Production of metal production in casting through tundish: A review

Jaywant Namdev Yadav[1] & Netra Pal Singh[2]

[1, 2]Department of Mechanical Engineering, Oriental University, Indore 453555, India

Corresponding author email id: jaywantyadav_hydro@rediffmail.com Contact: +91-9890584622

Abstract:

In the continuous casting the molten metal form ladle is not directly poured in the mold, it is poured in to tundish for assuring continuous flow and refining purposes. Tundish not only assures the continuous flow but also performs inclusion removal process. Design parameters of tundish comprises critical dominance over the quality of metal production. In this review, the parameters affecting the tundish over the metal production quality are reviewed. The parameters affecting the tundish are the fluid flow, flow modifiers utilized, residence time distribution (RTD), temperature distribution in tundish, inclusion removal efficiency, etc. Fluid flow modifiers utilized in optimizing the fluid flow are weir, dam, baffle and turbulence inhibiter (impact pad). All the parameters which affects the metal production through tundish are estimated and presented. It is concluded that the shape and size of tundish, inclusion removal efficiency, residence time distribution (RTD), types and locations of flow modifiers, the ladle to tundish and tundish to mold flowrate, the number of inlet and outlet strands and shrouds are the parameters which affects the quality of metal production through tundish.

Keywords: Tundish, Continuous Casting, Flow Modifiers, Residence Time Distribution (RTD), Turbulence Inhibiter (TI), Inclusion Removal Efficiency.

1. Introduction

Holocene, the steel is produced through utilizing basic oxygen furnace (BOF) and electric arc furnace (EAF). The steel production through BOF comprises blowing of oxygen gas on the hot metal or scrap, and lime as additive is utilized for minimizing the carbon, phosphorus, sulfur and silicon [1]. The EAF comprises remelting and refining the steel scrap through utilizing oxygen gas injection and additives [2]. After melting the metal in the furnace, it is transfer to ladle, for handling and pouring it into the mold. Before transferring directly to the mold, it is poured in tundish, which refines it and assures the continues flow of molten metal to mold at required flowrate. Tundish is theoretically a shallow plate, but in casting industry, it is utilized for refining and maintaining proper continuous flow of molten metal to the mold [3]. Continues slab casting process consists continuous flow of metal into mold and its cooling, eventually obtaining a continuous production of steel slab [4]. Tundish is necessary in the continuous slab casting, as it assures the continuous flow metal to mold and also performs secondary refining through removing inclusions [5]. The quality of the steel produced depends on the tundish performance and efficiency. The tundish performance depends on various parameters, such as ladle cooling rate, residence time, metal flow characteristics, heat loss, insulation, tundish linings, shape or size of tundish, use of flow modifiers, etc. For investigating the proper performance of any tundish for specific operation requires detection and optimization of this parameters. In this review, the parameters which usually affects the quality of steel production in tundish are discovered. These parameters are discovered through reviewing research papers related to the optimization of tundish and its operation. The types and configurations of the tundish various with respect to specific requirements. They are classified based on shape, size, type of linings, types of flow modifiers utilized and number of outlet and inlet strands [5].

2. Parameters affecting the Quality of Metal Produced

The affects the quality of the steel production through tundish are discussed in the following sections. These parameters are shape and size of tundish, types and locations of flow modifiers (dam, weir, baffle, turbulence inhibiter (TI), gas injection), tundish lining material, residence temperature distribution (RTD), ladle cooling rate, flowrate of molten metal, molten metal temperature distribution in tundish and the types and/or number of inlet and outlet strands and shrouds. Every parameter affects the operation performance of the tundish in a particular way and eventually the metal quality. For developing optimum configuration of tundish and its efficient operation these parameters effects are necessary to be detected and studied.

2.1. Shape and Size of Tundish

The shape and size of the tundish is also a quality deciding factor of metal production. The shape of tundish defines the flow of molten metal from inlet ladle to the outlet mold. It is also observed larger the shape and size, larger the volume capacity of the tundish and more surface area for inclusion removal. Usually the shape and size depend on the casting operation volume flowrate requirements, but these parameters are also considered for optimum design. Some of the configurations with different shapes are shown in **Fig. 1**. In [5], the authors have presented the tundish technology for cleaner steel production. The concepts of non-metallic inclusions, fluid flow and turbulence, fluid flow characteristics, melt flow modeling techniques tundish operations, temperature control, and some novel emerging technologies in tundish are covered [5].

