Designing of Sub-entry Nozzle for Casting Defect-free Steel

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Abstract. Production of defect-free steel is a continuous demand for each & every steel maker. The design of refractories used in steel making process has a vital role on this. Manufacturing of cleaner steel is mostly attributed to the continuous casting process of the steel plant. Defects in steel mainly come from the non-metallic inclusions present in steel that are incorporated during various steel making process. During continuous casting, the main focus is to remove these inclusions to cast defect free steel. The flow pattern of molten steel in the mould plays a vital role in the removal of these impurities. The turbulence of the flowing steel in the mould should be such that more and more impurities will be floated at the meniscus of the mould and they will be captured by the casting powder. But, this turbulence should not be higher enough to capture the particles of casting powder inside the molten steel. So, in order to optimize the turbulent intensity and to get uniform distribution of temperature and velocity in the mould, the design of Sub-entry nozzle (SEN) is very crucial. SEN is used to guide the flow of steel from tundish to mould during continuous casting. The bore configuration and outlet design of SEN along with its immersed depth in the mould determine the flow pattern of steel inside the mould, which is the key factor to produce cleaner steel. This paper focuses on the different designing aspects of SEN to get an optimized and uniform flow of steel in the mould. The designing parameters include bore diameter, bore configuration, port shape, port angle, port dimension, number of ports and immersed depth of SEN inside the mould. Design optimization is done to improve the steel quality by removing the impurities.

1. Introduction
The present global economic crisis has compelled the steel makers to produce cleaner steel at lower cost. Many robust processes & sophisticated equipments are used to produce defect-free steel but it involves a lot of cost. This has opened up a challenge for the refractory makers to design refractories in such a way that defect-free steel can be casted without the use of high-cost sophisticated equipments.

Submerged nozzle or Sub-entry nozzle (SEN) is used for shrouding the flow of steel from tundish to mould during continuous casting of steel. It prevents re-oxidation and temperature drop of steel by prohibiting the exposure of steel to atmosphere. They are carbon bonded refractories. Generally, the body part of SEN is made of alumina-carbon and the slag band of SEN i.e., the portion of SEN that remains immersed into the pool of mould powder, is made of zirconia-carbon due to excellent corrosion resistance of zirconia against the nascent fluorides in mould powder.

Mould powder is given on the molten steel surface in the mould for lubrication & insulation of mould as well to protect steel from re-oxidation & freezing. It also absorbs the non-metallic inclusions from steel and makes cleaner steel. A part of SEN remains immersed inside this mould powder. During casting, the mould powder melts and flows in between mould and steel. For proper functioning of mould powder, temperature at the steel-mould powder interface should be optimum. Temperature
distribution depends on the turbulent intensity of flowing steel in the mould and distribution of turbulent intensity, in turn, depends on the design of SEN and velocity of steel coming out of SEN bore. If the turbulent intensity is more at the steel-mould powder interface, there is chance of mould powder infiltration in the steel which will cause defects. On the other hand, if the turbulent intensity is less at the mould surface, temperature will also be low. This will result into non-melting of mould powder and subsequent incorporation of inclusions & defects in steel. Moreover, the non-metallic inclusions in steel, coming from the refractories or other sources during secondary steel melting, do not get absorbed by the mould powder if it is non-melted. This again results into defects in steel. So, the design of SEN plays a very important role in producing defect-free steel.

2. Designing of SEN by varying number of ports
In bloom or billet casters, single bore SENs are mostly used. However in bigger blooms (more than 250 mm square or round), SENs having 4 side ports should be used. In single bore SENs, since the flow of steel is at the downward direction hence turbulent intensity at the steel-mould powder interface is lesser. Temperature is also low at steel-mould powder interface resulting into more chance of mould powder freezing which may cause centre segregation defects in steel. Figure 2 shows the mathematical modeling (Ansys Fluent CFD) of temperature distribution of single port and 4-port SEN in 300 mm square mould. Modelling is done following 2D symmetric, realizable k-ε model. 2 ports are shown here instead of 4 ports as this is 2D view. It is observed that temperature at meniscus is low in case of single port SEN which may cause mould powder freezing.
Figure 3 shows the velocity distribution, where it is found that the optimum velocity (0.2-0.4 m/s) is observed in 4-port SEN, but in case of single port SEN it is low. In figure 4, turbulence intensity distribution is shown. Turbulence Intensity for the 4-port SEN at the steel-mould powder interface is less than 0.05 N.m. Turbulence intensity adjacent to the walls are also very low and uniformly distributed throughout the mould. This condition is optimum for inclusion absorption at the meniscus.

