LMF CONTINUOUS TEMPERATURE MEASUREMENTS: RESULTS OF FIRST APPLICATION[1]

Paolo Galbiati [2]
Juan Sebastian López [2]
Francesco Memoli [3]
Cesare Giavani [3]
Fabio Bonacina [3]
Carlo Mapelli [4]
Dario Martelli [4]
Enrico Malfa [5]
Ugo Chiaretti [5]
Piero Frittella [5]

Abstract

One of the main purposes of LMF treatment is to ensure that the molten steel has the required temperature when the ladle is taken downstream. Dynamic process models have been developed for the on-line calculation of the temperature during the treatment. Accuracy of the process model still requires spot temperature measurements to adjust the calculation and to ensure that the liquid bath reaches the target temperature. The temperature measurement system developed in Tenaris Dalmine and described in this paper, considerably improve the LMF process allowing the Dynamic process models to evaluate the other process parameters based on the real-time bath temperature. Benefits of this new equipment are the reduced cost for temperature measurement.

Key words: Continuous temperature measurement; Optical temperature measurement; Non-contact temperature measurement; LMF temperature measurement; LMF process optimization.

MEDIÇÕES CONTÍNUAS DE TEMPERATURA NO FORNO PANELA: RESULTADOS DA PRIMEIRA APLICAÇÃO

Resumo

Um dos principais objetivos do tratamento no Forno Panela é assegurar que o aço líquido tenha a temperatura necessária quando a panela é transportada no processo a jusante. Modelos dinâmicos de processo foram desenvolvidos para o cálculo da temperatura em tempo real durante o tratamento. A precisão do modelo de processo ainda requer medições de temperatura locais para ajustar os cálculos e para assegurar que o aço líquido atinja a temperatura desejada. O sistema de medição de temperatura desenvolvido na Tenaris Dalmine e descrito neste trabalho melhora consideravelmente a operação no Forno Panela permitindo que os modelos dinâmicos de processo avaliem os outros parâmetros de processo baseados na temperatura do banho em tempo real. Benefícios deste novo equipamento são o custo reduzido para a medição de temperatura.

Palavras chave: Medição contínua de temperatura; Medição óptica de temperatura; Medição de temperatura sem contato; Medição de temperatura no forno panela; Otimização do processo do forno panela.

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[2] *Tenaris Dalmine*

[3] *Tenova SpA*

[4] *Politecnico di Milano*

[5] *Centro Sviluppo Materiali SpA*

Introduction

During Ladle Metallurgical Furnace (LMF) treatment, liquid bath temperature measurement is very important both for refining control and to ensure a correct temperature of the following treatment or process (normally continuous casting). One or more temperature measurements of the liquid bath are usually taken at intervals using a thermocouple located on the tip of a lance that is submerged into the bath by operators. It was tried several times to substitute intermittent and consumable thermocouple measurement using a continuous methodology, mainly optic methods. An optic methodology gives the possibility to maintain the sensor far from the bath, so that it is reusable indefinitely, and, in principle, to make a continuous on-line measurement. However, optic methods introduce different kind of problems not still solved. One of the bigger problems is caused by the presence of slag that covers the molten steel. This covering slag has generally a lower surface temperature respect to the molten steel due to its high emissivity and low thermal conductivity.

Attempts have been done to measure bath temperature through a submerged tuyere leaving a direct view of the molten steel or, alternately, by moving aside the covering slag. The first way was deeply investigated.(1,2). Using submerged tuyere already available on the plant for gas addition and stirring. It gave very good results when applicable, but for several processes it is not usable without strong plant modifications. For this reason Tenova, supported by Tenaris Dalmine and CSM, developed the second way (patent pending), i.e. by using a suitable gas flow jet able to move away the covering slag. However, this solution generates further and different issues that have to be solved. Hot slag can mix with molten steel on the pyrometer target: due to difference in emissivity of slag (high) and steel (low) the pyrometer temperature measurement can be affected by an error depending on the mixing areas. Furthermore, steel has also high reflectivity factor which may affect pyrometer measurement through light reflection on molten steel surface. In this paper the results of first on line tests, on a Tenaris Dalmine Ladle Furnace, and lance design based on CFD simulation are presented.

Tenova approach for LMF continuous temperature measurement

The instrument that is used to make continuous temperature measurement in the ladle furnace is called KTS, acronym for Key-Temperature Sampler.

The KTS is based on KT lances technology of Tenova, as a matter of fact it is formed by a water cooled copper body. In the body lance a nozzle-support for fibre optics pyrometer has been inserted. Its function is to measure, on-line and real-time, steel temperature This structure has been inserted in the roof of LF1 of Tenaris Dalmine. The high performance cooling system of KT lance allows to ensure proper working above the high temperature liquid steel bath and to protect internal fibre-optics and rest of the equipment from the high temperatures that are typical of ladle furnace.

Unlike the thermocouple, which penetrates in the bath, the pyrometer has no contact with bath; in fact, it measures steel's temperature using the emission product by the bath.

