# Modern Methods of Modeling Fluid Flow and Inclusions Motion in Tundish Bath: General View

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ABSTRACT: Tundish is one of the most important units in continuous casting technology. In tundish liquid steel must be homogenized and non-metallic inclusions must be transferred into the tundish slag. These goals can be realized by optimizing fluid flow in tundish. Optimization of tundish configuration and fluid flow in liquid steel are possible with investigation on the basis of physical and mathematical modeling. 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. 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 final product.

Flow optimization 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 refractory inserts minimizes the causes of the tundish refractory lining erosion as well as transportation of overlying slag and non-metallic inclusions into the mold. 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 the 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).

During physical modeling the criteria of hydrodynamic Froude similarity (Fr) and homo synchronizing (Ho) were observed. To demonstrate the present approach, careful analysis comprising two steps was carried out. In the first step, as it is illustrated in Fig. 1 and Fig. 2, flow dynamics phenomena in the physical model were investigated to check efficiency of transverse dams, argon injection 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 sawdust of varying 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.

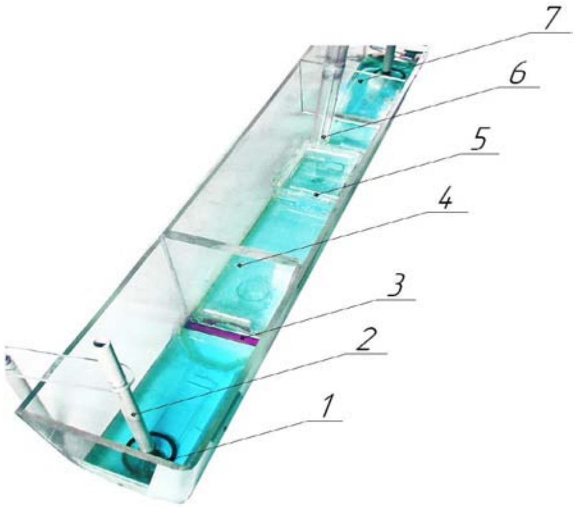


*Fig. 1. Experimental tundish model : 1 - porous rink; 2 – stopper; 3 – argon beam-block; 4 – filter wall; 5 – tundish box; 6 – ladle shroud; 7 - slag dam*

*Fig. 2. General pictures of development of fluid flow and movement of solid-liquid inclusions (black) in non-symmetric tundish with turbulence inhibitor and filter walls*

Also Residence Time Distribution (RTD), flow volume and the flotation of the solid non-metallic inclusions were analyzed. The sensor is executed in the form of two platinum electrodes through which the electric current passes. These sensors are connected in measuring process under the bridge scheme (Wheatstone bridge) [3]. For this the indicator (concentrated salt solution) enters the zone of an arrangement of one of the sensors that discomposes the bridge scheme.

Because both density and molecular viscosity of water and steel are in equal ratio 1:7, also the kinematic viscosities are almost the same (Table 1). Because of this similarity 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 (ν = μ/ρ) [m$^2$/s] | $10^{-6}$ | 0,913 x $10^{-6}$ |
| 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.

## 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 because 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 general 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].

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.

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

- Region of steel jet intense action (mixing velocity is V≈0.3 m/s).
- Eddy region near the dams (V≈0.2 m/s).
- Eddy region above the submerged nozzle (V≈0.15 m/s, velocity near the steel surface is V<0.015m/s).
- 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 when compared to the initial form of tundish. Dams promote turn of a flow backwards. As a result of it the flow comes closer to the surface and the time of stay in tundish increases, which 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 design without dams (Table 2).

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 50-90 seconds. From a depth 400-450 mm (areas of high velocity) of inclusion measuring 150 micrometers (μm) emerge after 40-200 seconds in a laminar flow and after 20-30 seconds in turbulent flow, inclusions measuring 500 μm - after 5-15 seconds in both modes. For the inclusions measuring a 100 μm minimum time of emerging from this depth exceeds 100 s (in a turbulent flow). Thus, independently to emerge from a depth 400-450 mm can only inclusions by a size more than 150-200 μm in a turbulent flow and more than 200-300 μm 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 μm and less with the large degree of probability can get in mold caster.

| 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 and numerical (in brackets) modeling for tundish with and without of dams.*

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:

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

## 4. Numerical Modeling of Full Scale Industrial Tundish

This part was carried out in Finland and a commercial CFD tool was applied for calculations. Both a slab and a bloom tundish were studied. Particle simulation was carried out in the bloom tundish.

### *4.1 Validation Using Steel Plant Experiments*

Validation was made using slab tundish which 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.

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. The elemental analysis was carried out during the first 29 tons cast steel (Fig. 3).

