Combined Modeling of Inclusions Behavior During Tundish Process

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In recent years, mathematical modeling has become more popular because of the developments both in computer hardware and software. However, in order to use a mathematical model many issues like used effect of mesh density, influence of different turbulence and non-turbulent model must be studied [1, 2].

1. INTRODUCTION

Recent trends in continuous casting practice have seen the introduction of new technology developments aimed at sustained efficiency of manufacturing process and optimization of liquid steel flow motion in the tundish facility. The tundish plays a very important role with respect to the quality of the product made.

Flow optimizing can be achieved through the shaping of inside tundish configuration, using flow control devices such as turbulence inhibitors, impact pads, dams, weirs, refractory inserts, etc. The latter enables to minimize the causes bringing about erosion of the tundish refractory lining as well as incorporation of overlying slag layer and non-metallic inclusions into the mold. However, one cannot doubt the fact that the application of similar methods to tundishes of different geometry must be preceded by thorough examination of hydrodynamics in the tundish bath to prevent adverse effects. Emphasis of the present research was placed on the improvement of the specific tundish characteristics in respect to both cost and quality [1]. Set optimization tasks are performed by combining cold hydrodynamic model experiments provided theory of similarity considered and three-dimensional mathematic simulation techniques. Commercial CFD tool (Finland) and in-house tool (Ukraine) were applied.

2. PHYSICAL MODELING OF TUNDISH

Physical modeling gives significant insights into the flow behaviour in a tundish. However, due to limitations of the method, like the lack of natural convection, exact knowledge of e.g. inclusion separation is difficult to obtain.

Proper selections and validations must be made before the results of the mathematical simulations can be trusted.

Specific principal criteria for physical modeling are:

- geometric similarity;
- kinetic similarity (a similarity of velocities in corresponding times);
- dynamic similarity of forces;
- thermal similarity (of temperatures, thermal gradients and thermal flows).

To demonstrate the present approach, careful analysis was carried comprising two steps. In the first step, as it is illustrated in Fig. 1, flow dynamics phenomena in the physical model were investigated to check efficiency of transverse dams and damping devices located under submerged nozzle (a 1/2 scale model [1]). The test vessel made of transparent acrylic resin is placed on two columns, four meters high, and via pipeline connected with the sliding shutter assembly model supplied with a detachable submerged nozzle. Water, oil and saw dust of different density were used in the model and the dynamics of the solid non-metallic inclusions motion were video recorded from the top of the vessel. Also Residence Time Distribution (RTD), flow volume, and the flotation of the solid non-metallic inclusions were analyzed (Fig. 2).