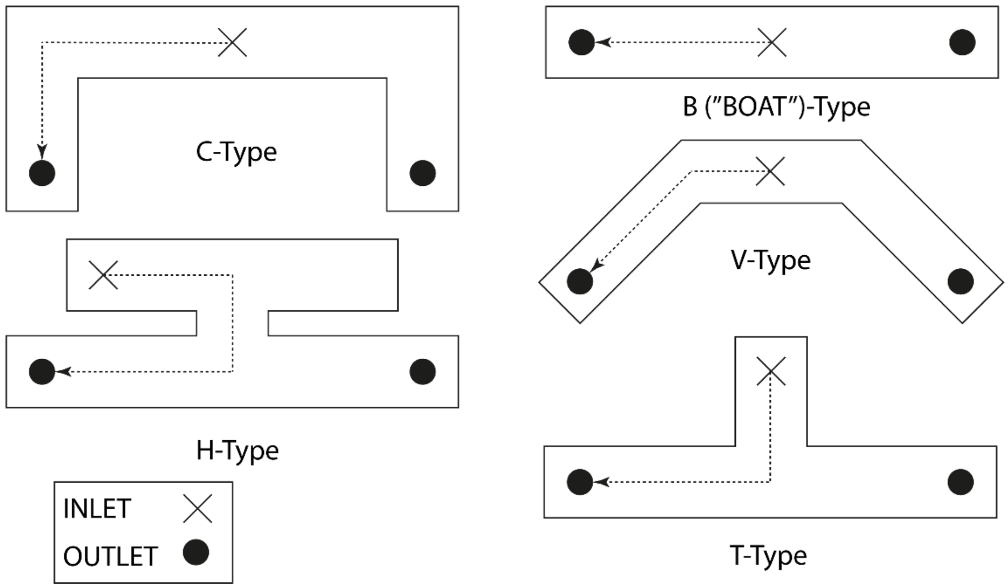

Fig. 1. Plan views of different tundish shapes with inlet and outlet locations [5].

2.2. Types and Locations of Flow Modifiers

The flow modifiers are deployed in the tundish for controlling or guiding the fluid flow for proper inclusion removal and minimizing the turbulence in the flow. The smother the flow the better the inclusion removal and lesser the residence time, also better the quality of the metal production. Some examples of flow modifiers deployed in tundish are dam, weir, baffle, turbulence inhibiter (TI), impact pad, etc. in some of the tundish the insertion of micro bubble through gas injection is deployed as the flow modifier in order to achieve better inclusion removal from molten metal. Several modeling approaches are utilized for investigating the melt flow in tundish and some of them are classified and shown in **Fig. 2**.

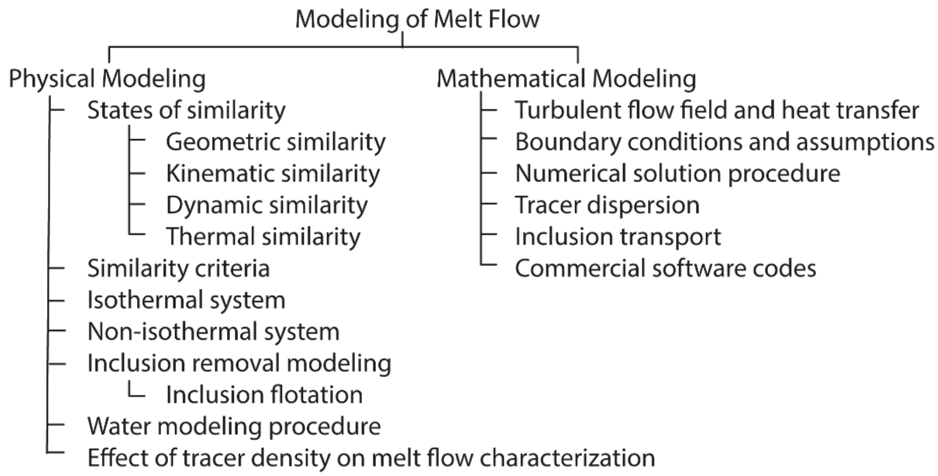

Fig. 2 Melt flow modeling approaches classification for tundish [5]

