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Improvement of Ladle Shroud Designs and its Effect on Fluid Flow Behaviour for Steelmaking through Computational Fluid Dynamics

Daniel Gonzalez-Morales[1], Mihaiela Minea Isac[1], Roderick Guthrie[1]
[1]McGill Metals Processing Centre, McGill University
3610 University Street, Wong Bldg. Room 2M040, Montreal, Canada
daniel.gonzalezmorales@mail.mcgill.ca; mihaiela.isac@mcgill.ca; roderick.guthrie@mcgill.ca.

Abstract **-** Currently, roughly two billion tonnes of steel are produced every year, using the ladle-tundish-continuous casting machines approach. The Ladle Shroud is an important device in Steelmaking, protecting the molten steel from oxidation during its transfer from the ladle into a tundish set below. The internal contours of Refractory Ladle Shrouds supposedly protecting it from re-oxidation to compromise steel properties can often result in air inhalation, unless this is compensated by argon gas shrouding. Either way, this presently leads to gas entrainment in the liquid jet of steel passing down through the shroud. The result is a turbulent, two, or three phase (with slag entrainment), flow within the shroud. Physical Modelling, and mathematical modelling (CFD) have been used to propose radically new designs to eliminate these two-phase flows. This then should allow the enhanced cleaning of steel by using microbubbles to remove sub-50 micron-inclusions. For the present results, the CFD ANSYS-Fluent v. 19.0 code has been used to study existing designs and to test new ladle shroud design concepts, by predicting transient multiphase flows during start-up and steady state operations. These have been confirmed using full-scale water models. The verified predictions are being used as a baseline for optimising the design of ladle shrouds for industrial applications within the steel industry. A significant improvement in steel quality and properties is anticipated.

Keywords**:** Ladle Shroud, Multiphase flow, Steelmaking, Water Modelling

1. Introduction

The ladle shroud is an essential device in modern steelmaking, connecting steel flow from the ladle into the tundish, thereby protecting the molten steel from the atmosphere to avoid its re-oxidation, and the formation of re-oxidation products. A few new ladle shroud designs have been proposed in recent years to improve steelmaking operations. For example, dissipative, and trumpet/conical designs. A dissipative design will enhance the intermixing phenomena within the ladle shroud-tundish system [1-4], while a trumpet design aims to reduce the velocity and turbulence of the steel entering into the tundish, reducing slag entrainment, nozzle clogging, slag entrainment and better mixing behaviour within the tundish [1, 3, 5, 6]. The use of a trumpet or reverse taper ladle shroud has become more common in the steelmaking industry lately, owing to the advantages it provides over the conventional constant diameter designs [6]. The study of ladle shroud designs has focused on the steady-state regime, together with a single-phase flow being, using physical and mathematical modelling [1, 3, 6-8]. More recently, some transient phenomena associated with "start-up", ladle changes, and argon shrouding interactions, have also been studied [5, 9, 10]. Figure 1 depicts a modern Steelmaking Ladle-Tundish system with the Ladle Shroud connection, showing some these phenomena, such as argon injection with the generation of a Tundish Open Eye (TOE)

Some LS designs have been proposed to optimize the incoming flow into the tundish in steelmaking operations [4]. Innovative Ladle Shroud designs, such as the Trumpet (TLS) and Conical (CLS) ladle shroud designs have been proposed and studied. Two different studies [1, 3] studied the effects of a Dissipative Ladle Shroud (DLS) in a tundish with mathematical and experimental modelling. The objective of the DLS is to decrease turbulence in the entering flow, and thereby reduce turbulence within the overall LS-Tundish system. The effects of these said shrouds on mixing phenomena in a tundish were studied in detail. Zhang, Fang, Deng, Liu, and Ni. [5] published an analysis of the effect of two different trumpet shaped Ladle Shrouds on the multi-phase fluid flow of a five-strand tundish through mathematical and physical modelling. The authors used the VOF model to model the steel-slag-air interactions. It was found that by increasing the inner exit diameter of the Ladle Shroud, the turbulence near the slag-steel interface was reduced, meaning that less slag entrainment will be possible. Nonetheless, during a ladle-change, one must double the inlet flow of steel through the ladle shroud. Recently, Zhang and coworkers [6] compared a standard, a trumpet, and a conical, ladle shroud, using steady state and single phase simulations, which were validated with RTD (Residence Time Distribution) curves in water model experiments. During the industrial tests, the diverging conical design presented less turbulence and less fluctuations.

Similarly, during Ladle Shroud operations, it is known that air suction is a possibility since the pressure field generated within the ladle shroud can be expected to be negative at the ladle nozzle - ladle shroud joint [11]. To avoid this air inhalation in practice, argon shrouding is used industrially, to try to prevent air ingress by suction, which can affect the liquid steel quality. It has been found that an argon shrouding flow of more than one-third that of the steel flow rate was needed to avoid air ingress, experimentally [7, 12]. However, if the argon flow is too high, it will produce a large Tundish Open Eye (TOE) in the tundish, and this normally causes subsequent slag entrainment and further steel re-oxidation products [13-16].