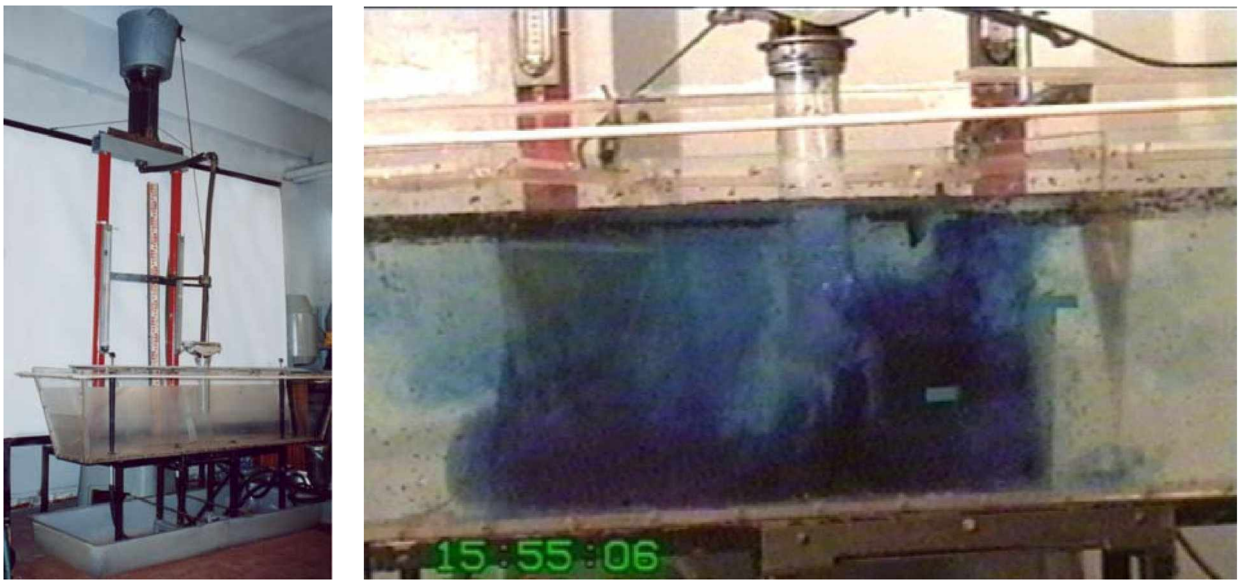


Fig. 1. Experimental tundish model used in the present investigation

Because density and molecular viscosity of water and steel are in equal ratio 1:7, the kinematic viscosity is almost the same (Tab. 1), and so water can be used to simulate steel in the water model. Additional benefits provided by water are, of course, safety handling and visibility.

Property	Water (20°C)	Steel (1600°C)
Molecular viscosity (μ) [kg/m·s]	0,001	0,0064

Density (ρ) [kg/m^3]	1000	7014
Kinematic viscosity ($\nu = \mu/\rho$) [m^2/s]	10^{-6}	$0{,}913 \times 10^{-6}$
Surface tension (σ) [N/m]	0,073	1,6

Tab. 1. Physical properties of water at 20°C and steel at 1600°C

To measure flow velocity, tracing measurement technique was adopted. To measure “residence time”, i.e. the period in which the elements of one flux stay in the tundish from their inflow into the bath till the outflow from the tundish into continuous casting mold, chemical measurement methods using gauging sensors were employed.

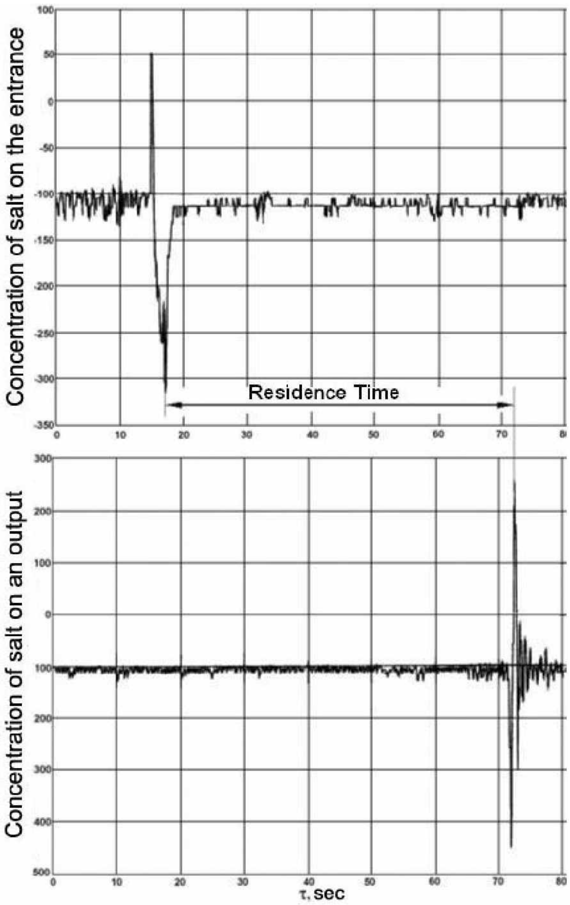


Fig. 2. The registered resident time.

