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Argon Gas Flow through
Nozzle Refractories

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Acknowledgements

- Continuous Casting Consortium at UIUC
  (Accumold, Algoma, Corus, Labein, LWB Refractories, Nucor, Mittal Riverdale, Postech)
- COMSOL, Inc. (FEMLab 3.0)
- Other Graduate students,
  Kun Xu, Francois Harvengt, Julien Nuttin
- R. Nunnington & D. Griffin, LWB (data)
Reasons for Argon Gas Injection into Nozzles

- Argon reduces air aspiration and reoxidation by increasing pressure inside nozzle and replacing air aspiration with argon
- Film of gas forms on nozzle walls to prevent inclusion attachment
- Inclusions attach to bubbles, which carry them away
- Gas increases flow turbulence, dislodging inclusions from nozzle walls
- Argon retards chemical reactions with nozzle walls
- Argon bubble buoyancy changes flow pattern in nozzle and especially in mold

Objectives

Determine steady argon gas velocity and bubble size distribution exiting nozzle walls and effects of:
- Nozzle thermal conductivity
- Gas sealing at nozzle – top plate junction
- Gas inlet pressure (back pressure)
- Nozzle refractory permeability
- Nozzle refractory geometry:
  - Nozzle shape
  - Number of argon slits
  - Slit location (single slit)
Governing Phenomena & equations
(axisymmetric FEM model of nozzle)

- Temperature Distribution in nozzle wall
  \[ \frac{k}{r} \frac{\partial T}{\partial r} + \frac{\partial}{\partial r} \left( \frac{k}{r} \frac{\partial T}{\partial r} \right) = 0 \]

- Effects of pressure and temperature on gas expansion
  \[ PV = nRT \]

- Gas diffusion through porous refractory
  \[ \frac{K_p}{P} \left( \frac{\partial P}{\partial r} \right)^2 - \frac{K_p}{T} \left( \frac{\partial T}{\partial r} \right) \left( \frac{\partial P}{\partial r} \right) + \frac{\partial}{\partial r} \left( K_p \frac{\partial P}{\partial r} \right) + \frac{K_d}{r} \frac{\partial P}{\partial r} + \frac{K_d}{r} \frac{\partial P}{\partial z} + \frac{K_d}{P} \left( \frac{\partial P}{\partial z} \right)^2 = 0 \]

Base Conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet pressure</td>
<td>( P_m )</td>
</tr>
<tr>
<td>Pressure at nozzle inside wall &amp; ambient</td>
<td>( P_w )</td>
</tr>
<tr>
<td>Specific permeability</td>
<td>( K_p )</td>
</tr>
<tr>
<td>Dynamic Viscosity</td>
<td>( \mu )</td>
</tr>
<tr>
<td>Permeability (( K_p/\mu ))</td>
<td>( K_{\mu} )</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>( k )</td>
</tr>
<tr>
<td>Heat transfer coefficient (nozzle exterior)</td>
<td>( h )</td>
</tr>
</tbody>
</table>

Note: keeping inlet pressure constant results in variable gas flow rate (depending on conditions and properties of nozzle)
Properties of Fired Dolomitic Tundish Nozzle

- Composition (wt%) 55.9 CaO; 38.9 MgO; 0.6 Al₂O₃; 0.9 SiO₂; 0.9 Fe₂O₃; 2.8 ZrO₂
- Bulk Density (g/cc) 2.92
- Porosity 14.4%
- Permeability 10.1 nPm
- Thermal Conductivity 2.6 W/mK @1100°C
- Specific Heat 0.25 kcal/Kg °C @1100 °C

Solving equations using conventional FEM (Femlab 3.0)

Adjust radii to account for temperature and pressure:

\[ \frac{r'}{r_2} = \left( \frac{r_1}{r_2} \right) \left( \frac{T_2}{T_1} \right) \left( \frac{P_2}{P_1} \right) \quad \quad \frac{r_2'}{r_1} = \left( \frac{r_1}{r_2} \right) \left( \frac{T_1}{T_2} \right) \left( \frac{P_1}{P_2} \right)^{-1} \]