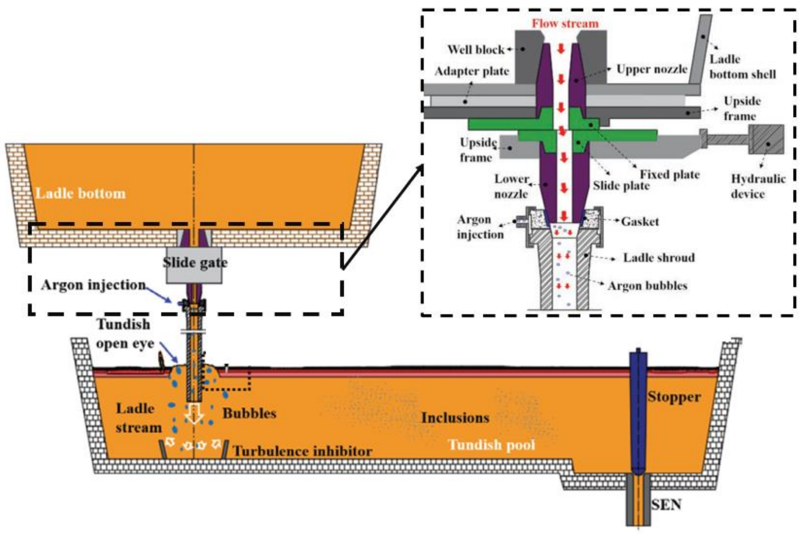

Fig. 1. Schematic of a Steelmaking Ladle-Tundish system and the Ladle Shroud connection. Taken and adapted from [4]

Research efforts have focused on a better understanding of the two-phase (argon-steel) flow generated in the Ladle Shroud via mathematical and physical modelling. In 2018, Mazumdar, Singh and Tiwari [17], addressed the use of the DPM (Discrete Phase Modelling) approach to correctly model two-phase flow within a Ladle Shroud. The DPM model initially assumes a bubbly flow with a gas volume fraction of around 10%. However, based on usual industrial argon flows, the volume fraction can be up to 25% [4]. In 2018, Singh and Mazumdar [12] published a comprehensive water modelling analysis of the two-phase Ladle Shroud systems and the effect of several variables e.g., nozzle and shroud diameters, shroud gas flow. In 2019, Singh and Mazumdar [7] used the VOF multi-phase model, to predict the steel-argon flow within the Ladle Shroud and to compare with the previously published experimental results [12]. It was concluded that a gas liquid flow ratio of around $Q_g/Q_l=0.4$ is needed to prevent any air ingress [12]. Some more recent work on physical and mathematical model by Mukherjee and Mazumdar [18-20] validated the use of full-scale water models to better study Ladle Shroud systems, given the Reynolds number similarity is maintained, and an isothermal approach is relatively valid [18].

Zhang and coworkers [10] performed VOF simulations of the multiphase fluid flow in a tundish during ladle change-overs, simulating three phases, steel, air and slag. The mathematical results, namely, the behaviour of the slag, were validated with a 1:3 water model. It was found that the VOF model can predict transient steel-air-slag interactions, e.g., slag entrapment and Tundish Open Eye (TOE). In 2021 Xu, Ling, Wang, Chang and Qiu. [21] investigated the effects of the Tundish cover powder and the ladle-change over on the Tundish air ingression and TOE. It was concluded that reoxidation will occur during a ladle-change over, because of air ingression through the Ladle Shroud and the exposure of the steel to ambient air caused by the formation of a TOE.

Recent experimental work by our research team [9, 22], on an industrial tapered Ladle Shroud design, as predicted with mathematical modelling, suggested that a turbulent multiphase flow would be developed during start-up within the

Ladle Shroud. This start-up phenomenon was confirmed quantitatively with water modelling. Additionally, 3D predictions of phenomena such as steel splashing and multiphase flow development during start-up were confirmed via mathematical modelling. An illustration of these findings is presented in **Error! Reference source not found.**. Also, these experiments quantified the strong potential for air ingression predicted mathematically (of around 300 L/min of air).

The purpose of the present work is to study through mathematical and physical modelling a new Ladle Shroud design with a convex and concave shape variation, as depicted in Figure 2. Convex, meaning that the section between the top of the ladle shroud (point A) and the point B, Figure 2 (b), is curved towards the centre of the ladle shroud. The concave variation means that said section is curved towards the walls of the ladle shroud, shown in Figure 2 (b). Computational Fluid Dynamics (CFD), using the commercial software ANSYS Fluent 19.1 © was used to predict the initial multiphase flow behaviour of the proposed design. This allowed us to make preliminary comparisons with the conventional reverse taper design performance [9, 22]. Water physical modelling with a full-scale plastic prototype was performed to assess the mathematical predictions of the fluid flow behaviour inside the Ladle Shroud and to analyse some practical aspects of the new Ladle Shroud operation.