Observing the different colouring of steel, the pyrometer can translate the different emissions recorded in temperature's values. During the first application the KTS has been inserted in order to aim on one of the two argon plugs (in particular the second argon plug). In this way a relevant argon flow rate permits to discover the steel, and allows to observe directly the steel.

Moreover, the support nozzle grants two fundamental functions: to-have a gas jet that purges the instrument and to penetrate the slag present on the bath, letting to the pyrometer a better “vision” of the molten steel compared with argon bubble only.

Installation at Tenaris Dalmine LF

The KTS has been inserted in the roof of TenarisDalmine LF1. In its internal body, as previously described, there is a pyrometer able to measure the steel’s temperature. The pyrometer is a digital and highly accurate instrument with fibre optic for non-contact temperature measurement between 300°C and 3,300°C. It can measure with three different modes:

- 2-color;
- mono-color;
- metal mode.

In the first mode two adjacent wavelengths are used to calculate the temperature. It calculates the temperature by rationing the radiation intensities of the two wavelengths in order to make the instrument less sensible from several troubles.

This ratio technique offers different advantages compared with the standard one-colour pyrometers. In fact, the temperature measurement is independent of the emissivity of the object in wide ranges, it is unaffected by dust and other contaminants in the field of view, it is unaffected by dirty viewing windows and the measuring object can be smaller than the spot size. In this way the instrument can switch a corrective coefficient K (emissivity slope). This variation allows, on equal measured temperature, to change the value that the instrument pulls out. In particular, since the pyrometer is affected by environment conditions, the K-factor must be regulated depending on the different operation conditions.

Additionally the pyrometer can be switched to one-colour mode and used like a conventional pyrometer.

The metal mode, on the other hand, allows measurements of metals and alloys with unknown K-factor.

The instrument is equipped with an optical fibre that passes through all the length of the lance in order to transfer the signal to an instrument that gives temperature in real time. This optical fibre can be used in very high ambient temperatures up to 250°C without cooling and it is unaffected by electromagnetic interferences.

Two different optical heads for different measuring distances and very small spot sizes are available.

The very short response time of only 2 ms facilitates the measurement of fastest heating processes.

The radiation, coming in through the optical head, is transported via the lens system into the mono glass fibre with flexible stainless steel protection tube where it is transmitted along to the converter. The optical head contains only the lens system, the electronics are located in the converter box. The transmission through the fibre optic cable is based on the principal of the total reflection by boundary surfaces of the glass fibres.

Results of on-line measurements

At the end of 2007 the new on-line pyrometer measuring system was started-up by Tenova on LF1 plant at Tenaris Dalmine. The first trials were carried on when slag uncovering was obtained only with a high argon rate from porous plugs.

The measuring system was previously tested off-line at CSM Laboratory in Rome (Italy) using a blackbody as light source. This pyrometer, with two-color setting, showed a measurement uncertainty lower then 0.6% at 1,500°C and a temperature reduction of about 15°C for a spot size reduction of 50% (at 1,200°C). Furthermore, theoretical emissivity ratio at pyrometer wavelengths (also named *k* factor or emissivity slope) was measured, assuming molten steel emissivity 0.3 μm at 0.9 μm and 0.2 μm at 1.6 μm and assuming the emissivity as a linear function for wavelength variations. Using such values the theoretical *k* factor of this pyrometer was calculated. Of course, this value is approximate because molten steel emissivity depends on temperature and compound content.

Data gathered by the on-line pyrometer measurement system was then compared with immersion thermocouple bath measurement. However, to make this comparison it was necessary to exclude some particular process conditions. Mainly it was considered only situations without arc power and with argon porous plugs rate higher than 350 l/min.

Furthermore three different pyrometer data filters have been implemented to reduce signal noise. These filters were named Ftr1, Ftr2 and Ftr3 and they work as hereafter described:

a) a set of “n” pyrometer measure is gathered consecutively. Such group of gathered measures is made of 30 consecutive measures for Ftr1, 60 consecutive measures for Ftr2 and 90 consecutive measures for Ftr3. Because the pyrometer was set on a frequency of 10 measures for second, consequently Ftr1 requires at least 3 sec. to work on-line, Ftr2 requires 6 sec. and Ftr3 requires 9 sec.
b) each pyrometer measure is controlled and subsequently rejected if the single measure is out of a defined temperature range. The range was fixed as 1400 °C as minimum acceptable temperature and 1750°C as maximum acceptable temperature.
c) the entire sample is then rejected if the number of unacceptable measures overcome 40% of the total measure of the sample.
d) the sample is then defined as “acceptable” if the standard deviation of the sample measures is lower than a defined value. It was accepted a standard deviation of the sample data up to 25°C.
e) the Average value or the Median of the sample (excluded the rejected value) is considered as the Filtered Pyrometer Measure (FPM), i.e. the suitable pyrometer temperature measure.

