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INVESITIGATION OF AIR ENTRAPMENT INTO AN ARGON OXYGEN DECARBURIZATION CONVERTER AT THE REDUCTION STAGE

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ABSTRACT

Some Argon Oxygen Decarburization (AOD) converter workers found the nitrogen content in the low nitrogen grade stainless steel sometimes is rather high during the reduction stage. They presumed that the extra nitrogen in the liquid steel may come from the air entrapped into the AOD converter from the gap between AOD mouth and exhaust gas hood. In order to study the possibility of air entrainment into the AOD during the reduction stage of stainless steel-making, a CFD model was constructed in the present work. The current simulation considered the species transfer model, combustion model and radiation model together and commercial CFD code FLUENT6.1 was used. Steady and unsteady simulation was carried out respectively. The simulation results show that air could not penetrate deeply inside AOD converter under steady conditions. However, under unsteady conditions such as suction ability oscillation in exhaust gas ventilation system, air could flow further into the AOD. This model provides much useful information for the AOD process.

NOMENCLATURE

Cp_j specific heat capacity of species j
F_s momentum source term
h sensible enthalpy
h_j sensible enthalpy of species j
$\vec{J}_j$ diffusion flux of species j
k_{eff} effective conductivity
p pressure
R_i the net rate of production of species i by chemical reaction.
S_h heat source related to chemical reaction and radiation.
t time
T temperature
$\mathbf{u}$ velocity
Y_i mass fraction of species i

ρ density
μ dynamic viscosity

INTRODUCTION

AOD (Argon Oxygen Decarburization) is popularly used in the stainless steel-making process. AOD has a top lance for oxygen injection and several bottom tuyeres to blow oxygen or inert gas. The inert gas is argon and nitrogen. Normally, the gas blowing stage can be divided into five steps for general stainless steel grade(Kupari,1999): Step 1 and step 2, blowing oxygen from lance until the carbon in the molten steel achieves 0.4%; Step 3, blowing oxygen from lance and mixture (1:1) of oxygen and inert gas (nitrogen or argon) from bottom tuyeres until the carbon in the liquid steel is about 0.16%; Step 4, blowing mixture (1:3) of oxygen and inert gas from bottom tuyeres as the target carbon level is shot; Step 5, the final process is blowing argon from tuyeres to remove extra nitrogen and reduce oxidized chromium by ferrosilicon, which is called the reduction stage. From the view point of economy, it is expected to use nitrogen as inert gas during step 3 and step 4 as much as possible. However, the blowing of nitrogen can lead much nitrogen dissolution in the molten steel which is not ideal for low nitrogen stainless grade. Hence, it is necessary to blow enough argon at the end of process to remove the nitrogen from the molten bath.

It is believed that nitrogen could be removed thoroughly enough in the current AOD process of AvestaPolarit Stainless Oy in Tornio. But some AOD workers found nitrogen level in the low nitrogen content grade stainless steel sometimes is a little high during the reduction stage in Tornio's AOD workshop. Except the possible error caused by the model used in the industrial operation to determine switch point from blowing nitrogen to argon, they also presumed that the extra nitrogen in the liquid steel may come from the air entrapped into the AOD furnace from the gap between AOD mouth and the exhaust gas hood. In order to study the possibility of air entrainment into the AOD during the reduction stage of stainless steel-making, a CFD model was constructed in the present work. Fig.1 is the schematic of the modelling domain.

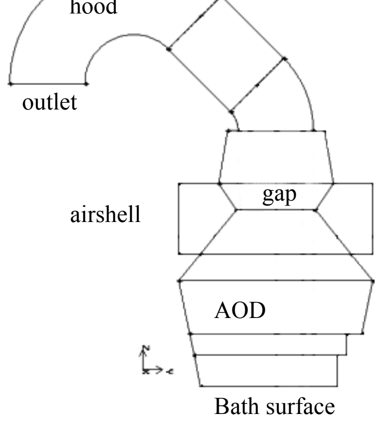


Figure 1: Schematic diagram of modelling domain.