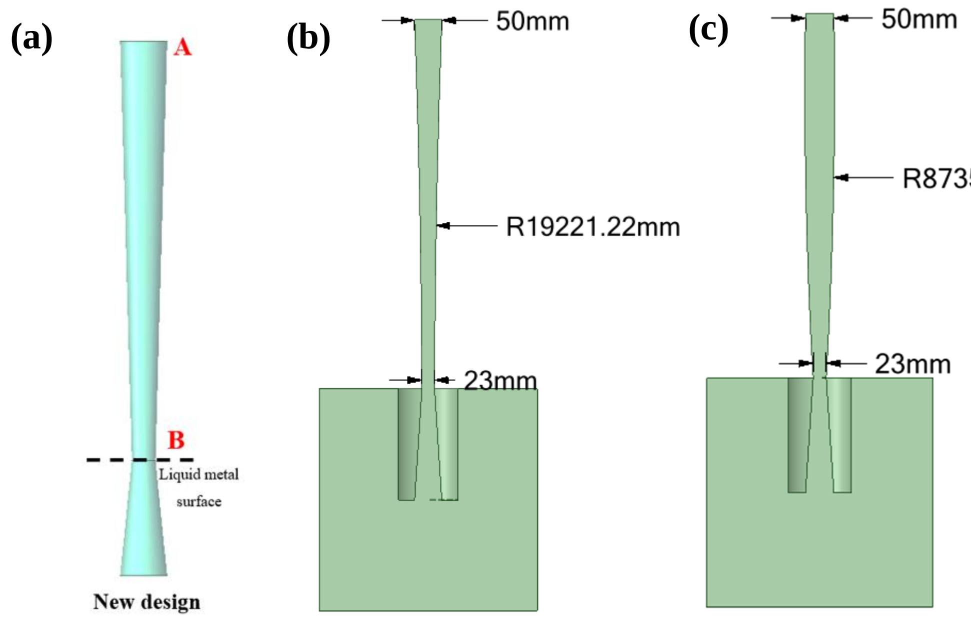

Fig. 2. (a) New Ladle Shroud design. (b) Convex and (c) Concave variations of the proposed design,

2. Methodology

A transient isothermal mathematical model was developed to initially test the new ladle shroud designs in a simplified geometry. Figure 3(a) presents the geometry, dimensions, and boundary conditions. The operational conditions and mathematical predictions of an previously studied, industrial reverse taper ladle shroud [9, 22] were considered for the present simulations, namely the inlet mass flow rate and the operational liquid height, to compare the performance and behaviour of both designs under similar process conditions. The boundary conditions for all cases, are: 1. Velocity inlet at 0.8 m/s, equivalent to a 100% opening at the slide gate during filling and a volume fraction of steel equal to 1; 2. Symmetry plane; 3. Solid circular Wall with a non-slip boundary condition; 4. Pressure outlet, with a 0-gauge pressure. For both cases, the system was initially assumed to be filled with air, volume fraction equal to 1.

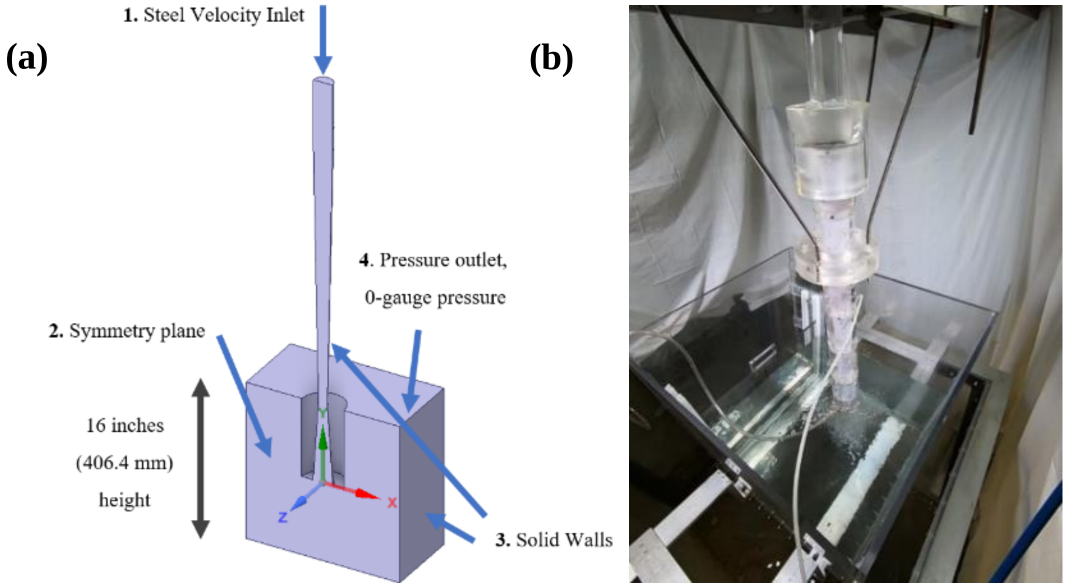

Fig. 3. Example of a geometry generated in SpaceClaim © and boundary conditions used for all the cases.