The continuous application of such data filters leaves to obtain continuously FPMs with low noise, however to obtain a single FPM comparable with the thermocouple measure it was necessary to fix two other conditions, defined as following:

a) the thermocouple measure was considered suitable up to 5 minutes before the instant it was taken. The result of this rule is that a single FPM can be compared with the temperature measure obtained with the thermocouple up to 5 minutes before the thermocouple measurement is obtained, i.e. out of this time range the thermocouple measures and the FPM cannot be compared.

b) the FPM with the lower standard deviation value, obtained during the 5 minutes time range, is selected and compared with the thermocouple temperature measure.

Figures 1 and 2 show two typical situations of pyrometer measurement with data filtering. The blue line shows pyrometer signal with filtering. The violet line shows the temperature measure obtained by immersion thermocouple. The green line shows the gap between pyrometer's lecture and thermocouple measure temperature. Finally the red line shows the percentage gap between pyrometer's lecture and thermocouple measure temperature.

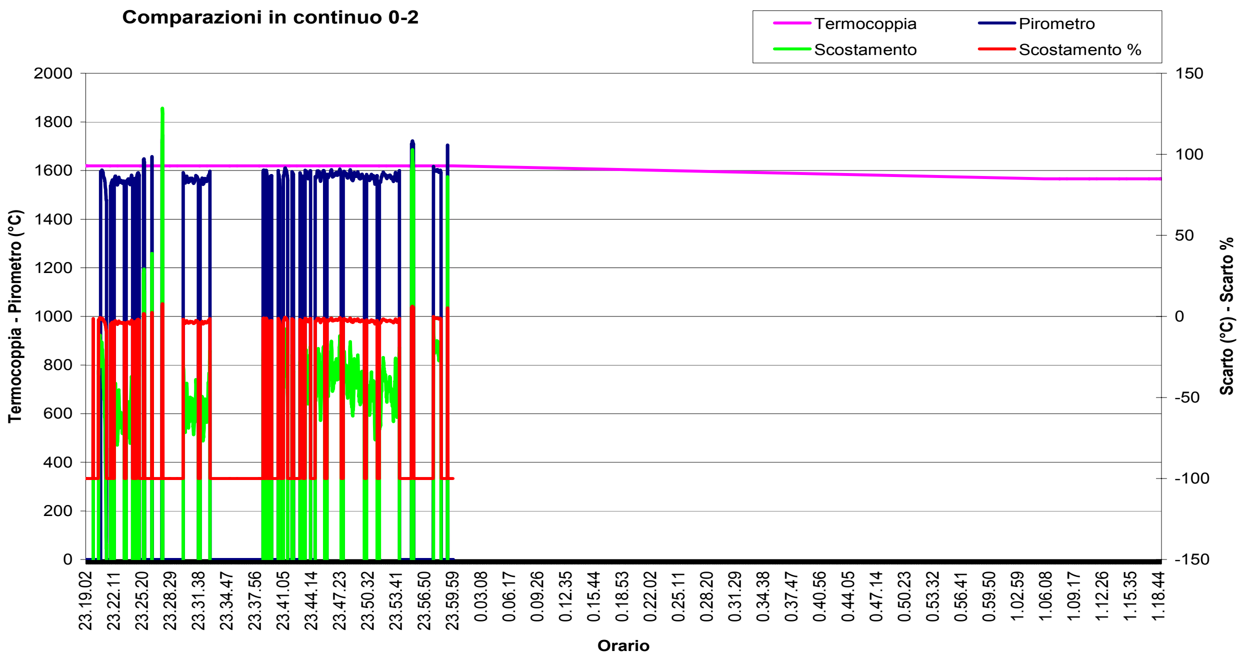


Figure 1 – Typical LF pyrometer bath measurement with data filtering and no arc

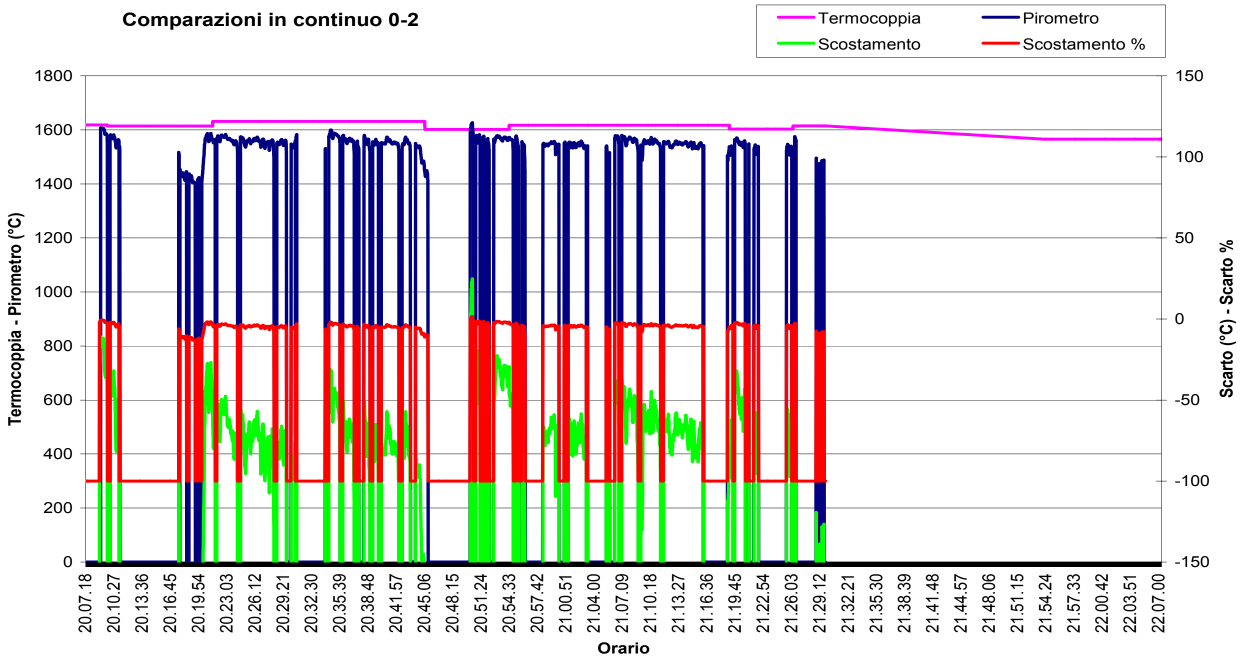


Figure 2 – Typical LF pyrometer bath measurement with data filtering with arc

By the analysis of LF process data with thermocouple measurements, and considering only process situations with no electric arc (as reported in Figure 1) it was possible to measure a constant average temperature offset between pyrometer filtered measurement and thermocouple measurement. Because during this first test pyrometer *k* factor was set to 1, to correct such low pyrometer temperature it was calculated a new *k* factor. This low value is caused by geometrical spot reduction caused by lance design that was not possible to change due to flow injection constraints.

