Effect of Ladle, Tundish and Mold Design on Melt Flow Parameters

S. N. Lekakh and D. G. C. Robertson

Missouri University of Science and Technology
1400 N. Bishop, Rolla, MO 65409
Phone: 573 341 6469
Email: lekakhs@mst.edu

Keywords: Modeling, Ladle, Tundish, Mold, Melt flow, Combined reactors

ABSTRACT

Qualitative and quantitative characterization of melt flow in Ar-stirred ladle, tundish, and mold is important for analysis and improvement of steelmaking process design. Several approaches are used for melt flow analysis, including industrial measurements, physical (water) modeling, and CFD simulations. In this article, an integrated CFD-combined reactors (CR) approach is used to generalize the melt flow parameters in metallurgical vessels. As the first step, CFD simulations were used to obtain the pattern and intensity of the melt flow in the vessels (ladle, tundish, or continuous caster mold). From these simulations, the characteristic curves were derived: the residence time distribution curves for “flow-through” systems (at tundish exit or at the surface of dendrite coherency for continuous casting) or the mixing curves for “closed” systems (e.g. ladle). In the next step, the melt flow was represented in a CR system consisting of a combination of unit reactors (Plug Flow, Mixer, and Recirculated Volume). To achieve similarity of melt flow in CFD and CR models, an inverse simulation was used to define the volumes of the unit reactors and the melt flow rates between them by matching the characteristic curves. This generalized approach was used for analysis of the effects of: (i) plug location in Ar-stirred ladles, (ii) tundish design, and (iii) SEN designs on melt flow in the mold.

INTRODUCTION

From a practical standpoint, the major objectives in the study of liquid steel processing can be classified into three levels:

Level 1: process understanding: For example, analysis of the kinetics of refining reaction and of the formation of non-metallic inclusions;
Level 2: process design: For example, optimization of the geometry of metallurgical vessels and of the choice of process parameters;
Level 3: process control: For example, on-line control of the ladle refining by integrating fast algorithms with sensors and process control devices.

Knowledge of the melt flow phenomena is essential to meet these objectives. Industrial measurements, experimental physical modeling methods, and CFD simulations have been intensively used to study melt flow [1-3]. These methods are very effective for visualization of melt flow (Level 1 objectives); however, they have limitations for meeting Level 2 and Level 3 objectives. For example, three-dimensional transient CFD simulations are time-consuming and too slow for application to on-line process control.

The combined reactors (CR) approach can be used to couple melt flow with the kinetics of chemical reactions. This approach is significantly less time-consuming than coupling multi-phase CFD models with chemistry in each computational cell (Figure 1). This approach was originally developed by Levenspiel [4] to analyze the effect of mixing on the kinetics of chemical processes in several interconnected vessels (reactors). Unit reactors include the ideal Continuous-Stirred-Tank Reactor (CSTR or Mixer) and Plug Flow Reactor (PF) and the Dispersed Plug Flow Reactor (DP) with internal “eddy diffusion” [6]. Dead Volume (DV) [5] and Recirculated volume (RV) [7] are also considered as unit reactors. A DV has no exchange with the main flow volume, while an RV has a small (“slow”) flow through it.

The melt flow pattern in a particular CR system can be represented by the Characteristic Parameter, which can be the Residence-Time Distribution (RTD) for continuous “flow through” vessels, e.g. tundish or continuous caster. The RTD curve
is obtained by short time tracer injection into the in-flow stream and measuring the tracer concentration in the out-flow stream. For metallurgical processes in a “closed” volume (e.g. ladle), the Mixing Curve is suggested as the characteristic parameter.

In this article, the CR approach is used for analysis of the effects of metallurgical vessel design, such as plug location in Ar-stirred ladles and tundish and SEN geometries, on the reactor performance (Level 2 objective). The approach includes several steps:

   Step 1: Three dimensional transient CFD modeling of the melt flow in a particular design of the metallurgical vessel, followed by
   Step 2: Choice of an “architecture” of the Combined Reactors (CR) based on the CFD results, and
   Step 3: Inverse simulations to match the Characteristic Curves (RTD or Mixing Curves) obtained from CFD and CR.

This matching was achieved by varying the volumes of the unit reactors and the flow rates between them. This approach allows the investigator to combine high complexity with short simulation times (Figure 1).

