Simulation Studies of Liquid Slag Flow Patterns at High Temperatures

BTP-2 (MTY401U4M)

Under the Guidance of:

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Presented by:

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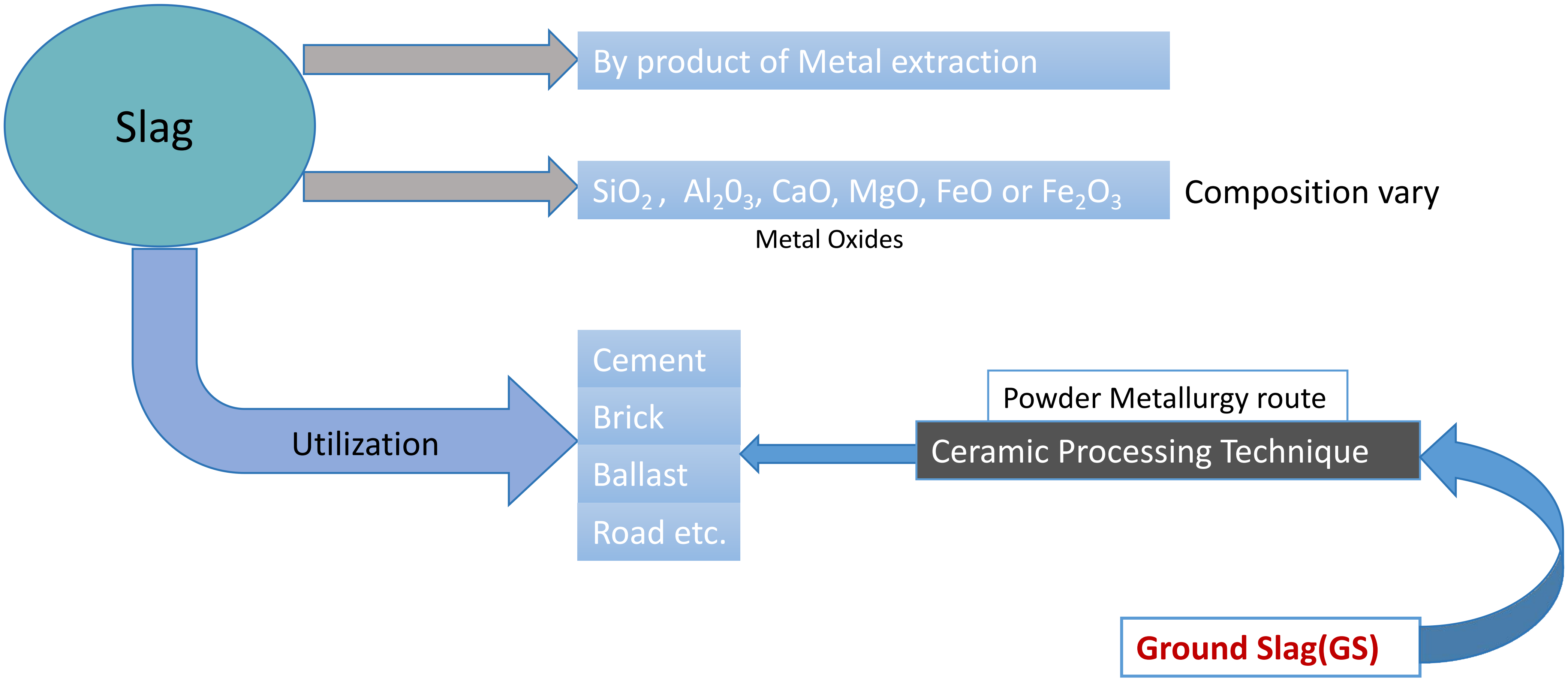
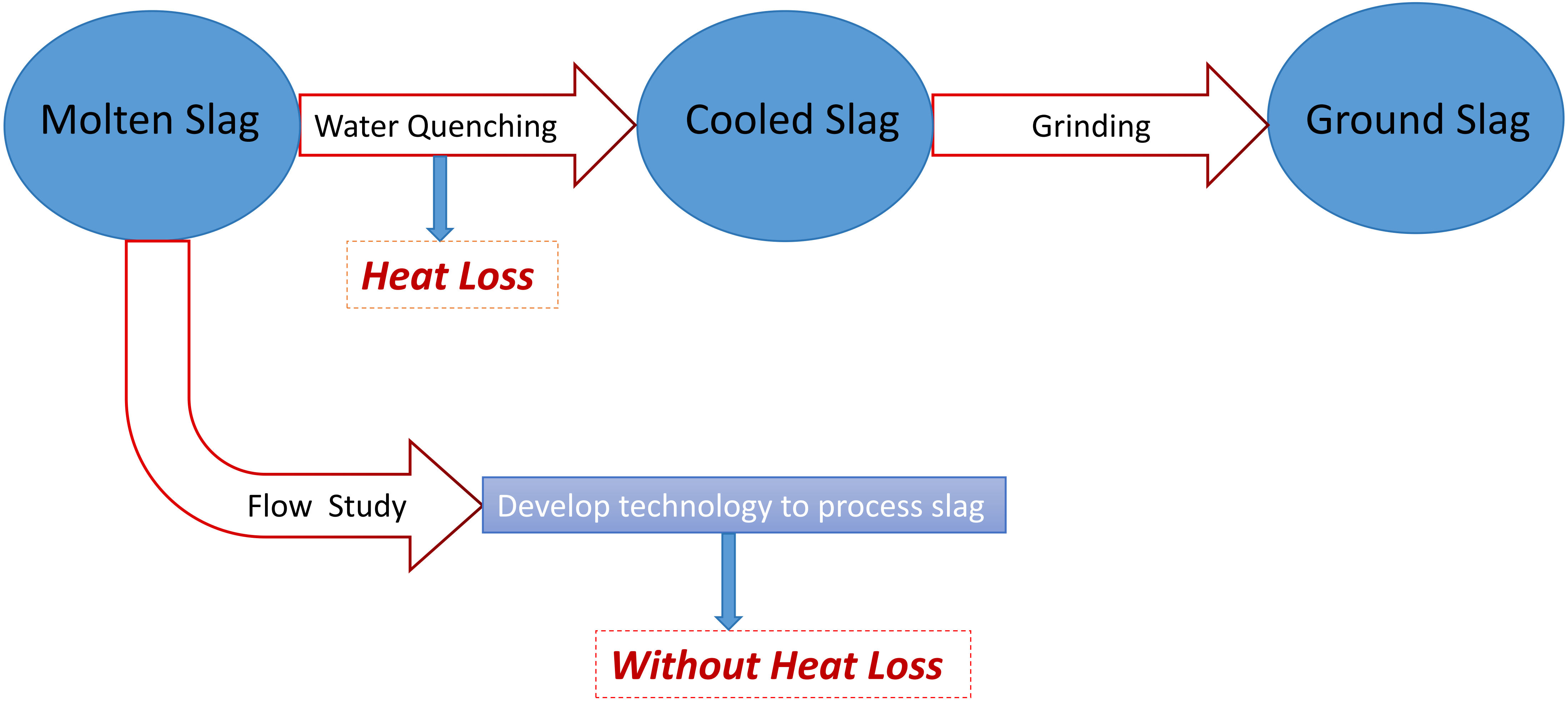
Background


Slag
By product of Metal extraction
SiO_2 , Al_20_3, CaO, MgO, FeO or Fe_2O_3
Composition vary
Metal Oxides
Utilization
Cement
Brick
Ballast
Road etc.
Powder Metallurgy route
Ceramic Processing Technique
Ground Slag(GS)

Objective


Molten Slag
Water Quenching
Cooled Slag
Grinding
Ground Slag
Heat Loss
Flow Study
Develop technology to process slag
Without Heat Loss