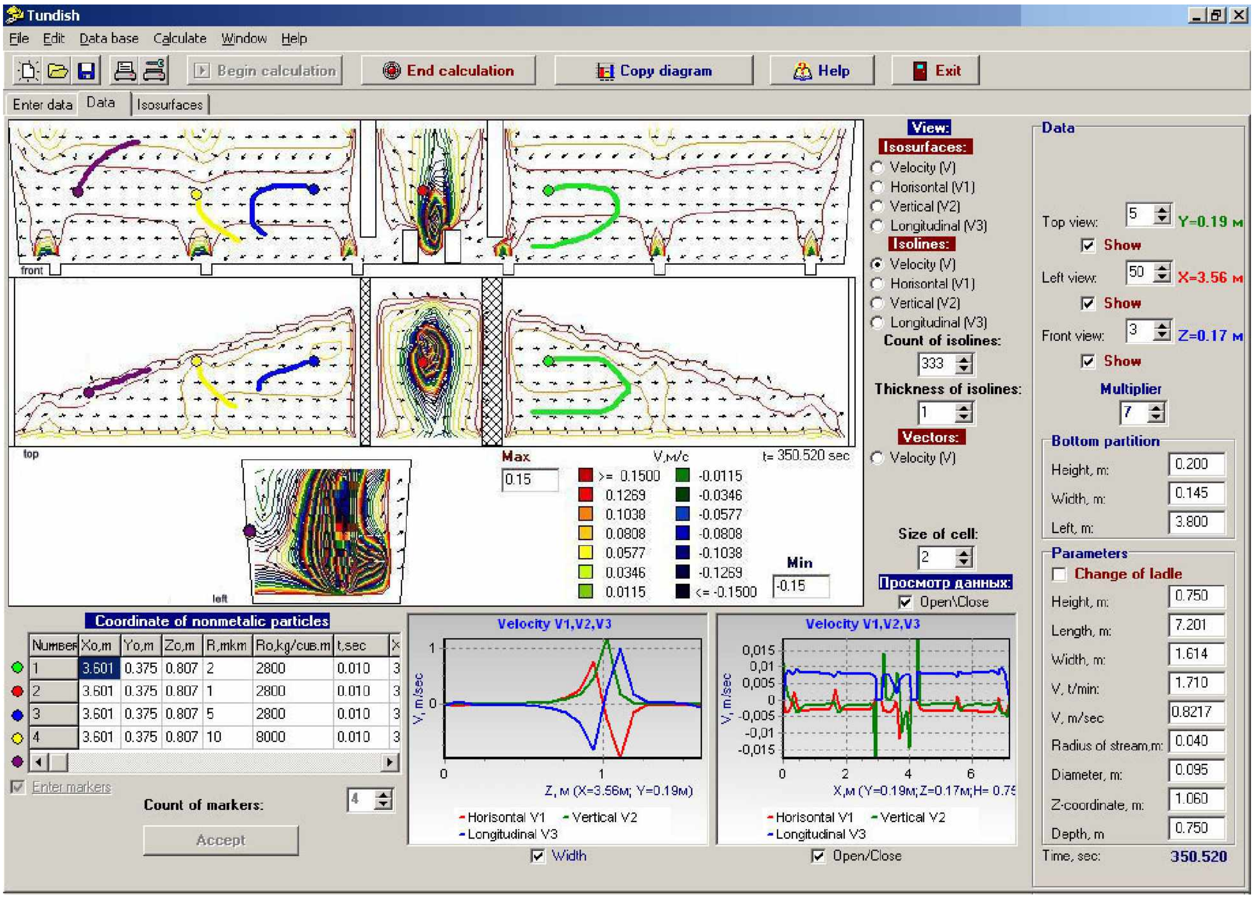
3. NUMERICAL MODELING OF WATER MODEL

In the second step, measurements and observation results deduced experimentally were compared with three-dimensional mathematic model. This part was carried out in Ukraine. The original model of transient turbulent flow mixing and computer program TUNDISH consistent with it were both developed by the Ukrainian authors of the present paper.