Table 1 presents the properties of the materials used in mathematical modelling. For the non-isothermal study, MgO was assumed as the refractory material of the ladle shroud. The density and viscosity of the gas phases (air and argon) were referenced to 1873 K, based on previous work [7, 23].

Table 1: Materials properties

	Steel (liquid)	Air (gas)
Density, ρ [kg/m^3]	7000	0.5
Kinematic viscosity, μ [Pas]	0.0056	1.78×10^{-5}
Heat conductivity, k [W/m K]	41	0.0242
Heat Capacity, Cp [J/kg K]	760	1006.43
Surface tensión, σ [N/m]	1.7	-

The CFD ANSYS Fluent 19.1 © was used to solve the multiphase flow using the following governing equations, which incorporated the Finite Volume Method (FVM). The equations solved by the software are presented below:

1. The Volume of Fluid (VOF) multi-phase model continuity equation:

$$\frac{1}{\rho_q}\left[\frac{\partial}{\partial t}(\alpha_q\rho_q) + \nabla\cdot(\alpha_p\rho_p\vec{v}_q) = \sum_{p=1}^{n}(\dot{m}_{pq} - \dot{m}_{qp})\right] \tag{1}$$

$$\sum_{q=1}^{n}\alpha_q = 1 \tag{2}$$

where ρ, α, and $\vec{u}$ correspond to the density, time, phase volume fraction and velocity, respectively for the qth phase (steel, air, or argon), t corresponds to the time and $\dot{m}_{pq}$ and $\dot{m}_{qp}$ correspond to the mass transfer from phase p to phase q and from phase q to phase p, respectively. Equation (2) indicates a constraint, where the sum of all the phase volume fractions must always equal unity. In this way, the volume fraction of the phases can be calculated via this constraint.

2. The VOF Explicit formulation discretization equation:

$$\frac{\alpha_q^{n+1}\rho_q^{n+1} - \alpha_q^n \rho_q^n}{\Delta t} V + \sum_f \left(\rho_q U_f^n \alpha_{q,f}^n\right) = \left[\sum_{p=1}^{n} \left(\dot{m}_{pq} - \dot{m}_{qp}\right)\right] V \tag{3}$$

Equation (3) corresponds to the discretization of the volume fraction via the explicit formulation equation in a time dependent manner, where *n*, $\alpha_{q,f}^n$, V and U_f^n correspond to the index of a previous time step, the face value of the qth phase volume fraction, the volume of the cell and the normal volume flux through the face, respectively.

3. The momentum transport equation:

$$\rho \frac{\partial \vec{v}}{\partial t} + \rho(\vec{v} \cdot \nabla)\vec{v} = -\nabla p + \mu_{eff} \cdot \nabla^2 \vec{v} + \rho \vec{g} \tag{4}$$

$$\rho = \sum \alpha_q \rho_q \tag{5}$$

$$\mu_{eff} = \mu_t + \sum \alpha_q \mu_q \tag{6}$$

Equation (4) corresponds to a single momentum equation, which is solved and shared for all the phases. Equation (4) depends on the volume fractions of the phases via ρ and μ_{eff} which are calculated via equation (5) and (6) to obtain the volume fraction averaged density and effective viscosity, which includes μ_t, the turbulent viscosity calculated by the turbulence model. $\vec{v}$, p and $\vec{g}$ correspond to the mixture velocity, pressure, and gravity, respectively.

4. The standard k-ε Turbulence Model:

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon} \tag{8}$$

$$\frac{\partial(\rho k)}{\partial t} + \nabla \cdot (\rho \vec{v} k) = \nabla \left[\left(\mu + \frac{\mu_t}{\sigma_k}\right) \nabla k\right] + G_k - \rho\varepsilon \tag{9}$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \nabla \cdot (\rho \vec{v} \varepsilon) = \nabla \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right) \nabla \varepsilon\right] + C_1 \frac{\varepsilon}{k} G_k - C_2 \frac{\varepsilon^2}{k} \rho \tag{10}$$

Equation (8) corresponds to the definition of the turbulent viscosity, where C_μ is a model constant (0.09) and k corresponds to the turbulence kinetic energy and ε to the dissipation rate. Both terms are solved via equations (9) and (10), respectively. $G_k$corresponds to the generation of turbulence kinetic energy due to shear work, and σ_k, σ_ε, C_1 and C_2 correspond to model constants, with values 1.0, 1.3, 1.43 and 1.92, respectively.

