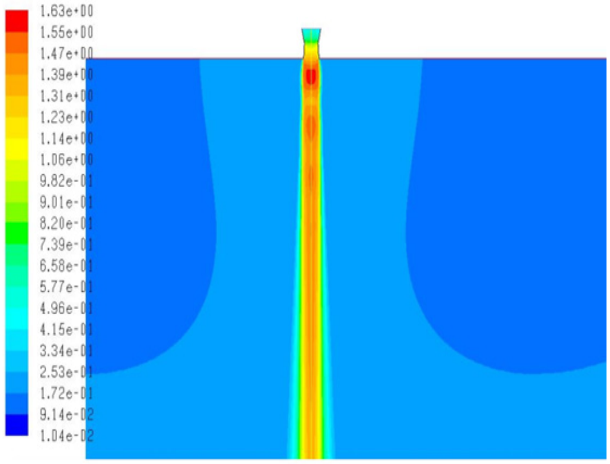

Fig. 5. Outline of the Mach number to an ambient pressure of 400 mbar.

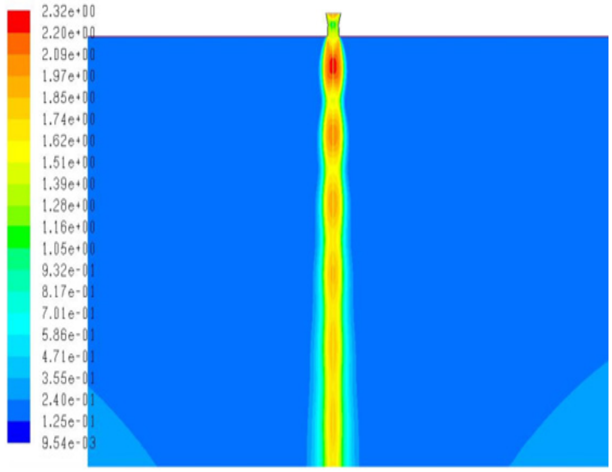

Fig. 6. Contours of Mach number to an ambient pressure of 200 mbar.

is used as the temperature inside the inverter, which is approximately 1600°C.

Interpreting the results of the flow patterns

Fig. 5 shows the profile of the Mach number at an ambient pressure (400 mbar). We note that it does not show a rapid decrease in speed, but its weakness is due to the oscillations. What we can see is that the nozzle is working properly for this ambient pressure.

Fig. 6 shows the outline of the Mach number at an ambient pressure of 200 mbar. A sub relaxation is clearly displayed for this model. We also observe a series of expansions and contractions in the flow which gives a discontinuous appearance.

In Fig. 7, we see a relaxation, similar to that shown for the ambient pressure of 200 mbar, with a strong swing through the jet.

At the ambient pressure of 10 mbar (Fig. 8), the expansion of the jet is very significant, and followed by further expansion, which is due to the low external pressure.

This explains the phenomena that exist at the jet exit [9]. If the gases are less relaxed (i.e. not relaxed enough), they continue to expand outside of the nozzle, first diverging. If the gases are much relaxed (too relaxed), their static pressure will be lower than the external pressure, which will be able to compress them, by decreasing the diameter of the jet. The outflow will be initially converging.

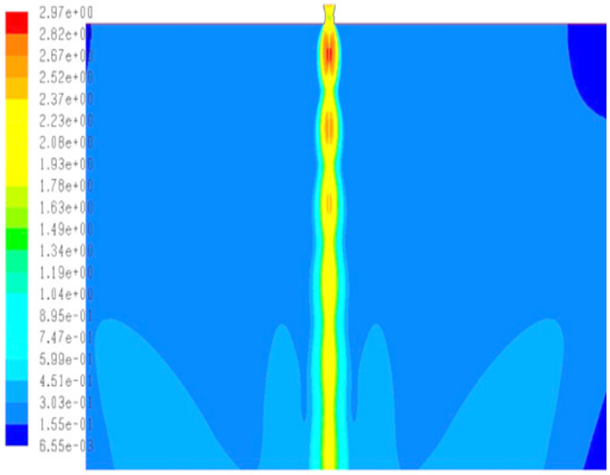

Fig. 7. Contours of Mach number to an ambient pressure of 100 mbar.