*Authors developed and used TUNDISH b*ecause *commercial CFD*-software *are general with a lot of parameters and authors developed a specific turbulence* *model for tundish conditions. Since application field can be extremely wide, problems can be expected if trying to solve tundish phenomena using commercial software. In general, it is very important to check that case geometry and other basic information are correct, since these can affect greatly the simulation results. As an example of the default values, for instance for momentum advection problems, some tools use a first-order upwind differencing method as the default. This method is robust and sufficiently accurate in most situations, although, as in any first-order method, it introduces numerical diffusion into the solution. The third-order upwind differencing method is much more accurate but it is not as robust as the lower order methods and it does not always produce stable solutions in the presence of free surfaces [2].*

Program window (TUNDISH) is plotted in Fig. 3. Theoretical values for the tundish of six-strand CCM were specified for the particular continuous casting machine. Steel weight in the tundish is 32-34 tons, tundish length is 7,3 m, distance between strands is 1,1 m and steel height is 0,80-0,85 m.

Through consideration of hydraulic flow phenomena, it was shown that, the creation of better conditions for entrapped impurities separation and extension of tundish life cycle are attained by setting lower and upper dams in the area of downward steel jet. Schematic diagram of dams placing is shown in Fig. 4.



Number	Xo,m	Yo,m	Zo,m	R,mkm	Ro,kg/cub.m	t,sec
1	3.601	0.375	0.807	2	2800	0.010
2	3.601	0.375	0.807	1	2800	0.010
3	3.601	0.375	0.807	5	2800	0.010
4	3.601	0.375	0.807	10	8000	0.010

Fig. 3. TUNDISH program window: estimated values for steel flow in the six-strand tundish

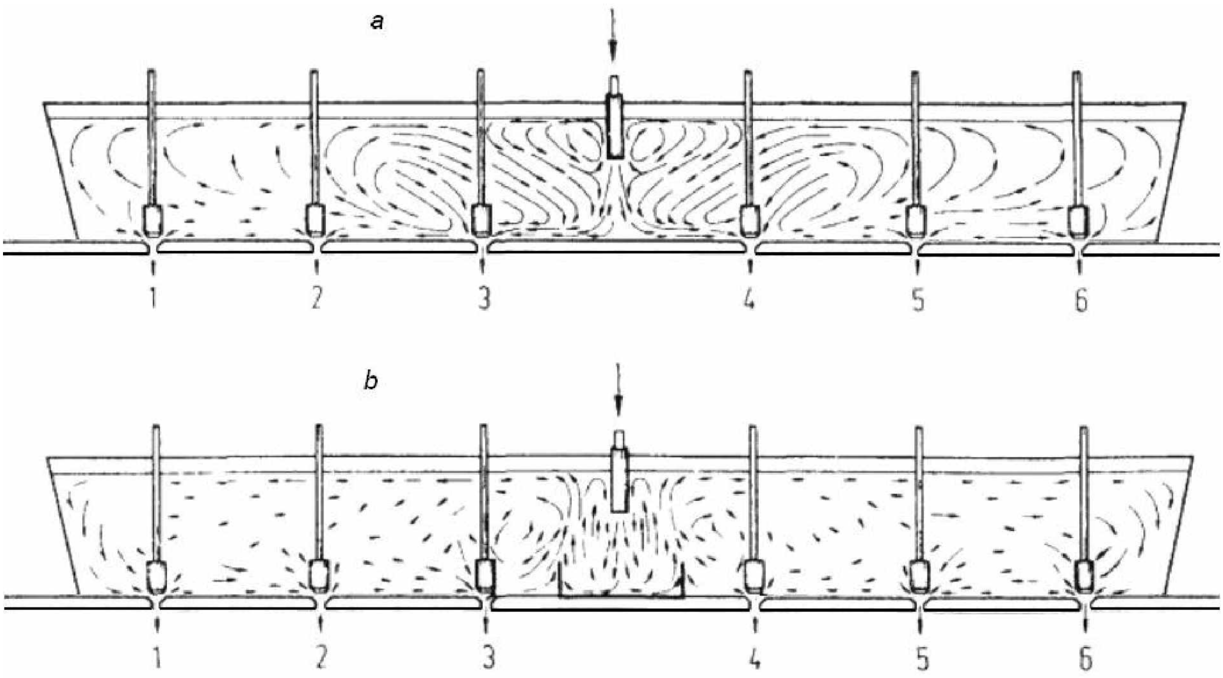


Fig. 4. Flow patterns in the six-strand tundish: a) no dams applied; b) lower dams applied in the incoming area.

