IIT Kanpur

Assignment 4 MSE629

Physical and Mathematical Modelling of Steelmaking Process

STEADY STATE TURBULENT FLOW IN THE SCALED DOWN INDUSTRIAL TUNDISH

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Background

In continuous steel casting, the tundish is essential for managing molten steel flow, temperature control, and impurity removal between the ladle and casting Molds. These functions are crucial for ensuring high-quality steel production. Residence time distribution (RTD) analysis helps engineers assess tundish flow patterns, identifying dead zones, well-mixed regions, and plug flow areas. Optimizing these flow patterns using flow control devices (FCDs) like dams and turbulence inhibitors can improve steel cleanliness and overall process efficiency.

The goal of this assignment is to predict the metallurgical performance of the tundish specified in the assignment through CFD modelling, enabling precise analysis of fluid dynamics and RTD.

Problem Statement

This problem involves a scaled-down (0.15 scale) water model of a tundish in steelmaking, designed to simulate fluid flow and residence time distribution (RTD) characteristics within the vessel. The model assumes a steady, three-dimensional, incompressible, and turbulent flow of water—a Newtonian fluid with a density of 1000 kg/m^3 and viscosity of 0.001 kg/(m·s). Water enters a circular cross-section pipe at an average velocity of 1.37 m/s, yielding a Reynolds number (Re) of 13700, which confirms turbulent flow. The inlet temperature is set at 25°C, ensuring constant fluid properties for accurate simulations.

Fluid Properties

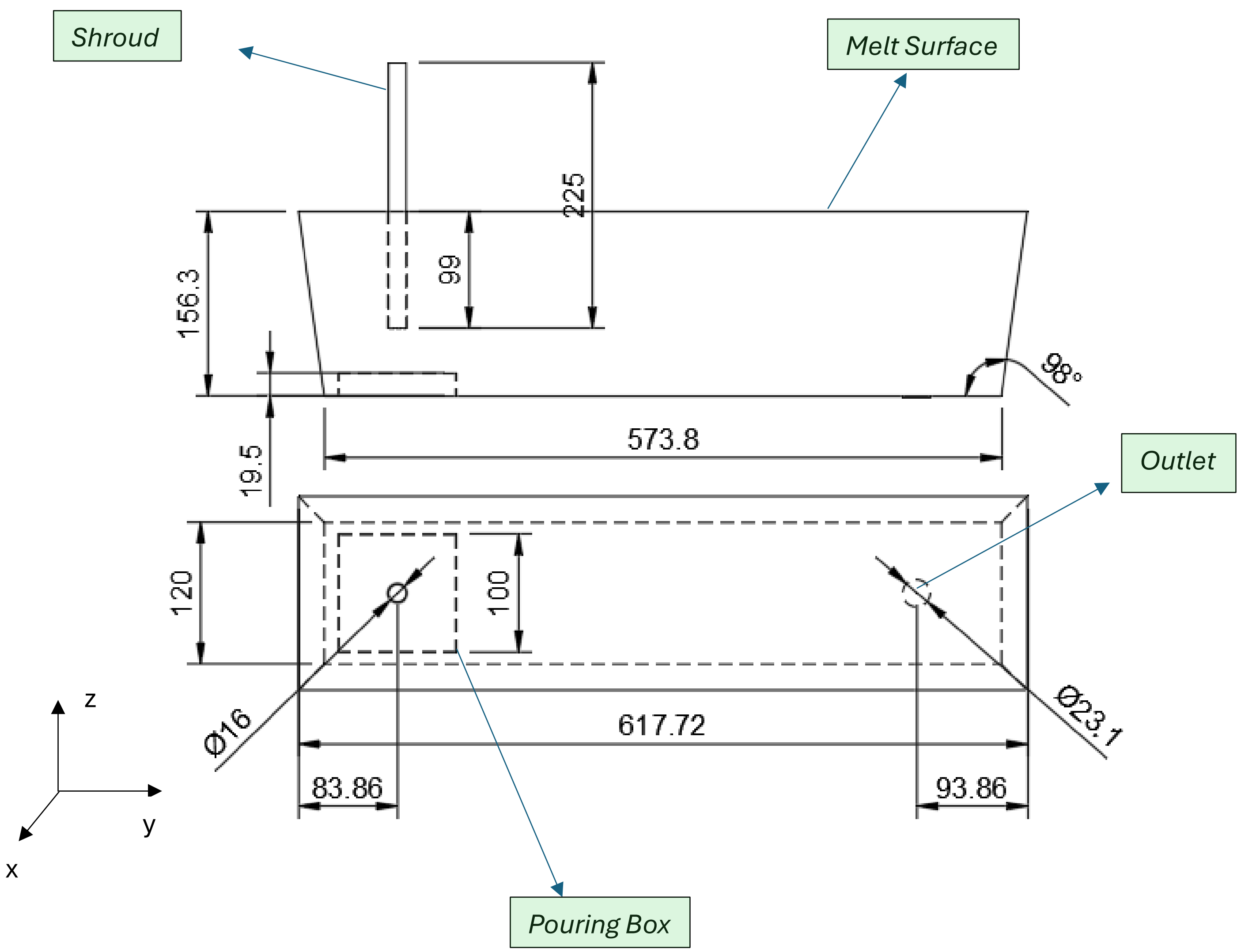
Density	1000 kg/m^3
Viscosity	0.001 kg/ms