According to the literatures (Gou, 1993 and Snoeijer, 2002), several mathematical models have been installed to simulate the exhaust system of converter. However, there is little report on the modelling of gas flowing and species transportation in AOD system during the reduction stage. The current work will give a description of CFD model and results of gas distribution in AOD reduction process.

MODEL DESCRIPTION

Conservation Equations

Steady and unsteady modelling was carried out respectively in present research. Some assumptions are given for the CFD models: gas flow is considered as one phase; temperatures of walls of AOD and hood are treated as fixed values; the simulation is about the reduction stage of AOD process (only blow argon from the bottom tuyeres); some boundary conditions, such as temperature and composition of gas initiated from bursting bubble area on the melts bath, are presumed since there are not measured values available at moment. Fluid flow is turbulent in the modelling system. Turbulent momentum transferring, energy transferring including radiation and species transferring with volume reaction are modelled together.

The governing conservation equations used in the CFD modelling are listed below.

Continuous equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \qquad (1)$$

Momentum conservation equation

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u}) = -\nabla p + \nabla . \mu \nabla \mathbf{u} + \mathbf{F}_s \qquad (2)$$

Standard k-ε transport equation was applied to derive turbulent variables. For the region near wall, standard wall function is used to treat the viscous layer.

Energy conservation equation

$$\frac{\partial}{\partial t}(\rho h) + \nabla \cdot (\mathbf{u} \rho h) = \nabla \cdot \left(k_{eff} \nabla T - \sum_j h_j \overrightarrow{J_j} \right) + S_h \qquad (3)$$

Here h is sensible enthalpy, defined as $h = \sum_j Y_j h_j$ (Y_j is the mass fraction of species j, $h_j = \int_{T_{ref}}^{T} Cp_j dT$).The first two terms on the right-hand side of Equation (3) represents energy transfer due to conduction, species diffusion. The last source term is linked with heat of radiation and chemical reactions.

The radiation model used in this problem is Discrete Transfer Radiation Model (Shah, 1979 and Carvalho, 1991). The main assumption of the DTRM is that the radiation leaving the surface element in a certain range of solid angles can be approximated by a single ray.

Species transportation equation and combustion reaction

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho \mathbf{u} Y_i) = -\nabla \cdot \overrightarrow{J_i} + R_i \qquad (4)$$

An equation of form (4) will be solved for *N-1* species where *N* is the total number of fluid phase chemical species present in the system. Since the mass fraction of the species must sum to unity, the *N*th mass fraction is determined as one minus the sum of *N-1* solved mass fractions. To minimize numerical error, the *N*th species should be selected as that species with the overall largest mass fraction. Six species were included in the gas: argon, nitrogen, oxygen, carbon monoxide, carbo dioxide and vapour.

For current simulation, the only chemical reaction is combustion of carbon monoxide with oxygen. As we know, CO popping up from melts bath will burn quickly as it meets the air from atmosphere. Obviously, the overall combustion rate is controlled by turbulent mixing. Thus eddy-dissipation model (Magnussen and Hjertager, 1976) is employed for the solution of R_i.

Materials Properties of Mixture Gas

The properties of mixture gas are dependent on the composition and temperature. The density of mixture gas is defined by incompressible-ideal-gas methods. Mixing-law is employed to express the specific heat capacity of mixture gas. The mixture's specific heat capacity is computed as a mass fraction of the pure species heat capacities. Each pure specie heat capacity is defined by piecewise-polynomial function of temperature. For thermal conductivity calculation of mixture gas, Ideal-gas-mixing law is used here. Individual species thermal conductivity is taken as a constant because heat conduction does not play an important role in the heat transfer of the whole model domain. Computation of viscosity of mixture is also implemented by ideal-gas-mixing law. Sutherland's viscosity law with three coefficients is employed for the derivation of each specie molecular viscosity. Mass diffusivity of mixture is considered as constant since the molecular diffusion is relative small if compared with convection transfer.

Because carbon dioxide and vapour can not be simply treated as grey gases, special model was applied to determine mixture gas absorption coefficient for radiation calculation. Weighted-sum-of-grey-gases model in FLUENT6.1 is used here for the calculation of absorption coefficient in this model. WASGGM is a reasonable compromise between the oversimplified grey gas model and a complete model which takes into account particular absorption bands.