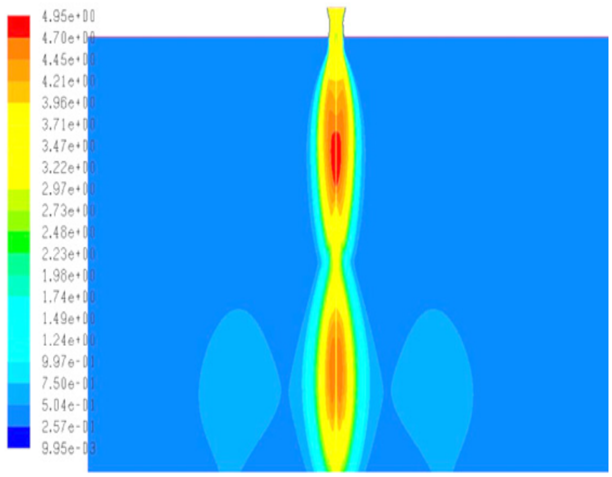

Fig. 8. Contours of Mach number to an ambient pressure of 10 mbar.

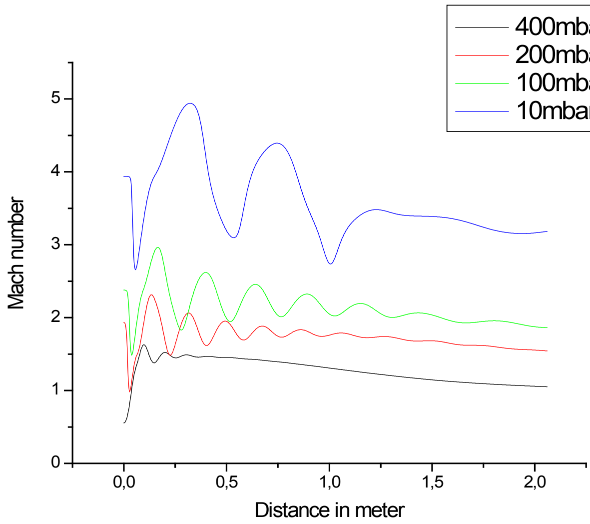

Fig. 9. The Mach number profile of long distance.

Blowing velocity

The simulation results showing the profile of the Mach number are shown in Fig. 9. We study the behaviour of the jet for an ambient temperature of 1873 K and for different outlet pressures (400 mbar, 200 mbar, 100 mbar and 10 mbar).

The profile of the Mach number changes throughout the jet for the four surrounding pressures.

For the pressure of 400 mbar, we note that the Mach number reaches a peak value after which it decreases slightly with small oscillations. The oscillation becomes more important when the surrounding pressure falls down to 200 mbar. We also note that for this pressure, the value of the Mach number in the spray area is high, in contribution to the pressure of 400 mbar. The same goes for the surrounding pressure of 100 mbar. However, the fluctuation is very important. The last profile is at the pressure of 10 mbar. It shows a very high value of the Mach number; after which it falls again, reaching another peak. It has the shape shown in Fig. 8. According to these results, we note that for high ambient pressures, Mach number has achieved reasonable values. By contrast, for a very low ambient pressure (10 mbar), it shows the flow of an unstable fluid, with exaggerated fluctuations (which explains the expansion and contraction of the jet in the contours of Fig. 8).

The influence of temperature

Impacts on the jet velocity

Three different temperatures (1873 K, 1000 K and 293.15 K) and three ambient pressures (400 mbar, 200

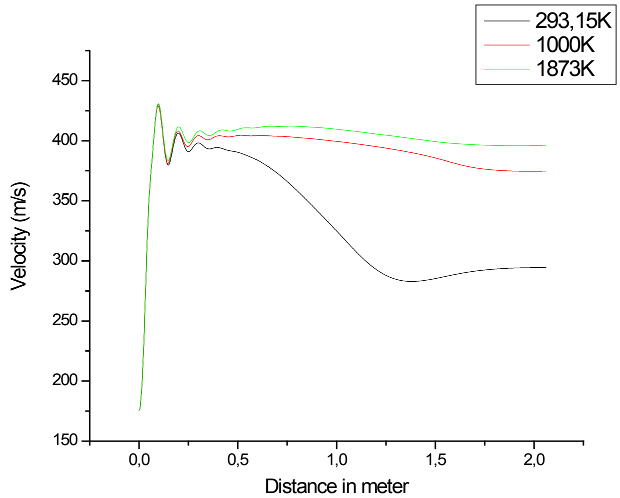

Fig. 10 a. Axial velocity over the distance of the jet for a pressure of 400 mbar.