![Figure 1. Complexity of experimental and simulation methods to study steel making processes versus simulation time.](image)

**METHODOLOGY**

FLUENT 12.0 CFD software [9] was used to solve multiple cases of 3-D transient multiphase (gas-liquid steel) turbulent melt flow: (i) in a ladle with different locations of bottom Ar-plugs, (ii) several designs of a tundish and (iii) a continuous casting mold. The assumption of isothermal melt flow in the ladle and the tundish was adequate for the purposes of this paper. Coupling heat transfer and turbulent melt flow was used in simulation of the mold. After achievement of a quasi-steady-state flow, the “species transport” was activated to allow the derivation of the characteristic curves. The physical properties of the tracer were the same those of liquid steel, and molecular diffusion of species was ignored. The main details of the CFD simulations used here were as described in reference [7]. In the next step, an architecture of the Combined Reactors (CR) was developed based on overview of the flow pattern obtained from CFD. Figure 2 shows Residence Time Distribution (RTD) curves from CFD simulations and from two different CR architectures (after optimization) for the same tundish [7]. The CR architecture including the DV does not adequately represent the actual RTD (Figure 2a) while the combination of recirculation loops (Mixer-RV) gives a very close match (Figure 2b).

![Figure 2. Comparison of RTD curves in a tundish (CFD simulations versus Combined Reactors): a) CR architecture with Dead Volume (DV) and (b) CR with three Mixer-RV loops” [7].](image)
Figure 2 shows that a reasonable similarity between the CFD and the CR models was achieved by inverse optimization using a suitable architecture. The best CR architecture consisted of a combination of one Plug Flow Reactor (PF) and two or three Mixers, each loop-connected with Recirculated Volumes (RV) [7]. Additional tests showed that the melt flow in the tundish could also be well characterized by a CR architecture which included an Eddy Diffusion or Dispersed Plug Flow unit reactor [6] instead of Mixer-RV loops. In the CR architecture several parameters, such as the reactor volumes and the flow rates between Mixers and RV, needed to be calculated. This was done by building a CR mass conservation spreadsheet in Microsoft EXCEL with calculation of the characteristic curve for an arbitrary set of parameters (reactor volumes and flow rates); (iv) optimization of these parameters by fitting the CR characteristic curve to the “true” CFD characteristic curve. A function (φ) was minimized (Eq. 1) with the built-in EXCEL Solver:

\[
φ = \sum (C_i^{CFD} - C_i^{CR})^2 \rightarrow \min
\]  

(Eq. 1)

**EFFECT OF DESIGN METALLURGICAL VESSELS AND PROCESS PARAMETERS ON MELT FLOW**

**Ar-stirred ladle.** CFD simulations were performed for 100 ton ladle (1 m bottom radius (r), 1.2 m top radius, and 3.4 m height) with different locations of bottom Ar-plugs (Fig. 3a): case A - one central plug #1, case B – one plug #2 at 0.5r, and case C – two plugs #3 and #4 located on 0.5r and r apart (Figure 3a). To obtain the general geometry of the melt streams and their flow rate, iso-values of vertical (Z-direction) velocity (Vz) were plotted at different levels from the bottom. Figures 3b, 3c and 3d show the maps of the negative (downward) melt Z-velocity and geometry of the rising plume (empty area) for these three cases at 20 CFM Ar-flow rate (total in ladle).

![Figure 3](image)

**Figure 3.** Effect of locations of Ar plugs on the bottom of 100 t ladle (a) on vertical velocity (Vz) values at different horizontal levels: b) for plug #1, c) plug #2, and d) two plugs #3 and #4 at 20 CFM Ar-flow rate in each plug.

Both, Ar-flow rate and plug locations in the bottom of the ladle affected the average downward vertical melt velocity (Vz) and melt mixing: increasing Ar-flow intensified melt downward flow at deep locations and the ladle with two plugs had the largest average absolute values of Vz (Fig. 4). The downward flow rate was calculated based on the average Vz value over the area of downward flow (colored sections in Fig. 4) and melt density.