Boundary Conditions

The initial gas inside AOD furnace rises from the bubble area on the melts bath surface. For the present model, the plane closely parallel to the melts bath surface is selected as the gas inlet. However, the gas distribution on the inlet plane is not homogenous since gas mainly flows from bursting bubble swarms. The bubble areas are illustrated below (Mure, 2002):

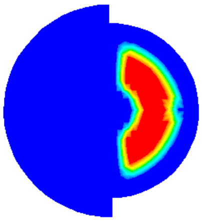


Figure 2: Bubble swarm on the bath surface (red area).

Additional definition was given to the inlet boundary conditions by the User-defined Function (UDF) coding which can be dynamically loaded with the FLUENT solver to enhance the standard features of the code.

The gas mass fraction in the bursting bubble is assumed as 90% argon and 10% CO during the reduction stage. The initial temperature of gas from the inlet is assumed as the temperature of molten stainless steel.

Fixed temperatures were given to set thermal conditions of the boundary walls of the computing domain. The temperatures of boundary walls are given according to industry experiences and literature data since there are no available measurements now.

The boundary type of hood outlet is pressure-outlet. The initial gauge pressure of hood outlet is set to -300 Pascal.

Numerical Solving Process

Hexahedral cell was chosen as the meshing element and more than 40000 cells (the average mesh sizes ranges from 0.1 m to 0.2 m) were generated in the three dimensional computing domain.

Segregated solver is used for this CFD simulation. Special skills have been used in order to obtain better and fast convergence during solving process for steady conditions. Computation iterating process began with only flow equations at the initial stage of computing. Then turbulence was included in the iteration after initial fluid field information was obtained. As the flow fields without species and chemical reaction had been solved, the next step would contain energy and species transferring computing to achieve convergence. Finally, chemical reaction was included in the solving process. The selection of discretization is as following: pressure interpolation scheme is standard; SIMPLE is applied to pressure-velocity coupling; Momentum, turbulence kinetic energy, turbulence dissipation rate, species and energy equations use first order upwind at the beginning. Based on the converged solution with the discretization scheme of first order upwind, second-order upwind will be employed finally in order to reduce numerical diffusion errors.

If the residuals of all solved variables drop three orders, surface integral of imbalance mass stop fluctuation and temperature of surface integral on the monitored surface is constant after many numbers of iteration, the solution can be thought as convergence. Meanwhile, grids independence check has been carried out to ensure the results do not depend on the meshes

For unsteady state simulation, the calculation began with the data obtained from steady modelling. The time step is 0.05 s.

RESULTS

Since nitrogen in the computing domain is from air outside of the converter, nitrogen distribution in the simulation system also suggests air entrainment into the AOD. The following results will show the nitrogen distribution derived from steady and unsteady state respectively.

Nitrogen Distribution under Steady Conditions

Steady conditions here mean that gauge pressure at the outlet of hood is kept constant of -300 Pascal in addition to the blowing rate of argon from bottom tuyeres is stable during the reduction process.

The gas flow velocity field near the AOD mouth is shown in Fig.3, which suggest that most hot gas from converter will flow directly to the ventilation hood. Most air from atmosphere would be sucked into exhaust gas hood through the gap between converter mouth and hood. For this stable case, no entrapped air flow into converter was observed here.

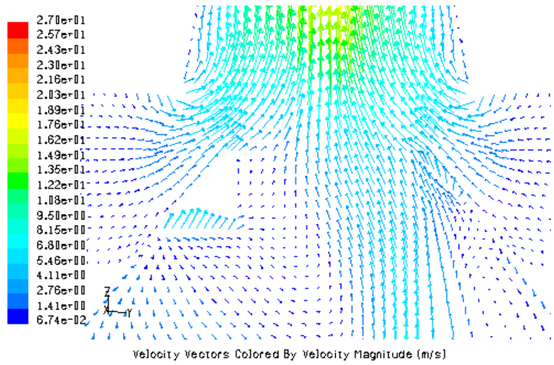


Figure 3: Velocity vector of mixture gas on the symmetric plane near the mouth of AOD.

