Effects of Clogging, Argon Injection and Casting Conditions on Flow Rate and Air Aspiration in Submerged Entry Nozzles

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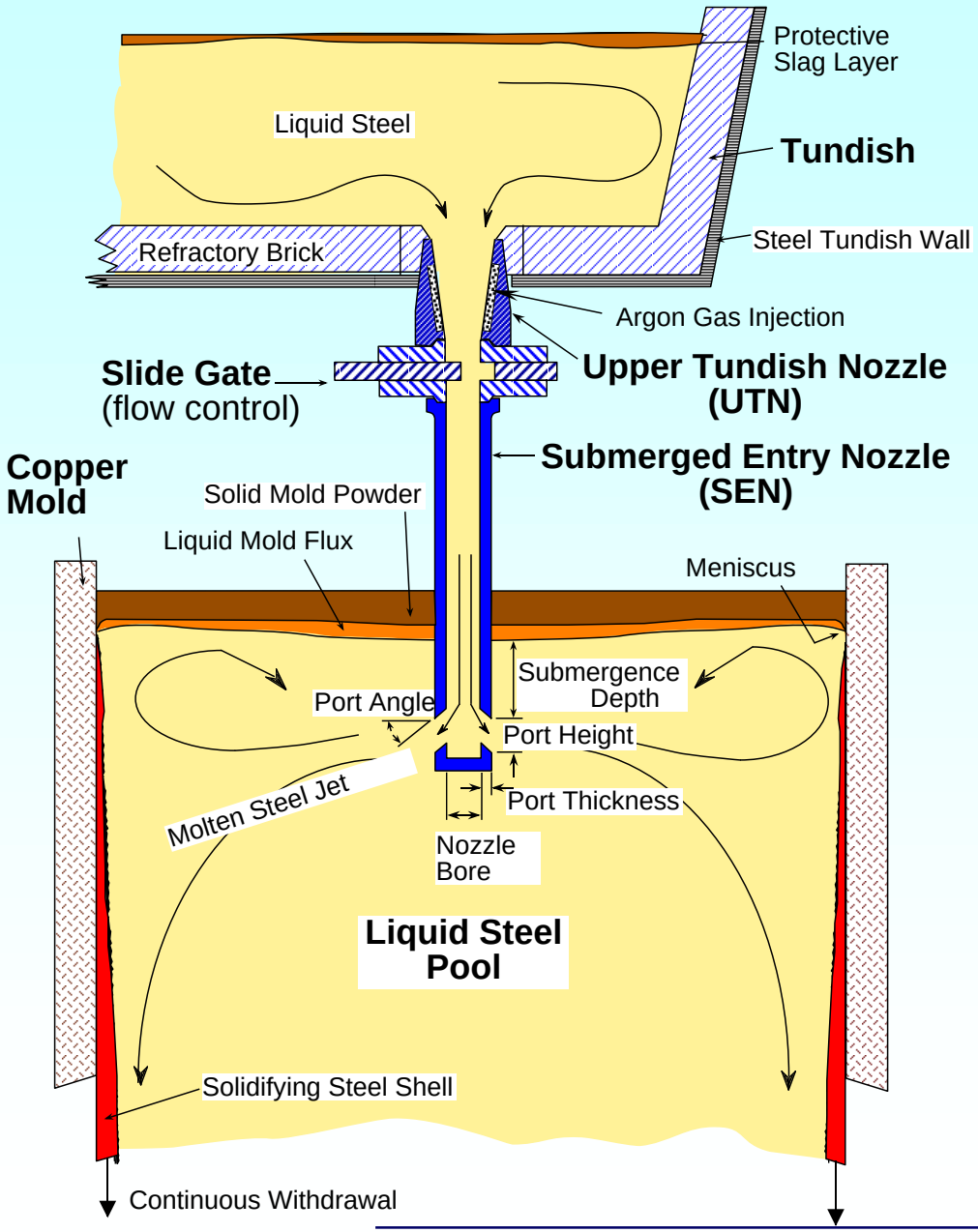
Outline

- Introduction
- Modeling multiphase flow of liquid steel-argon bubbles in slide-gate nozzles
- Development of the model describing interrelated effects of casting conditions, clogging and argon injection
- Effects of clogging (initial and severe)
- Effects on air aspiration (minimum pressure)
- Conclusion

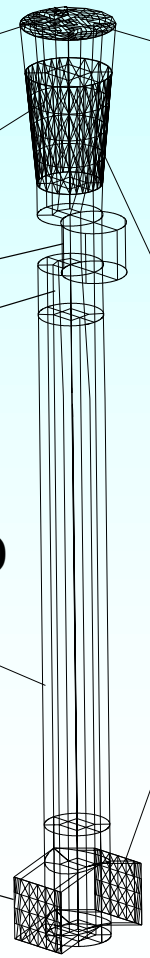
Introduction

- Argon injection into the nozzle is an efficient and widely employed method to reduce nozzle clogging
- Both clogging and argon injection greatly affect flow pattern in nozzle and mold
- Tundish nozzle geometry is one of the few variables that is both very influential on the continuous casting process and relatively inexpensive to change
- Casting operation variables are interrelated

Schematic of Continuous Casting Tundish, Nozzle, and Mold



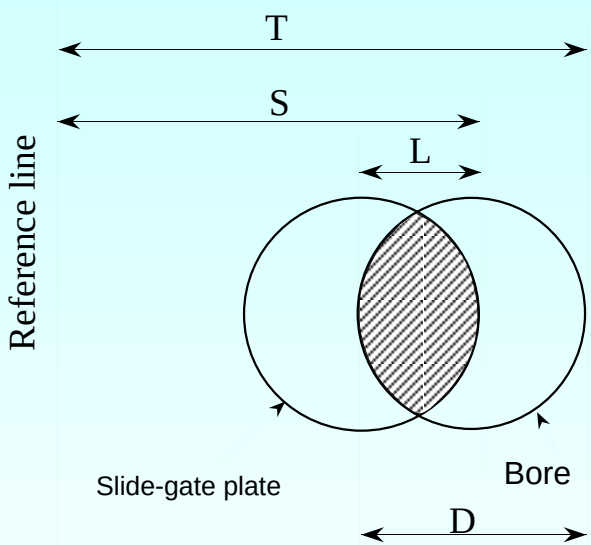
Computational Domain and Boundary Conditions

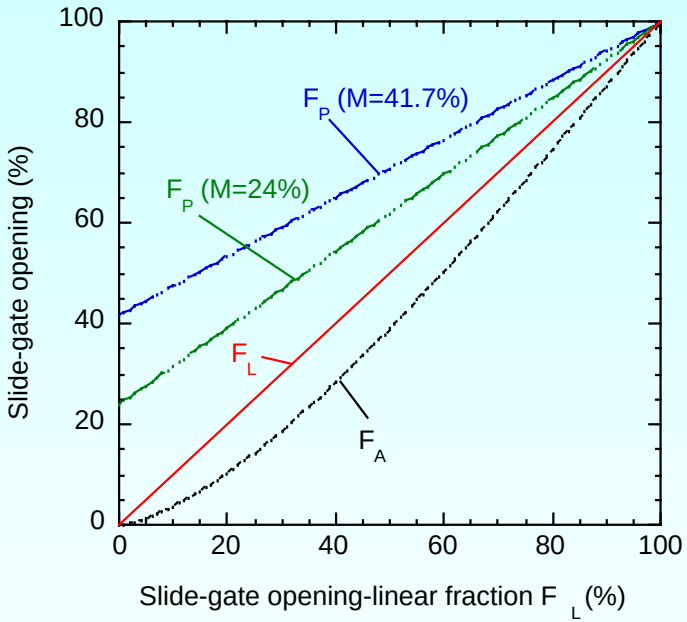


Simulation Conditions

Variable	*Value*	*Notes*
Casting Speed V_C (m/min)	0.2, 0.5, 1, 1.5, 2.0, 2.3	For 8”x52” slab
Gate Opening F_L (%)	40, 50, 60, 70, 100	Linear opening
Argon Flow Rate Q_G (SPLM)	0, 5, 10	“cold” argon
Nozzle Bore Diameter D_B (mm)	60, 70, 78, 90	Also simulates clogging

Definitions of Slide-Gate Opening and Their Conversions





$$F_L = \frac{L}{D} \qquad F_P = \frac{S}{T}$$

$$F_P = (1 - M)F_L + M \qquad M = \frac{T - D}{T}$$

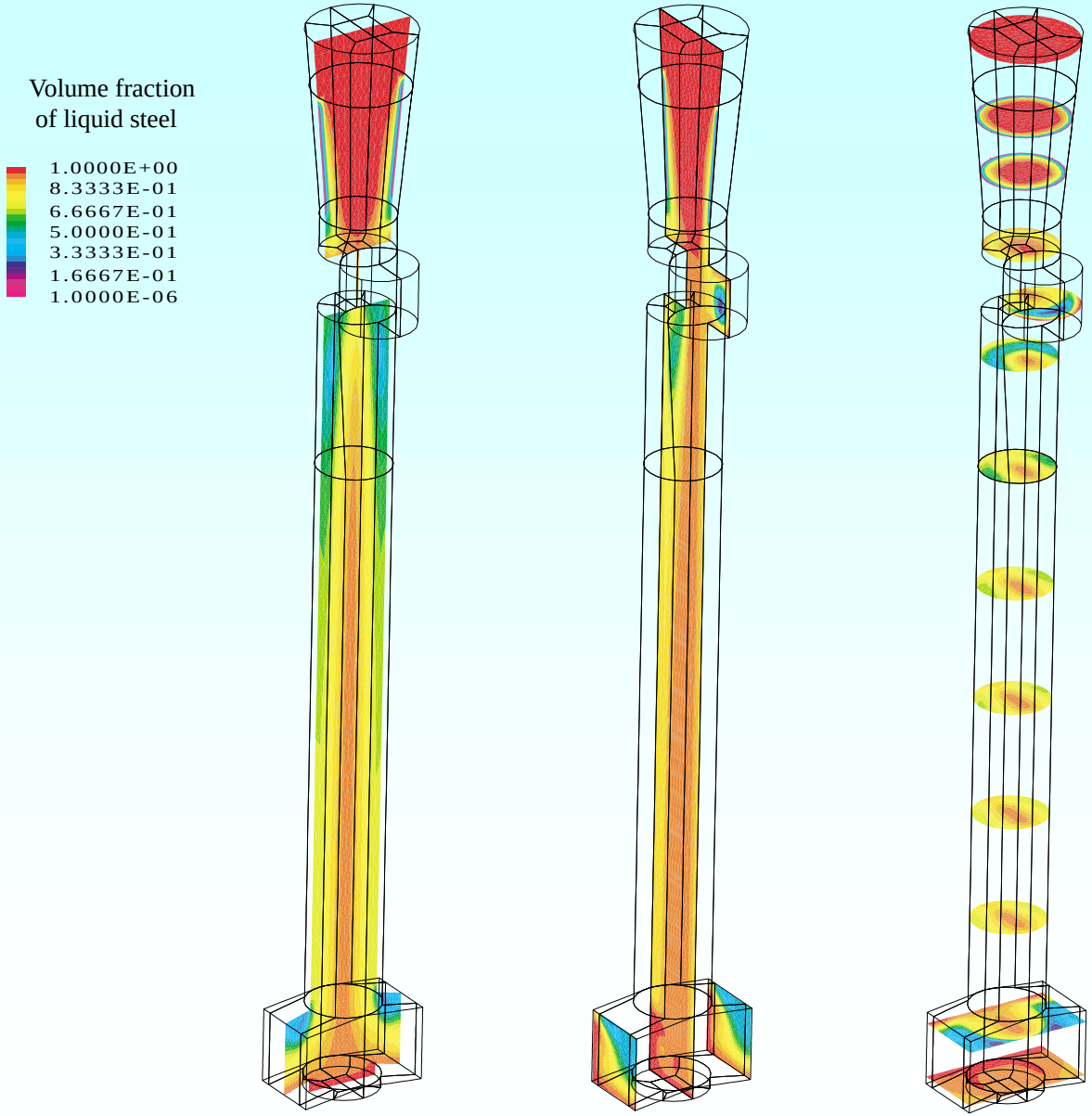
$$F_A = \frac{Shadow\ Area}{Bore\ Area}$$

$$F_A = \frac{2}{\pi}\cos^{-1}(1 - F_L) - \frac{2}{\pi}(1 - F_L)\sqrt{1 - (1 - F_L)^2}$$

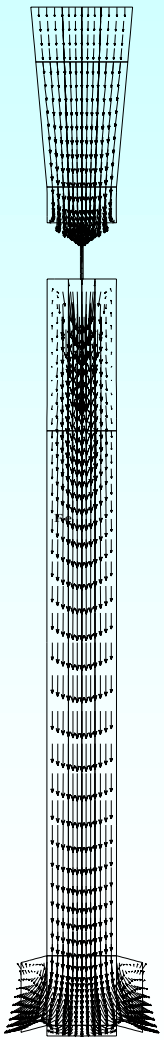
Liquid Steel-Argon Bubble Multiphase Flow Model

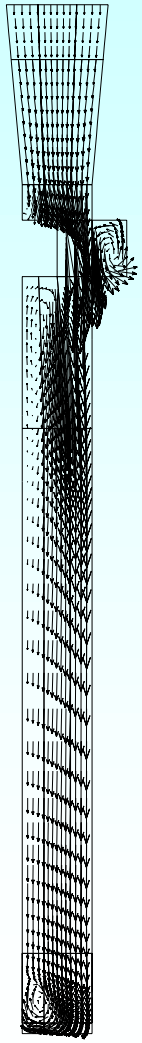
- "Multi-fluid" Eulerian multiphase model
  - one solution field for each phase
- Coupling achieved through inter-phase drag between liquid and gas bubbles.
- K-ε model for turbulence
- Validated with velocity measurements using PIV on a 0.4 scale water model and reported on
  - H. Bai and B.G. Thomas, "Two Phase Flow in Tundish Nozzles During Continuous Casting of Steel" (Paper presented at Materials Processing in the Computer Age III, TMS Annual Meeting, Nashville, TN, 2000).