2.2.1. Dam

Dam is a simple type of flow modifier deployed in tundish, for guiding the fluid flow in upper direction. Dam is a plate place din the perpendicular direction of flow, which is constructed as from lower surface to some extent to upper. In [9], the authors have performed numerical and physical modeling for comparing the motion of inclusions and transportation of molten steel through round and elliptical shape tundish [6-7]. Along with captivating the molten metal, the tundish also comprises the function of decreasing the macro-inclusions and flacking its flotation. In the study, the round and elliptical shape tundish are examined through multi-heat teeming ingot. The physical modeling setup consists round shape and elliptical shape tundish with flowmeter, tractor filler, bar, Residence Time Distribution (RTD) system and data acquisition system as common. In physical modeling the C curve was utilized through stimulus responding method [8]. The numerical simulation was performed through utilizing software FLUENT, k-ε two-equation model, continuity equation and momentum equation. In results, it is discovered that round shape tundish with flow control devices, comprises short molten steel time, prominent dead volume and less efficient inclusion removal. In elliptical shape tundish, the residence time is lengthened by 1.6 times and also raised by 6%, decrease from 18% to 13% in dead volume,68% increase in ratio of plug volume to dead volume and eventually 17% increase in inclusion floatation efficiency. It is also observed that there is decrease from 2.5 to 1.6 mm in equivalent diameter of single defect and no intensity defect in elliptical shape tundish. Total oxygen content is also decreased by 30% [9]. **Fig. 3** shows the schematic representation of tundish with some flow modifiers, which are dam, weir, baffle and turbulence inhibiter (TI) [9].In [12], the authors have performed fractal theory analysis through mathematical model for Al_2O_3 inclusion analysis on low-carbon aluminum killed steel in tundish. A fractal agglomerating-growth model was instituted [10-11].

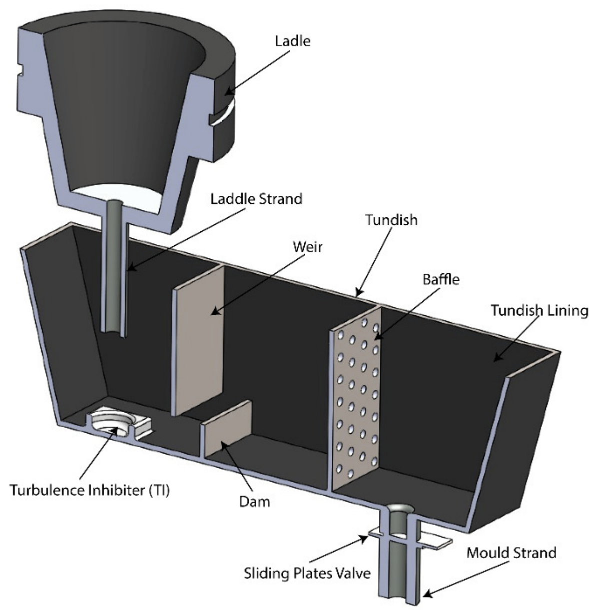

Fig. 3 Schematic representation of tundish with some flow modifiers [5]

It is discovered that the monomer and agglomerated inclusion particles were accumulated at the swirl flows occurring at both sides of inlet, space between the weir and dam and space above outlet. It is also found that the agglomerated inclusions with hydrodynamic diameter of 8 to 9.8 microns are formed quickly then the inclusions with 11 microns diameter. The density of agglomerated inclusions can be controlled through residence time. It is discovered that density of agglomerated inclusions first increases rapidly and starts to decrease after some period [12].