Figure 4 is the nitrogen contour on the symmetric plane of the simulated domain. The picture shows that ventilation pipe is filled with large amount of nitrogen which suggests intensively air ingression into hood through the gap between hood and AOD. No obviously air entrainment into AOD converter is observed from the contour of mass fraction of nitrogen.

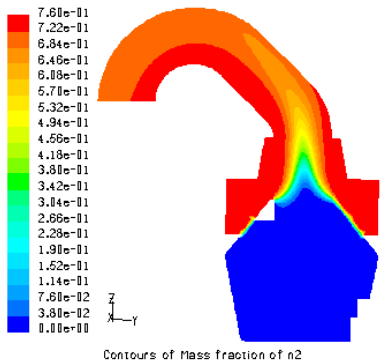


Figure 4: Nitrogen contour on the symmetric plane of computing domain.

Figure 5 shows the nitrogen content along the height of AOD converter at different positions on the symmetric plane. The mass fraction of nitrogen inside converter is much lower than 2.5%. However, the content of nitrogen will jump quickly to about 45% at some positions very close to the mouth plane of AOD.

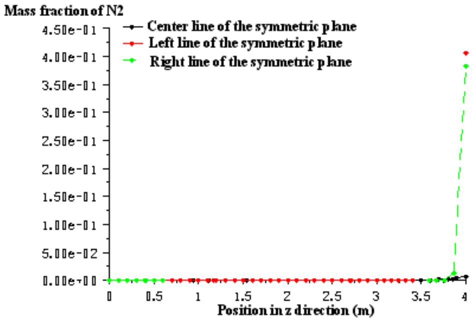


Figure 5: Nitrogen distribution along the height of AOD at different positions on the symmetric plane.

The nitrogen contour and distribution on the mouth plane of AOD converter are shown in Fig.6 and Fig.7. The nitrogen content is high near the edge of the AOD mouth and low at the centre of mouth. This result indicates that most hot gas inside converter flow directly from the centre part of AOD and pushes away the intruded cold air. Cold air from outside only slips along the side edges of the AOD mouth into converter. However, the depth of cold air ingress inside AOD is not very deep as shown in Fig.4.

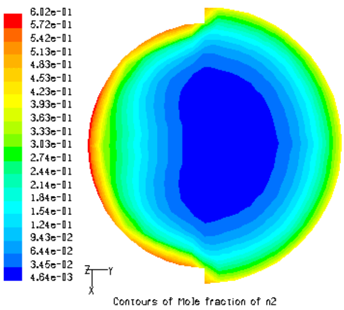


Figure 6: Nitrogen contour on the mouth plane of AOD.

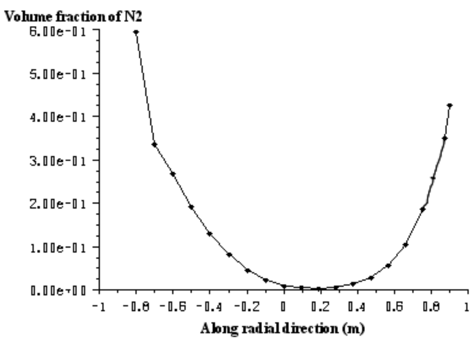


Figure 7: Nitrogen distribution along the diameter of AOD mouth.

So under steady conditions during reduction stage, it is impossible for large amount of air to be entrapped deeply into AOD converter. Most air will be sucked by the ventilation system into the hood pipe through the gap between AOD and hood. The explanation of this phenomenon is that hot argon and other gas flowing up from converter prevent ambient air from penetrating into the AOD further. From the view point of fluid dynamics and heat transferring, the gas from the bottom of converter is about more than 1000℃, ambient air less than 100 ℃ can be heated quickly as it meets the hot gas(the heated air will expand and flow upwards), which could not give many chances for the nitrogen penetrating deeply into the converter.