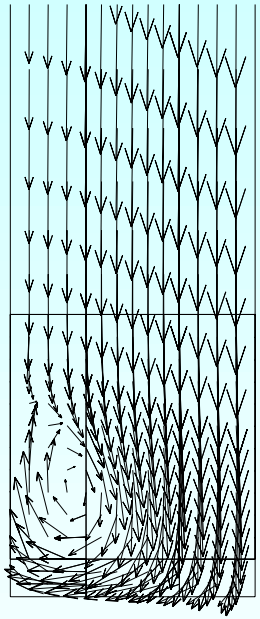
Argon Distribution in Nozzle

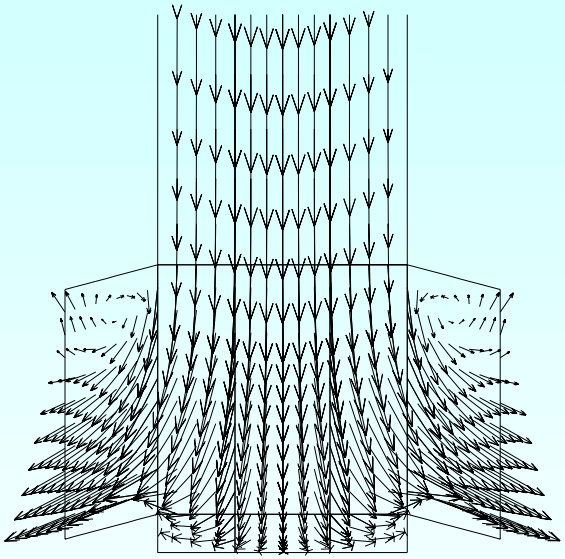


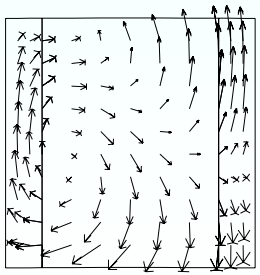
Flow Pattern in Nozzle

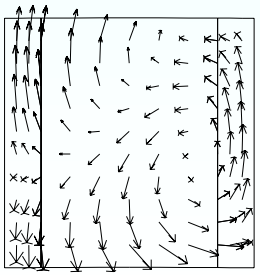




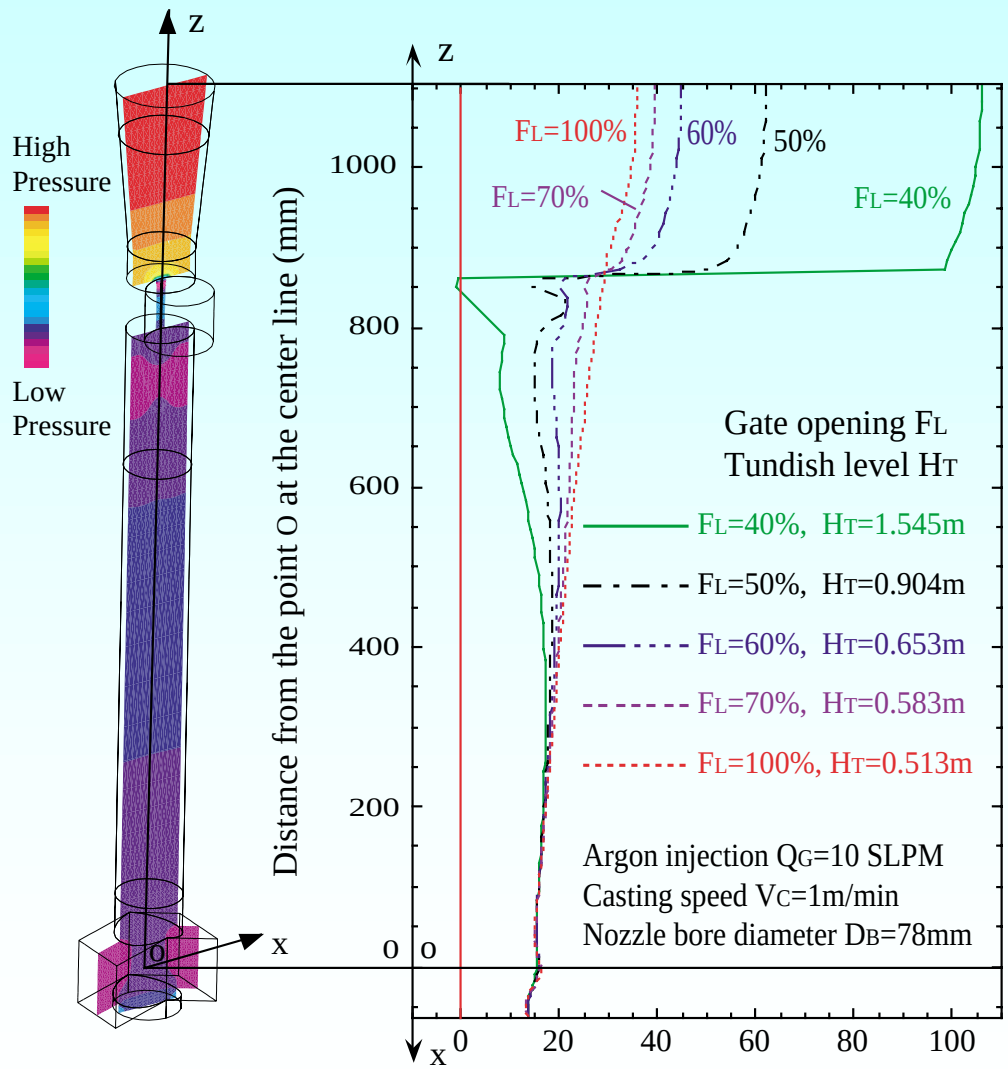




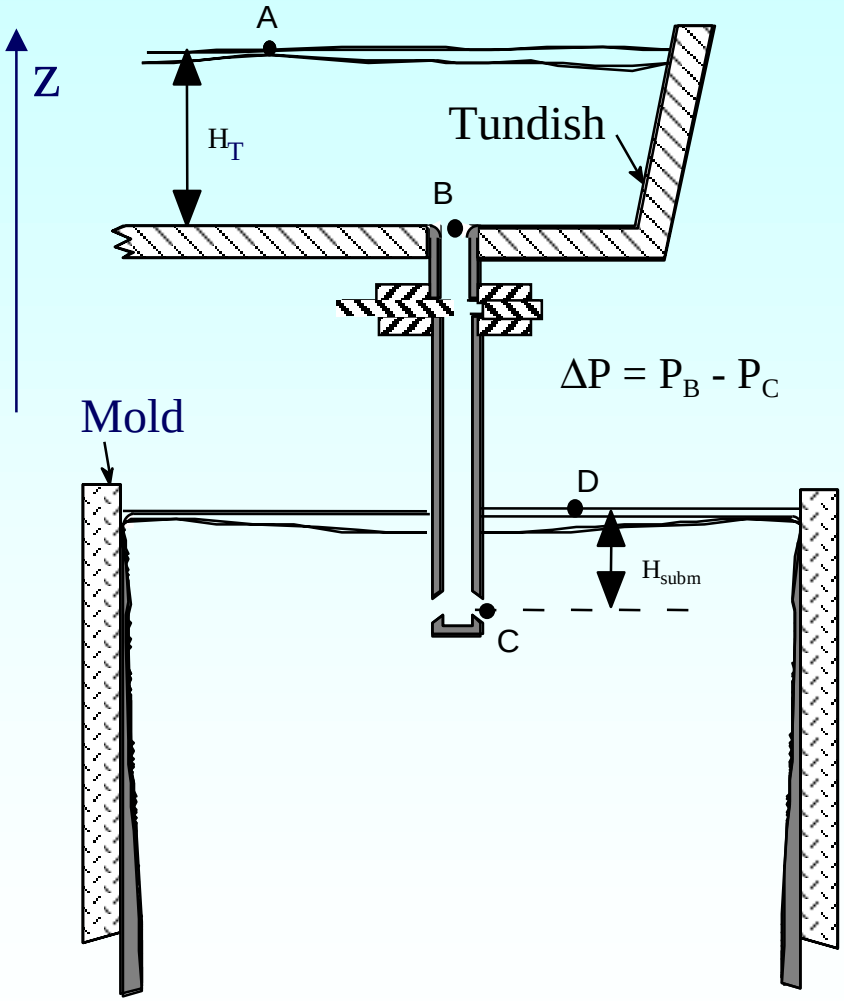




Pressure Distribution in Nozzle



Bernoulli's Equation



(1) Apply Bernoulli's Equation on A and B:

$$P_A + \tfrac{1}{2}\rho U_A^2 + \rho g Z_A = P_B + \tfrac{1}{2}\rho U_B^2 + \rho g Z_B$$

Or

$$0 + 0 + \rho g H_T = P_B + \tfrac{1}{2}\rho U_B^2 + 0$$

$$H_T = \frac{P_B + \tfrac{1}{2}\rho U_B^2}{\rho g}$$

(2) Nozzle pressure drop $\Delta P = P_B - P_C$

(3) Apply Bernoulli's Equation on C and D:

$$P_C + \tfrac{1}{2}\rho U_C^2 + \rho g Z_C = P_D + \tfrac{1}{2}\rho U_D^2 + \rho g Z_D$$

Or

$$P_C + \tfrac{1}{2}\rho U_C^2 + 0 = 0 + 0 + \rho g H_{subm}$$

$$P_C = \rho g H_{subm} - \tfrac{1}{2}\rho U_C^2$$

Combining (1),(2) and (3) gives Tundish Bath Depth

$$H_T = \frac{\Delta P + \rho g H_{subm} + \tfrac{1}{2}\rho (U_B^2 - U_C^2)}{\rho g}$$

Multivariable Curve Fitting for Tundish Bath Depth

H_T
Tundish bath depth

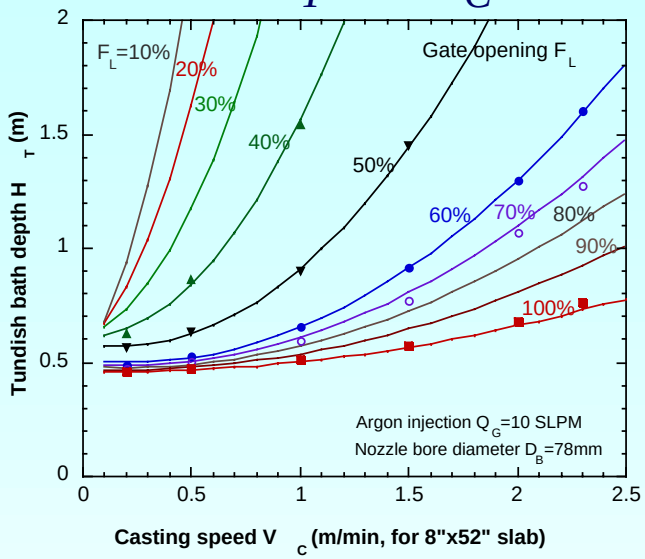
V_C
Casting speed

F_L
Gate opening

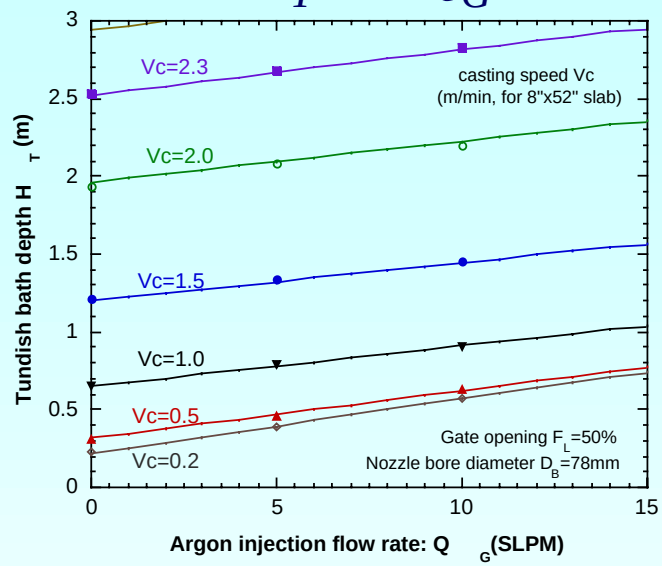
Q_G
Argon flow rate

D_B
Nozzle bore dia.

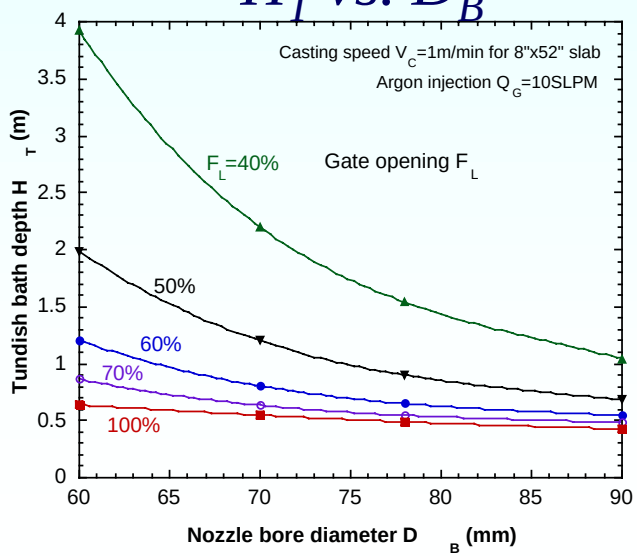
H_T vs. V_C



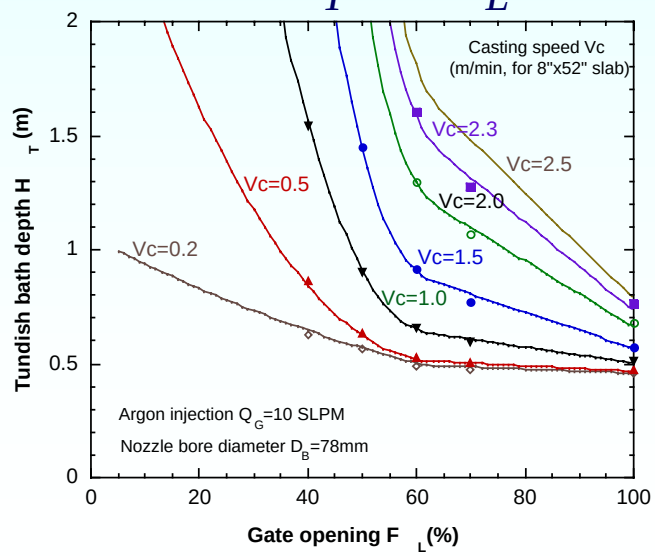
H_T vs. Q_G



H_T vs. D_B



H_T vs. F_L



Multivariable Curve Fitting Model for Tundish Bath Depth

$$H_T = \left(a_1 V_C^2 + a_2 V_C + a_3\right)\left(a_4 F_L^2 + a_5 F_L + a_6\right)$$
$$\left(a_7 Q_G + a_8\right)\left(a_9 D_B^3 + a_{10} D_B^2 + a_{11} D_B + a_{12}\right)$$