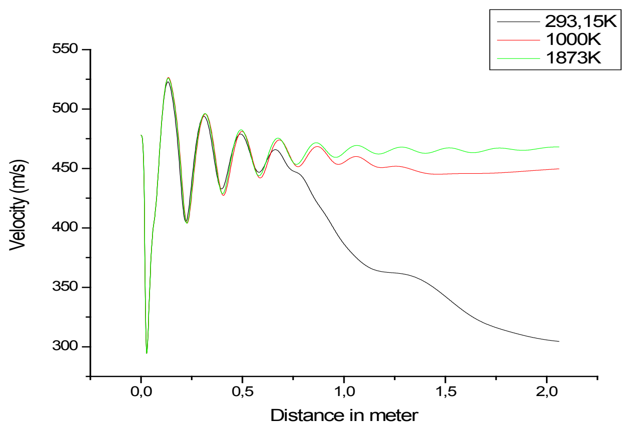

Fig. 10 b. Axial velocity over the distance of the jet for a pressure of 200 mbar.

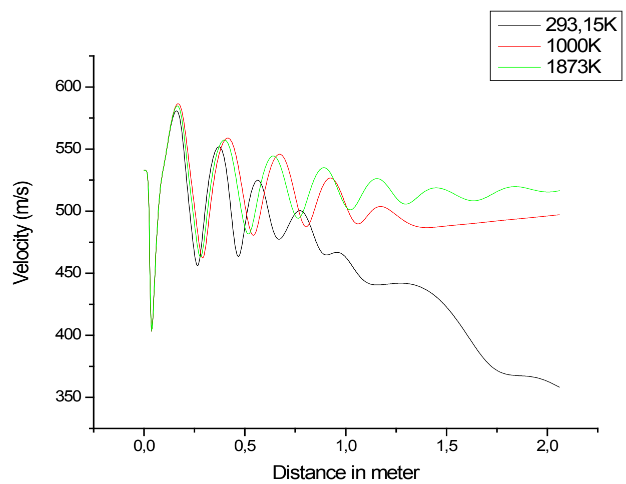

Fig. 10 c. Axial velocity over the distance of the jet for a pressure of 100 mbar.

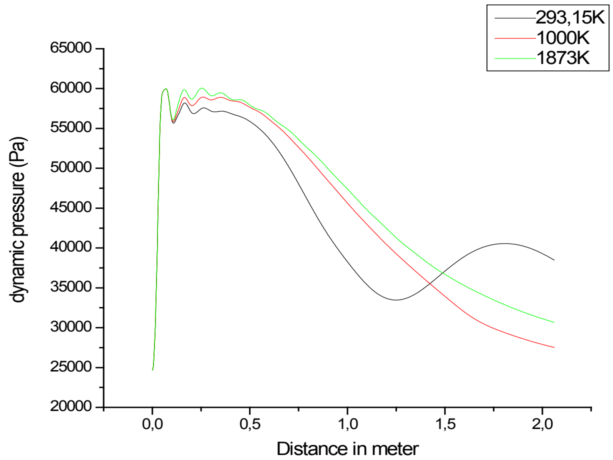

Fig. 11 a. Dynamic pressure according to the distance from the jet for an ambient pressure of 400 mbar.

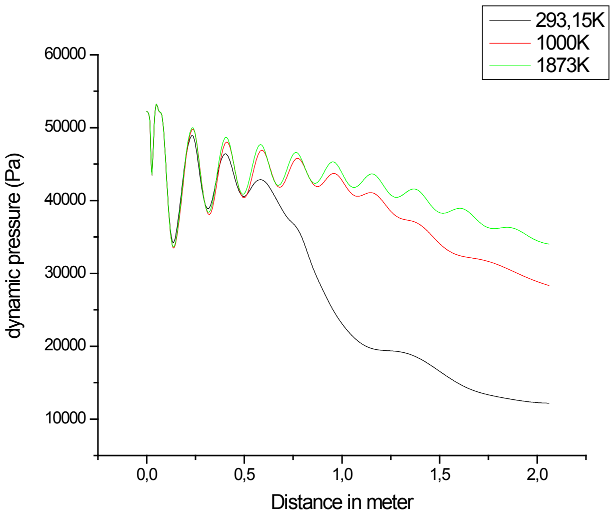

Fig. 11b. Dynamic pressure according to the distance from the jet for an ambient pressure of 200 mbar.