The nitrogen content at the outlet of the exhaust gas hood in the computing domain is shown in Fig.8 and Fig.9 respectively. The results indicate that the volume fraction of nitrogen at the end of hood ranges from 73.5% to 78%. The nitrogen does not distribute evenly on the outlet plane. The calculated nitrogen content is quite similar to the measured data at the same position of exhaust gas hood. The measured nitrogen in the industry of this AOD is about 73% to 75%.

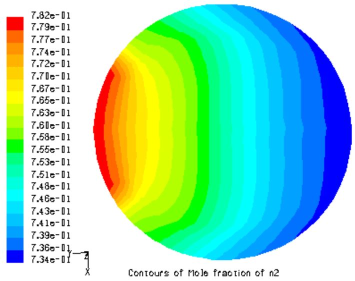


Figure 8: Nitrogen contour at the outlet of hood.

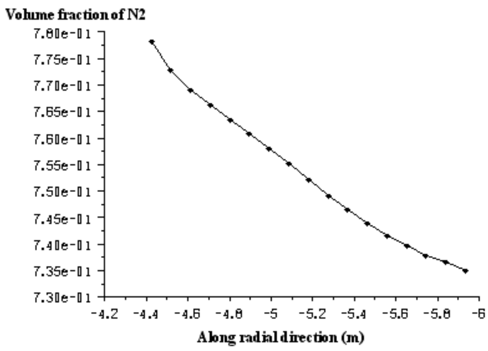


Figure 9: Nitrogen distribution along the diameter of the outlet of hood.

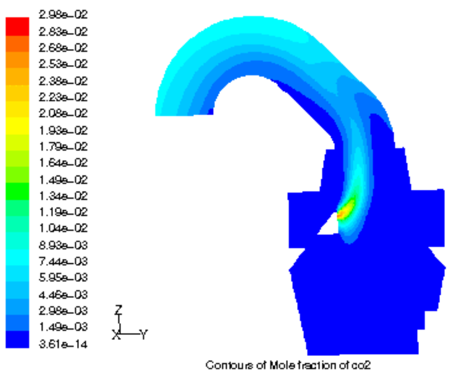


Figure 10: Carbon dioxide distribution on the symmetric plane of AOD

It is very interesting to take a look at the carbon dioxide distribution in the computing domain. Figure 10 shows that carbon dioxide is produced at the areas a little above the left part of AOD mouth, which indicate that carbon monoxide mix quite well with the air here.

Nitrogen Distribution under Unsteady Conditions

According to the industry experience, the suction ability of the ventilation system could oscillate suddenly due to some unexpected factors. The sudden falling of suction ability in the ventilation hood would bring side effects such as the hot gas escape from the converter. It is necessary to study the possibility of air entrainment into AOD converter under such unsteady conditions.

Unsteady condition relative to suction ability oscillating of ventilation hood was implemented by changing the pressure at the outlet of hood in present simulation. The assumed alteration of local gauge pressure at the outlet of hood during one oscillation period is indicated in Fig.11.