However, as an average low pyrometer temperature may be corrected modifying *k* factor, the standard deviation of this measure cannot be modified without changing the measurement set up. The measured pyrometer temperature standard deviation was about 20°C for the best filtering method. Assuming a Gaussian distribution of the errors, 20°C of standard deviation correspond to an error of about ± 20°C for 68% of measurements and ± 40°C for 95% of measurement respect to the immersion thermocouple measurement. With the objective to reduce that difference Tenova applied a new measurement system including the high jet gas flow from the KTS System.

Numerical simulation of jet impingement on slag and molten metal

Model set up:

Since 60s, the physical (water) models at laboratory scale have been used to investigate phenomena connected to the injection of gases in liquid bath by supersonic jets. Empirical correlations available in literature(3) are commonly used in the design of industrial reactors such as BOF, AOD and EAF, however a very limited number of experimental data that take into account the presence of slag are available. Today numerical approach is used to investigate jet impingement on liquids using 1:1 scale geometry and industrial operative conditions.(4) Numerical approach open also new opportunity to make a critical analysis of empirical correlation and verify the similitude criteria adopted in the physical models.(5,6)

To define the guideline for designing an injector able to “open the slag” and to allow a more stable measurement of molten metal bath temperature by KTS pyrometer, the CFD approach, developed by CSM to simulate injection of a gaseous jet in liquid bath,(6,7) has been used.

The CFD simulation is based on the Reynolds averaged Navier-Stokes (RANS) equations. Details of numerical schemes and models used for the of supersonic jet representation are reported in Malfa et al.(8) e Harris et al.(9) In particular the k-ω Wilcox 98 turbulence model is used to overcome the well known “round-jet/planar-jet anomaly”.(10) Example of comparison between experimental(11) and calculated data are reported in Figure 3.

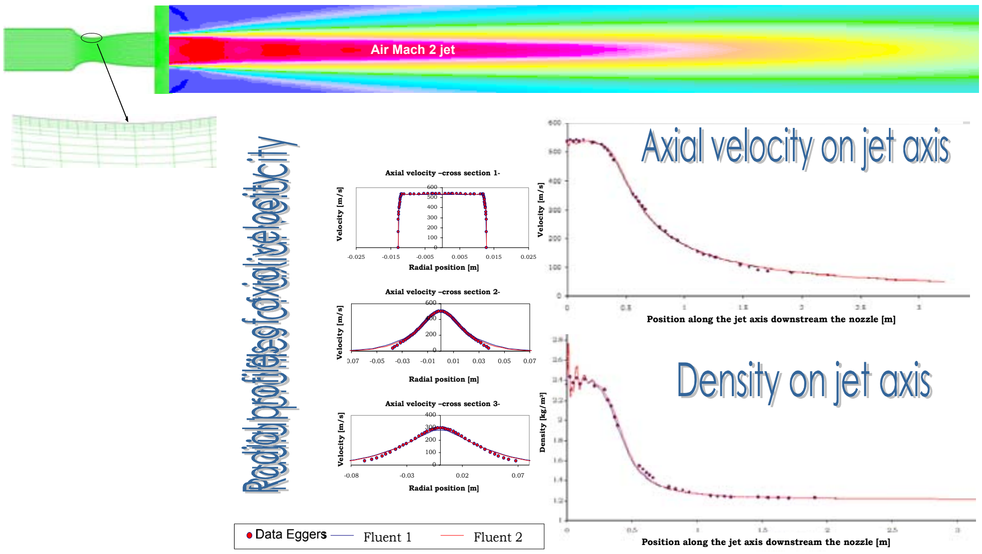


Figure 3 – Simulation of Mach 2.22 jet generated by C-D nozzle Geometry and experimental data by Eggers.(10)

