Physical Modelling of a Continuous Casting Tundish: a Parametric Study of Residence Time Distribution Curves

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Abstract: More than 94% steelmaking and ironmaking are released in continuous casting process. Product quality is closely related to metal cleanness and non-metallic inclusions removal. So, lliquid metal flow in ladles, tundishes and moulds is recognised to be of great importance in the quality of these products.

The metal jet from the ladle to tundish tends to induce turbulent motions which can play important roles in non-metallic inclusions removal at the slag surface, thereby helping in the production of cleaner steel. To improve particle decantation, flow control devices such as dams and weirs are used.

The present work is an experimental study released using similarity criteria, through Reynolds and Froude numbers. A reduced scale (1/4) water model of an industrial tundish is used to visualise and measure different parameters of a tracer flow injected in water. The analysis of residence time distribution curves (RTD) by the combined model for different configurations is carried out to establish the interest of placing weirs in the amelioration of inclusions flotation and decantation.

Key-words: Continuous casting, Non-metallic inclusions decantation, Similarity criteria, Water model, Residence time, Combined model.

1 Introduction

The advance of iron and steelmaking is an important and complex process, the main requirements are: good strength and satisfactory plasticity, high wear and corrosion resistance, resistance to oxidation, and some other specific properties. New materials for various applications are continuously developed using advanced technologies [1].

The casting process has a great interest on the mechanical properties of materials. In this respect wide use of continuously cast iron is determined by its significance in a processing (high productivity, good quality, low cost and ecological safety) [1].

Since more than two decades, the continuous casting machine became an important process for steel and iron products elaboration. Product quality in this process is related to metal cleanness and non-metallic inclusions removal. This depends substantially on the turbulent flow taking place in its various engines, in ladles, tundishes and moulds [2], [3].

Multi or two-phase flows exist in many process industries [2] such as the continuous casting, where more than two phase flows can take place, molten steel, non metallic solid inclusions and gas bubbles.

The investigation of the metal liquid flows in a continuous casting machine remains directed overall towards two important modelling: numerical and physical modelling. Indeed, even if in situ tests are considered most adequate for the comprehension of the phenomenon and the improvement of the products quality, these operations remain inaccessible more especially as casting is done under very high temperature conditions, this prevents any measurement technique.

The numerical simulation is an interesting, rapid and inexpensive method to study such phenomenon. The computer CFD techniques allows to consider the turbulent biphasic flow taking place in the metallurgical distributer as well as the thermal aspect which has a great importance in the natural convection and the decantation of non-metallic inclusions at the slag surface [4],[5].

On another hand, the physical modelling investigation using a water model is an appreciable and efficient method, it allows to study the flow of molten steel because of the similar comportment existing between steel at casting temperatures (~1600 c°) and water at ambient conditions [6]-[13].

Indeed, the kinematic viscosity of molten steel at high temperatures of about 1600 c° has almost the same value that of water at ambient temperature (around 20 c°) [6].

As through ladle and mould, the flow taking place in the tundish is of great interest in the comprehension of the continuous casting phenomenology and in the study of the non metallic inclusions removal. The tundish plays an important role as a distributor but also as a real reactor where several harmful inclusions are decanted and fluid flow controlled. The use of control devices is an appreciable solution to improve the decantation of such non metallic inclusions and to control flow in the fluid bath, control devices can be weirs and /or dams.

Physical modelling can be realized on full or reduced scales, the second choice is usually preferred because dimension considerations.

This work consists in determining the role of placing flow control devices as weirs by analysing residence time distribution (RTD) curves and comparing series of results carried out on a one-four scaled water model.

2 Similarity Criteria

The similarity between prototype or industrial tundish and water model is due as said above, to the same kinematic viscosity of molten steel and that of water at ambient temperature.

This can be satisfied in full scale model through the two no dimensional numbers: Reynolds number which expresses the inertial forces to viscous ones ratio and the Froude number which represents the importance of flotation phenomenon by the ratio of the inertial forces to gravitational ones [6].

In reduced scale models, the similarity using the Re number is impossible to realize simultaneously with that of Froude; however, the value of the Re obtained with the model is sufficient to guarantee a turbulent flow. Under the conditions of a gravimetric flow, only, the Froude similarity criterion is then respected between model (m) and prototype (p) [6], [7]:

$$\frac{V_p^2}{gL_p} = \lambda \frac{V_m^{\ 2}}{gL_m} \tag{1}$$

Where:
- V is the fluid velocity.
- L is length of the tundish.
- λ is the scale factor.
- molten Steel: ρ = 7000 kg/m^3, μ = 5,7.10^{-3} kg/m.s.
- water: ρ = 1000 kg/m^3, μ = 10^{-3} kg/m.s.