Geometry

The geometry of this problem is a 0.15-scale tundish model with a circular cross-sectional pipe, where water flows in through a pouring box of 10 cm x 10 cm. Flow modifiers, like dams and pouring boxes, are strategically placed within the tundish to influence fluid behaviour, enhancing mixing and reducing dead zones. For accurate simulation, the geometry is meshed with 40,000–50,000 elements, using finer grids near the shroud entry and tundish exit to capture detailed fluid motion and ensure precise residence time distribution (RTD) analysis.

The table given below provided the scaled down dimensions with approximations wherever required.

Operating Parameters	***Full Scale Dimensions (m)***	***Scaled Down Dimensions (mm)***
Tundish Length (Top-Base)	4.2841-4.5626	630-573.8
Tundish Width (Top-Base)	0.840-1.1326	176.20-120
Melt Depth	1.042	156.3
Shroud Diameter	0.0881	15
Outlet Nozzle Diameter	0.154	23.1
Shroud Submergence Depth	0.66	99
Height Of the pouring box	0.13	19.5
Velocity at the Shroud (m/s)	1.37 m/s	0.5306 m/s
Side of the Square Pouring Box	0.67	100
Shroud positioned from nearest edge of melt plane	0.56	83.86
Outlet positioned from nearest edge of melt surface	0.62	93.86



Governing Equation.

The governing equation that will be applicable in the stated problem will be 3 Reynolds average Navier Stoke's Equation and 1 continuity equations and an auxiliary equation to calculate the turbulent viscosity.

Since it's a **steady state problem** with constant physical properties few terms will be automatically ruled out by the Ansys fluent.

$$\frac{\partial \rho}{\partial t} = 0; \frac{\partial(\rho\bar{\boldsymbol{u}})}{\partial t} = 0; \frac{\partial(\rho\bar{\boldsymbol{v}})}{\partial t} = 0; \frac{\partial(\rho\bar{\boldsymbol{w}})}{\partial t} = 0$$

1. X direction RANS

$$\left(\frac{\partial(\rho\bar{u}\bar{u})}{\partial x} + \frac{\partial(\rho\bar{u}\bar{v})}{\partial y} + \frac{\partial(\rho\bar{u}\bar{w})}{\partial z}\right) = -\frac{\partial P}{\partial x} + \left[\frac{\partial}{\partial x}\left(\mu_t\frac{\partial\bar{u}}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu_t\frac{\partial\bar{u}}{\partial y}\right) + \frac{\partial}{\partial z}\left(\mu_t\frac{\partial\bar{u}}{\partial z}\right)\right] + S_v$$