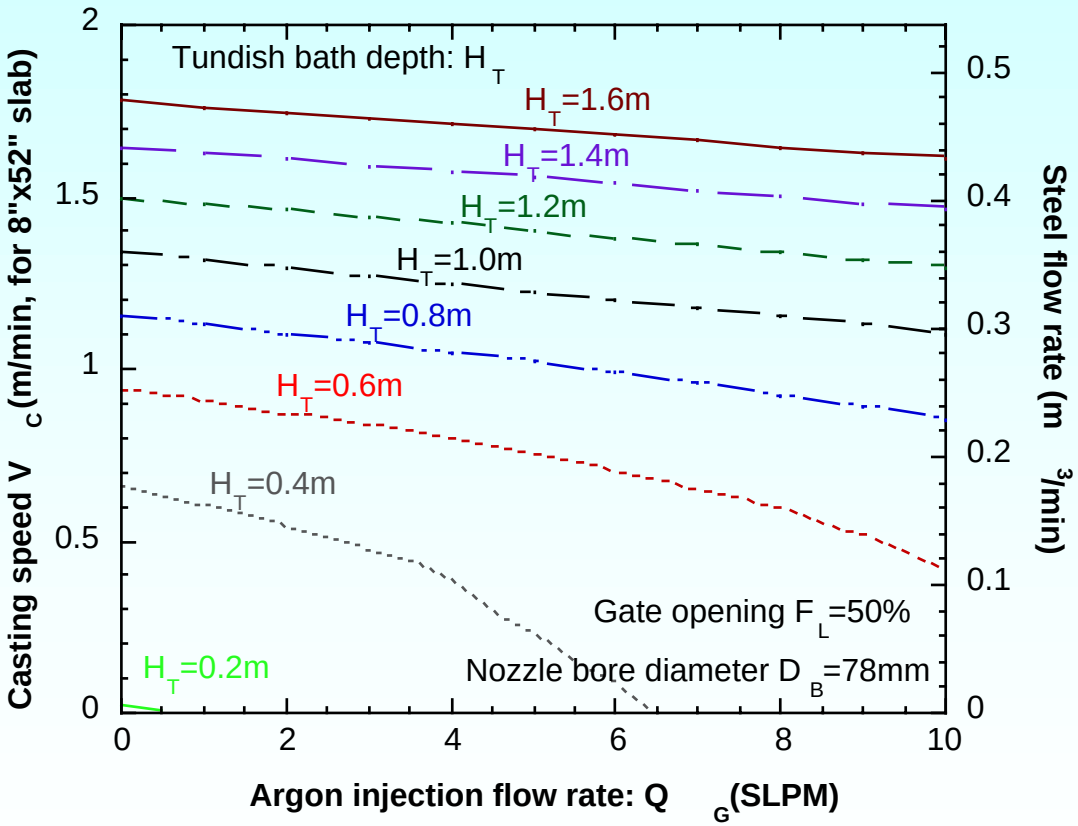
@ $F_L \leq 60\%$

$$H_T = \left(a_{13} V_C^2 + a_{14} V_C + a_{15}\right)\left(a_{16} F_L + a_{17}\right)$$
$$\left(a_{18} Q_G + a_{19}\right)\left(a_{20} D_B^3 + a_{21} D_B^2 + a_{22} D_B + a_{23}\right)$$

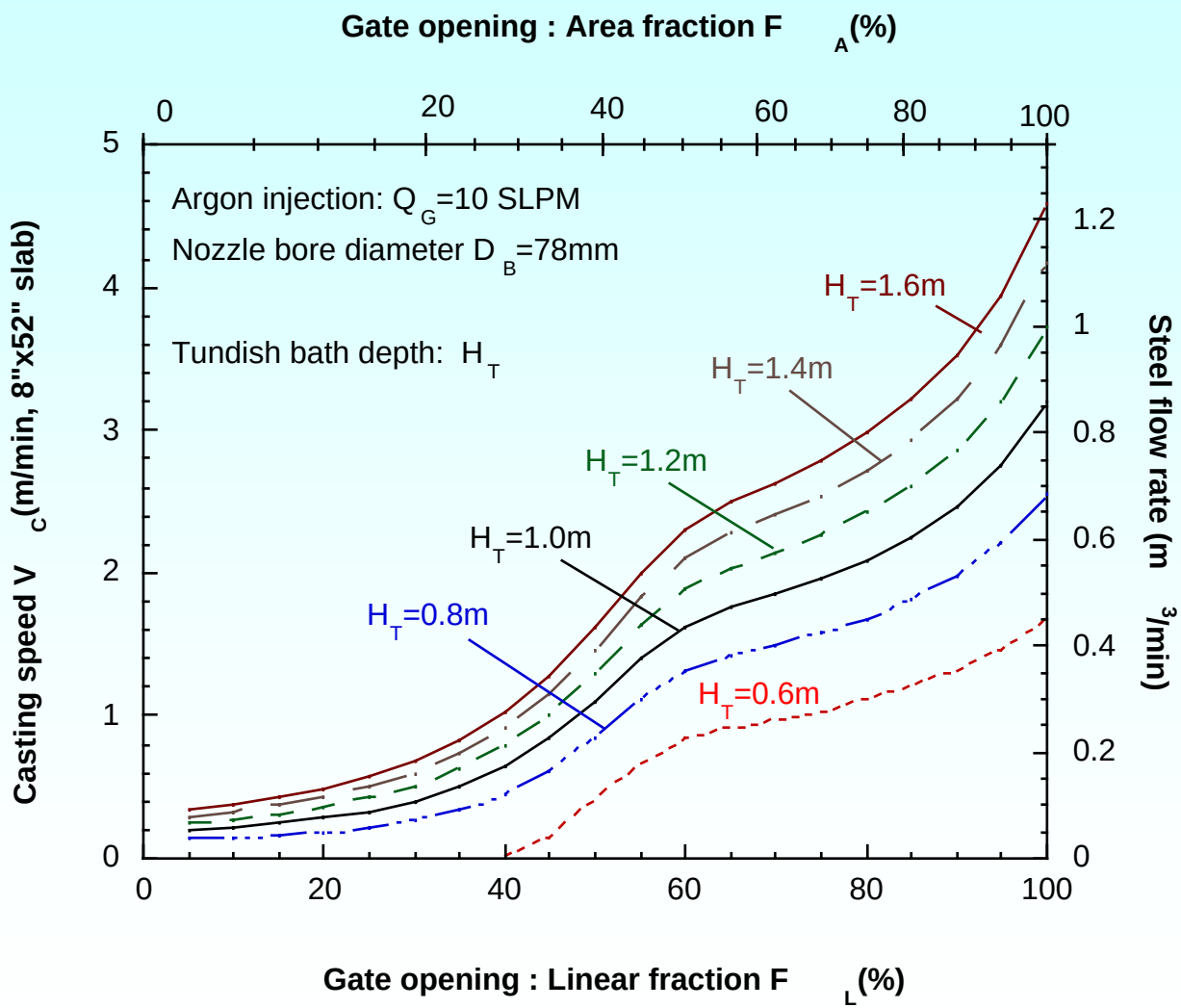
@ $F_L \geq 60\%$

H_T -- Tundish bath depth,
V_C -- Casting speed, F_L -- Gate opening ,
Q_G -- Argon flow rate, D_B -- Nozzle bore diameter

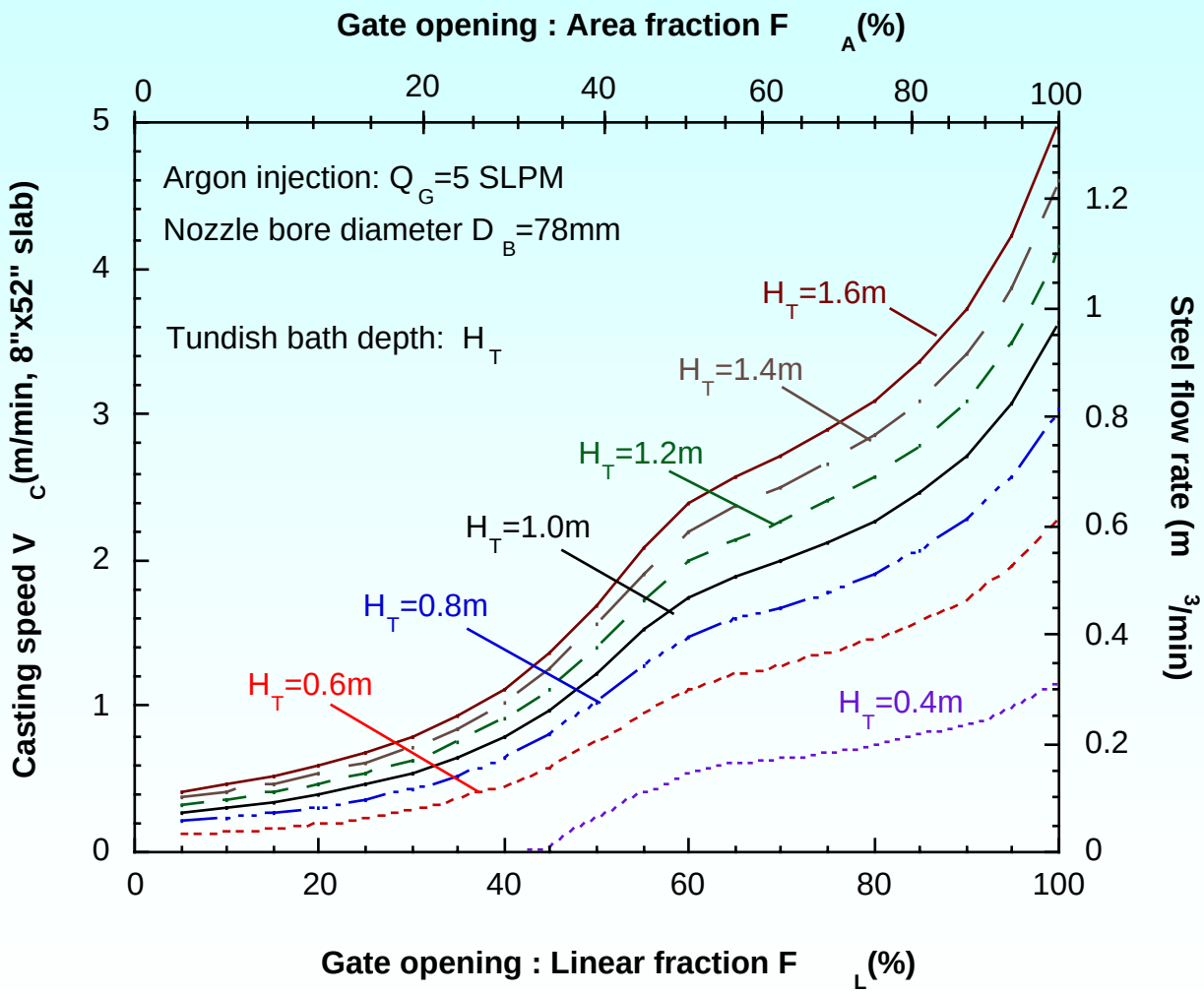
Effect of Argon Injection on Casting Speed



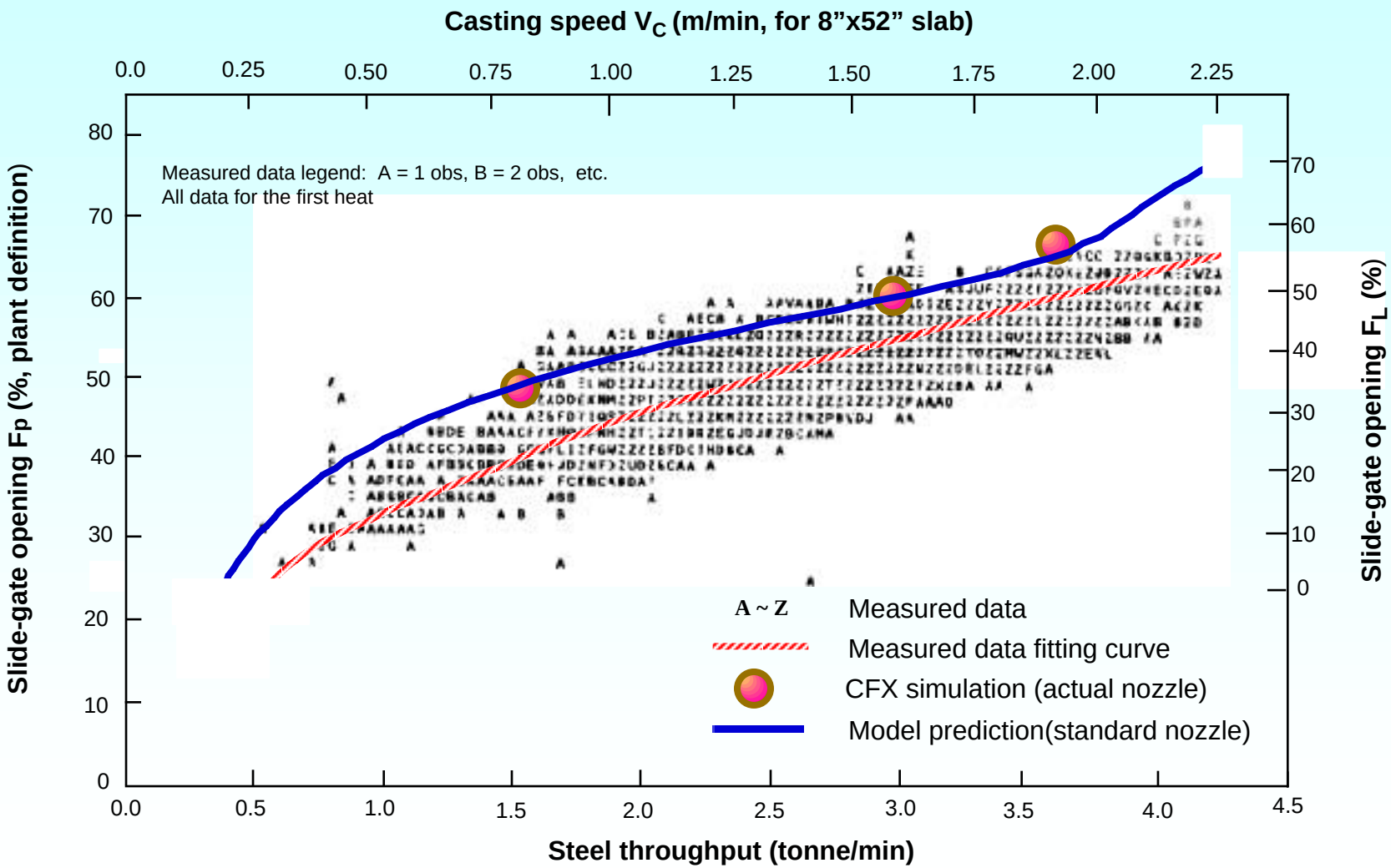
Casting Speed, Gate Opening and Tundish Bath Depth Relation