Authors have performed fluid flow analyses on single strand tundish for investigating the flow characteristics in the continuous casting process [14]. The CFD software ANSYS FLUENT 14.0 and experimental analysis through physical water model is utilized in this research research, along with the realizable k–ε equation for model turbulent phenomenon [13]. Through the tracer concentration at the outlet of tundish, the residence Time Distribution (RTD) curves were obtained for tundish consisting flow modifiers and for tundish without flow modifiers. Good agreement between the experimental and CFD results was discovered. The results present the importance of flow modifiers in increasing the residence time and the inclusion removal in the tundish. The improvement of 20% in the peak and minimum residence time in RTD was obtained for tundish with flow modifiers. Among the flow modifiers configurations comprising bare tundish, dam, baffle and turbo stop, the turbo stop provides optimal flow characteristics and improvement in level of inclusion removable [14].

2.2.2. Weir

Weir is also a simple type of flow modifier deployed in tundish for converging the metal flow in downward direction. In [16], the authors have developed a computational technique for investigating the molten steel and slag flow in the tundish with different configurations and the multiphase flow modeling is also utilized. The different tundish configurations in this research are first tundish with flat dam and weir and second tundish with curved dam and weir. For numerical modeling the commercial package FLUENT is utilized [15]. Form the results, it is discovered that the height liquid level slag is obtained narrower mould wall and lowest at vicinity of Submerged Entry Nozzle (SEN). The dam and weir are found to be effective in reducing turbulence at vicinity of SEN [16].In [18], the authors have developed a computational tool for improving the steel quality in continuous operating tundish. The computational tool investigates the turbulent fluid flow, temperature distribution and inclusion removal in the tundish. A novel configuration of tundish comprising weirs and dams is proposed for improving steel quality in tundish. In Eulerian flame Ansys CFX software is utilized in this research with Element based Finite Volume Method (EbFVM) [17]. The EbFVM method is utilized for analyzing the coupled turbulent flow and heat transfer model. For inclusion generation, random mechanism is utilized and for accounting the turbulence on the inclusion trajectories, the modified Lagrangain model is utilized. It is concluded that there is significant enhancement in the flow pattern and inclusion removal rates, due to addition of combined dams and weirs [18].

2.2.3. Baffle

Baffle is also deployed in tundish as flow modifier, it is a plate consisting holes utilized for promoting the inclusion removal up to certain dimensions. In [20], the authors have developed a metaphysical model for optimizing and investigating the fluid flow, heat transfer, and inclusion removal behavior of an odd number multistrand bloom casting tundish. The tundish utilized in this research is five-strand bloom casting tundish with five baffles and two turbulence inhibitors (TIs). The optimization and investigation in this research are carried out for enhancing the consistency through the strands and obtaining purity in molten steel. In order to assert the flow results and residence time distribution (RTD), the water model experiments are performed [19]. From the results, it is discovered that there is good agreement between the simulated steel flow and RTD curves results with the experimental ones. It is also discovered that after applying the optimized baffle and TI, there is total residence time is 595.0 s, increase in plug region volume by 4.8% and decrease in dead zone volume by 0.2%. There is 42.5 s residence time and 264.6 s residence time increase in the third strand, along with 0.0057 decrease in total average standard deviation. It is also observed that there is decrease from 28.6 K to 22.8 K in the maximum temperature from 28.6 K to 22.8 K in the inclusion removal rate particularly inclusions diameter ranging 10 microns to 100 microns. Eventually there is increase from 97.94 % to 98.73 % in qualification rates of flow detection and 97.3 % to 99.1 % in non-metallic inclusions. There is also enhancement in the consistency among the strands due to the optimization [20].

2.2.4. Turbulence Inhibiter (TI)

Turbulence inhibiter (TI) as the name itself presents this are flow modifiers deployed for minimizing the turbulence. They are also known as impact pads, in some of the applications. In [21], the authors have performed mathematical simulation on one-strand slab continuous casting tundish through the fluid flow and residence temperature distribution (RTD). It is observed that there is prominent "spring uprush" at the long shroud and turbulence inhibiter (TI) with extended lips. It is also observed that, there are four little "spring uprushes" at the TI without extended lips. The temperature at the right zone of stopper comprises half level of liquid surface heigh with temperature less than 1819 k, which means large dead zone is existed in initial tundish configuration. The optimum configuration of tundish comprises the height of such level as seventh of liquid surface height. Good agreement between the RTD curves and the physical modeling was discovered [21].