2. Y direction RANS

$$\left(\frac{\partial(\rho\bar{v}\bar{u})}{\partial x} + \frac{\partial(\rho\bar{v}\bar{v})}{\partial y} + \frac{\partial(\rho\bar{v}\bar{w})}{\partial z}\right) = -\frac{\partial P}{\partial y} + \left[\frac{\partial}{\partial x}\left(\mu_t\frac{\partial\bar{v}}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu_t\frac{\partial\bar{v}}{\partial y}\right) + \frac{\partial}{\partial z}\left(\mu_t\frac{\partial\bar{v}}{\partial z}\right)\right] + S_v$$

3. Z direction RANS

$$\left(\frac{\partial(\rho\bar{w}\bar{u})}{\partial x} + \frac{\partial(\rho\bar{w}\bar{v})}{\partial y} + \frac{\partial(\rho\bar{w}\bar{w})}{\partial z}\right) = -\frac{\partial P}{\partial z} + \left[\frac{\partial}{\partial x}\left(\mu_t\frac{\partial\bar{w}}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu_t\frac{\partial\bar{w}}{\partial y}\right) + \frac{\partial}{\partial z}\left(\mu_t\frac{\partial\bar{w}}{\partial z}\right)\right] + S_v$$

4. Continuity Equation

$$\frac{\partial\bar{u}}{\partial x} + \frac{\partial\bar{v}}{\partial y} + \frac{\partial\bar{w}}{\partial z} = 0$$

$\bar{\boldsymbol{w}}$ $\bar{\boldsymbol{u}}$ $\bar{\boldsymbol{v}}$ are the mean velocity

5. Eddy Viscosity Model (auxiliary equation)

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

μ_t turbulent Viscosity, k is the kinetic energy

C_μ Universal Constant, ε is the dissipation rate

Boundary Conditions

a) Inlet Velocity of water at the shroud

$w_m = \sqrt{\lambda}\, w_{FS}$ Relation found by equation the Froude's Number

$w_m = \sqrt{0.15} * 1.37$ w_m and w_{FS} are the inlet velocity of model

$w_m = 0.5306\ m/s$ and full scale respectively.

$\lambda = 0.15$ is the geometric scaling Factor

b) Free Melt Surface Symmetric Boundary Condition: $\frac{\partial \vec{v}}{\partial z} = 0$

c) No Slip Condition on the tundish, shroud and pouring box walls.

Selection of the Scheme and Convergence Criteria

SIMPLE scheme is opted for the simulation. Given below the convergence criteria for the model is chosen to be either 1000 iteration or residual value as per the table.

Unknowns	Residual
X velocity	10^{-3}
Y velocity	10^{-3}
Z velocity	10^{-3}
Pressure	10^{-3}
K and ε	10^{-3}

Detailed Report

Point (1)

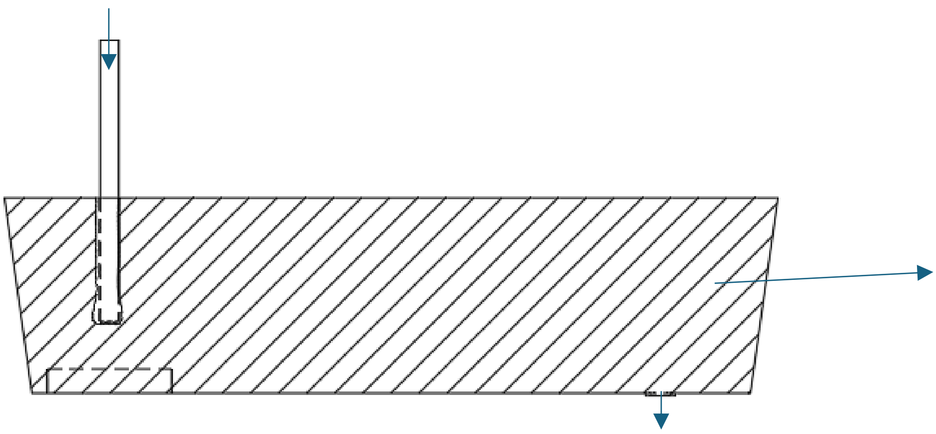
The nominal residence time is found out by the given Formula