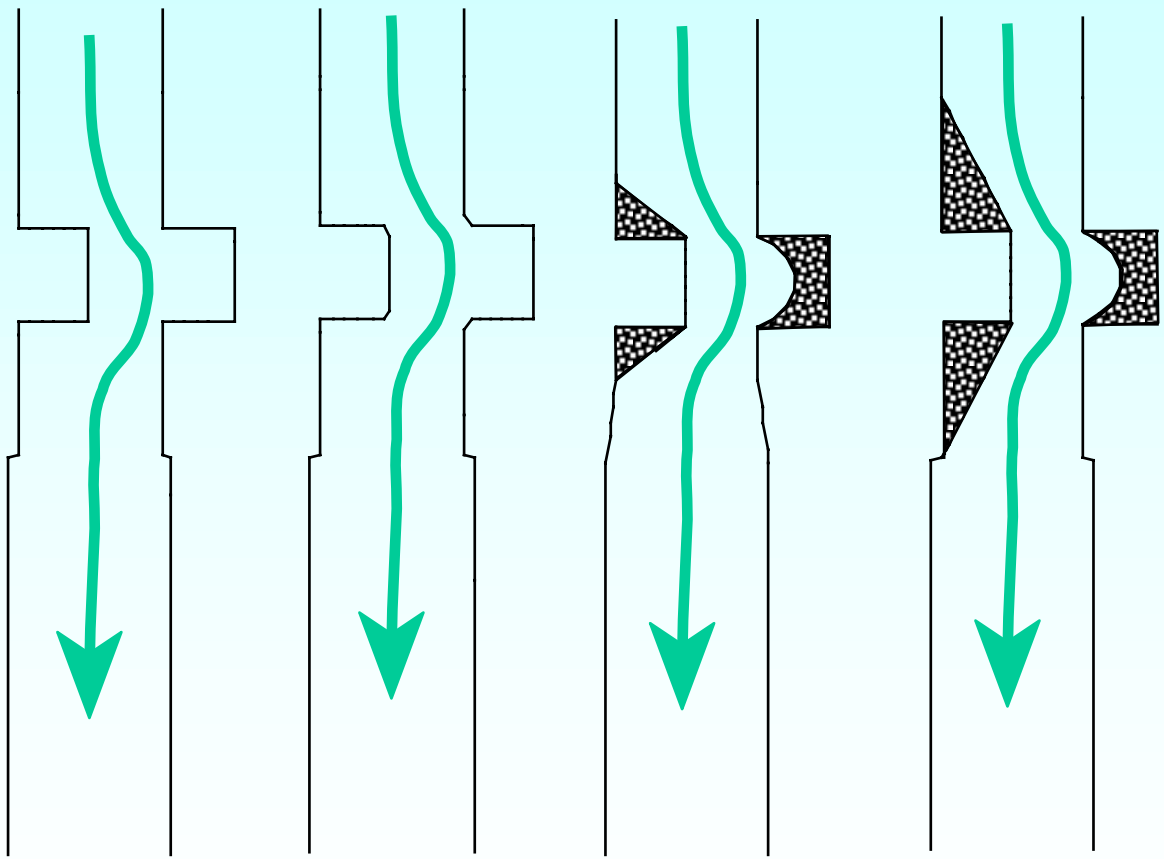
Casting Speed, Gate Opening and Tundish Bath Depth Relation



Comparison of Model Predictions with Plant Measurements

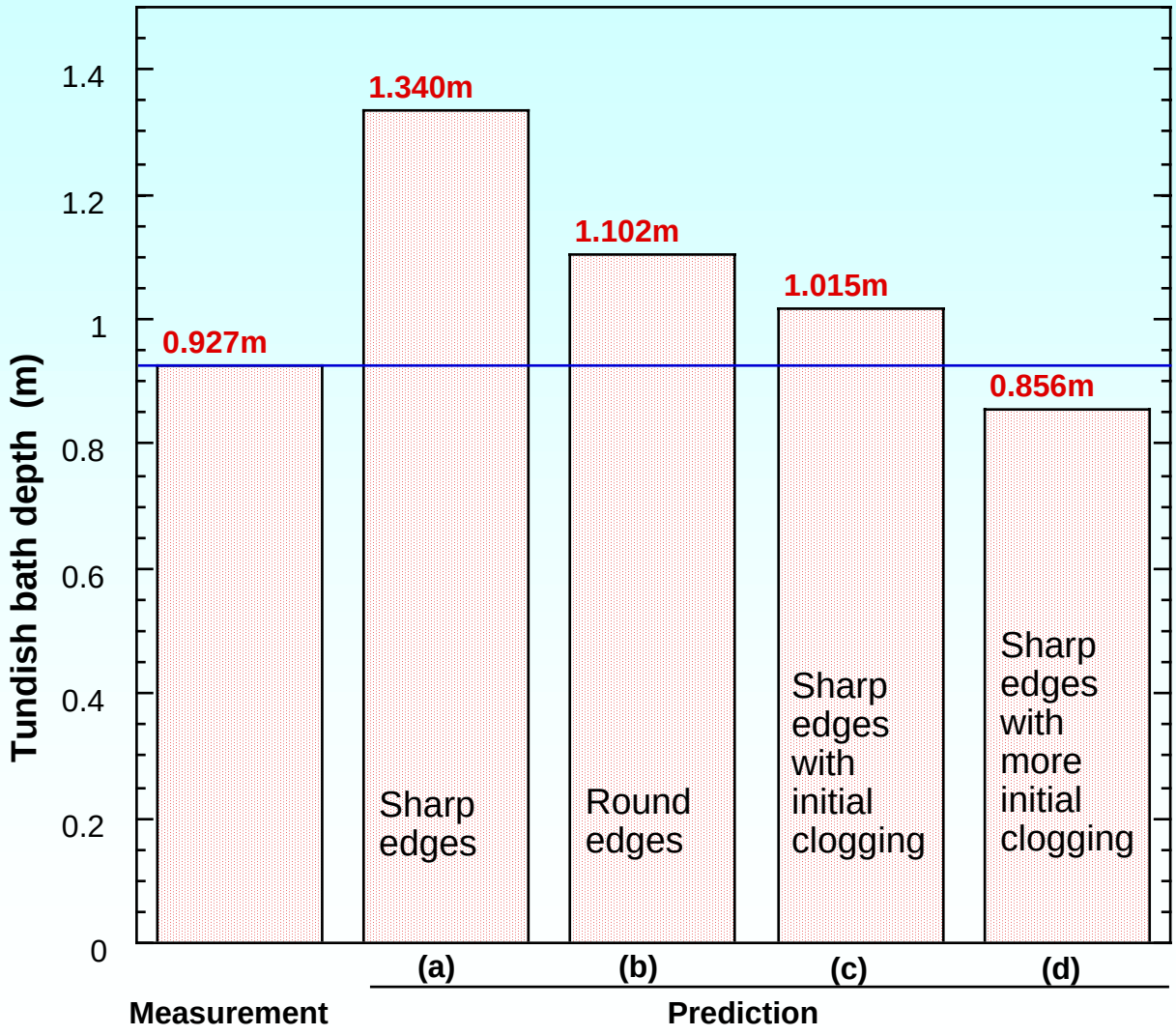


Schematic of Initial Clogging and Rounded Edges in Vicinity of the Slide-Gate

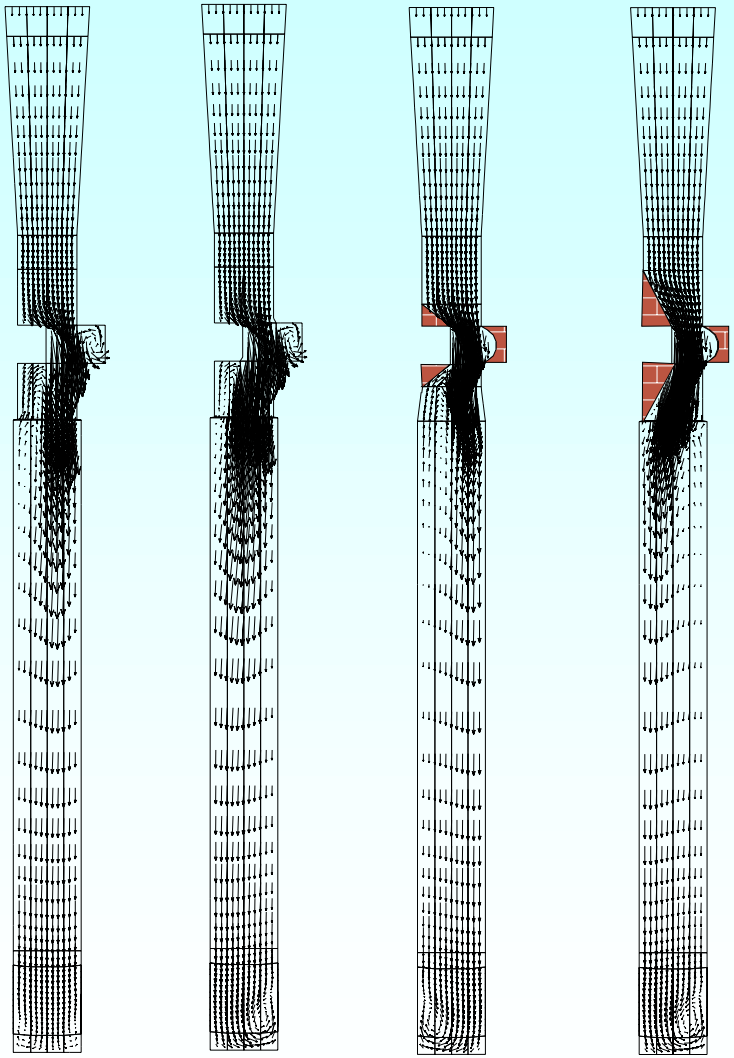


(a) Sharp edges (b) Rounded edges (c) Sharp edges with initial clogging (d)Sharp edges with more inital clogging