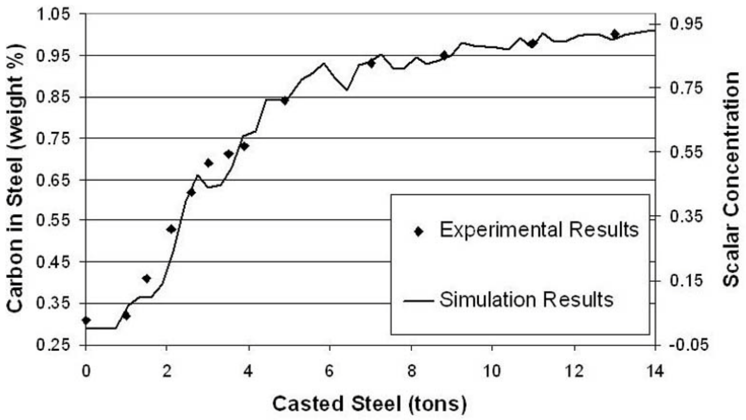


*Fig. 3: Carbon content during a steel grade change situation in tundish with turbulence inhibitor*

Since all the simulation results from full scaled industrial model are accurate when compared to available experimental data, the commercial CFD model is relatively well validated.

### *4.2 Particle Calculations in the Bloom Tundish*

In this part of the study inclusion calculations were performed during steady state situation and simultaneously with flow calculation. The steady state simulations were done in two parts: in the first part fluid level in the tundish was set to working level height and simulation was started. When only minimal changes in turbulent and kinetic energies were observed, which happened usually after software has simulated approximately 500 seconds, simulation was considered to be steady and it was terminated. In the second part results of the first simulation were used as restart data for the new simulation. This can be considered as steady state experiment of the water model. In the beginning of this second part of the simulations 10 000 particles were inserted to inlet flow and the number of particles going through outlets was monitored. From the walls particles were set to bounce back to the melt as well as when they came to in contact with the free surface. All particles had same density (3000 kg/m$^3$), but their diameters varied from 15 to 215 μm.

In particle calculations used tundish also had rectangular shape but it provides steel for two moulds. Because of the small tundish size, possibilities for new flow modifiers were relatively limited. Used practice included two low dams (Dam #1 in Fig.4). Since principal idea behind tundish dams is to direct flow closer to the surface, idea of using higher dams was first new alternative (Dam #2). Higher dams were equipped with emptying holes around the same height as top of the originally used dams to limit amount of scrapped metal at the end of the each casting sequence. Second modifier option was more complex dam variation (Dam #3). Variation included similar high dams as first option, but they were placed further away from the ladle nozzle. Ladle nozzle was changed from regular straight flow nozzle to nozzle which directs flow in 90 degree angle to both sides. Top weirs were also introduced to block fast nozzle flow from new nozzle design. Last option was tundish without any dams, only with rectangular turbulence inhibitor below straight ladle nozzle (Dam #4).

All options changed flow greatly in tundish. With first option with higher dams, interesting observation was the effect of emptying holes. Even though main flow pattern was towards the surface, high velocity flow through the emptying holes was clearly present. During the simulation this flow did not stay steady, but it could change dramatically even during short periods of time. Further studies showed that placement of the holes have effect in this kind of flow behaviour. Second and third tundish option both worked in similar way, even though they differ greatly in design. Changes in nozzle direct incoming flow towards the top weirs, which slows down flow velocity. Single turbulence inhibitor placed directly under the regular straight ladle nozzle seemed to work similarly killing the incoming flow. If the incoming flow hits directly to the center of flow control device, flow velocity was decreased significantly and flow was also directed towards the surface. All of which are good for particle separation.

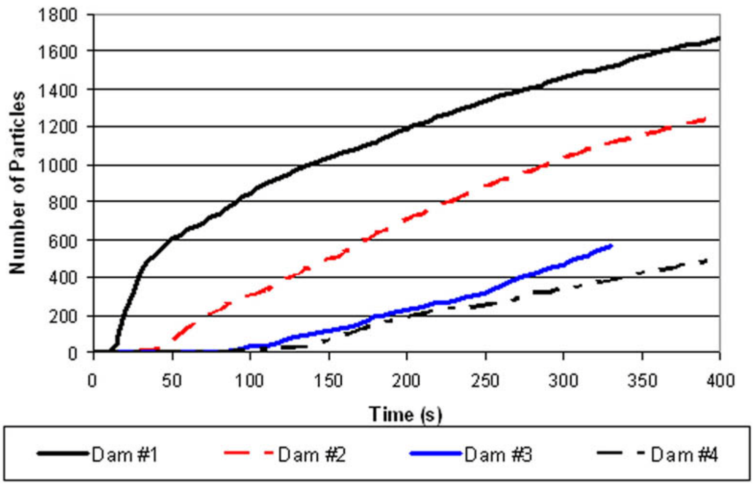


*Fig. 4 : Number of particles left from the tundish with different flow modifer options*

Simulation results showed all of the new tundish geometry options to be significantly better than low dams (Fig. 4). Best performance was observed with uniquely designed turbulence inhibitor.

## 5. DISCUSSION

Optimization of flow motion using dams ensures lengthening of molten steel residence time in the tundish thus excluding impurities from flowing into the mold. 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.

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 50-90 sec. Independently to emerge from a depth 400-450 mm for this time can only inclusions by a size more than 150-200 μm in a turbulent flow and more than 200-300 μm 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.

Results of the numerical modeling of industrial tundish agreed well with the physical modeling results. Both results showed clearly that with careful optimization of the tundish flow modifiers it is possible to make significant improvements to the quality of the final product and to the efficiency of tundish process.

## 6. BIBLIOGRAPHIES

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