$$T = \frac{V}{\dot{Q}}$$ Where T is the Nominal Residence Time

$$Effective\ Volume\ of\ the\ Tundish\ (V) = 0.01326059 \quad m^3$$

$$Volumetric\ Flow\ rate\ at\ the\ Inlet\ \dot{Q} \;=\; 9.2219 * 10^{-5}\ m^3/s$$

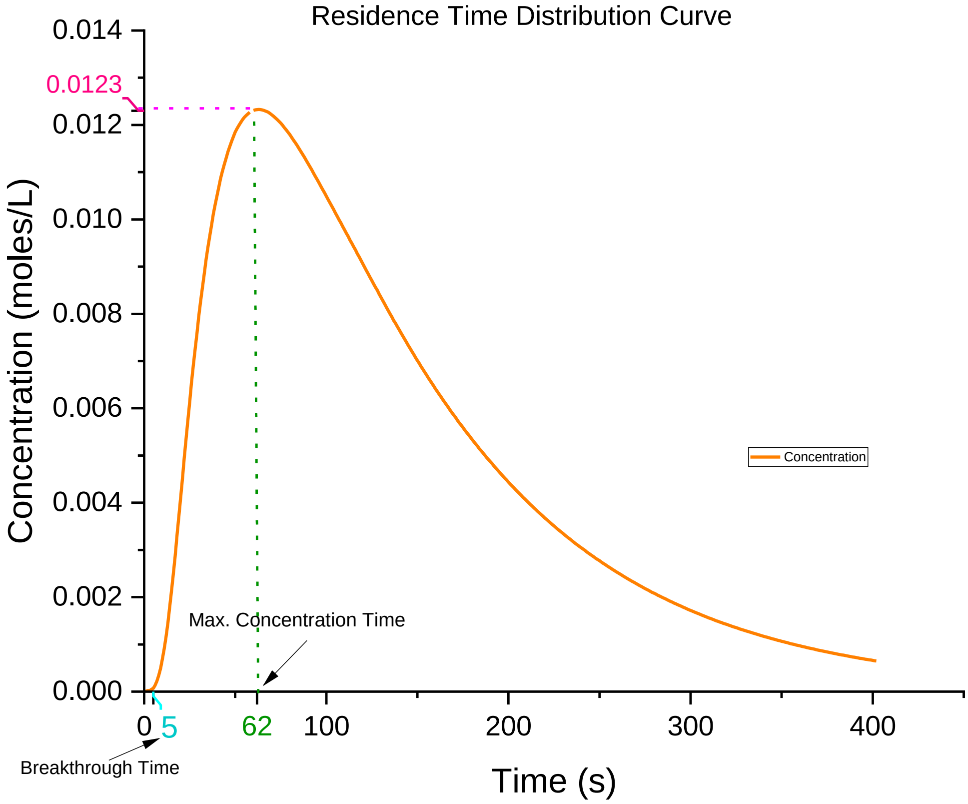
$$\boxed{T = 143.82\ s}$$



Effective Volume of Tundish

Point (2)

The **1 Molar tracer** was released during first the **second** at the inlet of the shroud and a probe was kept at the outlet to plot the concentration Vs Flow time for the calculation of the breakthrough time and Time at which maximum concentration was recorded.



Breakthrough Time: 5 seconds

Time for the maximum concentration recorded: 62 seconds

Point (3)

The mean residence time (τ) is calculated by the formula given below.