The interaction between jet and liquid is simulated using time dependent VOF (Volume Of Fluid) model with the Geometric Reconstruction Scheme.(12) To avoid not physical over-production of turbulence viscosity at gas/liquid interface a UDF has been implemented by CSM. Set-up of the model has been done simulating interaction between air jet and water (representative of traditional physical model) for which correlation and experimental data are available (Figure 4). Details of the validation work and generalization of correlation for supersonic jet with shrouding, has been reported in Malfa et al.(6) e Piacenza.(7)

In the frame of this work the model has been extended introducing a third liquid phase (to represent the slag over the molten metal bath) and the mixing and chemical reactions in gas phase (O_2, CO, CO_2, N_2). All the simulation has been performed using 2D axis-symmetric domain due to CPU time constrains: 25 hours with 4 SGI Altix processor for 2.0 seconds simulation on 2D axis-symmetric domain.

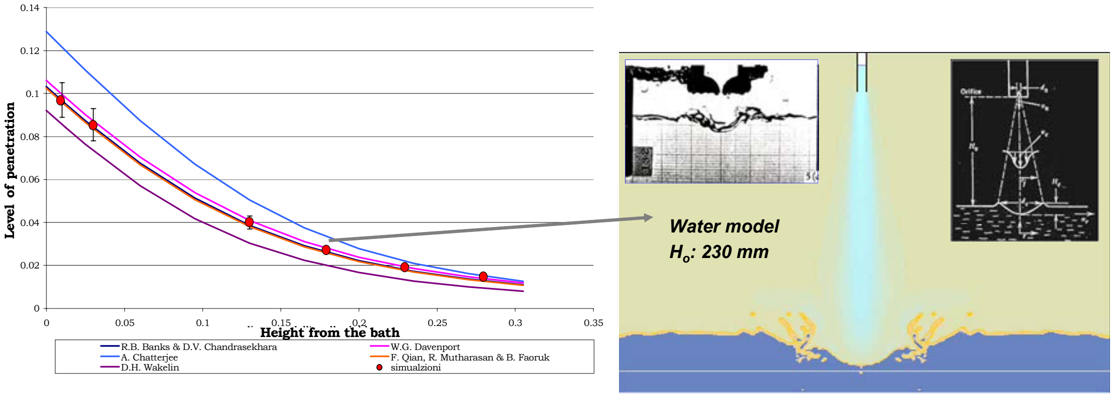


Figure 4 – Comparison between correlations for water models (jet penetration vs. lance height) and simulation performed with FLUENT 6.1.18 with CSM UDF.

Top blowing modelling:

The simulated domain (Figure 5) represents the portion of the LF in which the KTS is inserted. Only the KTS top blowing is taken into account and the molten metal is assumed covered by a layer of slag, therefore the simulation is representative of the operative condition in which the effect of bottom blowing (Ar) is not strong enough to generate an “open eye” in the LF.