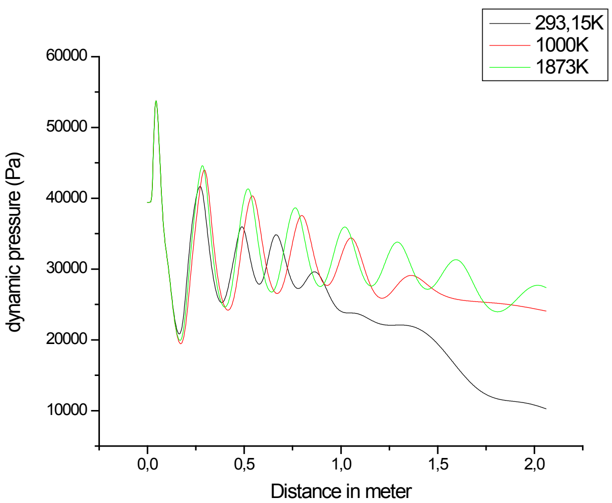

Fig. 11 c. Dynamic pressure according to the distance from the jet for an ambient pressure of 100 mbar.

mbar and 100 mbar) were used to simulate the thermal effect on the characteristics of the oxygen jet. The influence of the temperature on the jet velocity for various ambient pressures is shown in Fig.10 (a, b, c). It shows several curves with different oscillations for each surrounding pressure. Then, they become smooth throughout the blow. We note that for high temperatures, we will get fairly significant blowing speeds. Moreover, it should be noted that the oscillations increase, as the pressure decreases. This is due to a relaxation phenomenon.

Impact on the dynamic pressure

A rather powerful jet can produce a significant effect on the steel surface which leads to a good reaction and promotes agitation.

Fig.11a,b,c shows the influence of temperature on the dynamic pressure for the three ambient pressures. The temperature has a positive effect on the jet. From the results obtained, we find that the temperature has an effect on the dynamic pressure.

METALLURGICAL INTERPRETATION

In the steel industry, which uses the LD converter type, it is important to understand the phenomena that take place in the cavity, because it is in the latter that the majority of the decarburization occurs, when the oxygen jet reacts with carbon. We can say that the decarburization rate is proportional to the reaction zone.

From a practical point of view, it would be interesting to increase the decarburization rate in order to increase productivity. The understanding and mastery of this model will allow us to have a clearer vision of the phenomenon.

As mentioned in the introduction, the objective of this work is to simulate the phenomena that occur in a converter in the steel refining process and involve a supersonic gas jet on a bath of liquid steel.

With this model, it would be possible to predict the depth of penetration into the liquid. In the same way, it would also be possible to determine the most useful parameters for increasing the decarburization rate in the region outside of the cavity area. According to the study by Morshed Alamand and others, it was concluded that the dynamic pressure of the jet could be improved by increasing the ambient temperature [10]. It should be noted that it is impossible to change the temperature in an oxygen converter; and consequently, the air temperature changes at the start of the blowing.

We will also have the option to include the experimental data and the reactions of decarburization to better understand the mechanism in the penetration area.

CONCLUSIONS

The numerical simulation of the effect of the temperature and ambient pressure on the behaviour of the supersonic jet was investigated using the FLUENT computational code. We note that the temperature change has an impact on the speed of the jet; indicating that the elevated temperatures may enhance the speed of the jet and the impingement area.

It is a slightly low ambient pressure which can increase the dynamic pressure of the jet. Thus, a change in ambient temperature has a greater effect on the dynamic pressure. It should be noted that knowledge of the effects of temperature and pressure before may be used *a priori* in the design of the nozzle, and allow us to optimize the refining process.

In the second part of this work, we will integrate thermodynamics based on this model, which will allow us to have a good understanding of the phenomenon of decarburization.

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