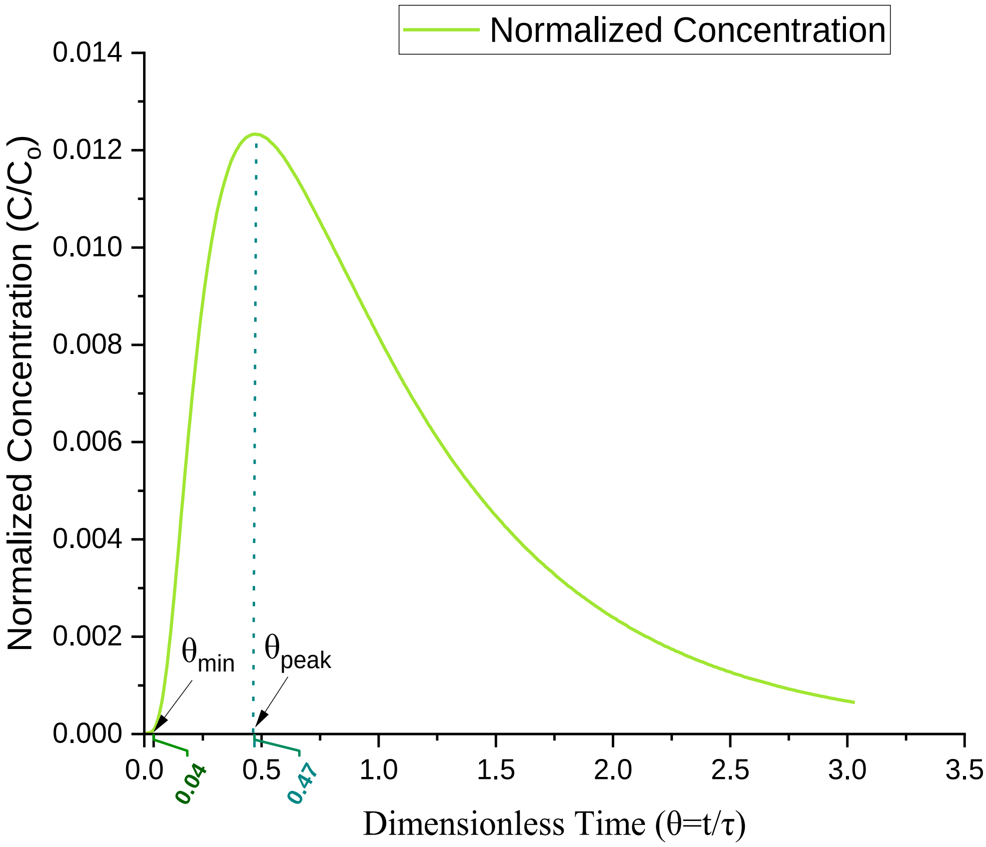
$$\tau = \frac{\int_0^\infty Ctdt}{\int_0^\infty Cdt}$$

The mean residence time τ was found out to **be 132.6 s**. The Dimensionless time θ was adjusted based on it.

$$\theta = \frac{t}{\tau}$$

The Normalized Concentration was based on the initial concentration of the tracer C_o=1 molar. $C' = \frac{C}{C_0}$

The adjusted plot is given below.



Point (4)

The fraction of dead flow is calculated by the formula given below:

$$V_{Df} = 1 - \theta_{avg}$$

$$\theta_{avg} = \frac{\int_0^2 C^{'}\theta d\theta}{\int_0^2 C^{'} d\theta}$$

$$V_{Pf} = \frac{\theta_{peak} + \theta_{min}}{2}$$

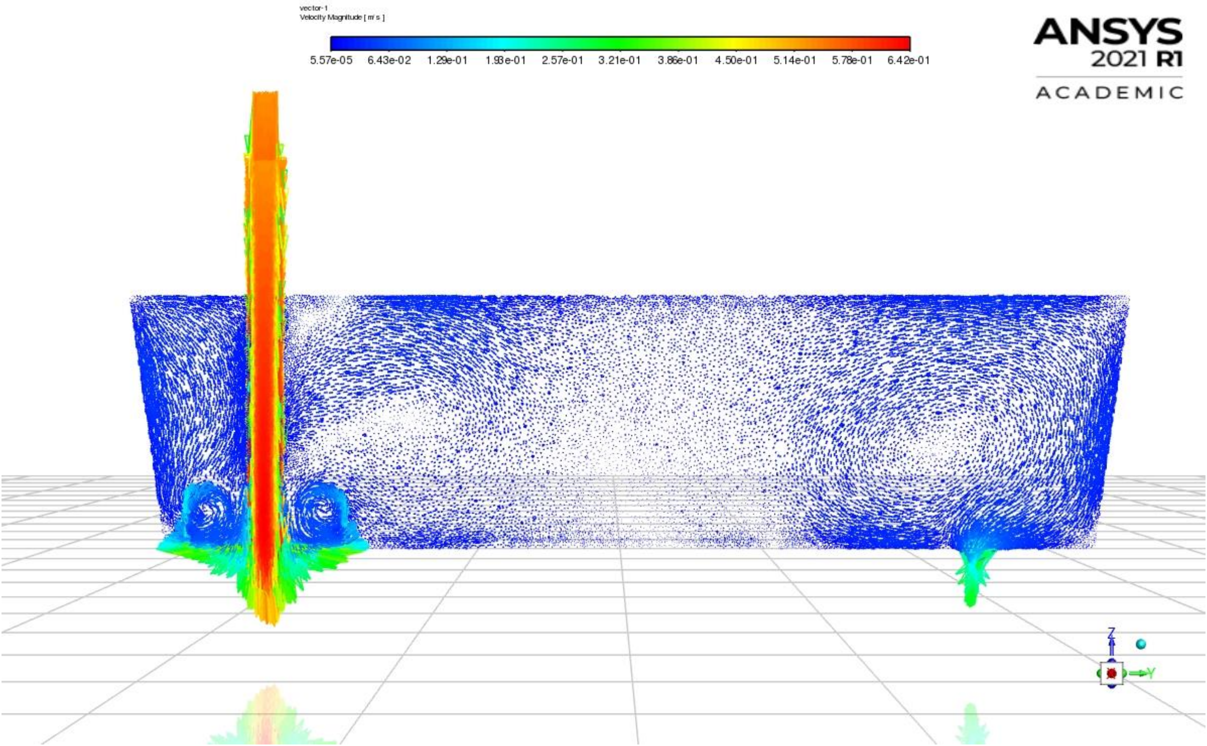
$$V_{Mf} = 1 - (V_{Pf} + V_{Df})$$

The Required values are calculated and tabulated below.

θ_{avg}	0.86
θ_{peak}	0.47
θ_{min}	0.04

Dead Flow Volume Fraction V_{Df}	0.14
Plug Flow Volume Fraction V_{PF}	0.26
Well Mixed Volume Fraction V_{MF}	0.60

Point (5)



From the above it is clear the eddies formed are contributing towards the dead flow of the tundish. The dead flow contributes to 14% of the volume which is decent enough have this value be large there would be more inclusions and crack entrapped in the steel.

To reduce the inclusion and homogenize the steel temperature and concentration well mixed flow is very important to measure its performance larger this value better will be the performance. In the tundish 60% of the flow is the well mixed which is a fair number.

With a plug flow volume fraction of **0.26**, only 26% of the tundish exhibits ideal plug flow behaviour. This relatively low value indicates limited direct flow from inlet to outlet, which may reduce the efficiency of minimizing temperature gradients and controlling inclusions

The tundish shows good homogenization with a high well-mixed volume fraction (**0.60**), but the presence of moderate dead zones (**0.14**) and low plug flow (**0.26**) indicates inefficiencies. Optimizing flow control to reduce dead zones and increase plug flow can enhance performance and improve the final product quality.