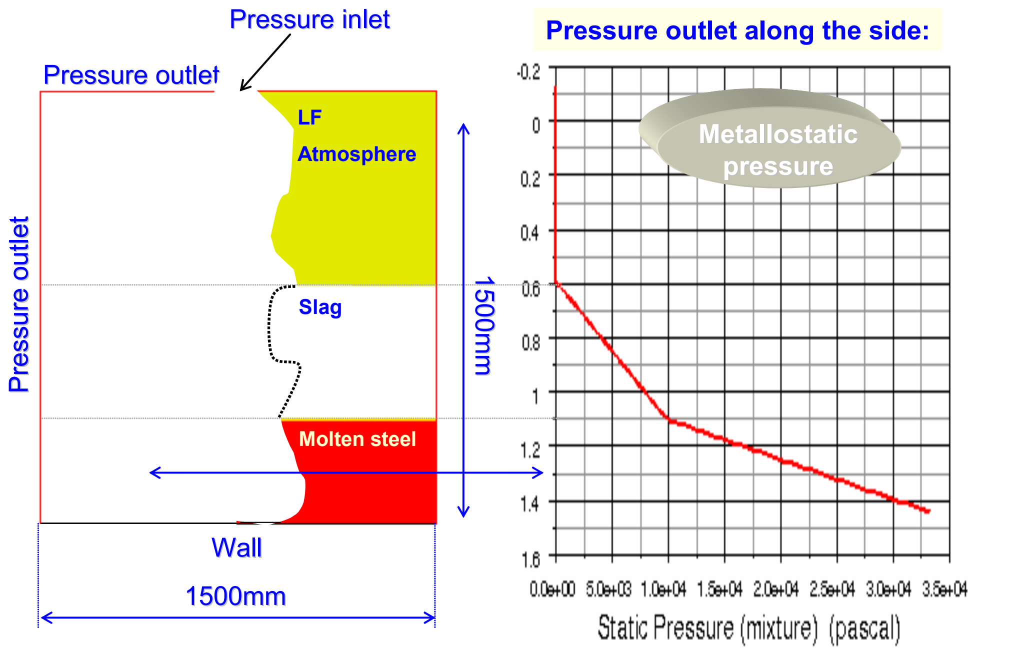
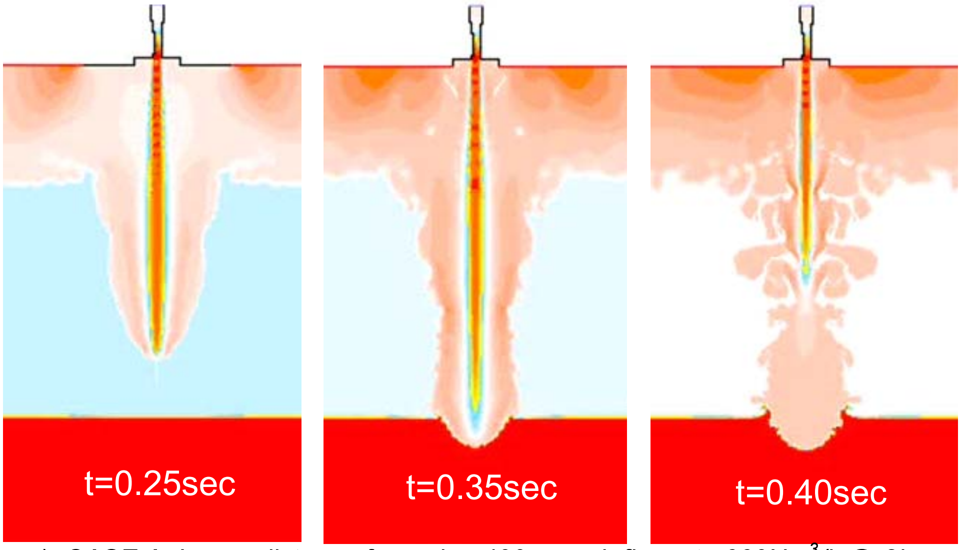


Figure 5 – Computational domain and boundary condition for KTS simulation.

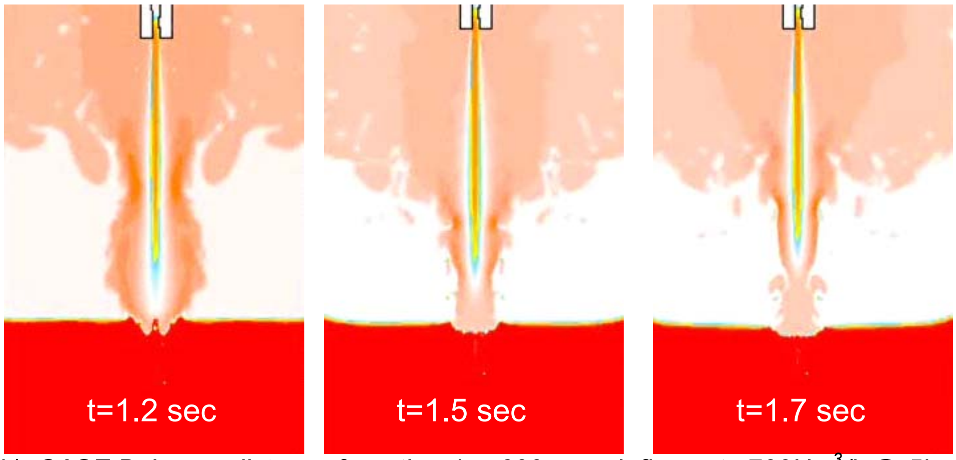
Several configurations in terms of flow rate, height of slag and relative position between lance tip and slag have been evaluated. Through the numerical approach it is possible to obtain detailed information about:

- the penetration of a supersonic jet generated by a top blowing in the slag and molten metal;
- the splash trajectories and the evaluation of the risks of lance clogging;
- the motion of slag and molten metal.

Since the process is highly transient detailed analysis of simulation results should require a video. Figure 6 shows the snapshot at different time frame of air jet/slag/molten metal interaction for two different configurations.



a) CASE A: Lance distance from slag 400mm, air flowrate 660Nm^3/h @ 2bar



b) CASE B: Lance distance from the slag 600mm, air flow rate 700Nm^3/h @ 5bar

Figure 6 – Snapshot of transient interaction process of supersonic air jet top-blowing with slag (white) and molten metal (red).