To obtain the residence time distribution curve in the water model, the solution injected into the flow as a tracer provides the concentration variation with flow time in the tundish.

The figure 1 illustrates a typical residence time distribution curve of the tracer. The pulsation curve represents the input signal and the response curve expresses the output signal of the conductivity versus time which has close relation with tracer concentration in the fluid flow [7].

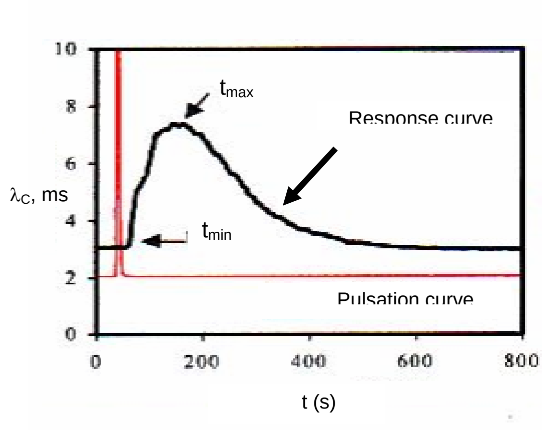


Fig.1: a typical RTD curve

The response curve obtained by measures gives the variation of conductivity (λ_c) with time flow (t) in the tundish; the characteristic parameters of the flow are set:

- Minimum time t_{min}: time recorded at the beginning of answer of the signal at outlet.
- Maximum time t_{max}: time when conductivity (or concentration) at the exit reaches its peak.
- Theoretical time is the ratio between volume of bath V and the corresponding volumetric flow rate Q:

$$t_{th} = \frac{V}{Q} \tag{2}$$

- Mean or average residence time t_{sm}: it is the mean time that can take the fluid particles in the tundish before leaving. It is defined according to the concentration time function c (t) in bath by:

$$t_{sm} = \frac{\int_0^\infty t.c(t).dt}{\int_0^\infty c(t).dt} \tag{3}$$

In practical case, the mean residence time is lower than theoretical time because of recirculation and dead zones in fluid flow.

3 Combined model

The simplest type of a combined model and that most frequently used for the characterization of flow in the tundishes supposes that three regions of flow are present in the total volume of fluid: the plug-flow, the mixed zone and the dead zone [6].

The active volume is obtained by considering that the fluid can be represented by a combination of plug-flow zone and a well mixed volume.

The answer of tracer impulse is given in residence time distribution curve. Referring to figure 2, the minimum non dimensional residence time corresponds to the fraction of plug-flow, and the maximum non dimensional concentration (C_{max}) is equal contrary to the fraction of well mixed volume.

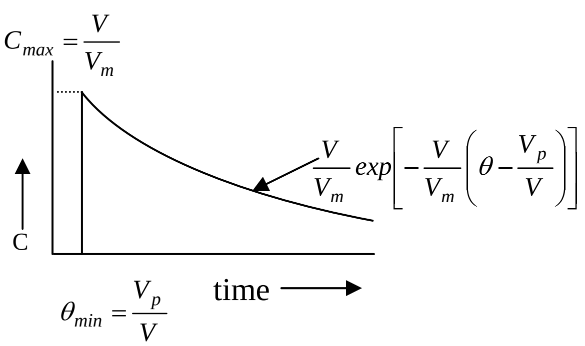


Fig.2: Curve for a combined model

For the simplicity of discussion, dead volume can be divided into two types. In the first type, the liquid in the dead zone is regarded as stagnant fluid so that the entering quantities of the liquid cannot reach this region.

In the second type, the fluid in this zone moves very slowly and consequently a certain fluid remains much longer in the tundish. In fact, the fluid in the dead region is exchanged continuously with the fluid in the active volume [6].

Thus, the fluid which remains in the tundish longer than twice the average residence time is regarded as dead volume.

The dead volume in more of tundishes, under normal work conditions, is of the second type and is characterized by a long truncation exceeding twice the average residence time. Thus, the fluid moving in the inactive or dead volume remains longer in the tundish with the detriment of another fluid. In other words, if a certain fluid takes a residence time much longer in the tundish, an equivalent quantity of another fluid will consequently have less residence time. More quickly moving metal can not spend the time necessary sufficient for the decantation and flotation of harmful non-metallic inclusions.