Solve simple axisymmetric equation:

\[ \frac{\partial}{\partial r} \left( K_D \frac{\partial P}{\partial r} \right) + K_D \frac{\partial P}{\partial r} + \frac{\partial}{\partial z} \left( K_D \frac{\partial P}{\partial z} \right) = 0 \]

Validate approach using 1-D analytical solution:
- Approximate result (appro) is very close to exact.
- Ignoring the thermal and pressure expansion effects (trans) is different.
Temperature Profile Through Nozzle Wall

Ratio of inside to outside radius temps:
Doloma: \( \frac{(1527+273)}{(608+273)} = 2.04 \)
Alumina-G: \( \frac{(1519+273)}{(1000+273)} = 1.41 \)

Radial distance from nozzle centerline, \( r \) [m]
Temperature °[C]

\( h = 40 \text{ W/m}^2\text{K} \)

Importance of temperature and pressure variation on gas flow

Pressure Distribution (Pa)

Velocity at inner wall [m/s]
Distance from nozzle bottom to top (m)
Effect of Slide-gate Top Plate

- No plate (max leakage from bottom)
- Top plate with no gap (min bottom leakage)
- Top plate with high-permeability wedge-gap (realistic leakage)

Effect of Leakage

- No plate (no leakage to side)
- Top plate with gap pressurized to 200kPa (from partial side leakage)
- Leakage all along exterior side between nozzle and can (from can thermal distortion)
Effect of Slide gate - top plate

Gas Flow into Steel

Gas Flow into Gap

Effect of Inlet Pressure

Gas Flow into Steel

Max Gas Flow into Gap

2-slit nozzle, base conditions, no T or P adjustment
Effect of Refractory Permeability

Effect of nozzle geometry

Pressure distribution

2-slit nozzle, base conditions, no T or P adjustment
Effect of Nozzle Geometry

Gas Flow into Steel

Max Gas Flow into Gap

base conditions, no axisymmetry, no T or P adjustment

Effect of location of annular gas-inlet slit

1-slit nozzle geometry
base conditions
no axisymmetry,
no T or P adjustment
Effect of slit location on gas flow profile

Bubble size distribution

- Bubble diameter entering nozzle depends on:
  - vertical steel velocity
  - gas flow rate per site (pore or hole)

- Depends on number of “active sites” in nozzle wall (to determine flow rate / pore)
- Should conduct experiments to measure this

Bubble diameter entering nozzle depends on:
- vertical steel velocity
- gas flow rate per site (pore or hole)

H. Bai & Thomas, Met Trans B, 2001
Water model experiment at Postech – Gogi Lee

- Upper nozzle
- Slide gate
- SEN (Submerged Entry Nozzle)
- SEN outlet
- Ar gas injection hole
- Separable part in red circle
- Dimension of each part
- Especially, the dimension of upper nozzle and slide gate and outlet part is need in detail

New 3rd part of top UTN

- 1st part of top UTN
- 2nd part of top UTN
- 3rd part of top UTN
- New design for square tube
- Remove of round tube
Planned water model experiments

Variables:
1. gas flow rate (Qg, ℓ/min)
2. liquid flow rate (V_l, m³/sec)
3. hole shape (porous refractory vs. machined holes)
4. manufacturing variations in porous refractory

Observe the bubble sizes according to permeability of refractory
Observe the bubble sizes according to hole spacing

Conclusions

• Model of argon gas flow through nozzle refractory has been developed, including important expansion effects from temperature and pressure changes
• Gas exits nozzle wall into steel with a profile that is closely associated with the annular slit where gas is injected
• Significant gas will leak into gap between nozzle bottom and top plate if there are leaks
• Thermal expansion of can would cause leakage that greatly changes gas flow rate and profile
• Gas flow increases with increasing inlet pressure or decreasing refractory permeability