In both cases supersonic velocity is produced by the C_D nozzle. The jet interacts with the environment and produces a region of turbulent mixing in which the entrainment of external gas mixture increases the jet diameter, and decreases the mean axial velocity moving far from the nozzle tip. Conventionally, the region outside the nozzle is subdivided into coherent (constant velocity), supersonic and subsonic zone. The length of these regions and the jet spreading angle are affected by the gas density and temperature in the LF.(13,14) In particular the presence of CO in the gas phase, reacting with O_2 in the air jet, generates the well known shrouding effect increasing the length of the coherent jet region. In such a way the air jet reaches the slag with supersonic velocity.

When the gas jet impinging onto a slag and molten metal interfaces forms a cavity on the liquid surface. The mechanisms of surface deformation can be classified as penetrating mode for the slag, where the cavity acquire the shape of a long and narrow cylinder, while as dimpling mode for molten metal.(15) The gas drags the slag/molten metal into its radial motion outward from the impact point along the free surface and causes the circulation of the slag/molten metal. The CASE A represent the conditions for which, in a short time, the cavity collapse due to the reduction of the coherence of the air jet: in the first 30 seconds the air react with the CO producing shrouding effect, after that the CO in the cavity is burn out and the jet coherent region is not long enough to reach the molten metal, due to the lack of the natural shrouding of CO. The phenomenon is periodic and it could give reason of the experimental test in which oscillation between low temperature (slag) and high temperature (molten metal temperature) values.

In the CASE B, to compensate the lack of the natural shrouding of CO, a greater flow rate and pressure of air jet has been used. However the simulations shows that the jet is not strong enough for maintain stable the cavity and win the slag waves, which periodically collapse into the cavity interrupting the jet. This does not allow having enough time to obtain a stable temperature measurement by pyrometer.

KTS lance design:

Based on CFD simulations the geometry of lance, lance height and flow rates and type of gas to be used for opening the slag in front of pyrometer installed in the KTS have been selected. The main criteria used have been:

- complete penetration of jet in the slag, having assumed the expected maximum slag height (500 mm). It is considered that the formation of a cavity in the molten metal, when stable, is a positive effect. The cavity, in fact, works as a black body respect to the pyrometer;
- compatibility of C-D nozzle geometry with optical constrain of pyrometer optical;
- minimization of gas flow rate;
- minimization of splash ejected to the nozzle by the strong reverse flow.

Figure 7 shows the results of the simulation in which inert gas is used for the main jet and shrouding oxygen for secondary ones. The shrouding jets works stabilizing the jet (length of coherent zone) and like a shield for the slag wave and droplet. Steady state flow conditions never occur, but after a certain period of time (less than 1 second), a quasi-steady-state flow condition is reached where the shape and depth of cavities is fully developed.

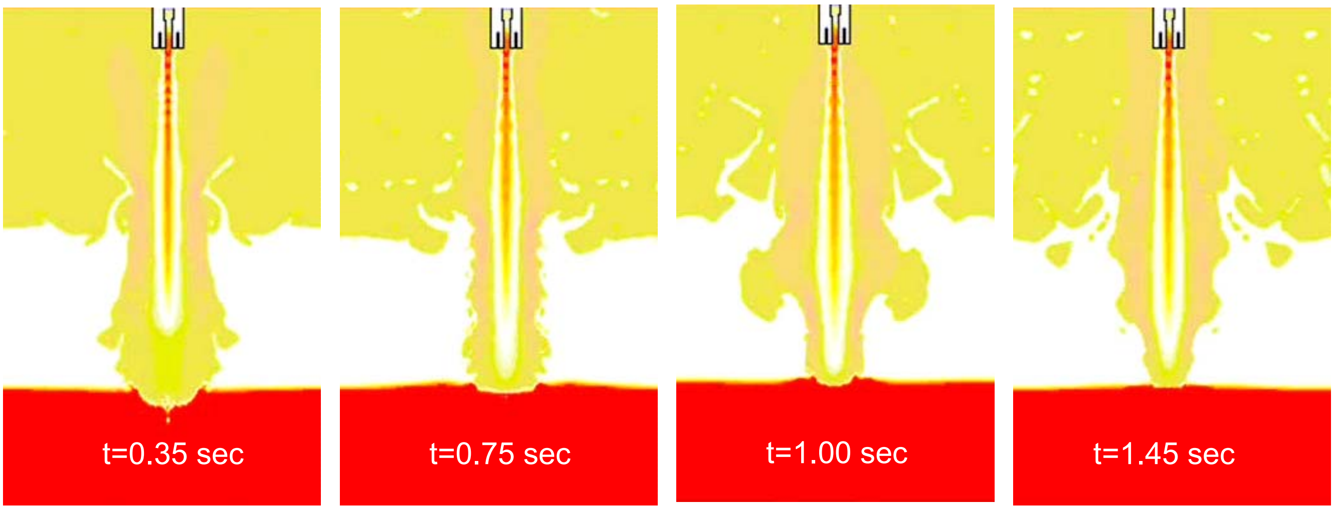


Figure 7 – Snapshot of transient interaction process of jet top-blowing with slag and liquid bath for optimized KTS configuration.