To consider a combined model composed of an active zone (plug-flow and well mixed flow) and dead zone, all volume of the system is V which is divided into active volume V_a and in dead volume V_d [6]. So, total flow rate through the system is Q which is also divided into Q_a through the active volume and Q_d through the dead region. For completely stagnant dead volume, Q_d will be zero and Q_a will be equal to Q.

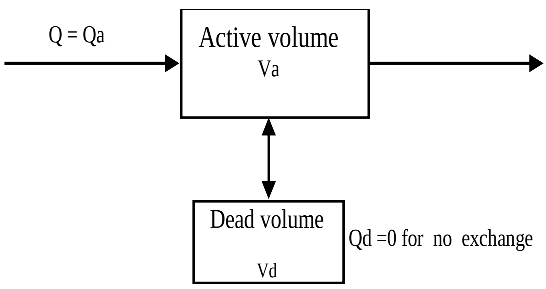


Fig.3: dead volume

Thus, these volumes can be calculated [9], [10] as:

- Accessible Volume V_{acc}: is the volume fluid taking part efficiently in the flow:

$$V_{acc} = t_{sm}.Q \tag{4}$$

- Plug-volume Vp: when the particles follow in some zones uniform and regular trajectories:

$$\frac{V_p}{V} = \frac{t_{\min} + t_{\max}}{2.t_{th}} \quad (5)$$

- Dead Volume V_d: indicates the regions where the particles don't participate enough in flow (very low velocities or recirculation zones):

$$\frac{V_d}{V} = 1 - \frac{V_{acc}}{V} = 1 - \frac{t_{sm}}{t_{th}} \quad (6)$$

- Mixed volume V_{mixed}: *is the volume of fluid without dead volume and plug-volume:*

$$V_{mixed} = V - V_p - V_d \quad (7)$$

- Active volume:

$$V_a = V_{mixed} + V_p = V - V_d \quad (8)$$

4 Methodology

A one-four scale water model of the industrial prototype is used for the experimental analysis.

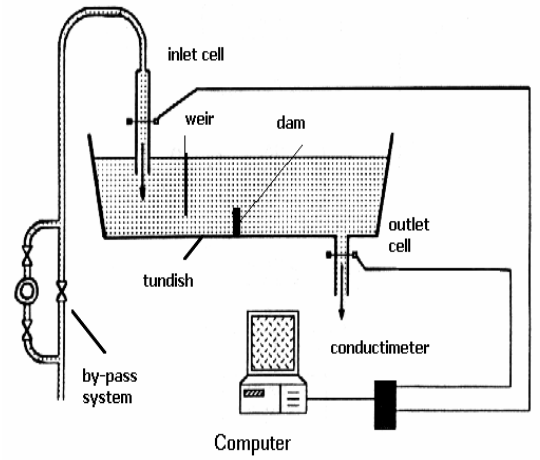
The tundish model is of a Plexiglas bath-tub form what dimensions and characteristics are presented on Table1.

Table 1

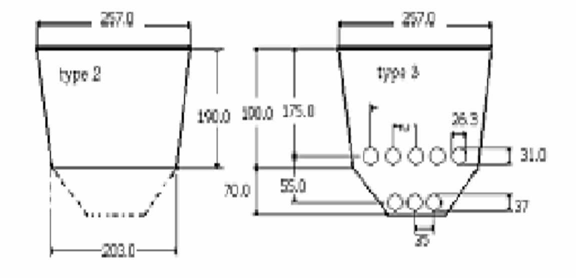
Tundish length at bottom	1039 mm
Tundish length at top	1100 mm
Tundish width at bottom	78 mm
Tundish width at top	257mm
Bath level	185 mm
Entry shroud diameter	16 mm
Exit shroud diameter	20 mm

To maintain a constant volumetric flow rate in test, a constant level of the liquid bath is imposed for a total volume of 35liters. Once the flow is established, we inject by a Dirac impulse, 200 ml of a dye solution tracer composed of $KMnO_4$ (10gr) + KCl (500gr) with a concentration of 100gr/l.

The tundish is provided of conductivity cells to detect the signal at entry and exit. These cells are connected to a computer, and a software program gives the response curves of input and output conductivity (concentration) according to time during the test schedule (Fig.2).



Schematic diagram of apparatus



Tested weirs geometry, trapezoidal opening section and weir with holes.

Fig.2: Experimental setup

5 Results and discussion

Several tests were carried out on the model for various cases. Four cases were considered with different forms of the weir that is placed at 1/3 of total length from entry. The tests were repeated for three different volumetric flow rates: 450 l/h, 750 l/h and 1000 l/h.