Study

Cold Model

Water or Wax

Computational Model

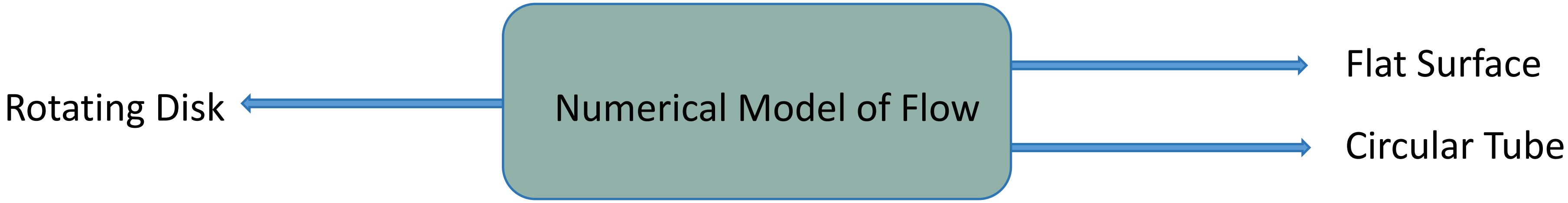
Flow Pattern

$$f(\rho, \mu, \sigma)$$

where $\rho =$ Density of slag(kg/m³)

$\mu =$ Viscosity of slag(Pa.s)

$\sigma =$ Surface tension(N/m)



Literature Data

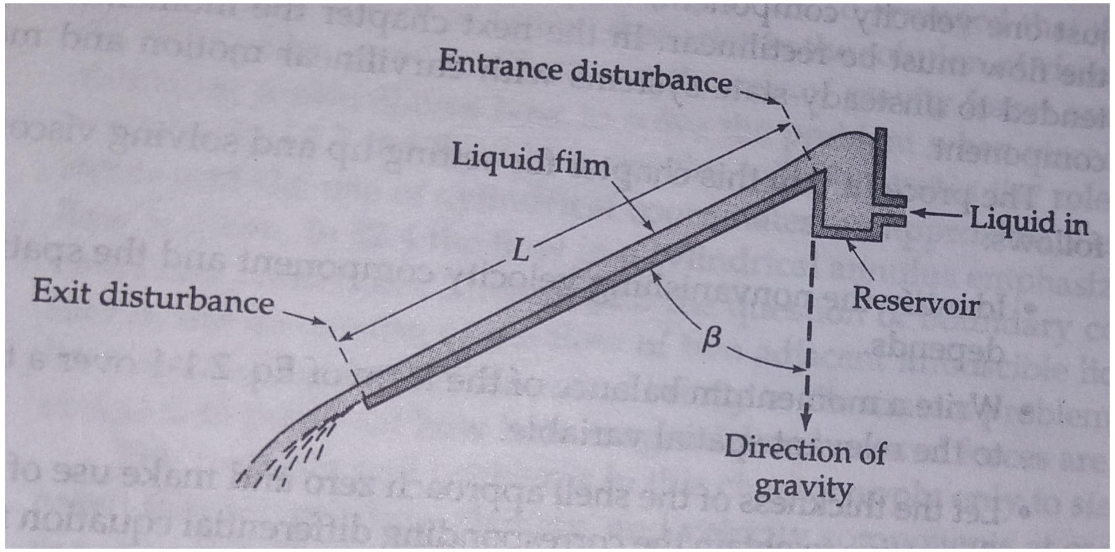
Research Paper	Model	Equation	Viscosity Range(Pa.s)
Jia, 2019, pp. 2-3	Arrhenius Temperature Model	$\eta = A \exp(E_\eta/RT)$	1.3 - 2.6
Hurst, 2000, pp. 1-2	Arrhenius Temperature Model	$\eta = e^{A} \cdot e^{\frac{B}{T}}$	0.7 - 32
Arman, 2017, pp. 2-7	Urbain composition model	$\eta = a \cdot T \cdot e^{\frac{b \cdot 10^3}{T}}$	0 - 15

1. Flat Surface

After Applying Shell Momentum Balance to Steady Flow

Second-order differential equation:

$$\frac{d^2 v_z}{dx^2} = -\frac{\rho g \cos\beta}{\mu}$$



Ref:- Transport Phenomena(R.Byron Bird, Warren E. Stewart, Edwin N. Lightfoot)

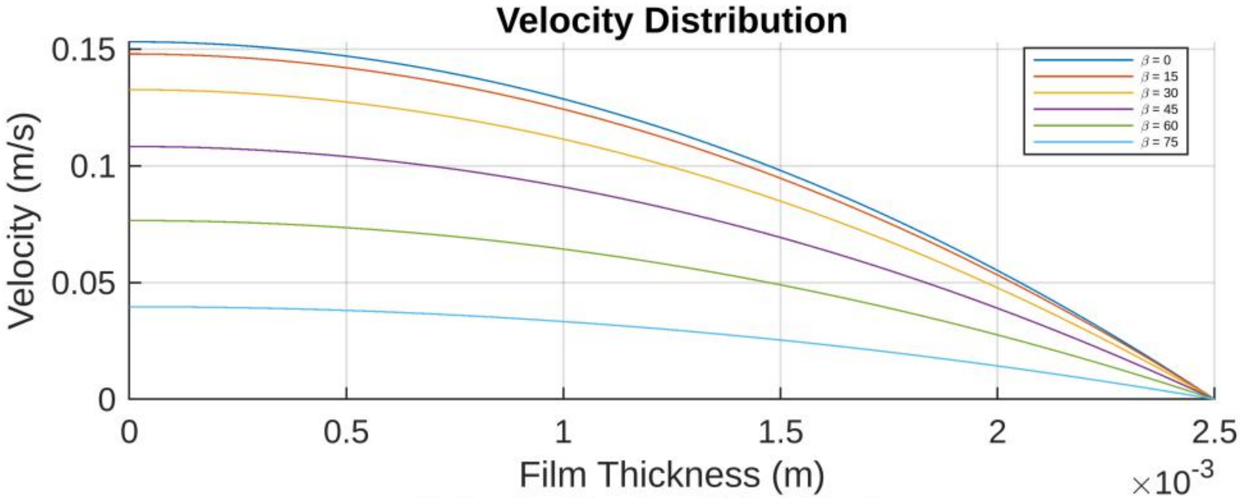
Boundary Conditions:

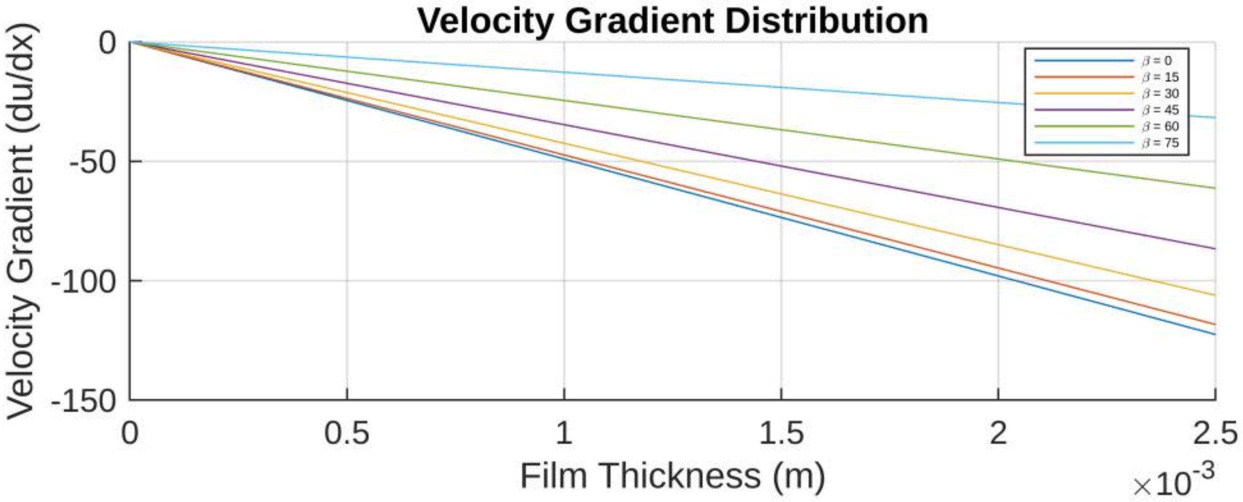
- $\frac{dv_z}{dx}$ =0 at x =0 (No shear at the fluid surface)
- v_z =0 at x =δ (No-slip condition at the solid surface)

Used Parameters:

