Lecture 39: illustration of physical modeling

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Key words: Physical modeling, water modelling

Tapping of molten steel

Let us design a 0.2- scale physical model to simulate the fluid flow behavior for tapping of steel in the ladle. Molten steel is plunged from a height of 4.5m. Molten steel enters at velocity 12m/s velocity. The volume flow rate is $0.12\ \mathrm{m}^3/\mathrm{s}$. The time required to fill the ladle of volume $40\mathrm{m}^3$ is 8 minutes. Viscosity of steel $= 7 \times 10^{-3}\ \frac{\mathrm{kg}}{\mathrm{m.s}}$ and density is $7000\ \frac{\mathrm{kg}}{\mathrm{m}^3}$

Diameter of the model ladle $\mathrm{d_m} = 0.2 \times 4.5 = 0.9\mathrm{m}$

Volume $\mathrm{V_m} = \lambda^3 \mathrm{V_p} = (0.2)^3 \times 40 = 0.32\ \mathrm{m3}$

Volumetric flow rate $\mathrm{Q_m} = \lambda^{5/2}\ \mathrm{Q_p} = (0.2)^{2.5} \times 0.12 = 2.47 \times 10^{-3} \frac{\mathrm{m}^3}{\mathrm{s}}$

In the physical model, water will be used to simulate the steel. We have to find velocity of the water in the model to perform experiments. Dynamic similarity is required.

$$\mathrm{Re_p} = \frac{\rho\ \mathrm{u}\ \mathrm{L_p}}{\mu} = \frac{7000 \times 10 \times 4.5}{0.007} = 4.5 \times 10^7$$

$$\mathrm{Fr_p} = \frac{\mathrm{u}^2}{\mathrm{g}\ \mathrm{L_p}} = \frac{10 \times 10}{9.81 \times 4.5} = 2.27$$

A very large value of Reynold's number in the prototype indicates that flow of steel melt is dominated by the inertial forces rather than viscous forces. Inertial force is also embedded in the Froude number hence Froude number similarity will be sufficient to find velocity of water in the model.

$$\frac{\mathrm{U_m}}{\mathrm{U_p}} = \left(\frac{\mathrm{L_m}}{\mathrm{L_p}}\right)^{0.5} = (0.2)^{0.5} = 0.447$$

$$\therefore \mathrm{U_m} = 5.34\mathrm{m/s}$$

The time of tapping in the model can be derived from

$$\frac{\mathrm{L_m}}{\mathrm{t_m}} \times \frac{\mathrm{t_p}}{\mathrm{L_p}} = \lambda^{0.5}$$

$\therefore \frac{t_m}{t_p} = \frac{L_m}{L_p} \times \lambda -^{0.5} = \lambda^{0.5}$

$\therefore t_m = t_p \times (0.2)^{0.5} = 3.6 \text{ minutes}$

Gas stirred ladle

Design a physical model of an industrial gas stirred ladle with an elliptical shape. Internal diameter of the ladle is 2.282m maximum and 2.082m minimum. Molten steel height is 2.46m and volume is 9.4m^3. Gas is injected at 70 Nl/min through the porous plug fitted at the bottom of the ladle. The scale of the physical model should be $1/3$. Bath temperature is $1600°\text{C}$.

The equations given in lecture 38 could be used to design the model. This is for your exercise.

Tundish model

Fluid flow in the tundish has been investigated thoroughly. Several investigators including the present author have studied behavior of steel melt flowing in a single and multi strand tundish. In the original installation of the continuous casting machine, role of tundish was to act as a distributor of molten steel to different molds at constant speed. It has soon been realized that tundish can be used to float inclusions or to add alloying elements during the process of continuous casting. To full fill the above objective it became necessary to modify the existing tundish design. Physical model of a tundish of single and multi strand casters has been designed by several investigators to study the fliuid flow behavior in the tundish

Design a physical model of a single strand slab caster tundish. The base length of the tundish is 3450mm, width 1100mm and height 1320mm. Tundish is rectangular shaped with slopping walls. Submerged ladle shroud diameter is 78mm. Volumetric flow rate of steel in the tundish is 224 l/min. Scale of physical model $= 0.5$.

Now we have to design a tundish. One must keep in mind the future modifications that would be required. We may require to modify the flow of fluid in the tundish. We have to make previsions to insert flow modifiers like dam and weir etc.

The dimensions of the model tundish are $1725\text{mm} \times 550\text{mm} \times 600\text{mm}$. The tundish is rectangular in cross section with slopping side walls. The tundish may be provided with the grooves to insert dams and weirs etc. A submerged stream is poured from the model ladle to the tundish.

Physical model of the tundish is designed to study the fluid flow behavior in terms of flow pattern and residence time distribution.

Solution: water will be used as an analogue of steel.

Base length of model tundish $= 0.5 \times 3450 = 1725\mathrm{mm}$

Width of the tundish $= 0.5 \times 1100 = 550\mathrm{mm}$

Height of tundish $= 0.5 \times 1320 = 660\mathrm{mm}$

Volumetric flow rate $= \lambda^{2.5} \times 224 = 40\ \mathrm{l/min}$

Dynamic similarity requires similarity in Reynold's and Froude number

$$\mathrm{Re_m} = \mathrm{Re_p}$$

$$\mathrm{Fr_m} = \mathrm{Re_p}$$

$$\mathrm{Re_p} = \frac{\mathrm{D\ u_p}}{\gamma}$$

u_p is velocity of steel, $\gamma = \frac{\mu}{\rho}$ kinematic viscosity of steel melt $= 1 \times 10^{-6}\ \mathrm{m^2/s}$. In the prototype tundish velocity of steel melt is not known. Putting value of $u_p = \frac{\dot{Q}}{\pi\ D2}$ in the Reynolds number, we get

$$\mathrm{Re_p} = \frac{4\ Q}{\pi\ D\ \gamma}$$

$$= \frac{4 \times 224 \times 10^6}{1000 \times 60 \times 3.14 \times 0.078} = 6 \times 10^4$$

Similarly one can calculate Froude number of the prototype

$$\mathrm{Fr_p} = \frac{u_p^2}{g\ D}$$

$$= \frac{16\ \dot{Q}^2}{\pi^2\ D^5\ g} = 16 \times \left(\frac{224}{1000 \times 60}\right)^2 \times \frac{1}{(3.14)^2 (0.078)^5 \times 9.81}$$

$$\mathrm{Fr_p} = 0.79$$

For the dynamic similarity both Reylold,s and Froude,s number should be same. As pointed out in lecture 38, both numbers can be made similar for scale factor 1. In the present model scale factor is 0.5, hence either Reyonld's number similarity can be observed or Froude number similarity.

It is shown (see the references given at the end of this lecture) that in turbulent flow, the transport of the momentum to the neighboring fluid layers occurs via eddies. There is a wide spectrum of eddies of different lengths in a fully developed turbulent flow. Based on the analysis of different lengths of the eddies in molten steel and water system, it is shown that the lengths of the eddies produced at the exit of the submerged shroud for water and steel are of the same order of magnitude, irrespective of the scale of the model and type of fluid. This suggests that within the turbulent flow regime the mechanism of flow of steel melt in the prototype and water in the model may not depend significantly on the absolute value of the Reynold,s number as long as flow is turbulent. Therefore Froude number similarity is considered

Following Froude number similarity model submerged ladle shroud diameter can be determined.

$$D_m = \left(\frac{16\times\dot{Q}^2}{\pi^2\times g}\right)^{1/5} \approx 38\text{mm}$$

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