Different configurations are chosen (Fig.2):

- Tundish number 1: bare tundish without control devices.
- Tundish number 2: equipped with a weir of trapezoidal opening section form of 56 mm height.
- Tundish number 3: equipped of a weir with a square opening section of 56x56 mm.
- Tundish number 4: is equipped of a weir with 8 holes.

The RTD curves were obtained for a maximum time chosen to be more than twice the theorical time

|3]. It is sufficient to obtain the relevant mean residence time for each arrangement of the tundish.

It was observed that for a same entry signal, the response curves at exit are not identical because of both flow rate and presence of weir, this difference has a great influence in the calculation of the volumes fractions taking part in the flow.

The most important characteristics of any tundish flow should consist of: a minimum spread of residence time and dead volume, contained mixing regions and surface-directed flow [11], [12].

The Tables 2 and 3 gather measurements and calculations carried out on water model of one-strand continuous casting tundishes. The effect of placing a weir in the tundish and the effect of volumetric flow rate chosen to optimise these characteristics are studied. These two parameters can play a negative or positive role according to whether active volume is important and dead volume is more restricted.

Table.2

Case	Q (l/h)	t_{th} (s)	t_{min} (s)	t_{max} (s)	t_{sm} (s)
Tundish 1	450	285.60	37	105	247.26
	750	171.36	29	113	156.15
	1000	128.52	17	81	121.12
Tundish 2	450	285.60	27	82	231.42
	750	171.36	24	67	137.34
	1000	128.52	17	87	117.49
Tundish 3	450	285.60	35	128	208.22
	750	171.36	15	63	133.48
	1000	128.52	19	78	123.69
Tundish 4	450	285.60	27	138	260.53
	750	171.36	22	98	157.16
	1000	128.52	17	76	118.62

Table.3

Case	Q (l/h)	V_d (%)	V_p (%)	V_{mixed} (%)
Tundish 1	450	13.42	24.86	61.72
	750	8.87	41.43	49.70
	1000	5.76	38.13	56.11
Tundish 2	450	18.97	19.08	61.95
	750	19.85	28.01	52.14
	1000	8.58	40.41	50.96
Tundish 3	450	27.09	28.54	44.37
	750	22.10	22.76	55.14
	1000	3.76	37.74	58.50
Tundish 4	450	8.78	28.89	62.33
	750	8.29	35.01	56.70
	1000	7.70	36.18	56.12

The results illustrate the evolution of the conductivity in the tundish for all the four configurations studied here, the output response signal shows the difference between the measures for a volumetric flow rate of **Q** = 450 l/h, 750 l/h and 1000 l/h respectively. These values of flow rate are obtained by similarity with continuous casting industrial rates which can vary in such machine between 1.5 to 3 tonne/min.

5.1 Case of flow rate = 450 l/h

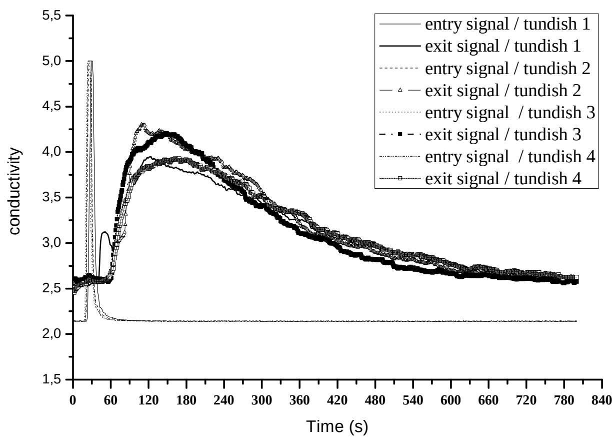


Fig.3: Residence time distribution curve for the flow rate=450 l/h

First, the RTD curves on Fig.3 show that input signal obtained by a Dirac impulse, is substantially same for all cases studied, the parameters for analysis are given by the output signal curves.

According to the curves and histograms on Fig.3 to 5, the graph indicates that the tallest curves correspond to tundish number 2 and 3 arrangements, where a good plug flow and mixed volume are obtained, whereas the tundishes 01 and 04 give shortest curves corresponding to important mean residence time, which is not recommended in continuous casting process, so the third case relates to good plug flow and moderate mixed volume.

The mean residence time is relatively important for all cases because of low flow rate except for the tundish number 3 (which have a weir of square flow passage), while the low dead volume is obtained for the tundish number 4 (weir with holes).