![Figure 4](image)

**Figure 4.** Effects of a) Ar flow rate and b) location of Ar-plug on average value of downward vertical velocity (Vz) at different melt levels in 100 t ladle.
Based on observation of the CFD simulated flow pattern (Figure 5a), the architecture of the Combined Reactors (CR) for the ladle was chosen as follows: the Ar-gas driven rising plume ($V_0$), top horizontal layer ($V_3$), central recirculated region ($V_2$), and slow flow bottom layer ($V_1$), as shown in Figure 5b. The bottom volume ($V_1$) was assumed to be a Plug Flow (PF) reactor and the others were assumed to be perfect Mixers. The small top volume $V_3$ was assumed as 4% of the total ladle volume, the volumes $V_1$ and $V_2$ were included in the inverse simulation and volume $V_0$ was calculated as the remainder. Flow rates between reactors $V_2$ and $V_1$ ($F_{21}$) and in the top of the rising plume $V_0$ ($F_{03}$) were included in the inverse simulation; all other flow rates were calculated based on mass conservation equations. The values of the four independent parameters were included in the inverse simulation and varied to achieve similarity of the CFD and CR mixing curves.

![Image of ladle and combined reactors](image)

**Figure 5.** a) Flow pattern (vector velocity) obtained from CFD simulation and b) adequate Combined Reactors (CR) architecture.

After achieving a quasi-steady state in the CFD simulation (as determined by average melt velocity), a tracer was injected in four symmetrical points near the top of the melt surface and the relative tracer concentration was plotted as a function of mixing time at different ladle levels. Figure 6a illustrates the CFD simulated tracer concentration curves for the bottom volume $V_1$ and the rising plume $V_0$ at 20 CFM Ar-flow rate. The concentration curve in the bottom volume had a delay period - typical of Plug Flow. The mixing time was calculated based on 95% criterion. Ar-flow rate affected the mixing time: 350 sec at 4 CFM and 220 sec at 20 CFM of Ar flow rate through central plug #1.

The similarity of melt flow in the CFD modeled Ar-stirred ladle and CR was achieved by inverse simulation. The tracer concentration (Mixing Curve) in the bottom reactor $V_1$ was used as the characteristic curve for the optimization. This region has a mixing delay when compared to the other ladle regions. After optimization of the reactor volumes and flows between them, the CR representation delivered an identical result to CFD Mixing Curve in the bottom volume $V_1$. The agreement was not as good in the rising plume; however, the Mixing Curves from both locations had similar averaged trends and average mixing time. The results of optimizations are shown in Figure 6b for the centrally located Ar-plug at different Ar flow rates. Increasing Ar flow rate significantly decreased the bottom plug volume $V_1$, had a minor effect on rising plume volume $V_0$, and increased recirculated ($F_{20}$) and plume ($F_{30}$) melt flow rates. The CR parameters numerically describe the effect of increased Ar-flow rate by simultaneously increasing the overall melt recirculation flow rate and the volume of the ladle regions involved in intensive mixing.
Both, the radial position and the number of porous plugs influence the chemical kinetics and thermal mixing in an industrial ladle [10]. In this article, three ladle designs were CFD modeled and the resulting mixing curves were used to obtain the CR equivalents. Simulated mixing kinetics (CR results) in the bottom region is shown in Figure 7a for two levels of Ar-flow rates. Increasing Ar-flow rate decreased mixing time in all three cases; however, the ladle with two mixing plugs provided significantly less mixing time. The location of the Ar-plug had a large effect on the reactor volumes in CR (Figures 7b and 7c). In particular, two plugs reduced the volume of the bottom reactor $V1$ and increased the plume volume $V0$ (Figure 7d).

Once the flow in the ladle is described then this can be coupled with the thermodynamics and kinetics of the metal-slag-gas reactions [8] to calculate the refining processes in the ladle. This action is shown in Figure 1 by the arrow connecting the CFD and Thermodynamics to Integrated Combined Reactors boxes.
In this article, the application of the integrated Combined Reactors (CR) approach is illustrated for the industrial case (Ar-stirred 100 ton ladle) described by Jonsson et al. in reference[12]. Assuming the local thermodynamic equilibrium in the top metal/slag volume (V3) in each time step (1 sec), the simulated de-S in the steel at the end of the process was in good agreement with the measured value (Figure 8a) and the chemistry of the melt at different locations can be easily simulated from the known melt flow rate between the reactors. The calculated effect of ladle design (plug number and location) and process parameters (Ar-flow rate) on the de-S kinetics is shown in Figures 8b and 8c. The two-plugs design is expected to give the fastest de-S kinetics. Another very interesting result is the predicted concentration differences in the different regions of the ladle early in the process. The mixing was only adequate for the liquid to be more-or-less uniform in composition (as required) at the end of the process. The CR approach for Ar-stirred ladle application has important advantages because it can quickly provide a detailed picture of the effect of ladle design and process parameters on steel mixing, refining, and temperature distribution.