- Density (ρ) = $800\,\mathrm{kg/m^3}$
- Gravitational Acceleration (g) = $9.8\,\mathrm{m/s^2}$
- Inclination Angle (h) = 60°
- Film Thickness (δ) = $2.5 \times 10^{-3}\,\mathrm{m}$
- Viscosity (μ) = $0.16\,\mathrm{Pa.s}$

Velocity Distribution due to Variation in Geometry





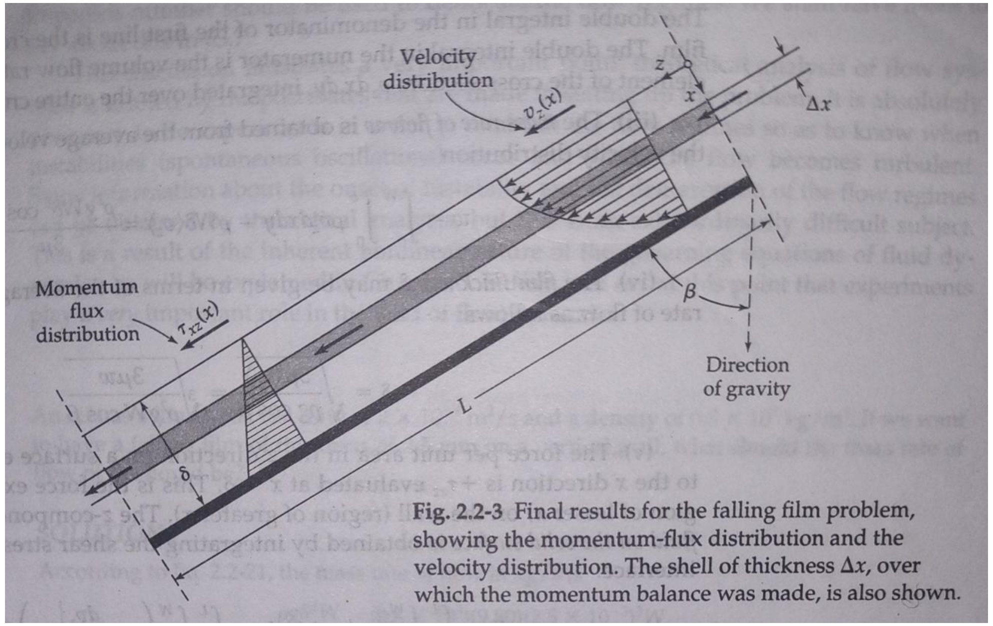
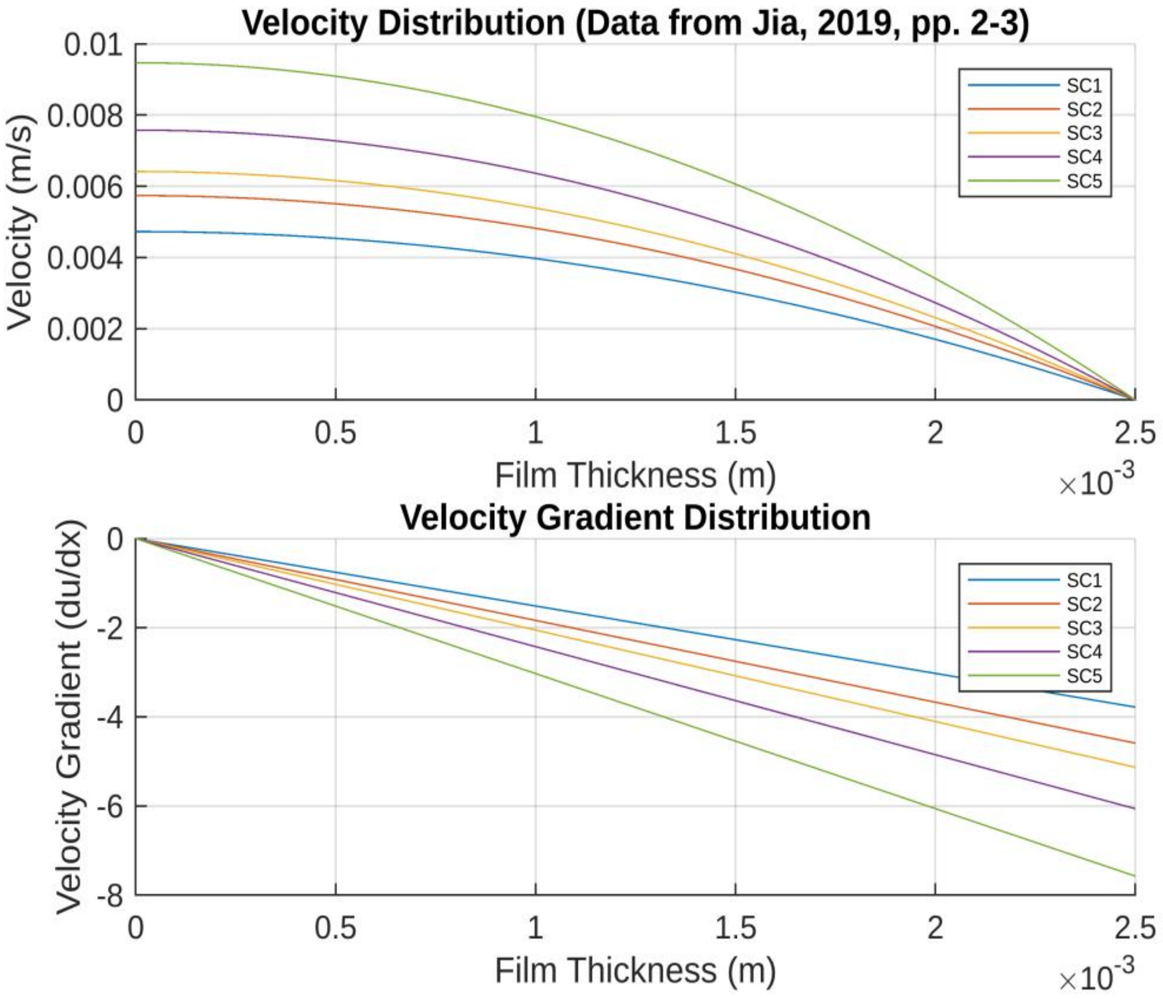
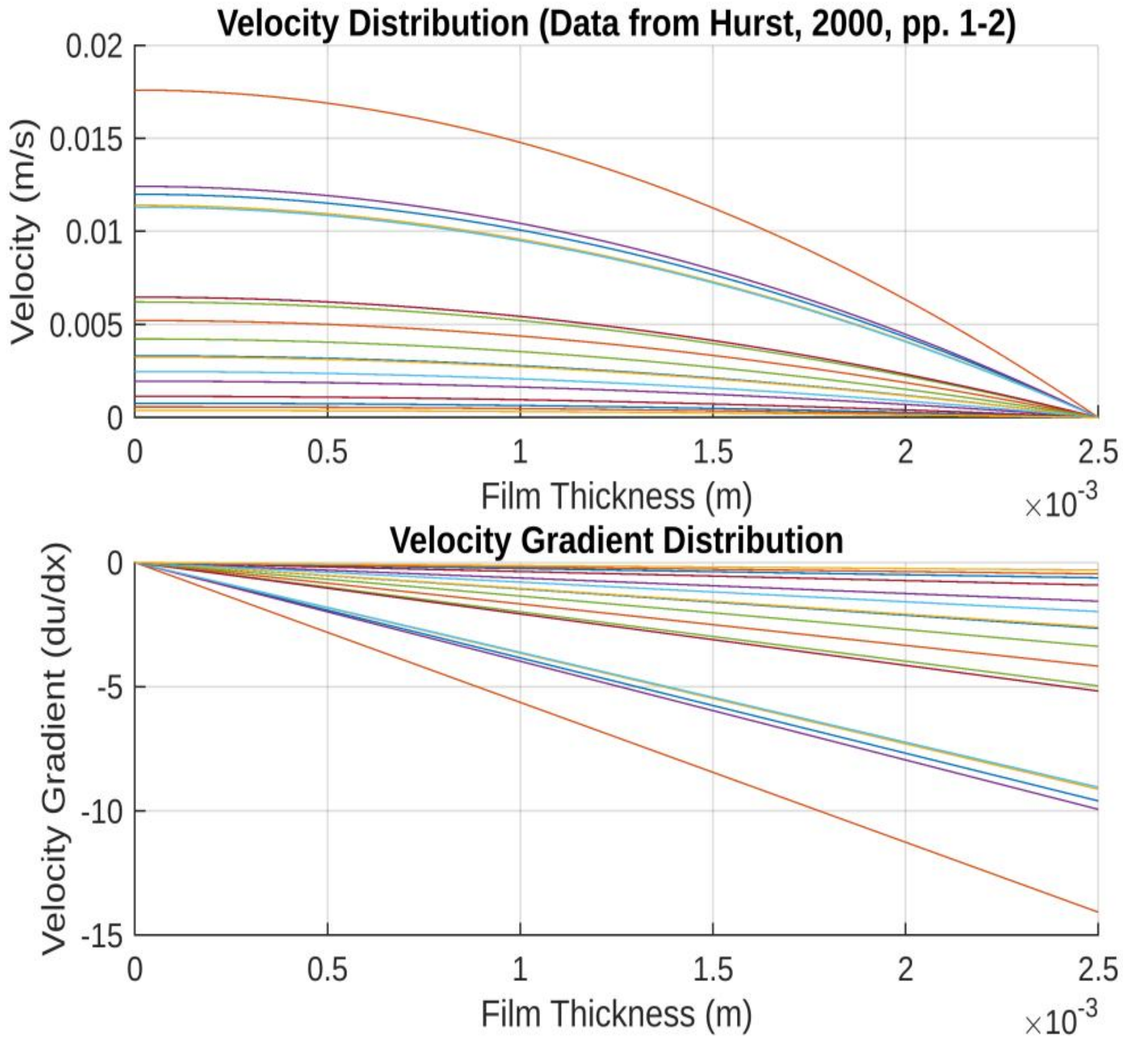