The analysis shows that the mixing area may be conditionally divided into the following regions:

1. Region of steel jet intense action (mixing velocity is V≈0.3 m/s).
2. Eddy region near the dams (V≈0.2 m/s).
3. Eddy region above the submerged nozzle (V≈0.15 m/s, velocity near the steel surface is V<0.015m/s).
4. Region of lower eddy behind the feeder, which is caused by downward steel jet (V≈0.07 m/s), and of upper eddy caused by the wall impact (V≈0.2 m/s). This region is believed to be the place of slag penetration into the molten steel.

Dams in tundish changes nature of flows as contrasted to by initial form of tundish. Dams promote turn of a flow backwards. As a result of it the flow comes nearer to a surface and the time of his stay in tundish increases, that provides a possibility of better admixtures distribution.

The flow modified with dams, decreases dead and mix volume and also increases both minimal and medium RTD, in comparison with without dams design (Tab. 2).

Tundish design	Strand №	Mix volume Vm (%)	Dead volume Vd (%)	Minimum RTD (s)	Medium RTD (s)
Without of dams	1 and 6	55 (53)	33 (37)	60 (64)	194 (215)
	2 and 5	50 (46)	41 (40)	22 (26)	163 (175)
	3 and 4	42 (40)	54 (58)	11 (14)	125 (134)

With of dams	1 and 6	75 (71)	6 (10)	80 (85)	265 (270)
	2 and 5	74 (70)	19 (24)	30 (37)	230 (245)
	3 and 4	62 (55)	37 (35)	18 (25)	175 (160)

Tab. 2. Results of physical (numerical) modeling for tundish with and without of dams.

The analysis of convective velocity in tundish without dams and computation velocity of emerging of admixture inclusions shows that mean time of moving of inclusions from the acting flow of metal to the end wall makes 50-90sec. From a depth 400-450 mm (areas of high velocity) of inclusion measuring 150 micrometers (mcm) emerge after 40-200sec in a laminar flow and after 20-30sec in turbulent flow, inclusions measuring 500 mcm - after 5-15sec in both modes. For the inclusions measuring a 100 mcm minimum time of emerging from this depth exceeds 100sec (in a turbulent flow). Thus, independently to emerge from a depth 400-450 mm can only inclusions by a size more than 150-200 mcm in a turbulent flow and more than 200-300 mcm in laminar flow. Because velocity of greater part of descending flow correlated with velocity of emerging of inclusions, considerable part of admixture inclusions measuring 400-500 mcm and less with the large degree of probability can get in mold caster.

Results obtained in the present study have provided thorough insight into overall process dynamics in the tundish facility; the model accurately describes the following important criteria for hydrodynamic properties assessment:

1) a more homogeneous flow is created in the detached turbulent mixing area;
2) detached killed zone and subsurface flow profile facilitates inclusions separation;
3) bath significant depth increases Residence Time of molten steel in the tundish.

4. NUMERICAL MODELING OF FULL SCALE INDUSTRIAL TUNDISH

This part were carried out in Finland and for calculations, a commercial CFD tool was applied.

4.1 Steel Plant Experiments

Used tundish has simple rectangular shape and it provides steel only for one mould. When ran at the working level, the tundish holds up approximately 28 tons of steel. Best way to monitor performance of different tundish configurations in the steel plant is to monitor elemental concentrations during the steel grade change. Results from these measurements resemble F-curve results from physical modeling. Measurements were taken from the mould and started immediately when *ladle of new steel grade was opened. In the first phase of the casting samples were taken every 0.5 meters of cast steel and later on every 1 meter and every 2 meters. During every grade change at least 10 samples were taken. Sub-entry nozzle in the mould is shaped so that it will produce double roll flow pattern to the mould. This flow pattern will force the incoming steel to the top part of the mould right after it enters giving it less time to mix with the previous steel grade. This gives a concentration reading close to the concentration actually coming from the tundish.*

Temperature measurements at the steel plant were taken manually using temperature probe. Measurements were taken three times during the cast from the middle of the tundish approximately 40 centimetres below the surface.