Tetrahedral meshes with approximately 600,000 cells were generated, with a maximum skewness of 0.70. The number of elements was defined after testing several meshes and obtaining mesh independent solutions. The simulations were run in the 288 core MMPC's High Performance Computer Cluster, which comprises one head node and 5 adjacent nodes with 64 GB each and an Intel Xeon © processor. A maximum of 20 iterations were set for each variable timestep and adjusted to conserve a global Courant (Co) number of 0.25 using the explicit VOF formulation presented in Equation (3). The time steps ranged from 1×10^{-7} to 1×10^{-5} seconds. All the variables' residuals were set at 1×10^{-6}. The coupled algorithm velocity–pressure coupling was used for the simulations.

Full-scale water modelling is an important method to study Steelmaking system like Ladle Shroud-Tundish systems [12, 18, 20, 23], owing to the Reynolds and Froude dimensional number similarities. A plastic full-scale model of the proposed Ladle Shroud design was constructed to perform water experiments to observe initial filling stages and steady state operation of the new Ladle Shroud design. The prototypes were constructed with 5 mm flexible acrylic sheet, with dimensions presented in **Error! Reference source not found.**. The edges were welded, and the complete part was inserted into a 76 mm diameter transparent PVC pipe, where 10 mm thick rings were manufactured and inserted inside the pipe to support the inclined walls of the new prototype. A picture of the physical model operational at the McGill Metals Processing Center (MMPC) laboratory shown in Figure 3 (b). More details about the construction of the tundish tank and the water modelling experiments can be found in [9]. Experiments with an inlet water velocity of 0.8 m/s (around 1.6 LPM) were performed to simulate the start-up/filling stages of operation. Video recordings and photographs were taken with a Nikon© D5300 camera to observe the fluid flow behaviour inside the system.

3. Results and Discussion

Figures 4 and 5 present the predicted steel volume fraction contours at different times, for both cases, on a transverse plane for 2D visualization. It can be observed that a falling stream is formed in the reverse taper ladle shroud design, as per Figure 4, and that the ladle shroud is not filled with steel, owing to its diverging ID. With respect to the proposed new ladle shroud design, it can be observed in Figure 5 that at 14.413 seconds the ladle shroud is practically filled with steel, avoiding any intermixing with the initial air within the system. This will reduce steel reoxidation. At 37.303 seconds, Figure 4 for the reverse tapered design, this predicts that a turbulent, multi-phase, flow is generated in the system, wherein air bubbles are generated within the falling stream of liquid steel. This will promote reoxidation of the liquid steel, whereas in Figure 5, at 32.143 seconds, a single-phase flow of liquid steel, with much less turbulence is generated. When the liquid steel completely fills the system, meaning quasi-steady state has been reached, between 56-58 seconds, for the reverse taper design, Figure 4, some gas bubbles are still present, whereas for the new ladle shroud design, Figure 5, a single-phase flow is reached.

From the previous analysis and results presented, the predicted results obtained via mathematical modelling predict improvements during the filling stage by using the proposed ladle shroud design, by avoiding the presented turbulent multi-phase flow observed in the reverse taper design and promoting a quiescent filling stage where the system is smoothly filled only with liquid steel. This advantage is expected to improve the steel quality and productivity of a steel plant with a relative low investment alternative, since the ladle shrouds are disposable equipment in most steelmaking plants.

Figure 6 presents the predicted contour for the absolute pressure in both designs at steady state operation, and as expected with the reverse taper design, Figure 6 (a), a negative pressure (below 1 atm) is predicted in the top part of the system, lower nozzle-ladle shroud joint, which will generate an air inflow if a perfect seal is not achieved in said joint. Figure 6 also shows the predicted velocity contours for both designs at steady state operation. From the velocity filed results, it can be observed that a high velocity (3 m/s) is achieved in the "vena contracta" of the new design, which can be used for the generation of microbubbles for later cleaning. As well, in both cases, the velocity of the steel leaving the ladle shroud and into the tank or tundish is about 1.2 m/s, meaning that no impacts on the casting rate and productivity can be expected by using the new design. The CFD comparison of the proposed ladle shroud design and a reverse taper design used currently in a steelmaking plant, is initial proof of the promising advantages and innovations of the proposed design, which can be very attractive and have the potential to be an important invention in the steelmaking industry. Water modelling has also been carried out to confirm the mathematical predictions and to provide stronger evidence of the advantages the proposed design can bring.