Fig. 2.2-3 Final results for the falling film problem, showing the momentum-flux distribution and the velocity distribution. The shell of thickness Δx, over which the momentum balance was made, is also shown.

Ref:- Transport Phenomena(R.Byron Bird, Warren E. Stewart, Edwin N. Lightfoot)

Velocity Distribution due to Variation in Viscosity





2. Circular Tube

After Applying Shell Momentum Balance to Steady Flow

Second-order differential equation:

$$\frac{d^2 v_z}{dr^2} = -\frac{(P_0 - P_L)}{L\mu} + \frac{1}{r}\frac{dv_z}{dr}$$

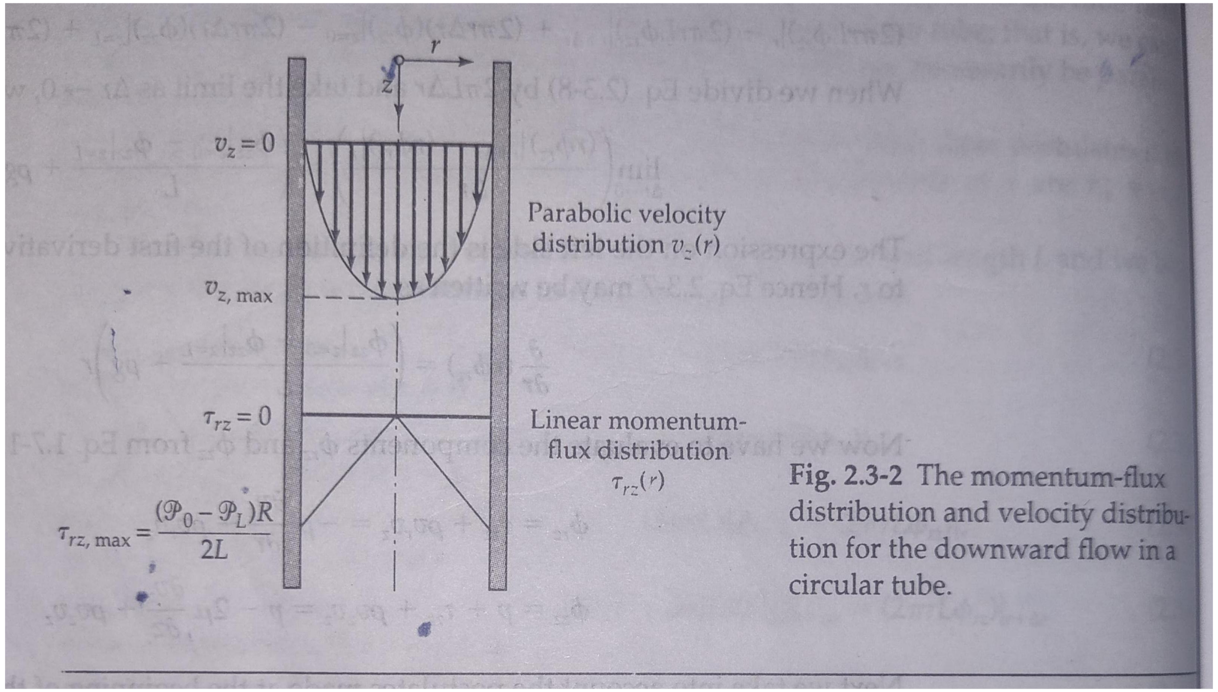


Fig. 2.3-2 The momentum-flux distribution and velocity distribution for the downward flow in a circular tube.

Ref:- Transport Phenomena(R.Byron Bird, Warren E. Stewart, Edwin N. Lightfoot)

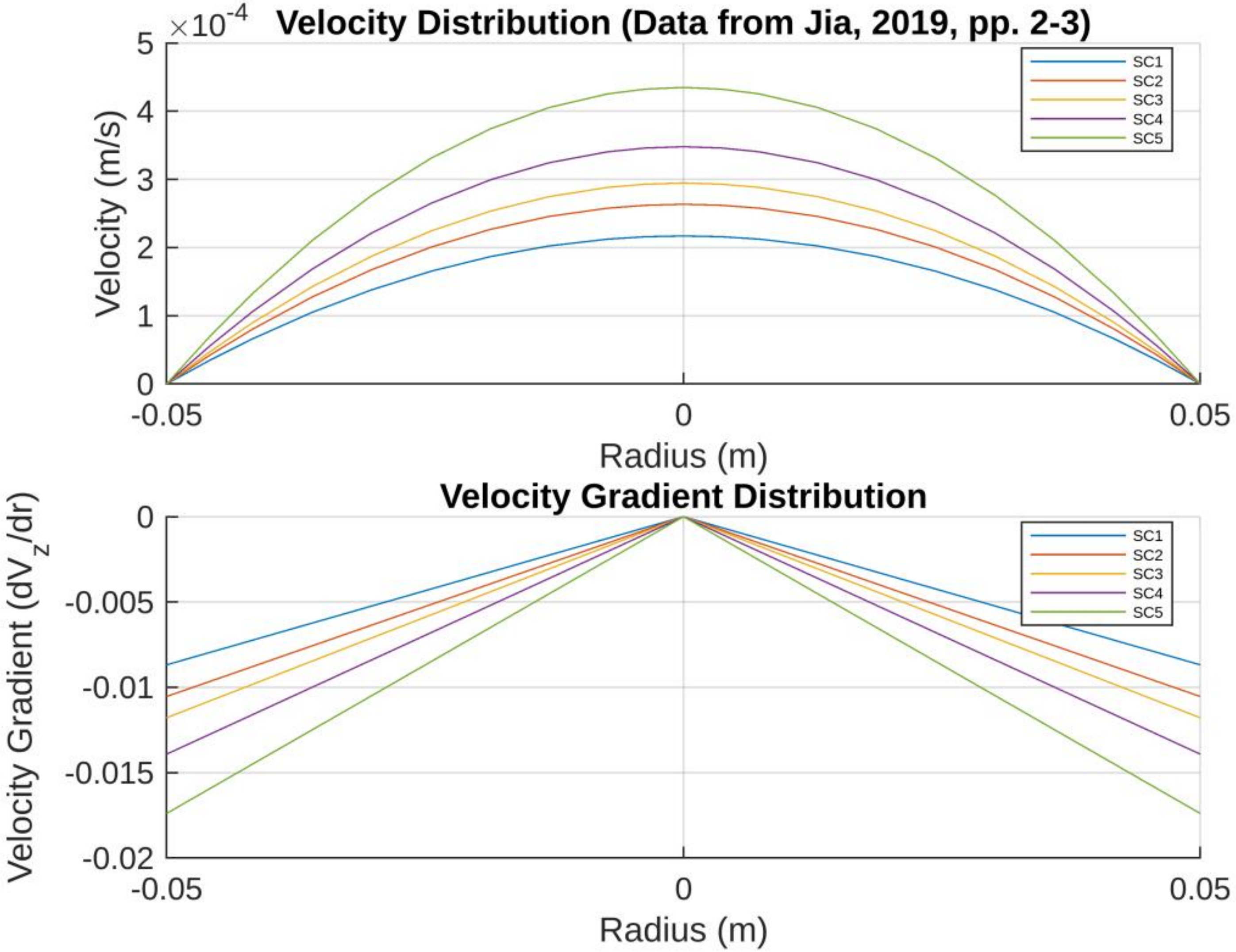
Boundary Conditions:

- $\frac{dv_z}{dr}$ =0 at r =0 (No shear at the tube center)
- Vz =0 at r =R (No-slip condition at the wall)

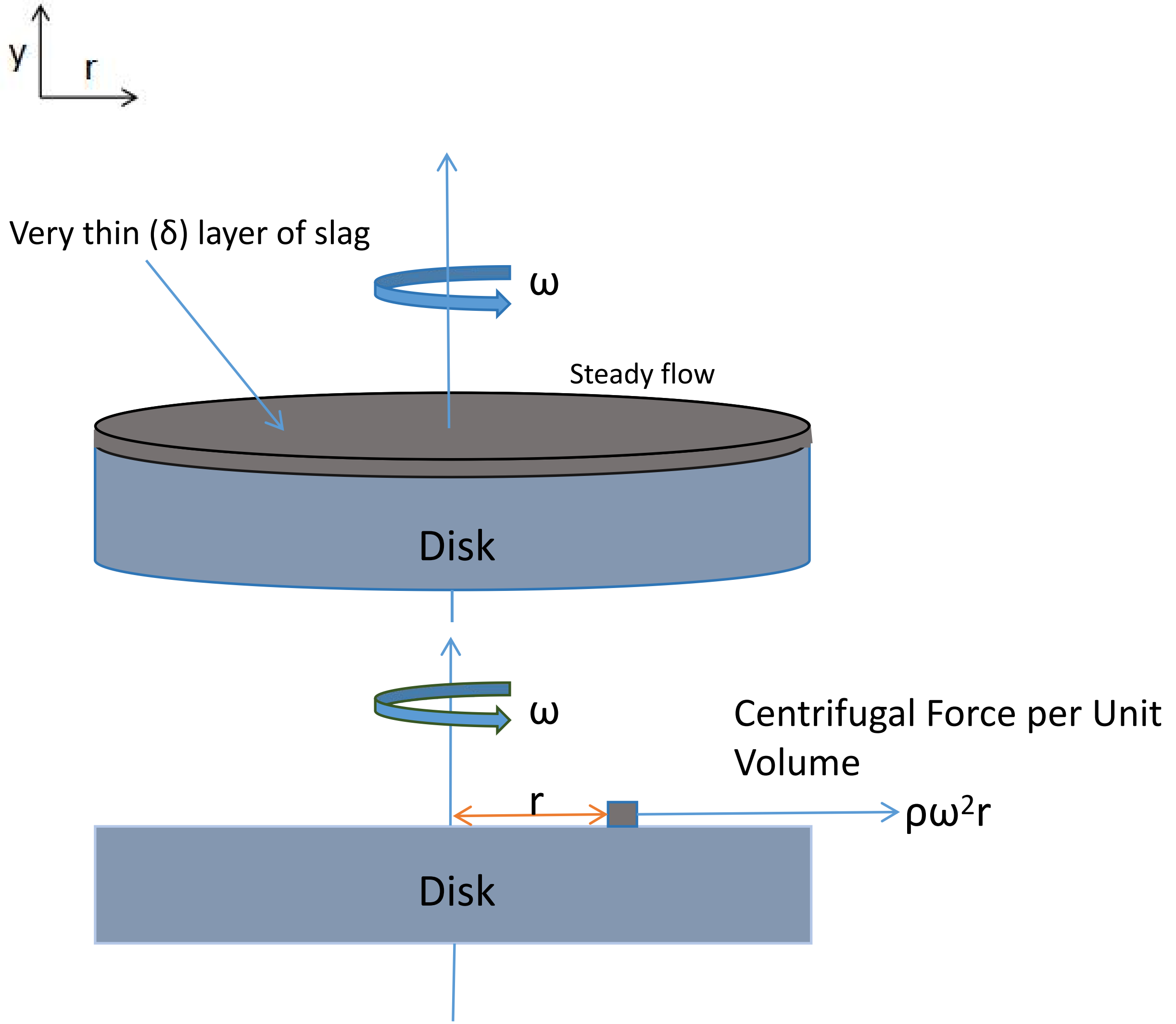
Used Parameters:

- Pressure at Start (P_0) = $1.0\,\mathrm{Pa}$
- Pressure at End (P_L) = $0.1\,\mathrm{Pa}$
- Tube Length (L) = $1.0\,\mathrm{m}$
- Density (ρ) = $800\,\mathrm{kg/m^3}$
- Gravitational Acceleration (g) = $9.8\,\mathrm{m/s^2}$
- Tube Radius (R) = $0.05\,\mathrm{m}$

Velocity Distribution due to Variation in Viscosity



3. Rotating Disk



Navier–Stokes equations:

Cauchy momentum equation *(convective form)*

$$\rho \frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t} = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \rho\,\mathbf{a}$$

$$\tau = -\mu \frac{du}{dy} \quad \text{(Newton's law of viscosity)}$$

$a = \omega^2 r$

Final Form of the Navier-Stokes Equation for a Rotating Disk :-

$$\frac{d^2 v_r}{dy^2} = -\frac{\rho \omega^2 r}{\mu}$$

Velocity Distribution due to Radial Variation

Second-order differential equation:

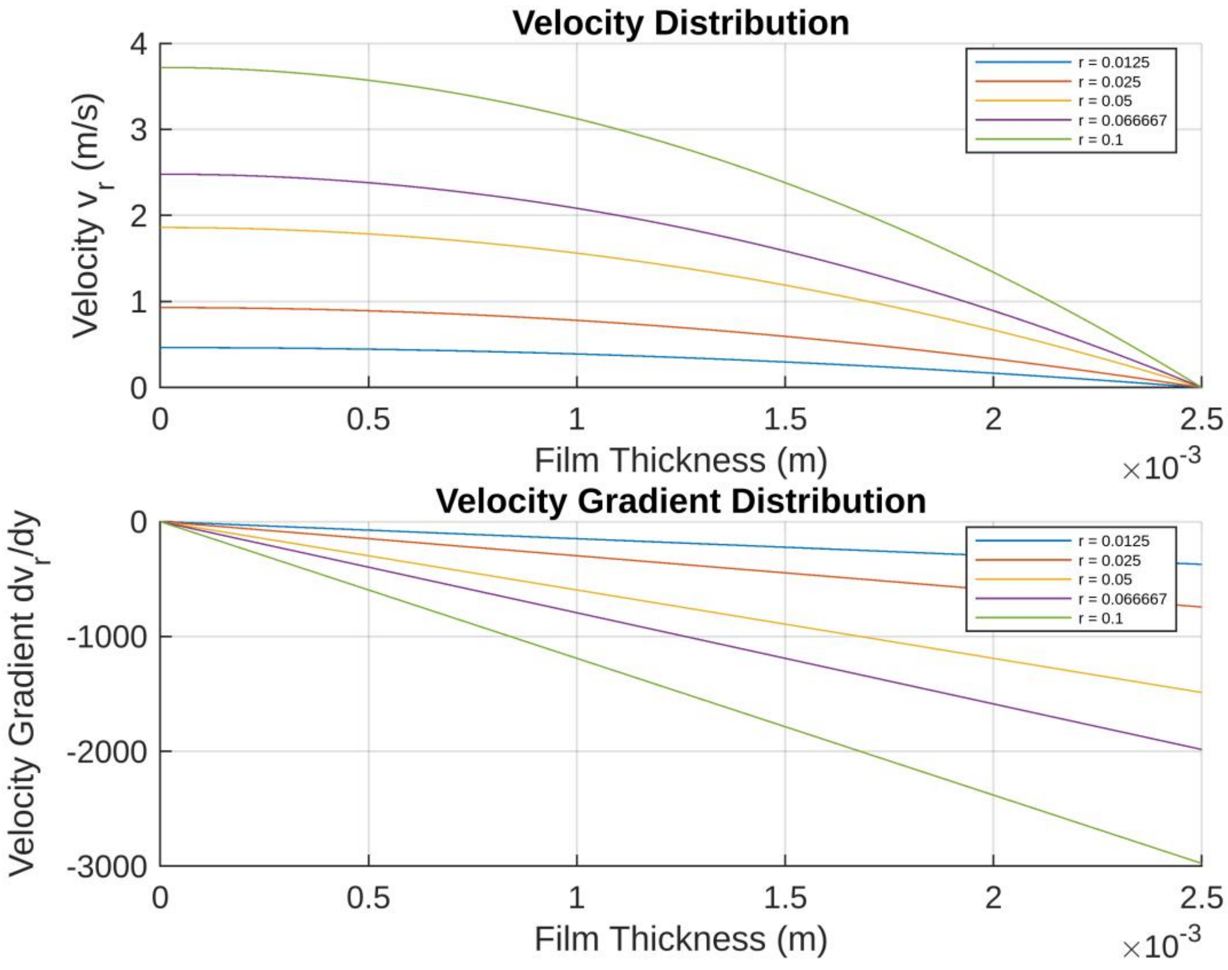
$$\frac{d^2 v_r}{dy^2} = \frac{\rho \omega^2 r}{\mu}$$

Boundary Conditions:

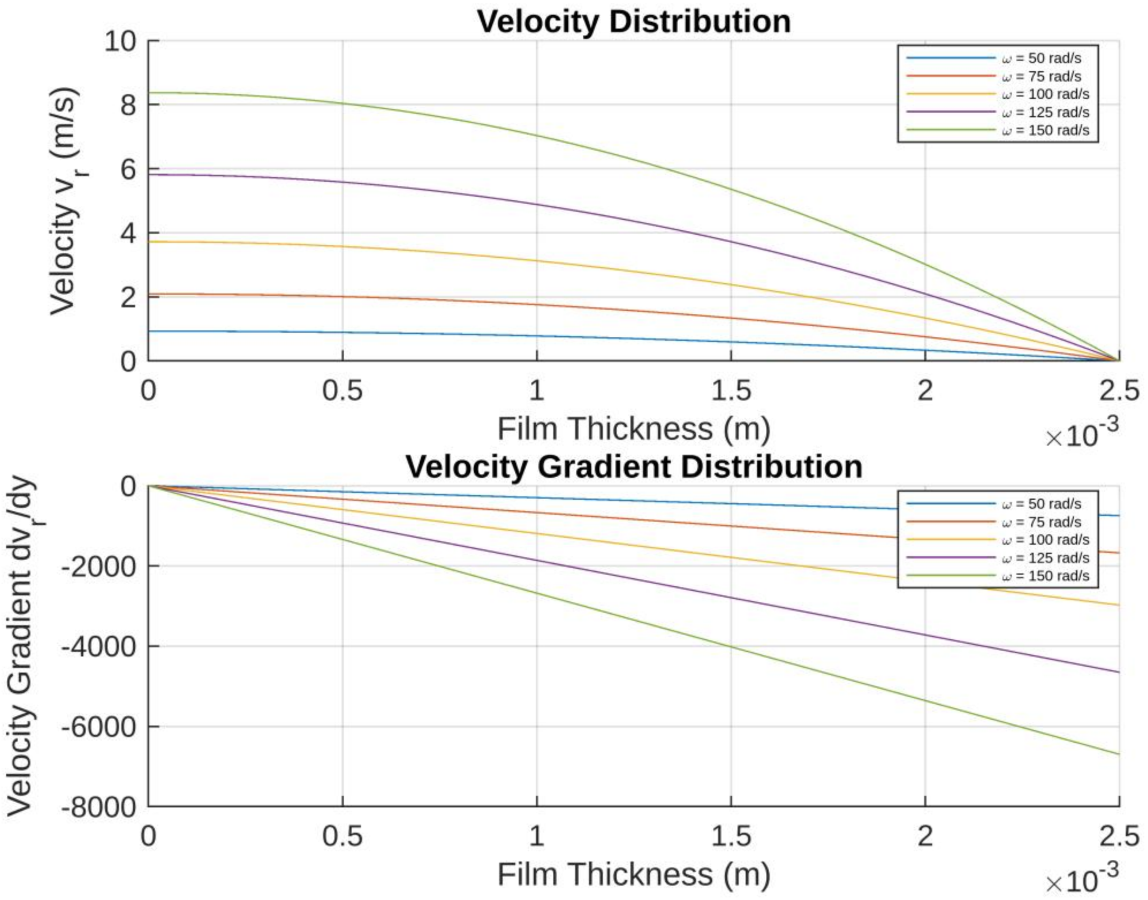
- $\frac{dv_r}{dy}$ =0 at y =0 (No shear at the fluid surface)
- v_r =0 at y =δ (No-slip condition at the disk surface)

Used Parameters:

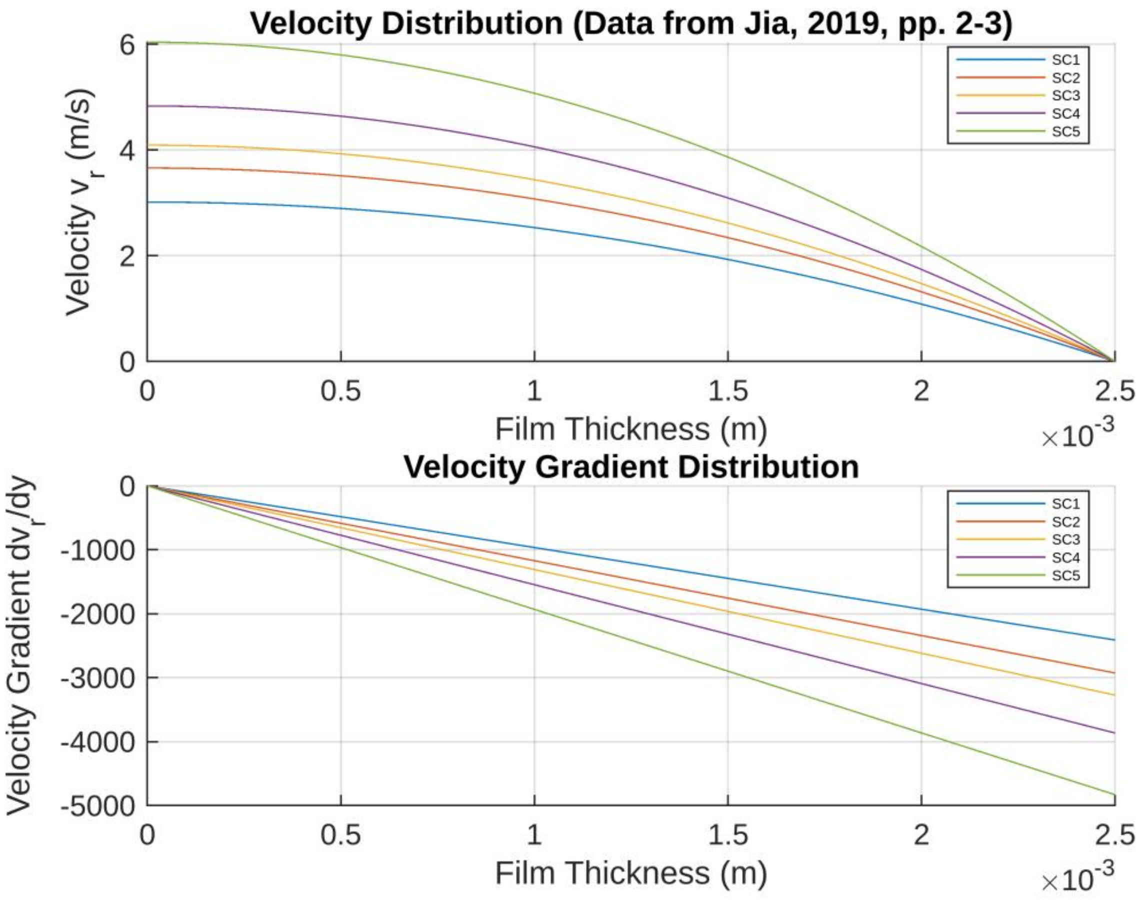
- Density $(\rho) = 2.5 \times 10^3\,\mathrm{kg/m^3}$
- Gravitational Acceleration $(g) = 9.8\,\mathrm{m/s^2}$
- Film Thickness $(\delta) = 2.5 \times 10^{-3}\,\mathrm{m}$
- Viscosity $(\mu) = 2.1\,\mathrm{Pa.s}$
- Rotational Speed $(\omega) = 100\,\mathrm{rad/s}$
- Disk Radius $(R) = 0.1\,\mathrm{m}$