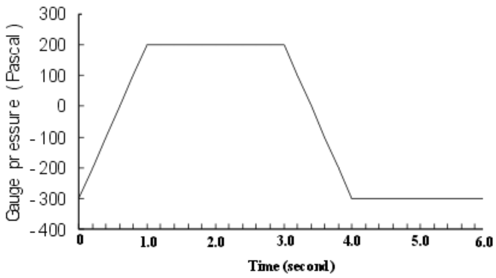
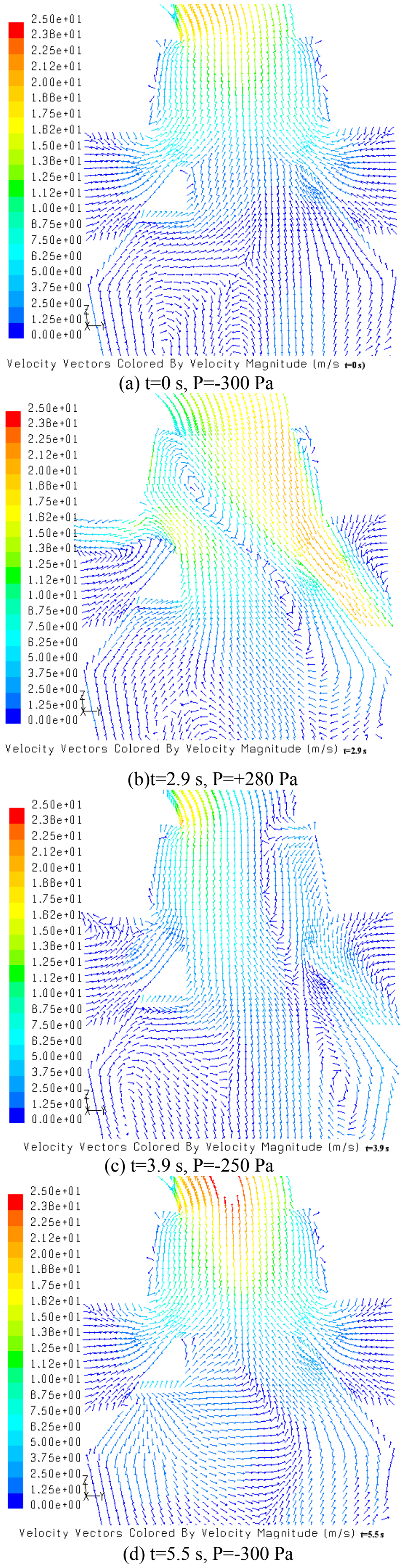


Figure 11: Illustration of Pressure oscillation period at the outlet of ventilation hood.

The gas flow velocity during one hood pressure oscillation is illustrated in Fig.12.

At the very beginning of pressure jumping, the velocity field is as same as that under the steady conditions and cold air is sucked into hood. Gas from converter flows upwards the ventilation pipe. As relative local pressure in the hood continuously climbs and keeps a positive value for some time, gas velocity in the hood will fall down and totally change the direction as shown in Fig.12 (b). Some exhaust gas could flow outside of hood through the gap to the atmospheres. On the other hand, hot gas from converter colliding with the reversed exhaust gas in the hood is forced to go back and flows through the gap to the atmospheres. When the pressure in the hood begins to drop and ventilation system is recovering the suction, the velocity field will change consequently despite the inertial effects caused delay as shown in Fig.12(c) and (d). Finally, the flow field will recover to the initial stage if the normal negative pressure at the outlet of hood is kept for an enough long time.

Figure 13 shows the nitrogen contour changing on the symmetric plane of the simulated domain during one period of pressure oscillation in the hood.



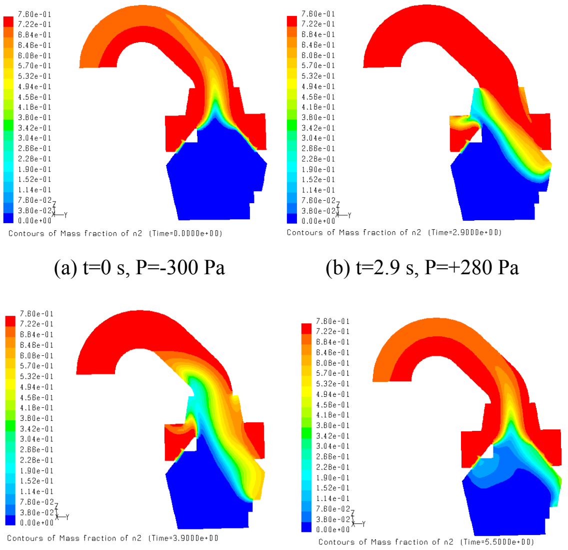
(a) t=0 s, P=-300 Pa

(b)t=2.9 s, P=+280 Pa

(c) t=3.9 s, P=-250 Pa

(d) t=5.5 s, P=-300 Pa

Figure 12: Gas flow pattern near AOD mouth while the pressure in the hood is changing (Here P is the relative pressure at the outlet of ventilation hood)



(a) t=0 s, P=-300 Pa (b) t=2.9 s, P=+280 Pa

(c) t=3.9 s, P=-250 Pa (d) t=5.5 s, P=-300 Pa

Figure 13: Change of nitrogen distribution on the symmetric plane of AOD during one suction oscillation period.