Effects of Initial Clogging and Rounded Edges



Effects of Initial Clogging and Rounded Edges on Flow Pattern



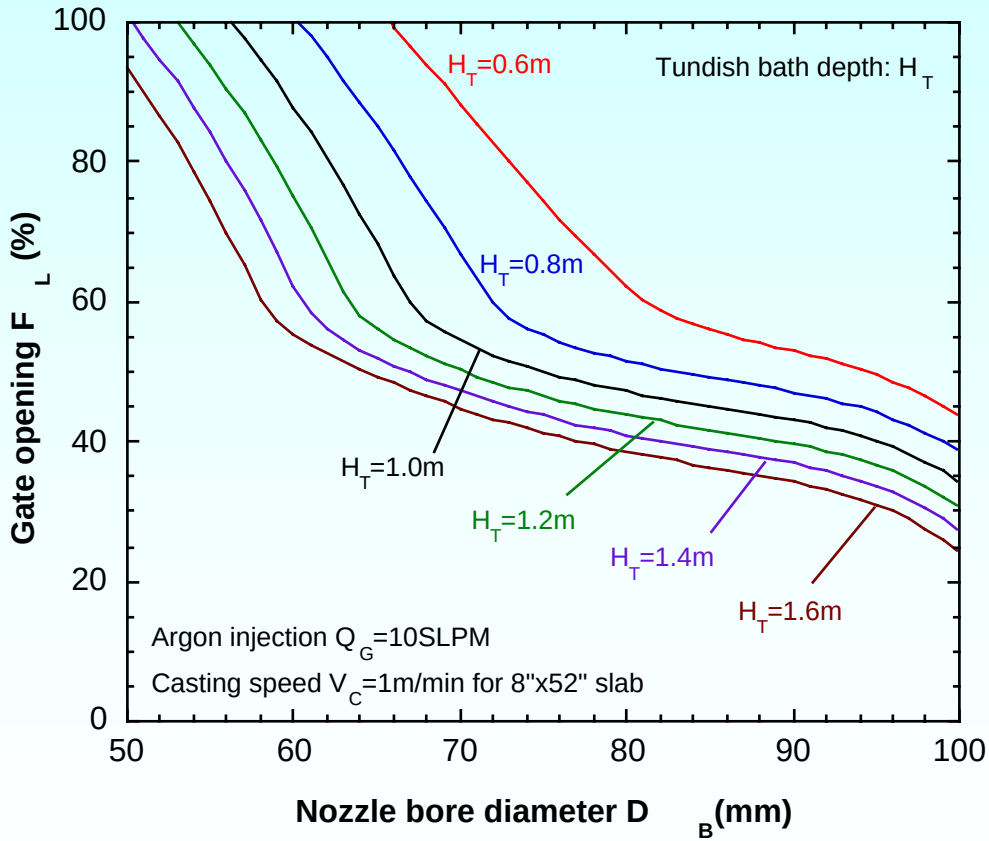
(a) Sharp edge

(b) Round edge

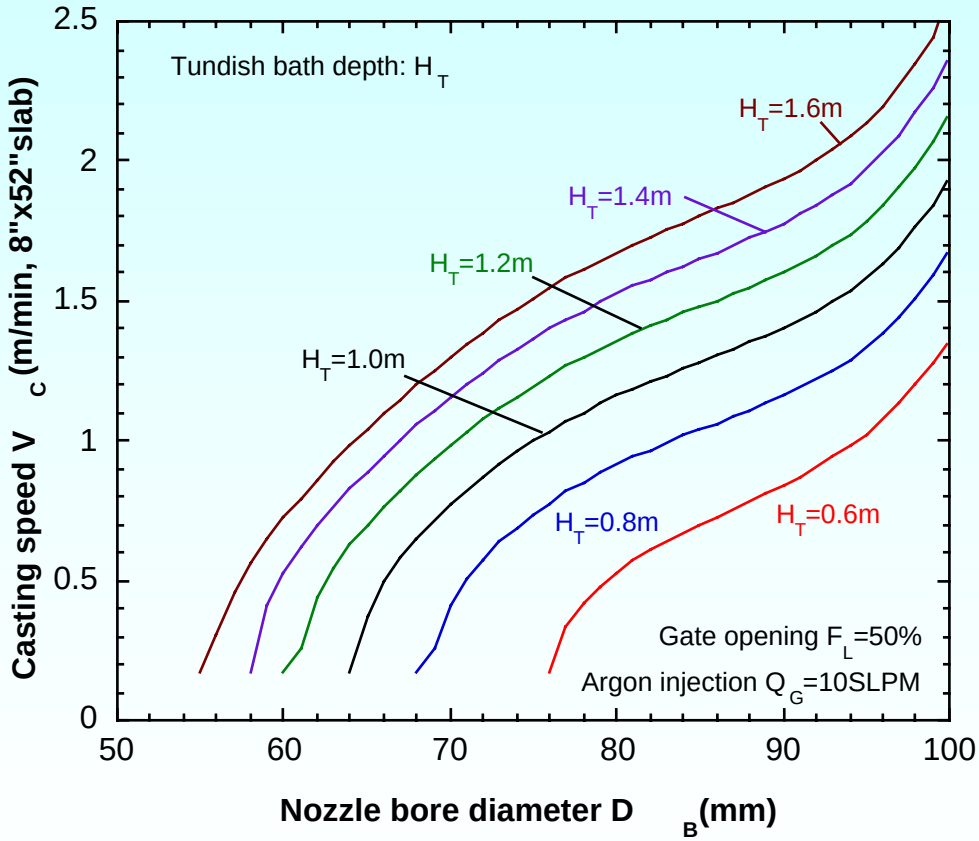
(c) Initial clogging

(d) More initial clogging

Effects of Clogging or Nozzle Bore Size



Effects of Clogging or Nozzle Bore Size



Curve Fitting for Minimum Pressure in Nozzle

P_L
Minimum pressure in nozzle

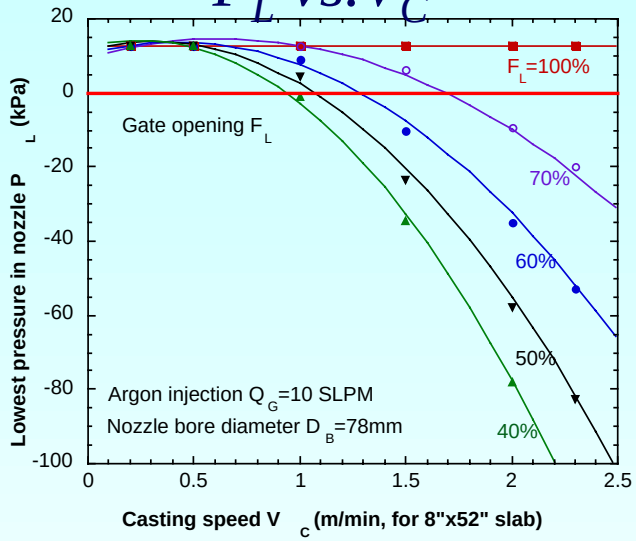
V_C
Casting speed

F_L
Gate opening

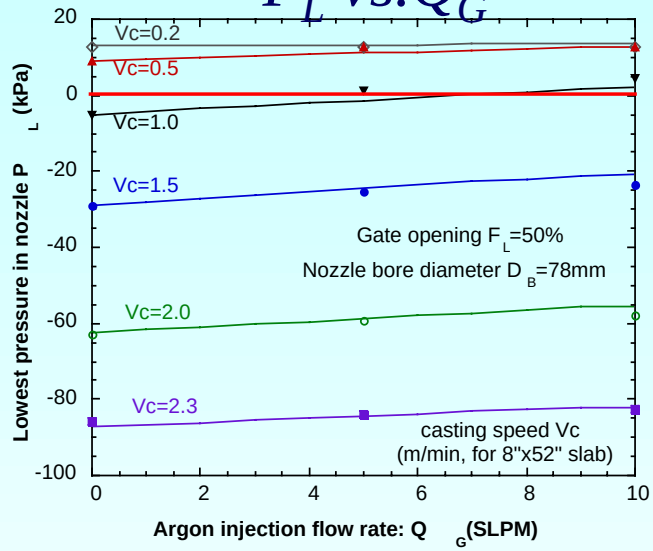
Q_G
Argon flow rate

D_B
Nozzle bore dia.

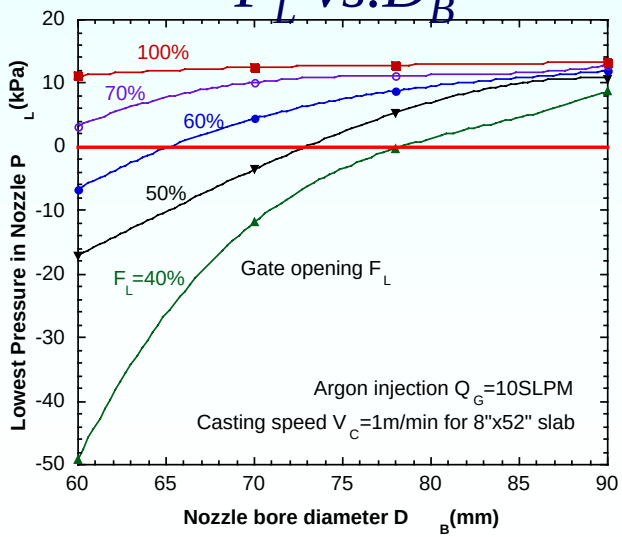
P_L vs. V_C



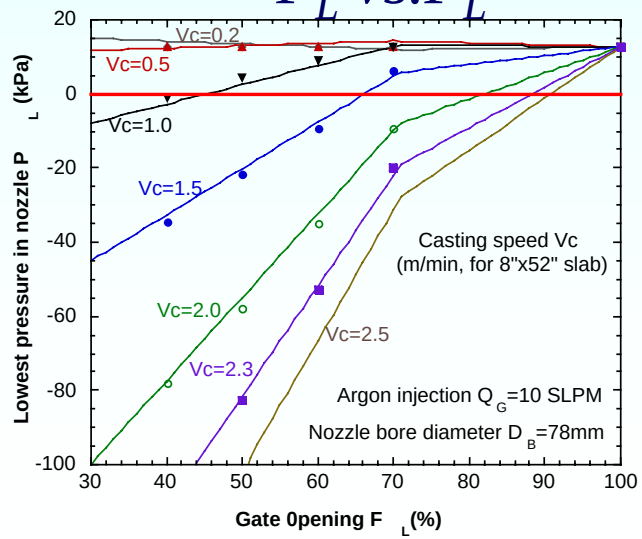
P_L vs. Q_G



P_L vs. D_B



P_L vs. F_L



Multivariable Curve Fitting Model for Minimum Pressure in Nozzle

$$P_L = \left(b_1 V_C^2 + b_2 V_C + b_3\right)\left(b_4 F_L + b_5\right)$$
$$\left(b_6 Q_G + b_7\right)\left(b_8 D_B^3 + b_9 D_B^2 + b_{10} D_B + b_{11}\right)$$

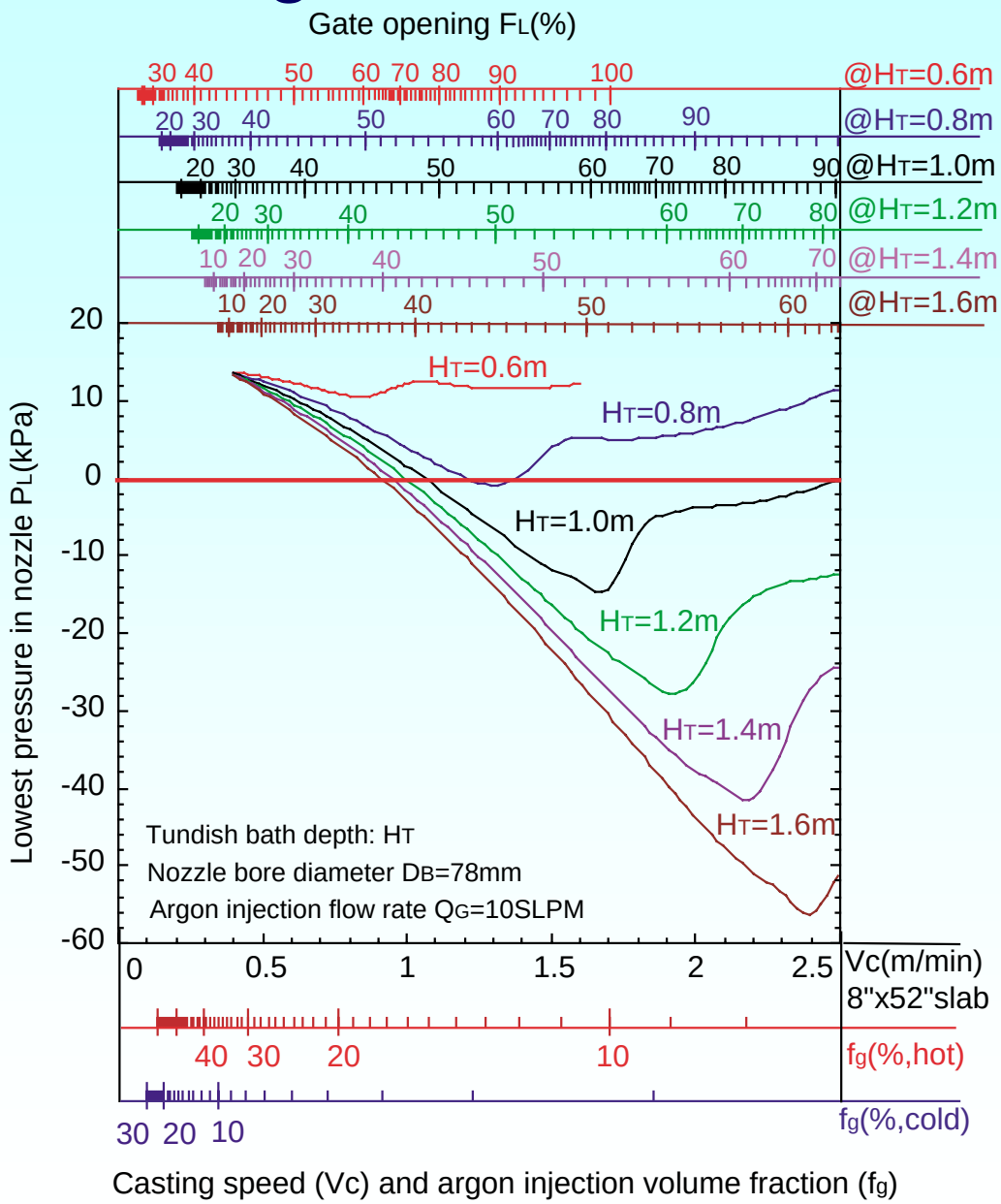
@ $F_L \leq 70\%$

$$P_L = \left(b_{12} V_C^2 + b_{13} V_C + b_{14}\right)\left(b_{15} F_L + b_{16}\right)$$
$$\left(b_{17} Q_G + b_{18}\right)\left(b_{19} D_B^3 + b_{20} D_B^2 + b_{21} D_B + b_{22}\right)$$

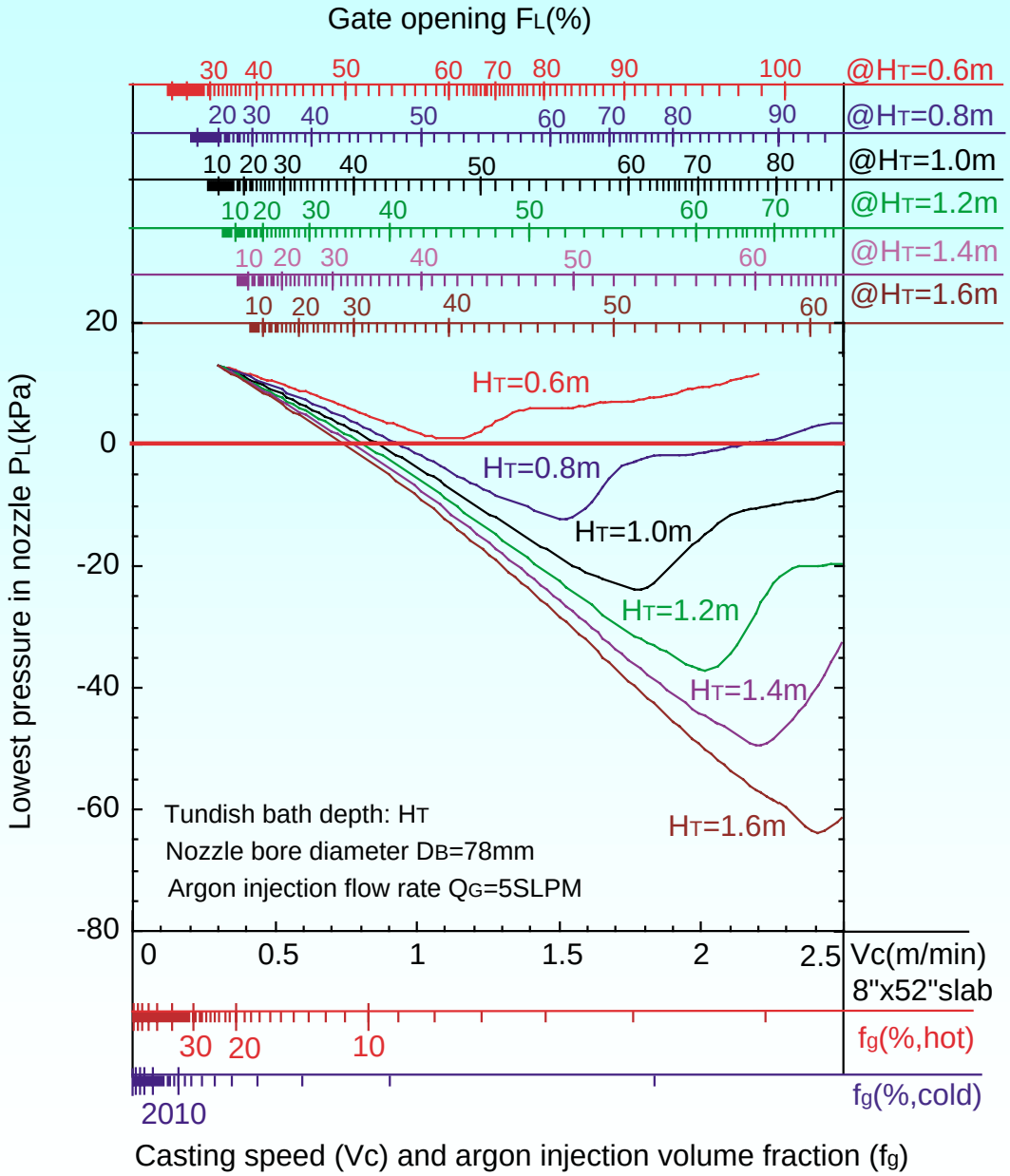
@ $F_L \geq 70\%$

P_L -- Minimum pressure in nozzle,
V_C -- Casting speed, F_L -- Gate opening ,
Q_G -- Argon flow rate, D_B -- Nozzle bore diameter