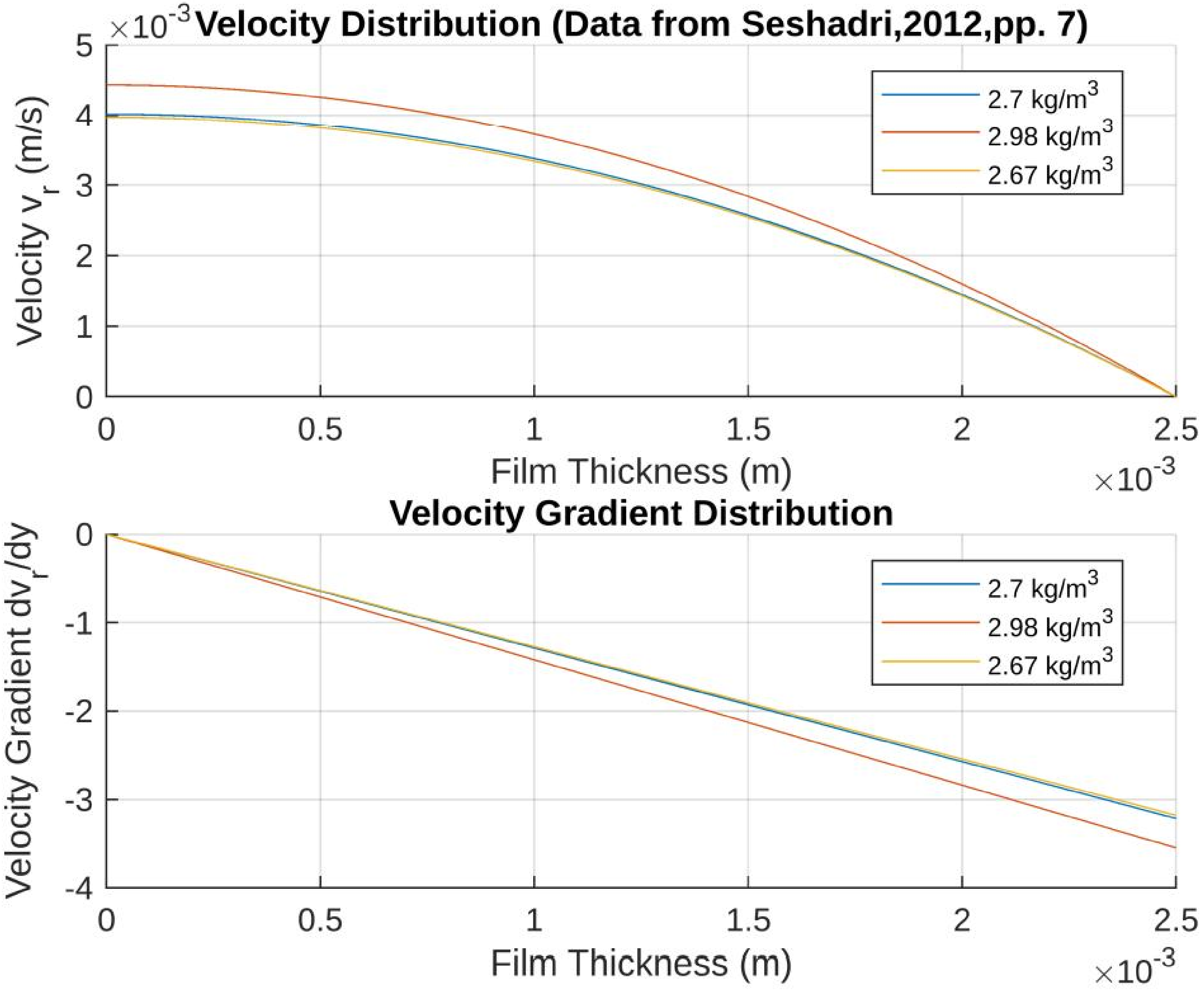
Velocity Distribution for Different Rotational Speeds (ω)



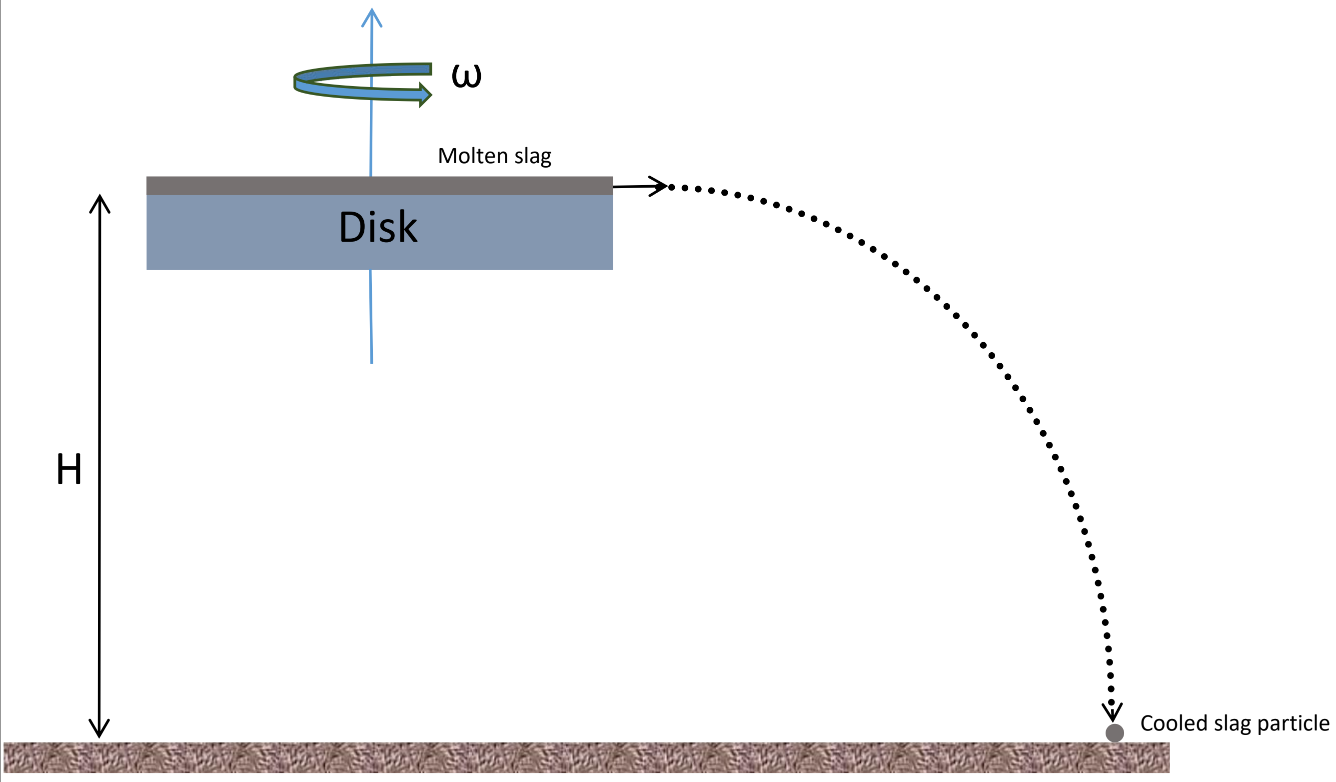
Velocity Distribution due to Variation in Viscosity