Another interesting thing is that during the process of suction ability recovering, high nitrogen area still occupies the right side of furnace for some time, as indicated in Fig.13 (d). Even after the pressure at the outlet of hood is kept as -300 Pascal for more than 1 second, the area near the right part of AOD mouth still has the nitrogen with fraction about 30% as shown in Fig.13 (d). So it is clear that nitrogen content on the right space near this AOD converter mouth could rise to a rather high value during the suction ability oscillation. One thing should be pointed out here that these results are only available to the AOD system with the geometry of Fig.1. If the geometric relationship between hood and AOD mouth is different, air entrainment under unsteady conditions may be quite different.

However, even at such above unstable situations, no significant high nitrogen containing is observed near the melts bath surface in these pictures. Figure 14 is the nitrogen content along the centreline of converter at different time of one pressure oscillating period. The results suggest that the nitrogen fraction is always far below 2% within the height of 1.5 meters from bath surface under different hood suction ability conditions.

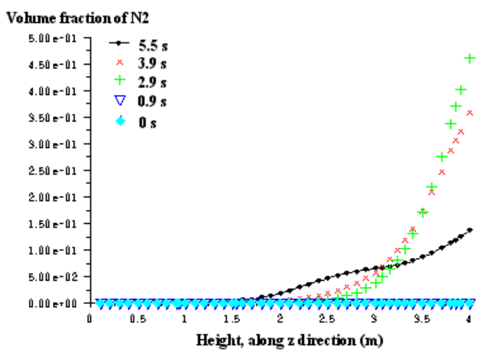


Figure14: Nitrogen fraction along the height of AOD. (Centreline of symmetric plane)

CONCLUSION

CFD model was installed to investigate the possible air entrainment into AOD converters under steady condition and unsteady conditions caused by suction ability oscillation in the ventilation system.

Derived results indicate that it is impossible for a large amount of cold air flowing deeply through the gap between AOD mouth and hood into the converter under normal steady conditions. Such kind of vast air intrusion may lead to serious nitrogen dissolution in the molten bath at reduction stage. The highest nitrogen content around the mouth of AOD is about 40%. Simulations results indicate that the mass fraction of nitrogen inside AOD converter during reduction stage is far below 2%.

The change of suction ability of ventilation hood in current simulated AOD system can lead to further entrainment of gas containing high fraction air into the converter than that under steady conditions. However, no obvious high nitrogen level is observed near the bath surface even under such kind of unsteady conditions. The mass fraction of nitrogen is also very low near melts surface.

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REFERENCES

KUPARI.P and HOOLI.P,(1999):, “Nitrogen control in AOD converter” *Material Science Forum,* **318-320**, 385-392.

GOU.H, IRONS.G.A and LU.W.-k.,(1993), “Mathematical modelling of postcombustion in a KOBM converter”, *Metallurgical transaction B*,**24B**,179-188.

SNOEIJER.A.B. et al., (2002) “Energy recovery and BOS stack emission reduction by controlling the combustion of waste gas”, *85th Steelmaking Conference Proceedings*, Mashville,Tennessee, USA, March 10-13,625-637.

SHAH N.G., (1979), “A new method of computation of radiant heat transfer in combustion”, PHD theses, Imperial College of Science and Technology, London, England.

CARVALHO,M.G., FARIAS.T and FONTES.P., (1991), “Predicting radiative heat transfer in absorbing, emitting, and scattering media using the discrete transfer method”, *Fundamentals of Radiation Heat Transfe*r, ASME HTD,**160**,17-26.

MAGNUSSEN.B.F and HIJERTAGER B.H., (1976), “One mathematical models of turbulent combustion with special emphasis on soot formation and combustion”, *16th Symp. (Int'l.) on Combustion,* The Combustion Institute.

MURE.P, (2002), “The effect of sidewall blowing on melt flows, mixing and oscillation of melt bath in a 150 ton AOD converter”, Master Thesis, University of Oulu, Finland.