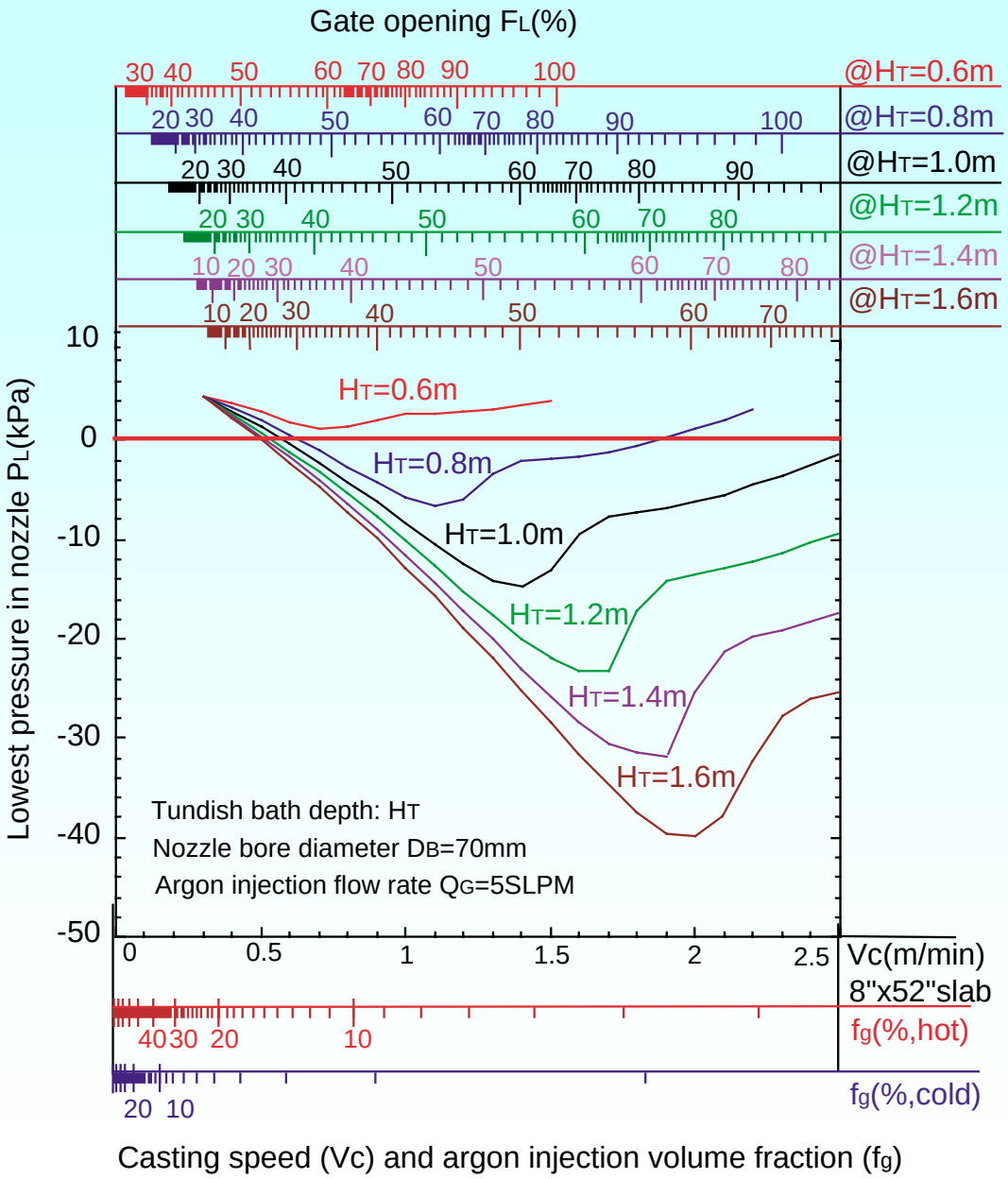
Effects of Casting Conditions on Air Aspiration



Effect of Argon Injection on Air Aspiration in Nozzle

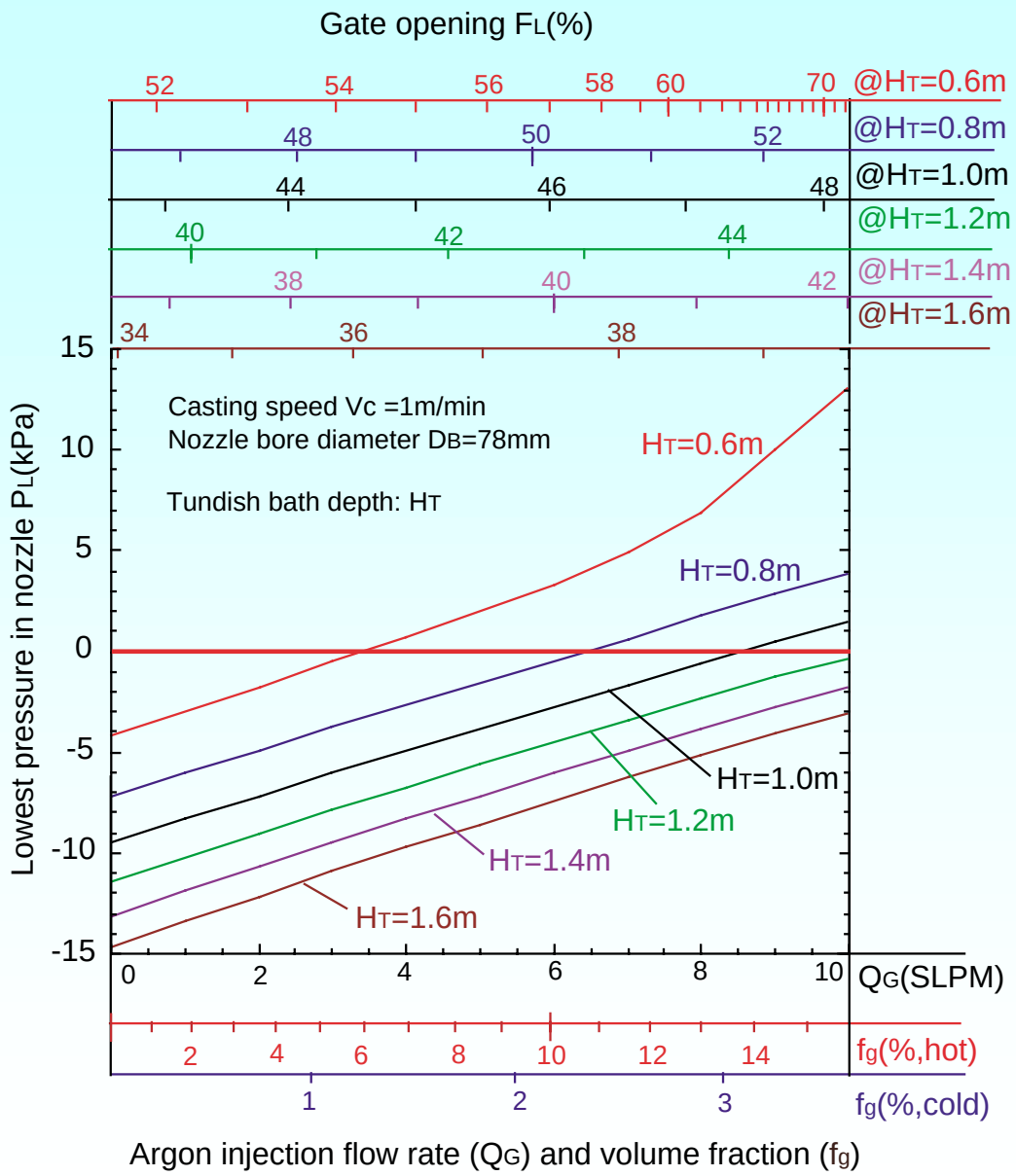


Effect of Argon Injection on Air Aspiration in Nozzle

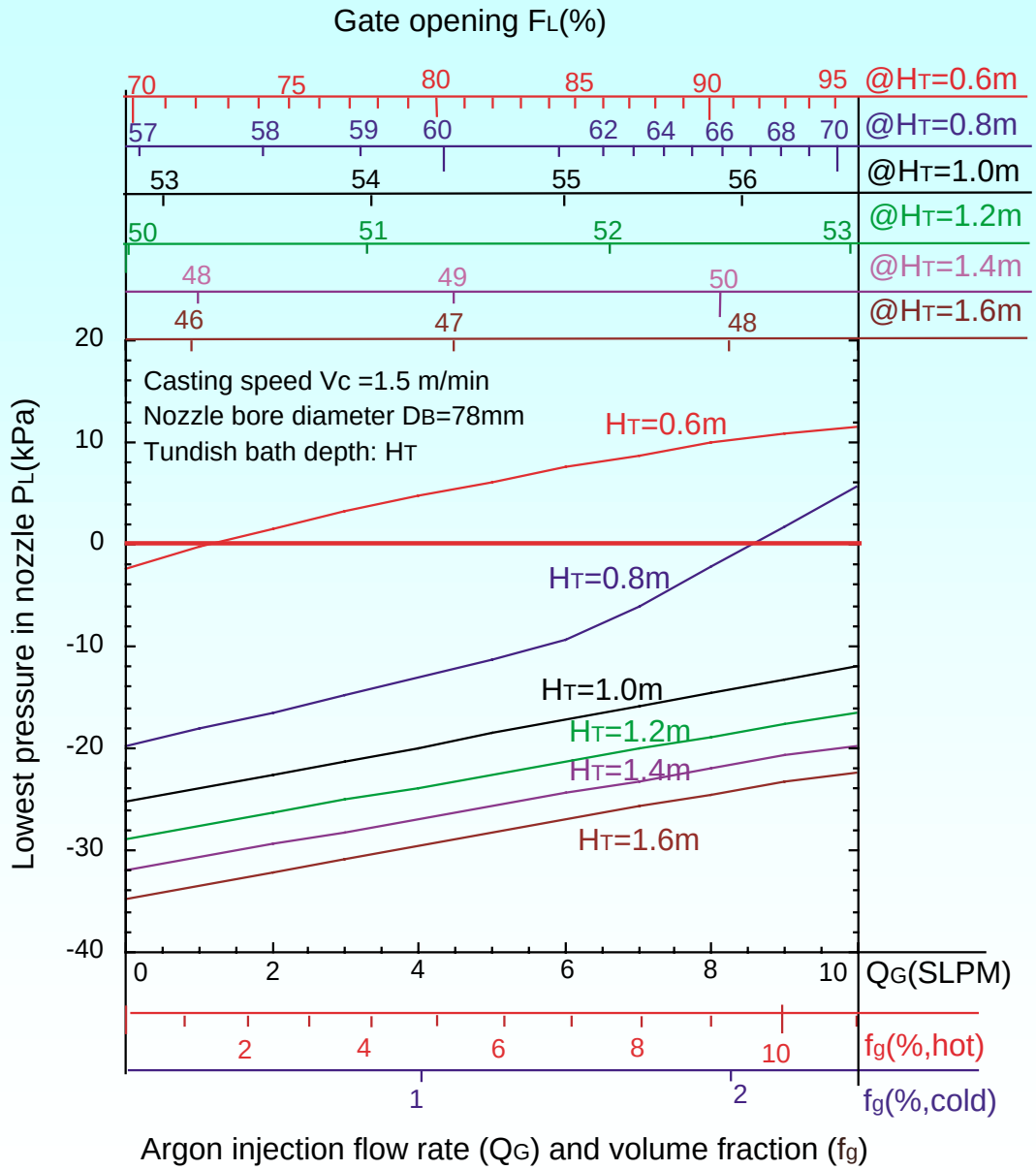


Casting speed (Vc) and argon injection volume fraction (f_g)