**Figure 8.** (a) CR simulated of de-S in 100 t ladle, (b) simulated effects of Ar-flow rate through central plug #1, and (c) effect of ladle plug design on melt desulfurization kinetics.

**Tundish.** The CR method is illustrated below for the single-strand tundish of 14 metric ton liquid steel capacity. The tundish had a trapezoidal shape with 10 degree vertical walls incline and 3 m long, 1 m wide and 0.8 m melt level. The melt flow rate was 2.6 t/min. This gave 340 seconds for the mean Residential Time (RT). The tundish had a submerged entry nozzle (SEN) of 250 mm OD, and 150 mm ID submerged 300 mm into the melt, and a 200 mm OD stopper rod above a 70 mm diameter exit nozzle. Three tundish design were compared: Case A - no flow control devices (Figure 9a), Case B - with flow control devices (Figure 9b), and Case 3 - with a bottom Ar mixing plug (4 CFM flow rate) under the SEN (Figure 9c) in a design similar to Figure 9a.
CFD modeling [7] showed that there was a substantial difference in the general flow patterns between these three tundish designs:

- poorly organized flow in the tundish without flow control devices (Figure 9a)
- mostly sequential flow with two easily recognized recirculation zones in the tundish with flow control devices (Figure 9b), and
- a vertical plume generated by Ar-bubbles near the SEN with a poorly organized flow pattern in the other parts of the tundish volume (Figure 9c).

The Residence Time Distribution (RTD) curve was used as the characteristic curve for the “flow through” tundish (Figure 10). The different flow patterns in these three cases provided significant differences in the shape of the RTD curves, plotted in terms of dimensionless concentration $C$ (exit tracer concentration times tundish volume divided by tracer dose) and dimensionless time $\Theta$ (ratio of process time to Mean Residence Time). The RTD curve for the tundish without flow control devices has a smooth bell-like shape. Flow control devices increased the peak value and shortened the time of its occurrence. Ar-mixing also moved the RTD curve to the left and significantly shortened the time when the tracer first reached the outlet, but it had no effect on the maximum value. Changing the melt flow rate (+/- 30%) had only a minor effect on the shape of RTD curves.

Figure 9. Tundish design and vector velocity in central vertical plane: a) no flow control, b) with flow control devices, and c) with Ar-mixing.

Figure 10. CFD simulated RTD curves for different tundish design.
Inverse optimization delivered a combination of the variables (Figure 11) which indicated that tundish design had a significant effect on the structure of CR. For example, for the tundish without flow control devices, RV volumes were negligible and can be omitted. In this case, the simplified CR structure consisted of a small Plug Flow volume connected to two or three in-line ideal Mixers. This is a reasonable CR representation of the CFD-visualized flow pattern. Flow control devices significantly changed the melt flow pattern (Figure 9b) and therefore the RTD curve (Figure 10). In this case, only the three Mixer/RV loops architecture was in a reasonable agreement with CFD flow pattern (Figure 11). The first loop had negligible RV volume; however, the two other loops had moderate Mixer/RV melt flow exchange. Finally, the CR structure for the Ar-stirred tundish consisted of a very small Plug Flow adjusted to the large well mixed volume with a small RV. Two more small recirculated loops were also predicted in this case. Comparison of CR reactor volumes for three different tundish design with the same melt volume and flow rate is given in Figure 11. The analysis of melt flow in the tundish using the suggested CR approach provides quantitative parameters described melt flow in a particular tundish design. The tundish design can be optimized based on formulated requirements.