4.2 Simulations in steady state

The biggest differences between the full scale and the downscaled tundish simulations can be found in the boundary conditions. First of all the inlet and the outlet velocities are much higher in the full scale model. Secondly heat transfer has been taken into account and fluid is changed from room temperature water to liquid steel. Heat transfer was modeled by using fixed heat flux for every interface [3]. Difference to water model was also the use of the Boussinesq approximation to take into account natural convection in the simulation.

Since no elemental analysis could be done during the steady state casting condition, in this project only possible way to validate the model in steady state was to monitor tundish temperatures. Experimental temperature measurements (average temperature of three manual measurements) and simulated temperatures (values saved every 20 seconds) from approximately same location are showed below (Tab. 3).

	Experimental	Simulation	Difference
Turbostop	1551.33	1548.82	2.51
Betker	1561.01	1558.89	2.12

Tab.3 : Temperatures in steady state (all temperatures in Celsius degrees)

Since the possibility to get real incoming temperatures for steel at the steel plant proved to be very difficult, boundary condition temperature in simulation was selected to be estimated temperature of the tundish. This temperature is probably around 5 degrees lower than real incoming temperature, based on the knowledge that temperature drop through the whole tundish is approximately 10 Celsius degrees and wanted overheat of the incoming flow is tried to keep around 30 to 40 degrees. Even when taking this to account results can be considered good. Temperature results of the steady state indicated that heat transfer boundary conditions are good enough and no changes were needed.

4.3 Simulating transient casting conditions

During the grade change situation differences in temperature measurements were approximately same as they were during steady state situations (Tab. 4).

	Experimental	Simulation	Difference
Turbostop	1542.66	1539.26	3.40
Betker	1537.67	1539.51	-1.84

Tab. 4: Temperatures during transient casting situation (all temperatures in Celsius degrees)

In the grade change situations main validation data was elemental analysis. The element to monitor differs depending on what kind of steel grades are cast. In this project it was found to be best to monitor carbon content, since the change in carbon content between cast grades was clear enough. Since the used tool does not simulate chemical reactions, there was no possibility to follow simulated carbon content. The elemental analysis was carried out during the first 29 tons cast steel (Fig. 5).

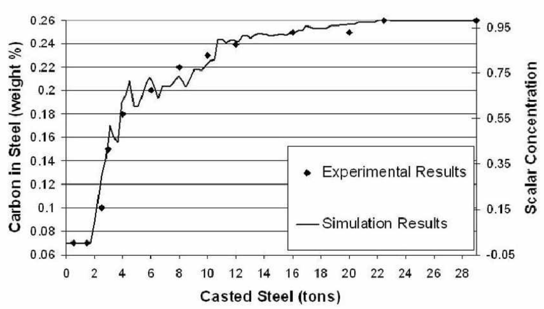


Fig. 5: Carbon content during a steel change situation in tundish with flow control device.

Since all the simulation results (temperature measurements and concentration curves) from full scaled industrial model are accurate when compared to available experimental data, the commercial CFD model is relatively well validated.

5. DISCUSSION

Provided liquid steel level falls due to some reasons, such as ladle change, dam region nears the steel surface, thereby turbulizing the surface, which in its turn results in high-intensity slag entrainment into the melt.

The analysis of convective velocity in tundish without dams and computation velocity of emerging of admixture inclusions shows that mean time of moving of inclusions from the acting flow of metal to the end wall makes 50-

90sec. Independently to emerge from a depth 400-450 mm for this time can only inclusions by a size more than 150-200 mcm in a turbulent flow and more than 200-300 mcm in laminar flow. The flow modified with dams, decreases dead and mix volume and also increases both minimal and medium RTD, in comparison with without dams design.

Hence, optimization of flow motion using dams ensures lengthening of molten steel Residence Time in the tundish thus excluding impurities from flowing into the mold as a consequence. Since some of the most serious quality problems occur during transients in the process, these findings will provide a foundation for future models addressing optimization features of flow motion. The new fundamental understanding will ultimately lead to optimized practices to upgrade in steel quality, its microstructure and cleanliness, process control improvement and cost saving.

5. REFERENCES

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