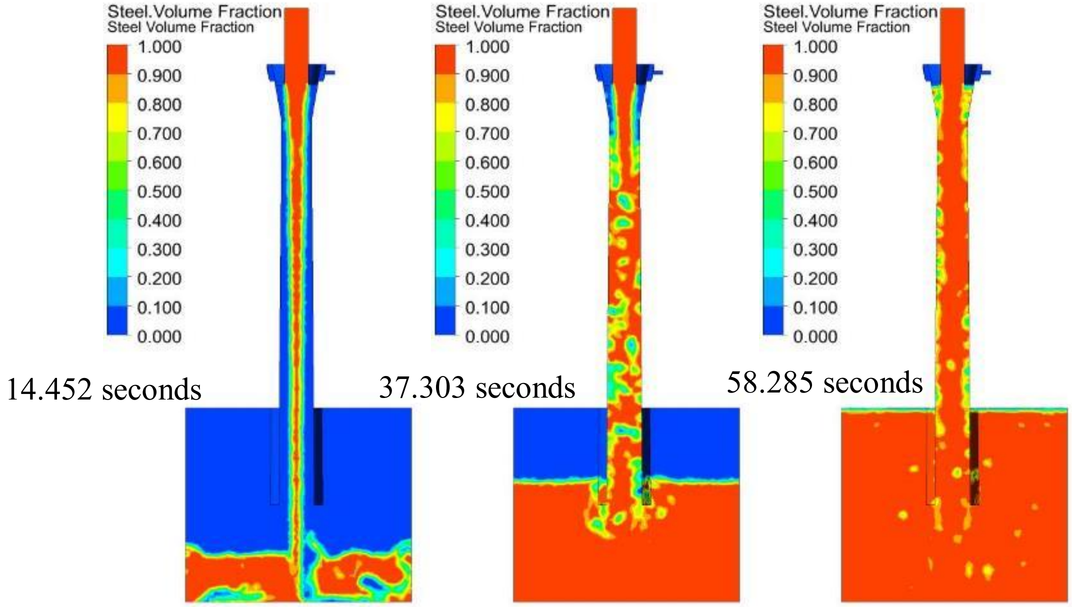

Fig. 4. Predicted Steel volume fraction contours on the symmetry plane for the reverse taper ladle shroud (a) [22] and for the proposed design first case (b) at different times.

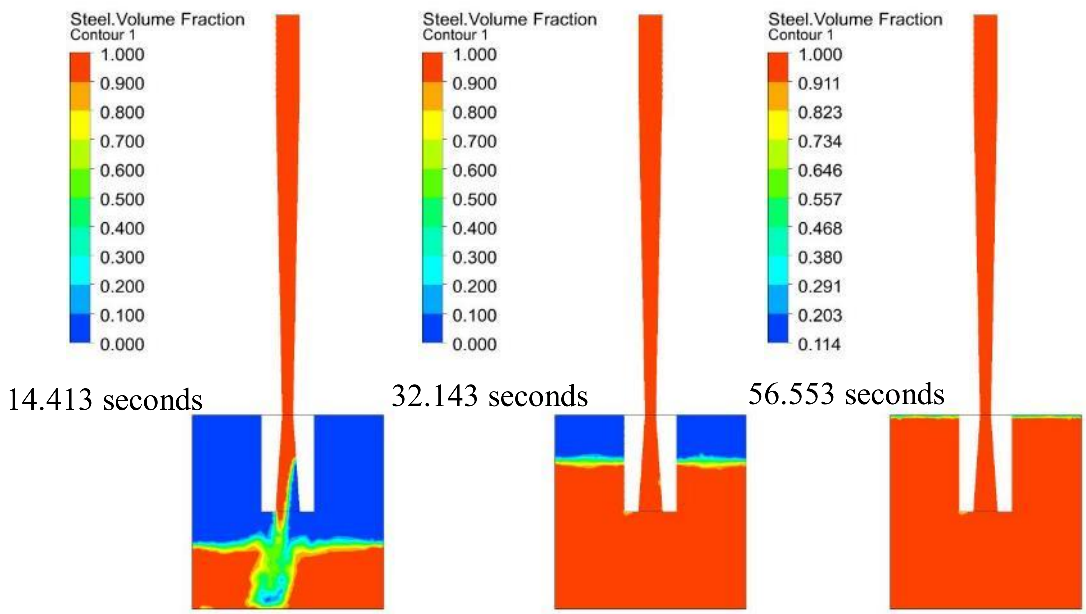

Fig. 5. Predicted Steel volume fraction contours on the symmetry plane for the reverse taper ladle shroud (a) [22] and for the proposed design first case (b) at different times.