The effect of slag level on the penetration in the molten metal is reported in figure 1.10: the designed configuration secures the penetration in the slag and the formation of a dimple in the molten metal up to the slag height of about 500 mm.

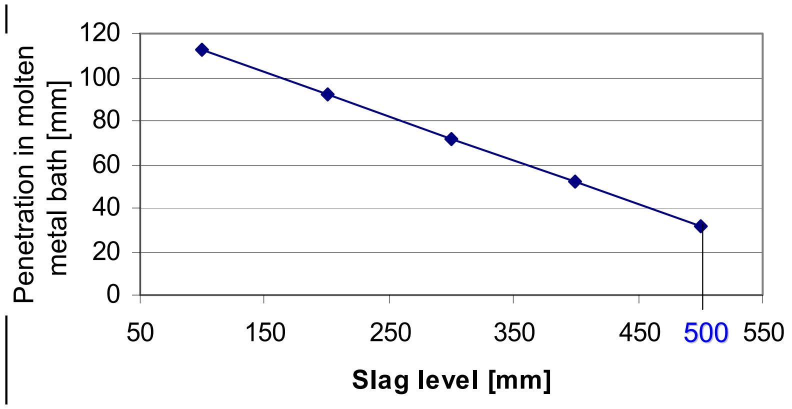


Figure 8 – The effect of slag level on the penetration in the molten metal.

Conclusion

First application of KTS at TenarisDalmine LF1 shows a big potential for the real-time temperature measurement of liquid bath temperature by pyrometer installed in a wall mounted cooling block. To enlarge the measurement range and to make more stable the design of a new gas injector has been performed.

Through the numerical approach detailed information about the penetration of a supersonic jet generated by a top lance in the molten metal, the risks of lance clogging and flow condition of slag and molten metal has been evaluated. This allowed the design of a new top lance producing a quasi-steady-state cavity, both in slag and molten metal, deep enough to ensure the measurement of the molten metal temperature by the pyrometer. Test of KTS equipped with the new injection system are scheduled in the next months at Tenaris Dalmine LF.

REFERENCES

1 Sugiura, M. et al., *Development of New Technique for Continuous Molten Steel Temperature Measurement*, Nippon steel Technical report No. 89 January 2004
2 Ramaseder, N., Heiss, J., *VAI-CON® Temp : continuous temperature monitoring in metallurgical vessels,* La Revue de Métallurgie-CIT Juin 2001.
3 Nordquist, P. Jönsson: *A study of the affect of nozzle diameter, lance height and flow rate on the depth of penetratione in a top blown water model,* divison of Metallurgy, Royal Institute of Technology, Sweden.
4 Odenthal, H-J: *Advantageous Numerical Simulation of the Converter Blowing Process*, Iron & Steel Technology, Vol.4, N011, November 2007
5 Nguyen, A. and Evans G.*, Computational Fluid Dynamics Modeling of Gas Jets Impinging onto Liquid Pool*, 3rd International Conference on CFD in Mineral and Process Industries, CSIRO, Melbourne, Australia, December 2003
6 Malfa, E. et others: *Numerical simulation of subsonic and supersonic jets impinging on liquid bath,* 2005 FLUENT USER Group Meeting, Milan, October 2005
7 Piacenza, L.: *Simulazione numerica di getti gassosi supersonici penetranti in un bagno liquido*, Degree Thesis, Università degli studi di Brescia, Facoltà di Ingegneria, Anno Accademico 2003-04
8 Malfa, E, et. others: *NUMERICAL SIMULATION OF A SUPERSONIC OXYGEN LANCE FOR INDUSTRIAL APPLICATION IN EAF*, SCANMET II 6-9 June 2004, LULEÅ

9 Harris, C. et others, *Industrial application of supersonic lance: the KT system. Mumerical simulation, operating practice, results&perspective*, AisTech2006, Cleveland, USA, May 1-4, 2006
10 D.C. Wilcox: *Turbulence modeling for CFD,* DCW Industries.
11 Eggers, J.M., Velocity Profiles and Eddy Viscosity Distributions Downstream of a Mach 2.22 Nozzle Exhausting to Quiescent Air, NASA TN D-3601, September 1966.
12 FLUENT6.2.16 Documentation.
13 Lau, Morris and Fisher, "Measurements in subsonic and supersonic free jets using laser velocimeter", Journal of Fluid Mechanics, 93, 1979
14 Thring, M.W. Newby M.P., "Combustion length of enclosed turbulent jet flames", Proc. 4th International Symposium Combustion, 789-796, Baltimora.
15 Mallot, N.A. : *Impinging Jet Flow in Two Phase Flow: the Basic Flow Pattern*J.Iron Steel Inst, October 1970