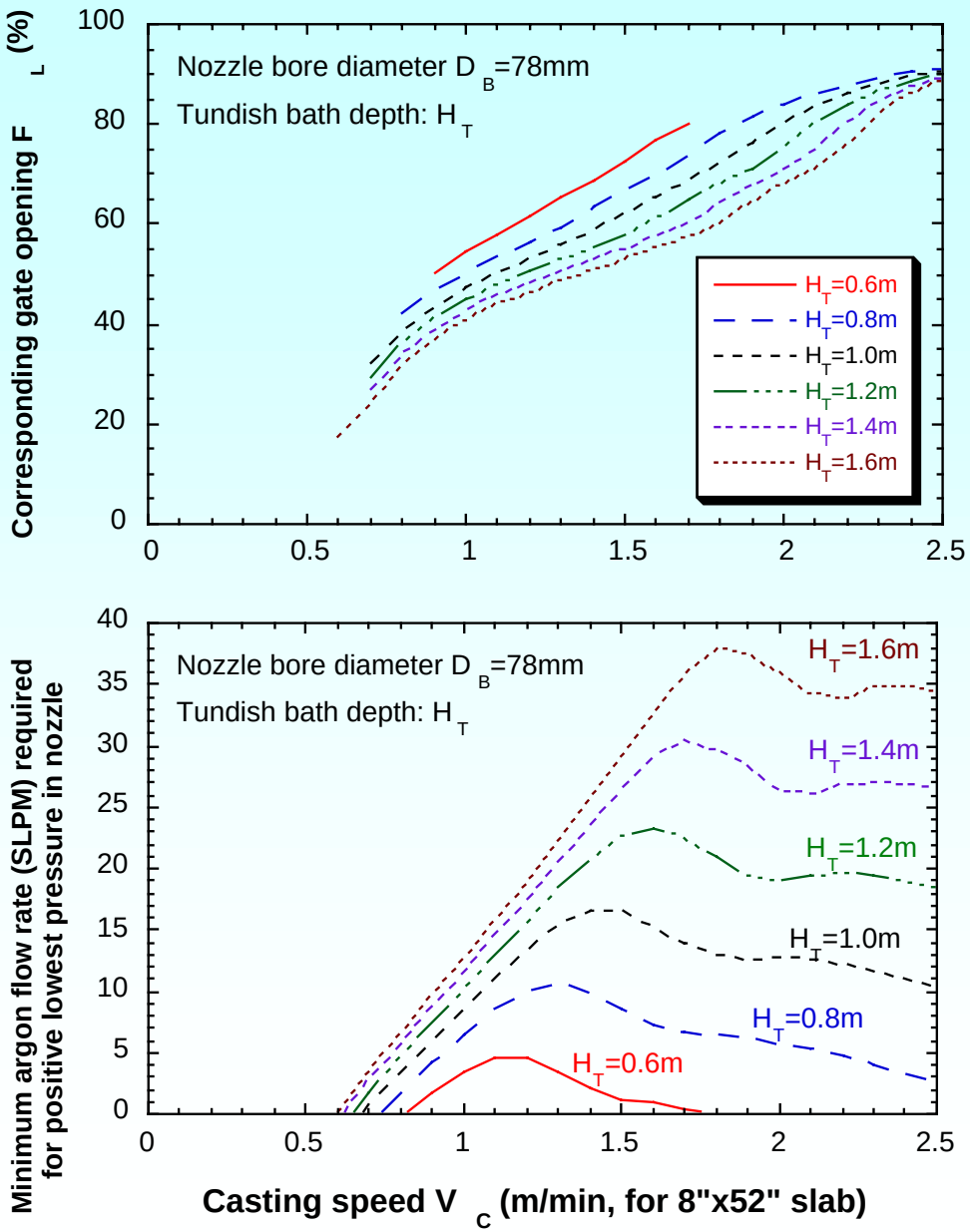
Effect of Argon Injection on Air Aspiration in Nozzle



Effect of Argon Injection on Air Aspiration in Nozzle



Minimum Argon Flow Rate Required to Eliminate Air Aspiration in Nozzle



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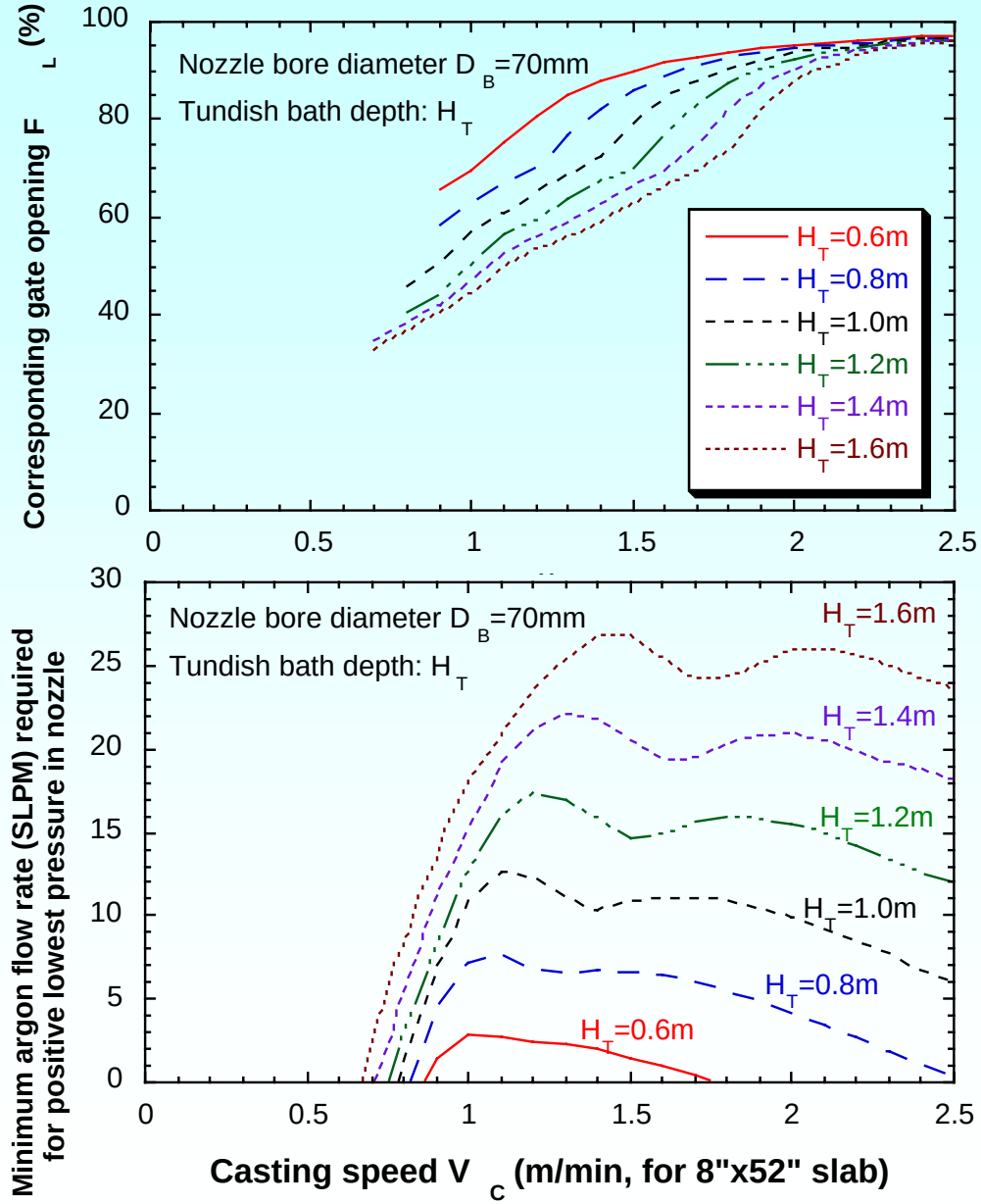


Observations

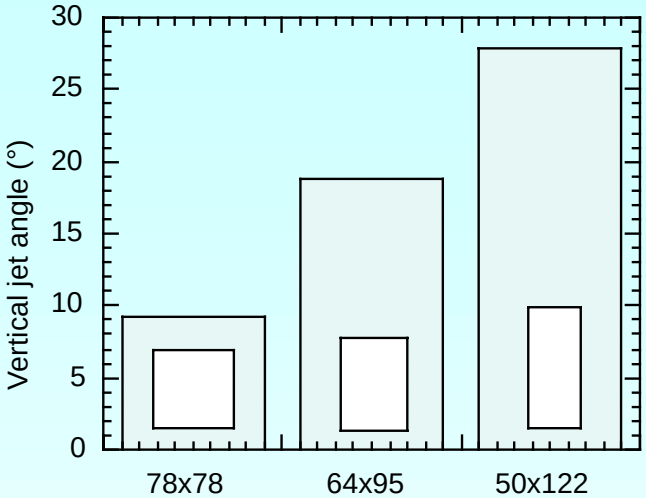
- **Clogging**
  - The clogging condition (Clogging Index) can be detected by comparing the measured steel flow rate to the theoretical value.
  - Initial clogging may enhance the flow due to a potential streamlining effect before it becomes great enough to restrict the flow channel.
- **Argon Injection**
  - Increasing argon injection may help to reduce air aspiration by increasing the minimum pressure below the slide gate.
  - More argon is needed at intermediate casting speeds and in deeper tundishes.
  - Less argon is needed during shallow tundish and low casting speed conditions in order to avoid detrimental effects on flow pattern.
  - Less argon is needed at high casting speed, when the slide gate is open wider and the potential for air aspiration is less.
  - The optimal argon flow rate depends on the casting speed, tundish level, nozzle bore diameter, and its influence on flow pattern in mold

Observations

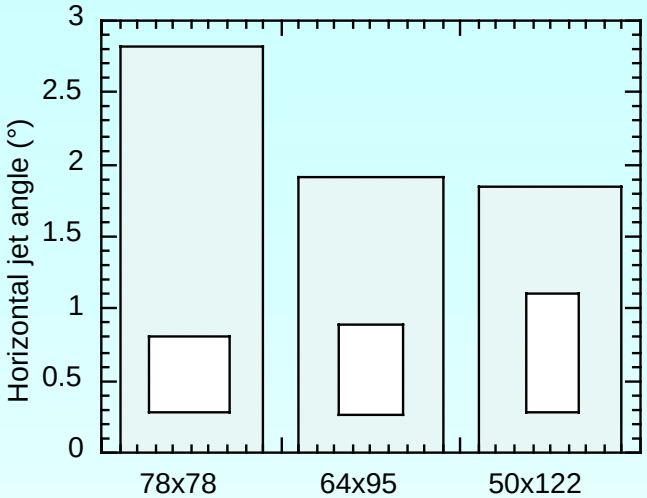
Operation Variables' Relation

- A small change in bath depth causes a larger change in casting speed at low casting speed than it does at high casting speed
- To maintain a constant low casting speed, a larger change in gate opening is needed to compensate for small changes in bath depth than maintaining a constant high casting speed
- For a fixed tundish bath depth, increasing argon injection will slightly slow down the casting speed unless the gate opening increases to compensate
- For a fixed tundish bath depth, casting speed is the most sensitive to gate opening changes at very large openings (F_L>90%) and in the intermediate range of gate opening (F_L=40%~60%).