Continuous casting mold. The SEN design, casting mold geometry, and casting speed all have a significant influence on steel quality through their effect on the flow pattern. Melt flow pattern is related to the occurrence of surface defects, slag entrainment, and other steel quality problems [13]. The integrated CFD - CR approach was used to describe the melt flow in the mold. CFD software [9] was used to solve coupled transient multiphase turbulent melt flow and heat transfer in continuous casting mold for a 1500 mm x 225 mm slab. Modeling was done for simplified geometry of ½ slab (750 mm x 225 mm domain width and square outports located on a central symmetry plane (Figure 12). A combination of vertical ($V_z$) and horizontal ($V_x$) vector velocity components ($V_z/V_x=-0.2/1$) were used to simulate the downwards velocity direction at entrance outport (Case A). The effect of Ar-injection (5 volume %) in SEN was investigated in Case B. The mold walls boundary conditions included downward translational movement at 1.5 m/min casting speed. Latent heat (220 000 J/kg) was introduced into melt enthalpy proportionally between the solidus (1480°C) and the liquidus (1500°C) temperatures. A rapid increase in melt viscosity from 0.007 kg/ms to 10 kg/ms at 1485-1490°C represented the development of dendrite coherency (DC) in the solidifying steel.

Figure 12a shows the melt flow map (vector velocity) in the ½ mold for studied cases: conventional (case A) and with Ar-injection (case B). Two specific melt rotation regions (upper and bottom rolls) can be clearly identified in both cases. Ar-injection had a large effect on the structure of both regions, decreasing the depth of the incoming jet penetration and raising it up to the edge of the mold. The buoyancy of the Ar-plume resulted in formation of this rising stream. In addition to qualitative analysis of flow patterns provided by vector velocity distribution, it is important to obtain some quantitative results for comparison of different cases. Near the top surface velocity plays an important role in slag entrainment (maximal limit) or surface freezing (minimal limit). Figures 12b and 12c demonstrate sub-surface (0.02 m below the top) melt velocity and temperature maps and for the studied cases using the same color scale. Ar-mixing redistributed near surface velocity and temperature.
Actual liquid steel mixing in the strand takes place only in the melt pool limited by the surface of dendrite coherency [14]. The coupled CFD simulation of transient turbulent melt flow and heat transfer in the continuous casting mold, together with the steel enthalpy and viscosity temperature functions were used to detect the shape of the iso-surface of dendrite coherency temperature and calculate the volume of the liquid pool (at constant 1530°C pouring temperature and 2000 W/m²K mold walls coefficient of heat transfer). The parameter chosen to characterize the melt flow in liquid pool in the strand was the evolution of the average tracer concentration detected on the dendrite coherency iso-surface (Figure 13a) assuming that mixing takes place only in the liquid pool. Ar-injection changed the flow patterns and transformed the shape of the characteristic curves.
Figure 13. Continuous casting mold: a) CFD simulated and inversed optimized RTD curves at dendrite coherency surface and b) effect of Ar-injection (Case B) on relative volumes of reactors.

The CFD simulation characteristic RTD curves were used for development of Combined Reactors representing the flow pattern in the continuous casting mold. The insert on Figure 13a illustrates the suggested CR architecture. This has two Mixers and one Recirculated Volume (RV). Figure 13a shows inverse simulated RTD curves (dashed curves) for both cases. SEN design had an effect on the shape and the volume of the liquid pool (designated as reactor volume in Figure13b) at the same casting speed. The conventional SEN design with downward outports and no argon (case A) has a large volume of Mixer 1. The connected Recirculated Volume (RV) was only about 10% of the total volume of the liquid pool. Ar-mixing significantly intensified the melt exchange between the RV and the Mixers.

For the continuous casting process, the suggested approach can be used together with traditional post-processing CFD analysis such as melt flow instability, turbulence, and meniscus surface geometry. There are several possible practical applications of the integrated CFD-CR approach, such as qualitative the assessment of the effect of mold design on characteristic melt flow regions and dynamic prediction of steel composition during grade transition [15].

CONCLUSIONS

A Combined Reactors method is suggested for the rapid and adequate representation of melt flow in the metallurgical vessels. The examples described were the Ar-stirred ladle, the tundish, and the continuous casting mold in steelmaking. CFD-modeling results were converted into melt flow in Combined Reactors, the architecture of which represented the different characteristic zones in metallurgical vessels. Similarity of melt flow between the CFD and Combined Reactors models was achieved by matching the characteristic curves for: (i) Mixing Kinetics in the ladle, (ii) Residence Time Distribution (RTD) curve at tundish exit, and (iii) RTD curve at dendrite coherency iso-surface in the strand.
The suggested integrated *Combined Reactors* approach can be used for the analysis of metallurgical vessel design and process parameters. This method can be used for on-line fast-running algorithm for the entire steelmaking process control.

**REFERENCES**