2.2.5. Gas Injection

Gas injection in the tundish refers as flow modifier and promotes better inclusion removal. Gas injection comprises injection of micro bubbles of gas in the steam of molten metal for obtaining better flow characteristics. In [22], the authors have promoted micro-bubbles in the upper ladle shroud through injecting gas by tiny orifices. The motion behavior of this bubbles in the delta shape tundish was investigated in the research. The impact pad, which is a conventional turbulence inhibitor (TI) is deployed in this tundish. A 3-D numerical modelling is deployed for accounting the motion behavior of the micro-bubbles on the impact pad flow in tundish and compared with full-scale water experimentation. It is discovered that there is increase from 14.33 to 37.09 % in the inclusion removal, for similar amount and size of bubbles [22].

2.3. Tundish Lining Material

The tundish lining materials affects the insulation of the tundish with the environmental temperature, it function is to reduce heat loss and slag inclusion in the molten metal. In [23], the authors have investigated different commercial MgO (Magnesium Oxide) materials for application as tundish lining. The microstructural and mechanical properties of this material samples is investigated foe thermal evolution during the tundish operation. The testing samples were produced with different water contents through drying and firing. The samples are classified as green, fired (at 1600°C) and sintered samples. The samples were investigated for microstructural characteristics comprising density, pore size distribution and SEM (Scanning Electron Microscope) observations along with mineralogical (X-Ray Diffraction XRD) and chemical composition. The mechanical compressive analysis on green and fired samples along with determination on high temperatureflexural strength (HMOR) (at 1360°C) and dynamic elastic modulus were estimated. The thermogravimetric analysis is also performed on the samples with different water content. The rapid drying, which is a failure mechanism is also analyzed. It is discovered that the water content was the most critical parameter affecting the porosity and mechanical properties of green sample, fired samples and sintered samples [23].

2.4. Residence Temperature Distribution (RTD)

Residence temperature distributions (RTD) in tundish is the temperature distribution of the molten metal when it is in rest condition in tundish. This distribution is obtained through placing thermocouple are different locations in tundish for recording the temperature distribution. In

[30], the authors have developed a mathematical model for simulating tracer mixing KCI (potassium chloride) solution in their earlier research. In that research good agreement was achieved between mathematical and experimental, which was for larger amount of tracer additions [24]. For a tundish with smaller amount of KCI sedition (which is 50ml), the Residence temperature Distribution (RTD) curves deviate from experimental. In this research, the RTD curves deviation is resolved by utilizing specific turbulent model. Some dissimilar turbulent models were utilized with density. Couple mixed composition fluid model, they are LVEL, Chen-Kim k–ε, MMK k–ε, Explicit Algebraic Reynolds Stress model (EARSM), Large Eddy Simulation (LES) and Wall Adapting Local-Eddy viscosity (WALE) [25-29]. The configurations of the addition of KCI solution were samples as 75 ml, 100 ml, 150 ml and 250 ml. It is discovered that the LEVL and WALE models have better agreement for RTD curves for CFD modeling and experimental. An issue similar butterfly effect is discovered, as the more tracer similar to amount in water sinks to the bottom due to density increase. This issue also effects the flow field severely and diverts the RTD curve. The 50 ml KCI addition slightly disturbs the flow with volume ratio of 0.2×10^{-3} [30]. Authors have performed physical modeling and industrial trails for investigating the flow characteristics and inclusion removal in a ten-strand continuous casting tundish. The results comprise, the inclusion removal efficiency is worst for minimum dimensionless residence time and best for maximum dimensionless residence time at exit of the strand. The results also show that for all inclusion sizes the inclusion distribution is similar in all strands. It is also discovered that the inclusion removal in the first strand for minimum dimensionless time is inferior from the former strand for minimum dimensionless mean residence time [31].

2.5. Ladle Cooling Rate

The cooling rate of the molten metal entering the tundish also affects the tundish operation. In [32], the authors have developed a transient and coupled computational model for estimating the flow fields, temperature fields, residence time distribution (RTD) and inclusion removal efficiency. This model is developed particularly for revealing the effect of actual cooling rate of ladle stream on persistent metallurgical performance of a tundish comprising typical single strand tundish with turbulence inhibiter (TI), web, dam and stopper. The mathematical and physical modelling results reveals that there is decrease in temperature difference (bulk flow for normal casting period, which is 11.3 to 2.6 K) with decrease in ladle stream cooling rate. It also shows that with decrease in dead volume fraction from 17.8% to 14.35% and increase in inclusion removal efficiency (at inclusions having diameter less than 50 microns). It is also discovered that the estimation of critical ladle stream cooling rate for tundish is important for enabling the persistent metallurgical properties throughout the casting stage. In this research the critical ladle stream cooling rate is 0.3 $K.min^{-1}$ [32].