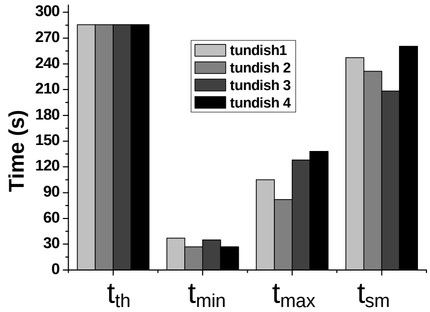


Fig.4: Time quantities for the tundishes studied for the flow rate = 450 l/h

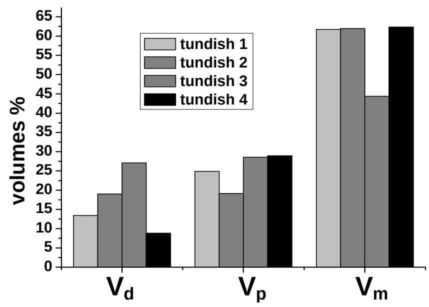


Fig.5: Volume fractions for tundishes studied (flow rate = 450 l/h)

5.2 Case of flow rate = 750 l/h

For the moderate flow rate (750 l/h), the RTD curve and histograms (see Fig. 6 to 8) show that best results are given for tundish number 4 where the mean residence time reaches the highest value, dead volume is minimum one and plug-flow and mixed zone are important comparing to the three other flow tundishes.

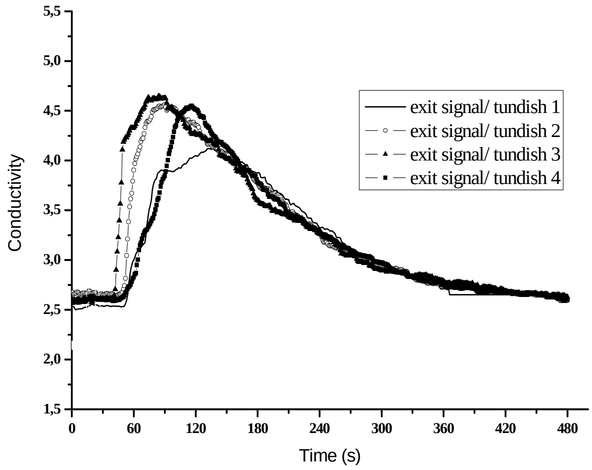


Fig.6: Residence time distribution curve for the flow rate = 750 l/h

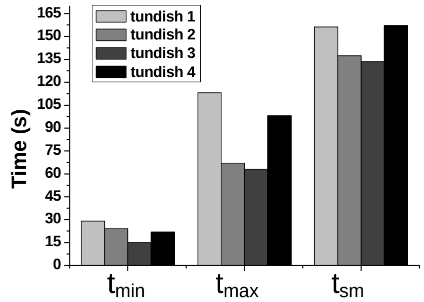


Fig.7: Time quantities for the tundishes for the flow rate = 750 l/h

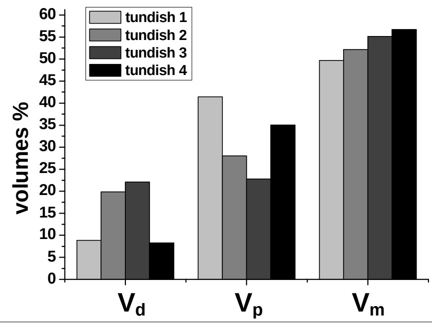


Fig.8: Volume fractions for tundishes (flow rate = 750 l/h)

5.3 Case of flow rate = 1000 l/h

For the maximum value of the flow rate = 1000 l/h, the RTD curves yield roughly similar results (Fig.9), the best values of mean residence time; dead volume fraction, plug flow and mixed zone are obtained for the case of tundish number 3 with weir of a square opening flow passage (Fig. 10, Fig.11).