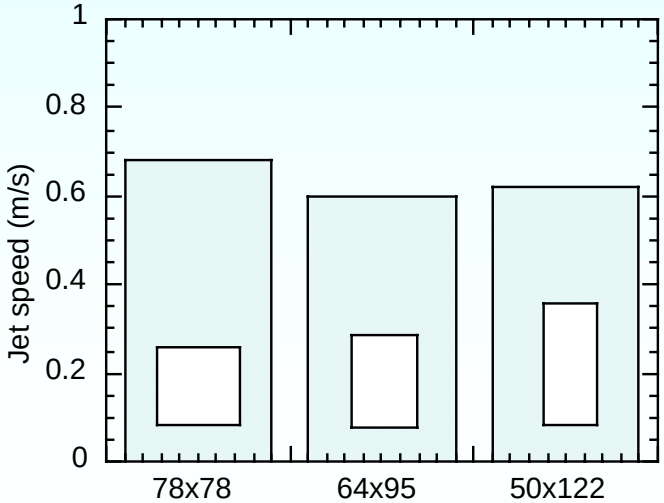
Effects of Port Shape



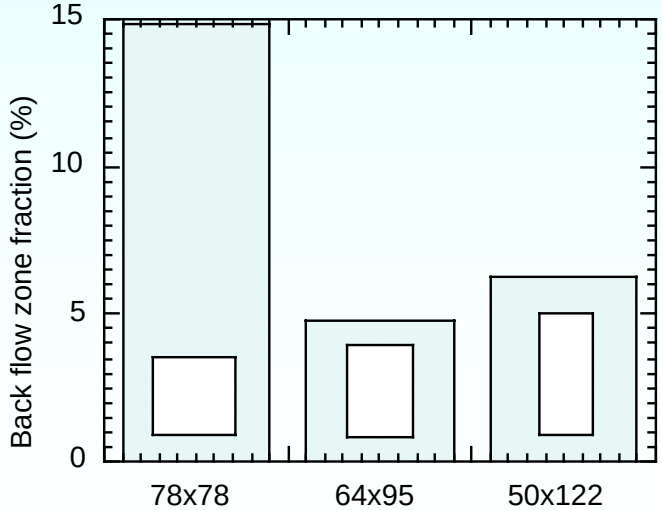
Vertical jet angle



Horizontal jet angle

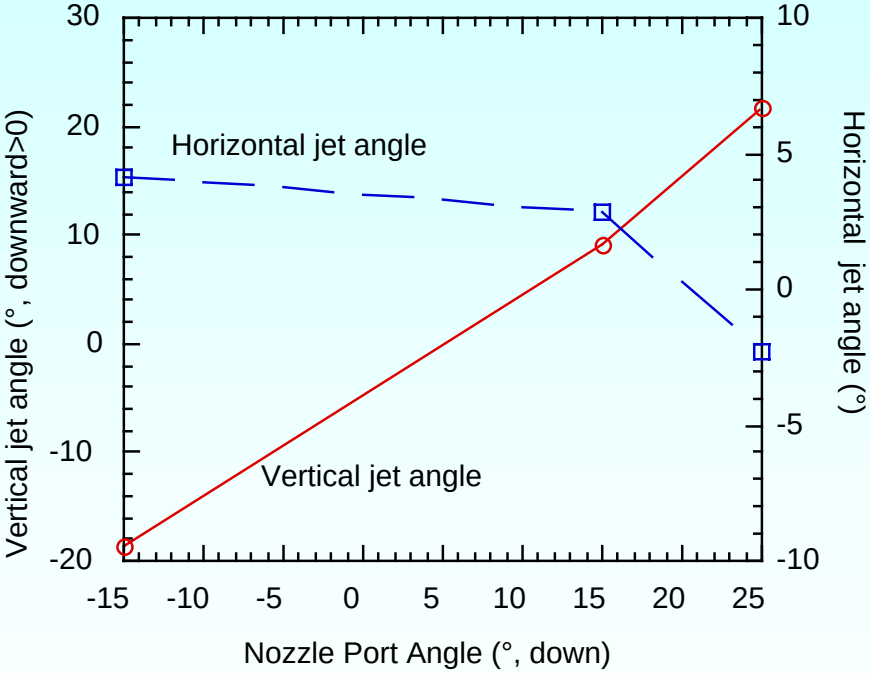


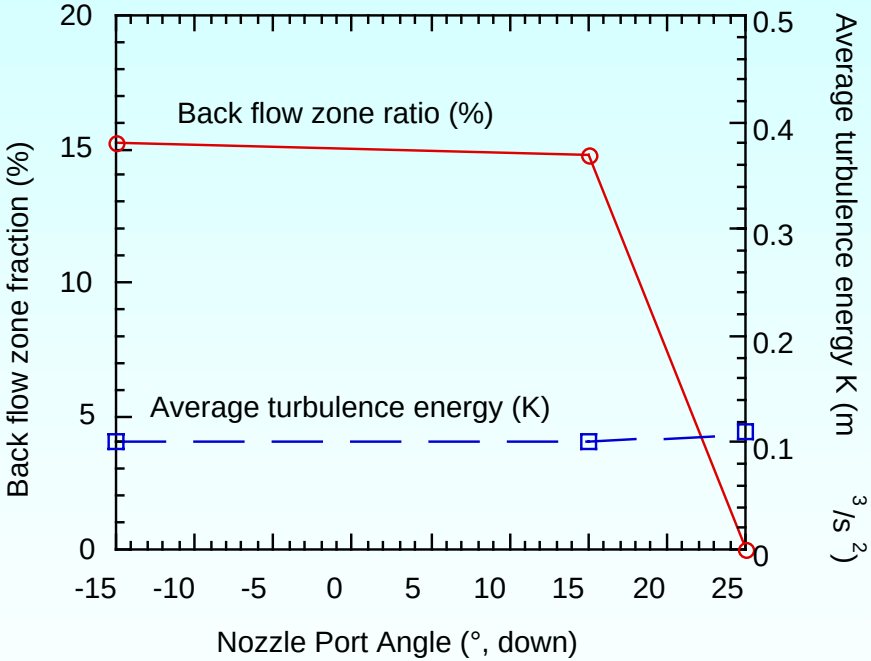
Jet speed



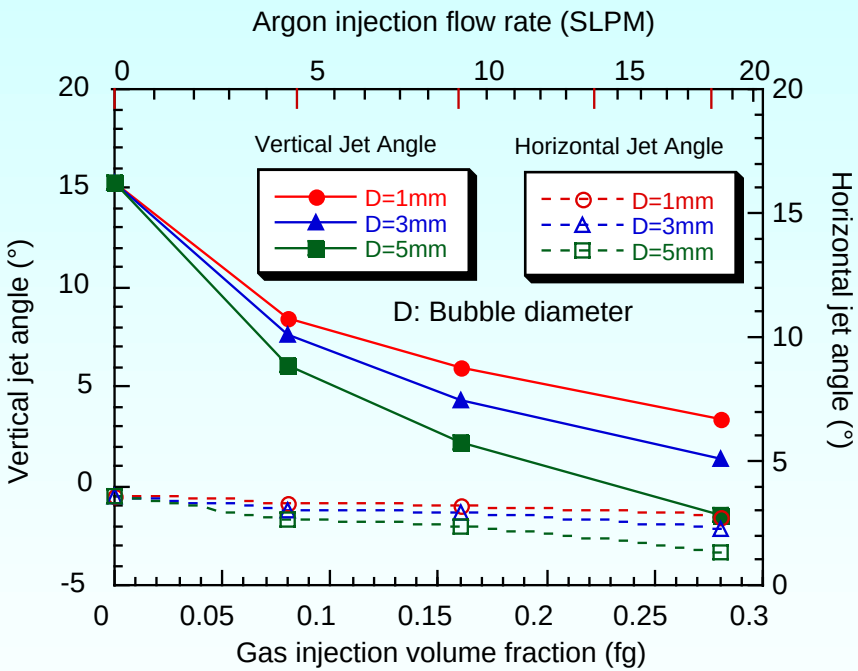
Back flow zone ratio

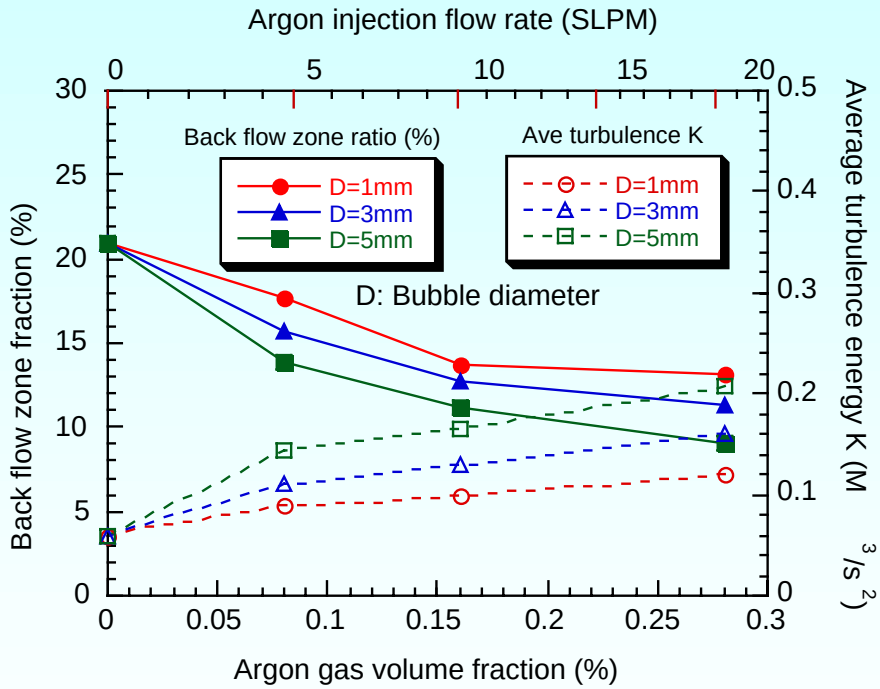
Effect of Port Angle



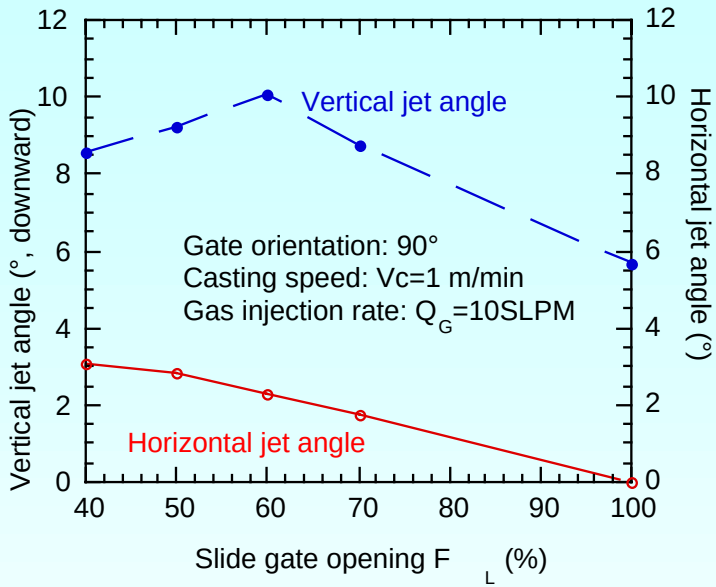


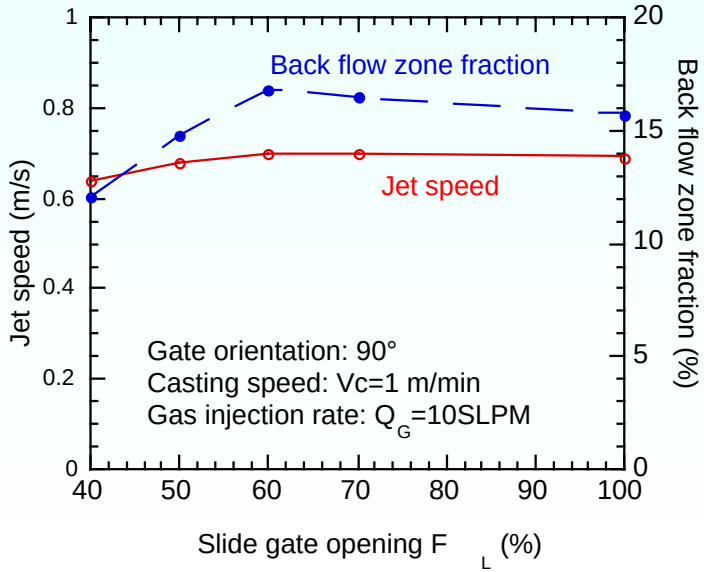
Effect of Bubble Size

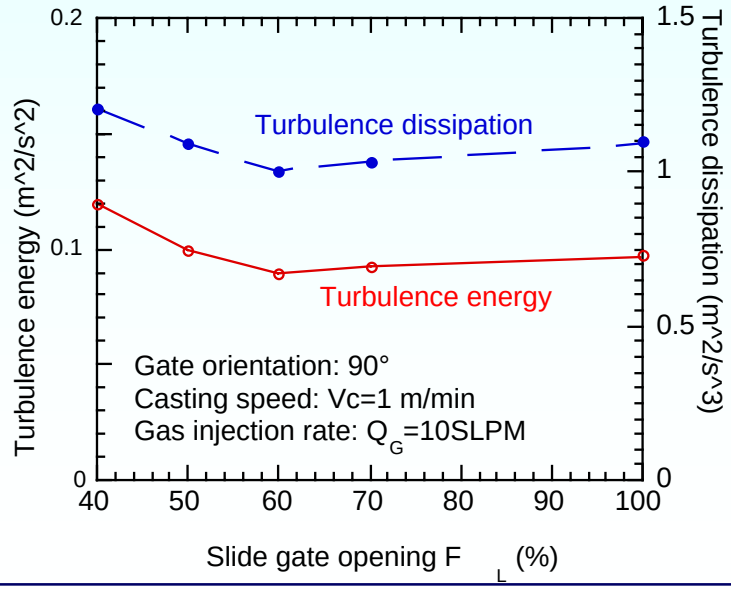




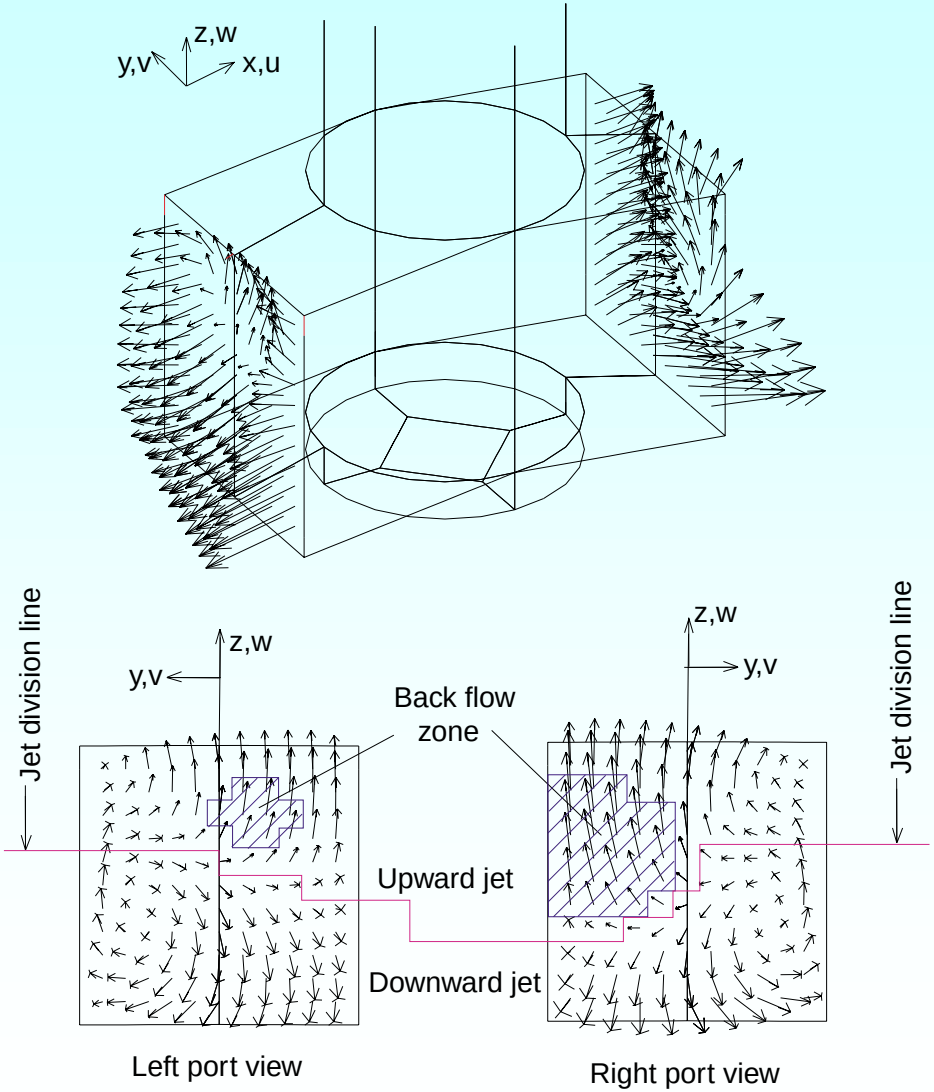
Effect of Gate Opening







Two Jets on Each Port



Comparing One Overall Jet with Two Separate Jets

	Left Port			Right Port		
Jet mode	Two-jets		One-jet	Two-jets		One-jet
Jet	Upward jet	Downward jet	Overall one-jet	Upward jet	Downward jet	Overall one-jet
Vertical jet angle	21.65° upward	8.30° downward	4.55° downward	20.59° upward	7.86° downward	2.41° downward
Jet speed (m/s)	0.56	0.81	0.76	0.67	0.87	0.81
Horizontal jet angle *	-4.70°	1.86°	1.06	-1.43	2.89	2.09
Back flow zone fraction			8.3%			20.1%
Area fraction of port occupied by jet	34.0%	57.7%	91.7%	31.3%	48.6%	79.9%
Liquid flow fraction carried by jet	8.7%	48.1%	56.8%	9.2%	34.0%	43.2%
Jet gas fraction	61.5%	10.9%	25.8%	61.3%	11.7%	30.7%
Gas flow fraction carried by jet	35.8%	15.1%	50.9%	37.5%	11.6%	49.1%