2.6. Flowrate of Molten Metal

The flowrate of the molten metal from the ladle to tundish and from tundish to mold, affects the fluid flow and the quality of metal production. In [35], the authors have performed numerical modeling for examining the separation efficiency for inclusion behavior in four stand asymmetric billet caster tundish. Open FOAM also known as open source CFD code was utilized for modeling inclusions along with the Lagrangian Particle Tracking approach [33-34]. Initially the Lagrangain particle class was specific in simple foam solver (open FOAM) and further this solver was customized for tracking the particles found in velocity field. The inclusions are modelled as sphere along with considering the various forces acting on them. It is concluded that increasing the flowrate at inlet, the separation efficiency decreases, this also decides the quality of steel produced. Turbulent flow is been encountered at the inlet and tundish impact pad region. Thermally induced flow is disadvantageous to the inclusion flotation, but there was similarity discovered in separation efficiency for isothermal and thermal induced flow [35].In [38], the authors have performed numerical simulation for mixing phenomenon inside the tundish, in order to investigate residual volume and outflow (throughput) rate. In this research for investigating the intermixed grade steel formation, and three-dimensional two-phase numerical model with Volume of Fluid (VOF) process along with level set interface tracking method is utilized [36-37]. The Geo-reconstruct and modified High-Resolution Interface Capturing (HRIC)are the interface tracking schemes, which are compared in this research. It is observed that the grade mixing is significantly affected by the residual volume. The advance pouring box (APB) is also tending to be considerable influencer in the mixing phenomenon is also slightly impacted by the outflow rate of the tundish [38].

2.7. Molten Metal Temperature Distribution in Tundish

The temperature distribution during the flow of molten metal and interaction with environment also affects the quality of metal production. In [39], the authors have performed numerical simulation for accounting effect of inlet cooling rate on fluid flow and temperature distribution in tundish. The variation of temperature along the stream in tundish prevails fluid flow and temperature distribution, but the fluid flow is a non-isothermal process. In this research, a Flexible Thin Slab Casting (FTSC) tundish is utilized for examining the effect of inlet cooling rate on fluid flow and temperature distribution through numerical simulation. The variation in inlet cooling rate inn this research is considered from 0.5 to 0.25 $°c.min^{-1}$. It is discovered that when the inlet cooling rate is 0.5 $°c.min^{-1}$, which results in temperature decrease in other zones and eventually results into degenerating the inclusion removal effect in tundish. It is also observed, hat when the inlet cooling rate is 0.25 °c.min^{-1}, the molten metal flows in horizontal direction. It is concluded that the temperature variation effects the fluid flow and for better fluid flow it is necessary to reduce heat loss rate [39].

2.8. Types and Number of Inlet and Outlet Strands and Shrouds

The type and number of strands affect the design of the tundish and also the fluid flow must be design with respect to it. This also affects the discharge flowrate of the tundish, and eventually affects the quality of metal productions. Some tundish with different shape and no. of strands inlet and ouletsare shown in **Fig. 4**. In [41], the authors have developed on modified tundish by welding radiation proof steel plates to exterior walls of billet caster tundish. This novel tundish modification is deployed for reducing the thermal loss by the molten metal in tundish during continuous casting process [40]. The investigation of this modified tundish is done based on effect of pressure in the vacuum chamber and the uniformity of temperature through the tundish. This tundish consists working layer (Magnesia brick), performance layer (Light Clay brick), thermal insulation layer (Asbestos board) and vacuum layer. This tundish is a fire strand billet caster tundish and after vacuum layer there are radiation proof steel plates welded to it. It is discovered that the conversion radiation coefficient is not sensitive to pressure and values of higher temperatures are 1.5 times the lower ones. Pressure is discovered to be the critical factor at 10^3 Pa is 100 times greater than at 10^2 Pa and local temperature difference at 10^2 Pa is 1 K higher than 10^5 Pa. It is discovered that the modified tundish achieved low superheat teeming of steel and improves the uniformity of temperature [41]. Literature to tundish operation and investigation for various factors is reviewed in this paper. Table 1 shows the parameters affecting the quality of metal production with respect to the references.