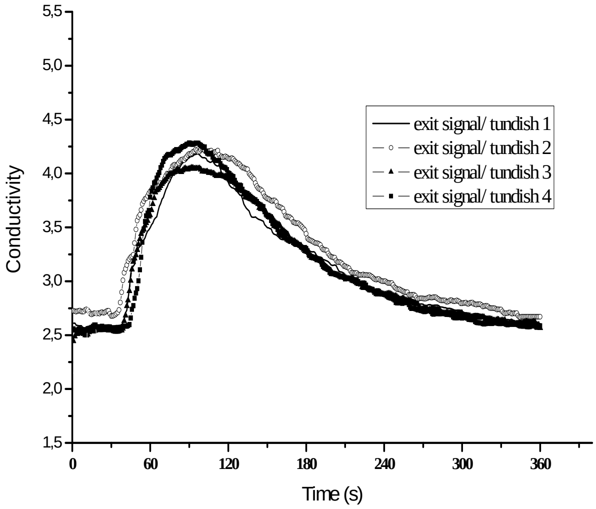


Fig.9: Residence time distribution curve for the flow rate = 1000 l/h

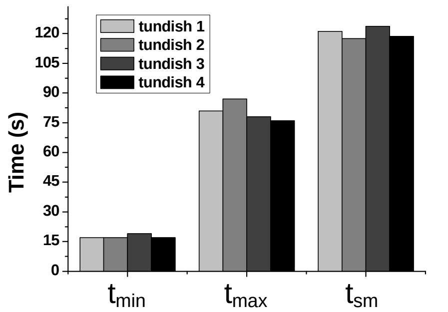


Fig.10: Time quantities for the tundishes studied for the flow rate = 1000 l/h

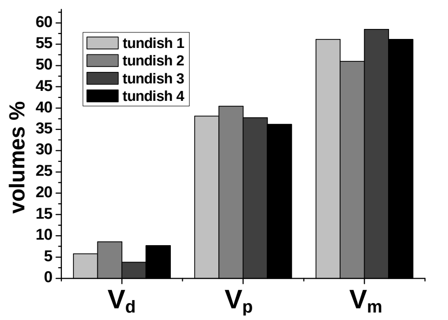


Fig.11: Volume fractions for tundishes studied (flow rat e= 1000 l/h)

5.4 Tundish bare

The influence of the volumetric flow rate on the tracer flow is presented on Fig.12 to 23 for the different configurations treated.

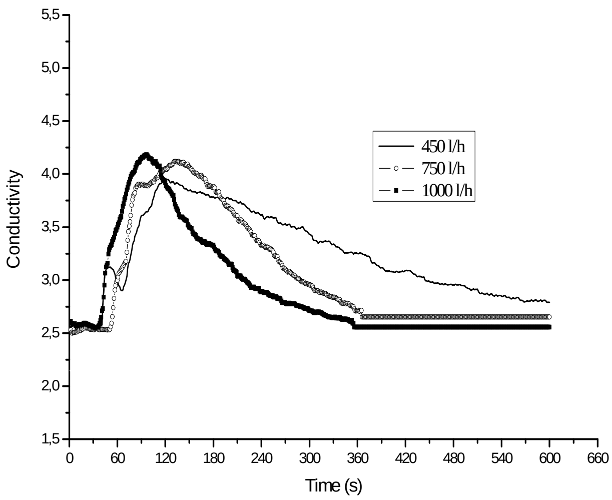


Fig. 12: Residence time distribution curves in tundish number 1

In the tundish bare, the maximum peaks of RTD curves are obtained for the highest flow rates of 750 and 1000 l/h, they correspond to important plug flows and low dead volumes. The more interesting mean residence time is given for the flow rate 750 l/h, for low rates, time is long and may cause important dead volumes and recirculation zones, while for high rates, flow is very rapid so that non metallic inclusions haven't enough time to float at surface.

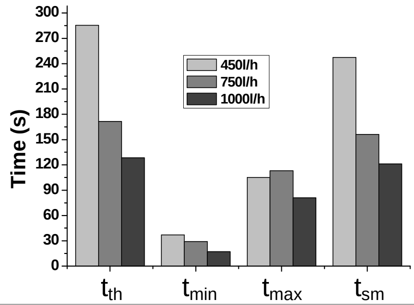


Fig.13: Time quantities for flow rates in tundish number 1

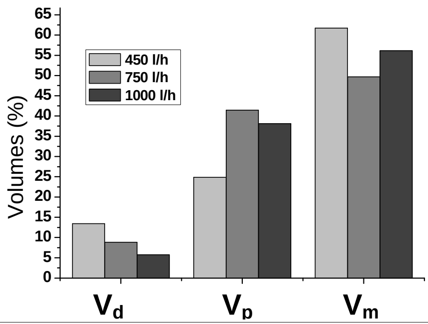


Fig.14: Volume fractions for tundish number 1

5.5 Tundish number 2 with first weir

This weir has a trapezoidal opening section at its bottom for passage of water Flow with a height of 56 mm (Fig.2).

In this case, although results of dead volume, plug-flow and mixed volume are best in the case of high flow rate, the same observation as the previous one can be done.