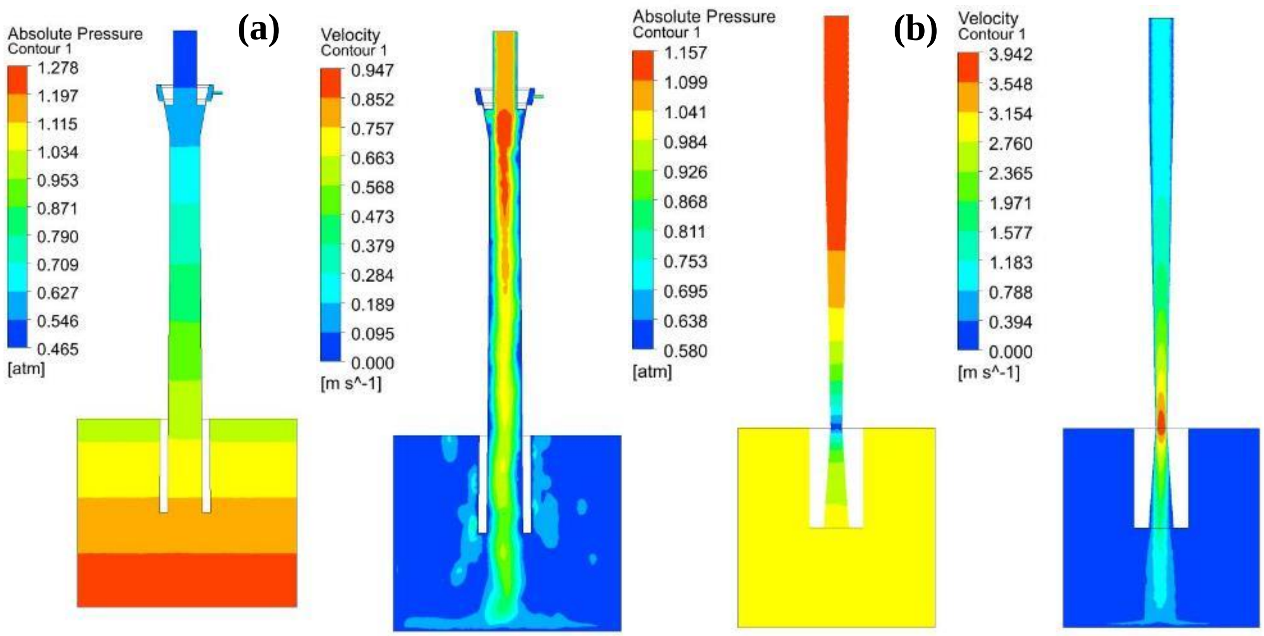

Fig.6. Predicted absolute pressure and velocity contours for a current reverse taper ladle shroud (a) [22] and for the proposed design first case (b) at quasi-steady state operation.

Figure 7 (a) presents different photographs at three different times of the filling stage of the water model of the conventional reverse taper Ladle Shroud design. A turbulent falling water stream collapses and generates air bubbles at 60 seconds. Figure 7 (b) presents similar results, but for the new Ladle Shroud design. Due to the new design, the falling collapsing water stream is not developed, and no gas bubbles are observed at 60 seconds of filling. A more quiescent filling is achieved with the new design, and validated by the mathematical predictions, compared to the conventional reverse taper design. Eliminating the turbulent multiphase flow using the new design will lead to improvements in the productivity of the steelmaking process, confirming the mathematical predictions of the fluid flow behaviour differences between the designs.

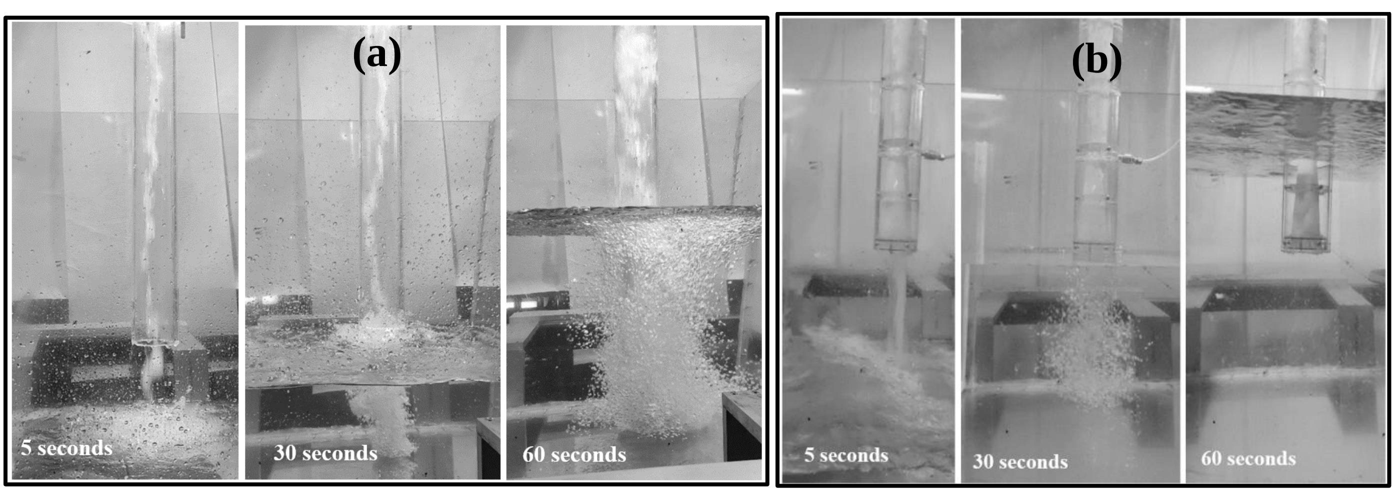

Fig. 7. Filling stages of the (a) reverse taper ladle shroud and the (b) new ladle shroud design tundish-tank water model at different times from front view.