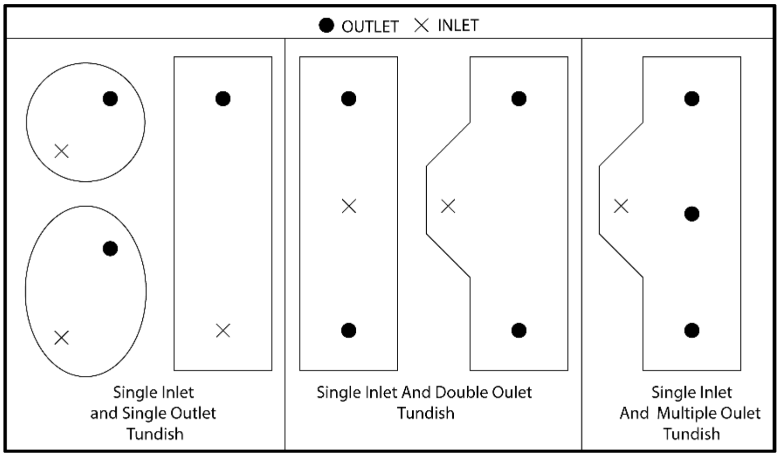

Fig. 1 Types of tundish based on number of inlets and outlets [41]

Table 1. Parameters affecting the quality of metal production through tundish with respective references.

Parameters		References
Shape and Size of Tundish		[5, 22]
Types and Locations of Flow Modifiers	Dam	[9, 12, 32, 16, 14, 18]
	Weir	[9, 12, 16, 18]
	Baffle	[9, 14, 20]
	Turbulence Inhibiter (TI)	[9, 21, 32]
	Gas Injection	[5, 22]
Tundish Lining Material		[23]
Residence Temperature Distribution (RTD)		[9, 12, 21, 32, 30, 31, 14, 20]
Ladle Cooling Rate		[39, 32]
Flowrate of Molten Metal		[5, 35]
Molten Metal Temperature Distribution in Tundish		[39, 18]
Types and Number of Inlet and Outlet Strands and Shrouds		[5, 21, 32, 31, 41, 14, 12]

Conclusions

The parameters which affects or dominates the quality of metal produced through casting, particularly through utilizing tundish are studied and investigated. After going through the literature, some conclusions are gained, which are presented in the following:

- The flow characteristics of the molten metal flow through the tundish affects inclusion removal efficiency and residence time, which eventually affects the quality of metal production.
- For optimizing the fluid flow in the tundish various shapes of tundish are utilized. The utilization of flow modifiers such as weir, dam, baffle, turbulence inhibiter, etc. their combination also plays essential role in fluid flow optimization in tundish. The fluid flow in tundish affects the quality of metal production.
- The ladle cooling rate, which means the inlet molten metal to tundish cooling rate also affect the residence time and temperature distribution in tundish. This residence time and temperature distribution further directly affects the inclusion removal process. This ladle cooling rate therefore affect the quality metal produced through tundish.
- The number of stands and shrouds in the tundish, also affects the fluid flow of molten metal in tundish. The fluid flow must be optimized with respect to the number of strands and shrouds with their types in tundish. So, this number of strands and then indirectly affects the quality of metal production.
- The inclusion removal process is mostly exercised through the fluid flow in tundish, but for increasing inclusion removal efficiency, the flow modifiers are utilized. Sometime the gas injection process is deployed as flow modifier. So, this gas injection process affects the inclusion removal efficiency and also the quality of the metal produced.

- Tundish mostly deployed in the continuous slab casting, where the tundish assures the continuous flow of molten metal with refining. In continuous casting the flowrate of molten metal from ladle to tundish and tundish to mold, this affects the fluid flow in tundish. So eventually this flowrate also affects the quality of metal production through tundish.

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