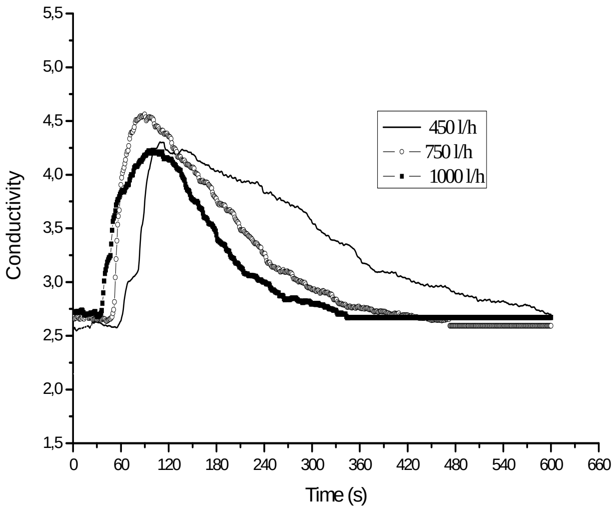


Fig. 15: Residence time distribution curves in tundish number 2

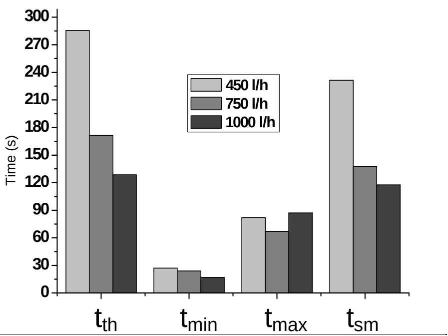


Fig.16: Time quantities for flow rates in tundish number 2

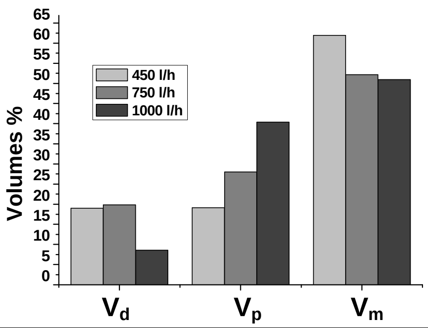


Fig.17: Volume fractions for tundish number 2

5.6 Tundish number 3 with second weir

This weir has a square opening section of 56mmx56mm at its bottom for passage of water Flow.

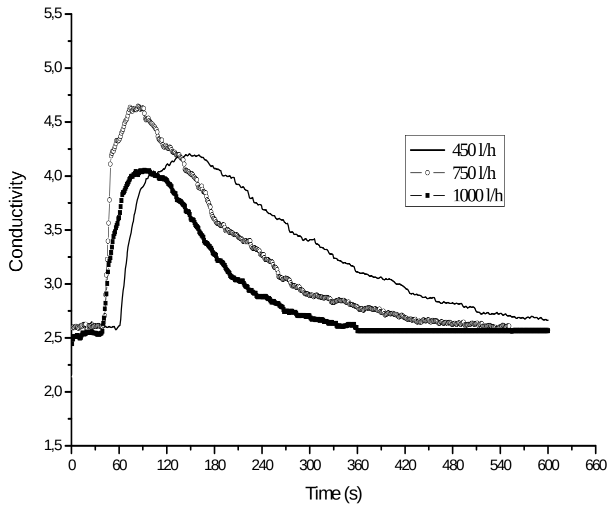


Fig. 18: Residence time distribution curves in tundish number 3

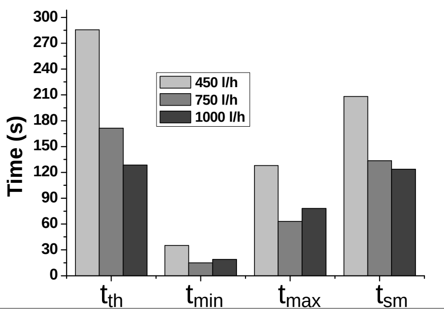


Fig.19: Time quantities for flow rates in tundish number 3

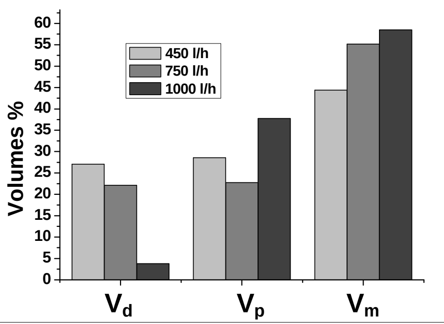


Fig.20: Volume fractions for tundish number 3

5.7 Tundish number 4 with third weir

This weir is completely closed with 8 holes all directed to bath surface. This configuration can help the inclusions removal.