Velocity Distribution due to Variation in Density



Setup



vertical height of the disc from the ground

$$H = \frac{1}{2} g t_{\text{flight}}^2 \qquad t_{\text{flight}} \geq t_{\text{cool}}$$

$$H \geq \frac{1}{2} g t_{\text{cool}}^2$$

According to Newton's Law of Cooling-

$$\frac{dQ}{dt} = -aA(T_p - T_g) - \varepsilon \sigma_0 A(T_p^4 - T_g^4)$$

$$Q = \underbrace{m c_p \Delta T}_{\text{Sensible Heat}} + \underbrace{m \Delta H_f}_{\text{Latent Heat}}$$

$$\boxed{\frac{dT_p}{dt} = \frac{\Delta H_f}{c_p} \cdot \frac{df}{dt} - \frac{6\left[\alpha(T_p - T_g) + \sigma_0 \varepsilon (T_p^4 - T_g^4)\right]}{\rho c_p d_p}}$$

$$\frac{df}{dt} = 22.11\left[\exp\left(\frac{-2643.68}{T_p}\right) - \exp\left(\frac{-4165.83}{T_p}\right)\right]$$

Variable	Description	Unit
$\frac{dT_p}{dt}$	Rate of change of particle temperature	____K/s
ΔH_f	Latent heat of fusion	209.2×10^3 J/kg
c_p	Specific heat capacity of the particle	1.247×10^3 J/(kg·K)
df/dt	Solid fraction change rate	____1/s
α	Convective heat transfer coefficient	372 W/(m^2·K)
T_p	Temperature of the particle	1723 K
T_g	Temperature of the surrounding gas	293 K
σ_0	Stefan-Boltzmann constant	5.67×10^-8 W/(m^2·K^4)
ε	Emissivity of the particle surface	0.9
ρ	Density of the particle	2.5×10^3 kg/m^3
d_p	Particle diameter	____m

Ref:- Li, Jun Guo, Hong Wei Lu, and Yu Zhu Zhang. "Cooling Mechanism of the Steel Slag Droplet Granulated by Gas Quenching Method." Advanced Materials Research 233 (2011): 870-876.

Modified Kitamura equation for particle diameter in the ligament breakup regime: -

$$\boxed{d_p = 1.9 \times 1.6 \times R\left(\left(\frac{4\rho Q}{\pi\mu R}\right)^{0.26} \cdot \left(\frac{\rho\omega^2 R^3}{\sigma}\right)^{-0.42} \cdot \left(\frac{\mu}{\sqrt{\rho\sigma R}}\right)^{0.38}\right) + C}$$

$$Q = 2\pi R\delta \cdot \frac{2}{3} V_{z,\max}$$

C=61 μm

Variable	Description	Values
d_p	Particle diameter	____m
R	Radius of disk	0.1 m
Q	Volumetric flow rate	____m^3/s
ρ	Density of fluid	2.5 * 10^3 kg/m^3
μ	Dynamic viscosity	2.1 Pa·s
δ	Film thickness	2.5 * 10^-3 m
$V_{z,\max}$	Maximum velocity	3.72024 m/s
ω	Angular velocity	100 rad/s
σ	Surface tension	0.45 N/m

Ref:- Prather, Cody A., et al. "Experimental and theoretical investigation of rotary atomization dynamics for control of microparticle size during spray congealing process." Powder Technology 418 (2023): 118278.

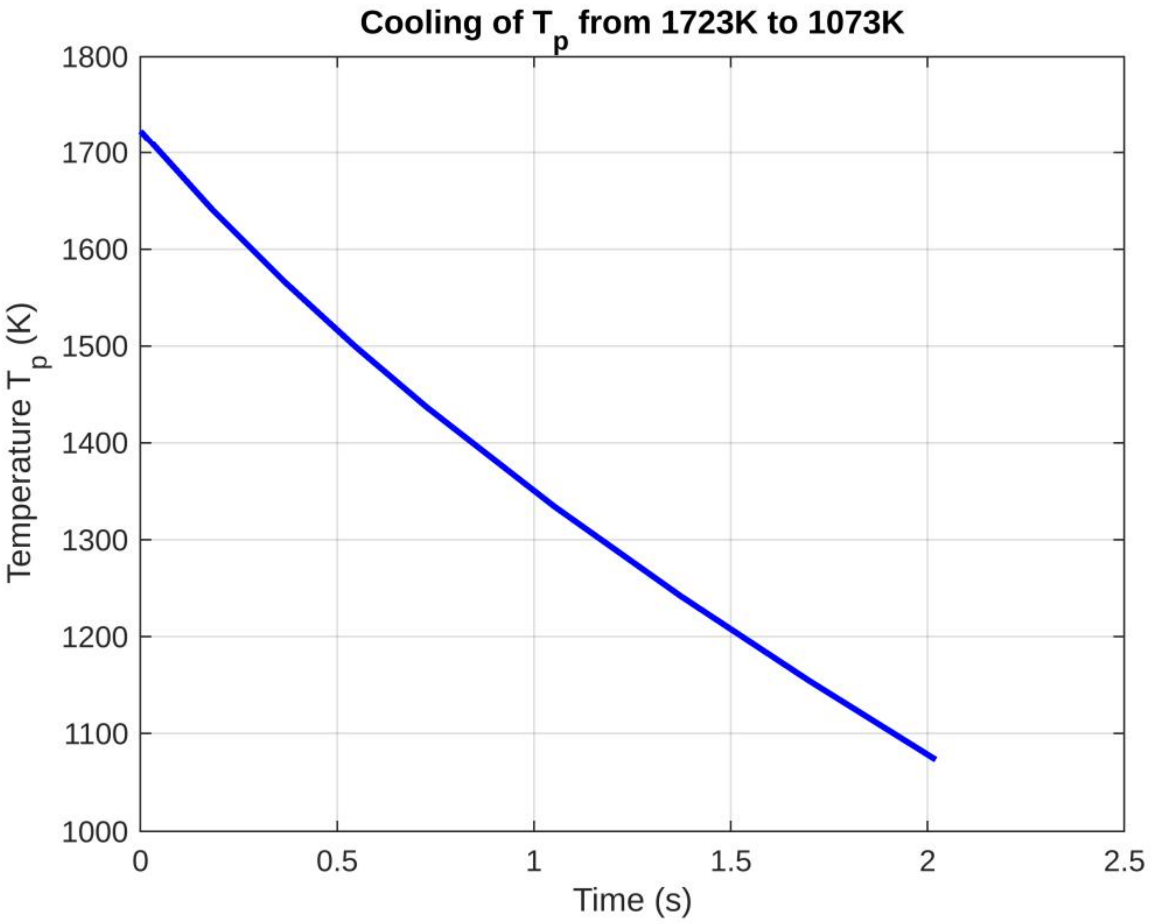
particle diameter d_p = 4.884 mm

First-Order Droplet Solidification ODE :-

$$\frac{dT_p}{dt} = 3709.2\left[\exp\left(\frac{-2643.68}{T_p}\right) - \exp\left(\frac{-4165.83}{T_p}\right)\right] + 43.1 - 0.47T_p - 2.01\times 10^{-11}T_p^4$$

T_{cool} = 2.021 s

Therefore, the minimum required height of the disc from the ground is: H_{min} = 20.01 m




Work Plan

	BTP – I (Till Mid-Sem)	BTP – I (Till End-Sem)	BTP – II (Till Mid-Sem)	BTP – II (Till End-Sem)
Problem Identification				
Literature				
Model Framework				
Model Enhancement				
Variation Geometry				
Variation µ				
Variation ρ				
Simulation Debugging				
Documentation and Report				

Completed	Not Started

Thank You

References:

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