CFD simulations were done for the convex and concave design variations and the predicted steel volume fraction contours during the filling stage are presented in Figures 8 and 9. For the convex design, it can be seen that at and 0.33 seconds, the top portion of the ladle shroud is readily filled with steel in a plug flow manner, displacing all the initial air in the system, and at 13.92 seconds the ladle shroud is filled with steel, single phase flow, and the liquid exits into the tundish and starts to fill up the tundish. This plug flow, avoiding the observed turbulent multiphase flow promoted with the reverse taper design, will increase the initial stability of the process, and will avoid entrained gas pockets inside the ladle shroud, which can lead to sudden gas expansions and lead to a condition called "blowback" that can disrupt dramatically Steelmaking operations. On the other hand, the concave design variations did not show this desired plug flow. For instance, it can observe that at 0.39 seconds, the ladle shroud is filled partially with liquid steel to then become completely filled at 13.73 seconds. This type of convex design can also be used for casting processes where it is desired to expel the initial gases in the system to avoid any undesired reactions, such as reoxidation., etc.

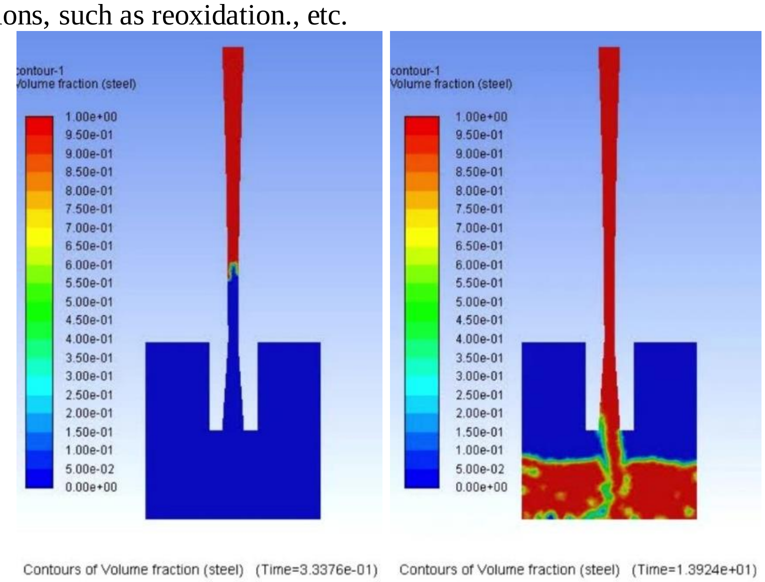

Fig. 8. Predicted steel volume fraction contours for the proposed design convex variation at different times.

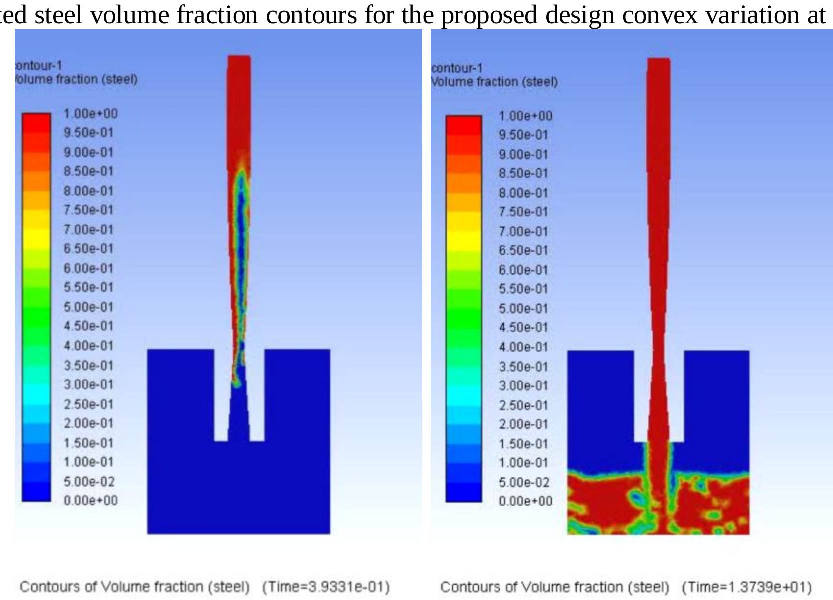

Fig. 9. Predicted steel volume fraction contours for the proposed design concave variation at different times.

4. Conclusions

The present work showcases how CFD and water model experiments can be used to explore new designs of Ladle Shroud in Steelmaking and potentially lead to large improvements in performance. The present converging-design shows some potential advantages: at the top joint of the ladle shroud, absolute pressure values close to atmospheric pressure are predicted. This will avoid air suction and hence the need for high argon shrouding gas flow rates.; a single-phase flow is promoted during the filling stages, potentially increasing the productivity of Steelmaking plants. The convex variation design showed an improved plug flow behaviour, rapidly displacing the initial air in the ladle shroud system. This principle can be used in other similar metal casting technologies, where liquid metal-gas reactions are to be avoided. A US Provisional Patent 2023, No. 63/453,502 [24], and an International Patent Application, WO 2024/19252334) has been filed for the presented converging-diverging Ladle Shroud.

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