3. Varying Immersed depth of SEN inside mould
Mathematical modelling is done in a mould section of 250 mm square and 500 mm height with different immersed depth of 180 mm, 150 mm and 120 mm. The temperature distribution is shown in figure 5. For 180 mm immersed depth, temperature is very low (around 500 K) at steel-mould powder interface adjacent to mould wall. This will result into non-melting of mould powder and substantial entrapment of inclusion in liquid steel. For 150 mm immersed depth, temperature is slightly more than previous case, but still lower (around 650 K) than required at steel-mould powder interface. Hence, there will be some entrapment of inclusion in liquid steel. For 150 mm immersed depth, temperature is around 800 K at steel-mould powder interface, which is closer to the required temperature of 1000 K. Hence, entrapment of inclusion in liquid steel will be less.
4. Effect of port angle on steel flow

In slab caster, the port angle of SEN plays a vital role on the flow pattern of steel in mould. In most slab casters, 2-port SENs are used. Molten steel coming out of the port has a double roll flow pattern in the mould. If flow intensity is more than optimum at the upper roll, then meniscus turbulence is more resulting into entrapment of mould powder inclusion in steel. On the other hand, if flow intensity is more than optimum in the lower roll, then chance of inclusion floatation is less and chance of mould powder freezing is more. Port angle is one of the parameters that determine the optimum distribution of flow of steel in mould.

Figure 6 shows that the jet angle or the angle of incoming steel with the mould surface changes with the port angle. For 10 deg port angle, the jet angle is 31 deg, for 15 deg port angle it is 33 deg and for 20 deg port angle it is 34 deg. If the jet hits the top half of the mould, then flow in upper roll will be more. Similarly, when the jet hits the bottom half of the mould, the flow in lower roll is more. For optimum flow pattern in which the linear velocity at the mould meniscus remains in between 0.2 to 0.4 m/s and turbulent intensity is below 0.05 N.m, jet angle should be such that the incoming steel hits 0.4-0.6 of the total mould height.

![Figure 6. Variation of jet angle with port angle](image1)

If the jet angle is very high and the incoming steel hits the mould wall beyond 0.6 of mould height, then there may be chance of break-out. For lesser section width, steel jet hits at lower part of the mould even with lower jet angles. Hence, port angle will be lower for lesser mould sections. In figure 7, it is seen that with same port angle & jet angle, the steel jet hits at lower part of mould when the casting section is bigger.

![Figure 7. Variation of jet trajectory with mould section](image2)
5. SEN with different bore diameters
In figure 8, the turbulent intensity contour has been shown for two different bore diameters 80 mm and 90 mm. It is found that with higher bore diameter the velocity of steel coming out of the port is less resulting into less turbulence at the meniscus. So, if high turbulence and mould powder entrapment is a problem, then bore diameter can be increased for optimized flow.

![Figure 8. Turbulent intensity contour for different bore diameter](image)

6. SEN with different port shapes
In figure 9, the turbulent intensity contour is shown for rectangular shaped port and oval shaped port. In rectangular port, turbulent intensity is less than 0.1 N.m at mould powder-steel interface. Hence, chance of mould powder freezing is there which will increase NMI in steel. In oval port, Turbulence intensity is more than 0.15 N.m which is optimum. Hence oval or round shaped port is always preferred over the angular ports for better flow patterns.

![Figure 9. Turbulent intensity contour for different port shapes](image)
7. Conclusion
Defect-free steel can be produced by optimizing the flow properties of steel in the mould. Optimum temperature distribution, velocity distribution and turbulent intensity inside the mould results into floatation & absorption of impurity at the mould surface by casting powder. Higher turbulent intensity at the mould meniscus may also result into entrapment of mould powder in steel. On the other hand, lower turbulent intensity can cause freezing of mould powder which may result into centre segregation defects in steel.

There are different design parameters of SEN that can be varied to get optimum flow pattern of molten steel inside the mould. The designing aspects of SEN include bore diameter, bore configuration, port shape, port angle, port dimension, number of ports and immersed depth of SEN inside the mould. With the optimized design of SEN, defect free steel can be produced through uniform and optimized flow pattern of steel in the mould.

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