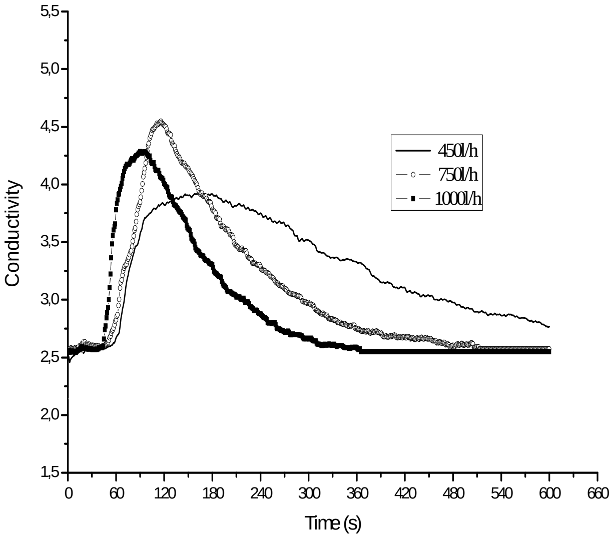


Fig.21: Residence time distribution for the 3 rates in tundish number 4

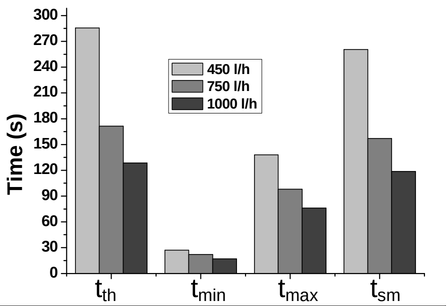


Fig.22: Time quantities for flow rates in tundish number 4

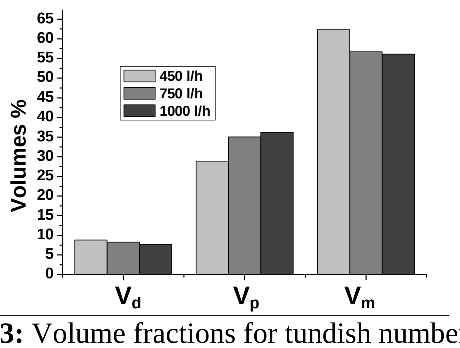


Fig.23: Volume fractions for tundish number 4

It appears clearly that the flow rate of 750 l/h presents in these last cases too (tundishes 3 and 4), good conditions for tundish flow considerations; the RTD curves have the maximum peaks, high plug flow and the dead volume fractions are low. For flow rate of 450 l/h, figures and histograms show a long mean residence time, it leads to dead regions causing inadequate decantation of non-metallic inclusions, bypassing of flow, reducing available volume and excessive heat loss and may cause skull formation. On another hand, a high flow of 1000 l/h can decrease the residence time appreciably, so that the inclusions removal will not be very efficient.

6 Conclusion

A bare tundish is the most usual configuration, it is characterised by a less residence time, large zone of recirculation and the difficulty of non metallic inclusions to float at slag surface. However, the use of a control device as weirs at a given location in the tundish helps in controlling the fluid flow, this contributes to reduce the dead volume in the previous case and optimise the inclusion removal at surface slag.

The physical simulation of metallurgical tundish systems has been investigated experimentally on a Plexiglas water model. For a one-four scale model, Froude similarity is satisfied.

Water model measures on four tundish configurations have been carried out. The analysis of residence time distribution curves provided the relevant results:

Comparing the different cases measured and calculated, one can notice that the dead volume fraction is relatively important for low flow rates, where the residence time is more important. It is not always true, that the lowest or highest residence time gives in all cases, best results for the dead, plug and mixed volumes.

For this purpose, several researchers have analysed the RTD curves of fluid flow through a combined model. This model adopt two approaches [3, 8], the total volume is composed of three separate volumes fractions: plug-volume, mixed volume and dead volume, which have been calculated above. The active zone in this case is an interaction between plug and mixed volume fractions. The other approach supposes that the active volume have exchanges with the dead zone.

- Using weir with holes is the best arrangement compared to the other three tundishes considered, it contributes to obtain minimum dead and mixed volumes fractions and maximum plug flow.
- The flow rate of 750 l/h provides the highest peaks of the RTD curves, which means important plug flow, very low dead volume fraction and normal mean residence time.
- The rate flow of 450 l/h yields to high mean residence time, this induces to important dead volumes and large mixed zones. While, the rate flow

of 1000 l/h is not recommended because of the low mean residence time obtained in several cases.

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