Effect of Aspiration Pressure on Convergent Nozzle Employed for Gas Atomization of Liquid Metals

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Abstract— Atomization is often chosen as one of powder production techniques because of high production rates and ability to make alloy powders of desired composition. In gas atomization process, liquid metal is broken into droplets to form powders upon solidification. Gas-metal interaction influences the break-up of liquid stream into droplets. The idea is to transfer kinetic energy from a high velocity jet-gas expanded through a nozzle, to a stream of liquid metal, resulting in fragmentation and break up into metal droplets. Gas atomization process is one of the widely used powder production technique and nozzles play an important role in the gas atomization process. The geometry of nozzles governs the gas to metal interaction. The selection of nozzle type and the flow geometry is the most important preset parameter for atomization process. The design of an atomizing nozzle determines degree of contact of liquid metal with the atomizing gas. Aspiration pressure is the optimum pressure developed at tip of the nozzle (at atomization zone) which will favor gas atomization process. In the present analysis, an attempt was made to analyze effect of atomization pressure and aspiration pressure for Convergent nozzle (C-nozzle) employed for gas atomization process using Computational Fluid Dynamics (CFD) techniques.

Key words: Gas Atomization, Convergent Nozzle, Aspiration Pressure, CFD

I. INTRODUCTION

A. Gas Atomization Process

Gas atomization process helps in production of a wide range of ultra-fine spherical metal powders which have very attractive material properties. In gas atomization process, atomization pressure plays an important role in determining particle size and surface morphology [1]. Atomizing nozzles have co-axially placed Metal Delivery Tube (MDT), which carry molten metal to atomizing zone [2, 3]. The flow properties of gas are considerably affected by the presence of MDT. In this process, inert gas (N2) is used an atomizing medium. Atomization technique has been extensively reviewed by Beddow [4], Grant et al [5] and Lewley [6].

Gas atomization process is one of widely used powder production technique. In gas atomization process, molten metal is melted and liquid metal is broken into individual particles to form powders. Gas atomization is one of the powder production method/technique. In this method, kinetic energy of a high velocity (greater than Mach 1) impinging inert gas jet disintegrates continuous metal flow into droplets. Nozzles are used to achieve the atomization through break-up of molten metal stream into droplets by fast flowing gas [7, 8, 9, 10]. The heart of the gas atomization process is the nozzle. The set-up for gas atomization of liquid metals using a C - nozzle assembly is shown in figure- 1

B. Aspiration Pressure

Aspiration Pressure is the pressure developed at the tip of Metal Delivery Tube (MDT). This is the optimum pressure for atomization to occur. Aspiration pressures for various protrusion lengths for C-nozzle is also been measured using CFD trails in gas-only condition (only considering the gas flow without melt flow) and are compared with those obtained from the numerical analysis and experimental results [11].

A protrusion length between 2mm and 3mm is found to be optimum for nozzles with a parallel portion attached at the end of the nozzle. This configuration gives rise to lowest aspiration pressure, which assists in melt flowing out of the MDT. This configuration is very much favorable for gas atomization process. Decrease in aspiration pressure with increase in protrusion length from 0 to 2mm is experimentally verified by available literatures [12].

When atomization gas pressure increases, aspiration pressure also increases and this may not be favorable for atomization process. A good correlation exists between gas only flow condition and melt-gas flow condition. In the present study, based on the closed couple C-nozzle configuration, a computational fluid flow model was used to investigate the effect of gas atomization pressure (P0) on gas flow field along with aspiration pressure [13].

By increasing gas atomization pressure, aspiration pressure also increases which in turn produce a weak sucking action on the melt flow or lead to a low velocity of melt flowing out of crucible. So aspiration pressure is directly affected by stagnation pressure [1].

In the present investigation, configurations considered was a C- nozzle with small parallel portion of various lengths (which is the extension of the MDT) and attached to its end. The analysis shows that pressure, velocity, temperature and density of atomizing gas at the exit of nozzle does not change much for various nozzle configurations, whereas turbulent kinetic energy is drastically reduced when a parallel portion is attached at the end of C-nozzle.
II. CFD TRAILS TO OBTAIN OPTIMUM ASPIRATION PRESSURE FOR C-NOZZLE

A. Description of physical model and parameters considered for numerical analysis of Mach number for CD nozzle

In the present investigation study, CFD trials have been carried on C-nozzle for plotting pressure. Geometric modeling and meshing of C-nozzle were carried out and results were plotted using fluent software. The C-nozzle parameters considered for simulation of 1M (Mach number, sonic) are shown in Table 1.

Boundary conditions applied were Pressure inlet, Pressure outlet, Wall and Symmetry. Viscous model was defined as Spalart-Allmaras for the fluid flow, solver as QUAD [14]. Inlet pressure of 0.3 MPa (3 Bar) and inlet temperature values of 300K were given as input. The iteration values were set as about 1000 initially and iterated until the solution converges [15]. Then results were plotted for pressure. Courant number controls the time step used by Fluent during inner iterations performed during each time step.

<table>
<thead>
<tr>
<th>Sl No</th>
<th>Nozzle Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Inlet diameter</td>
<td>23.35 mm</td>
</tr>
<tr>
<td>2</td>
<td>Outlet diameter</td>
<td>16.0 mm</td>
</tr>
<tr>
<td>3</td>
<td>Distance between inlet and outlet</td>
<td>14.78 mm</td>
</tr>
<tr>
<td>4</td>
<td>Inlet pressure</td>
<td>0.3 MPa</td>
</tr>
<tr>
<td>5</td>
<td>Gauge pressure</td>
<td>0.1 MPa</td>
</tr>
<tr>
<td>6</td>
<td>Exit velocity/Mach</td>
<td>1 Mach</td>
</tr>
<tr>
<td>7</td>
<td>Initial inlet gas temperature</td>
<td>300K</td>
</tr>
</tbody>
</table>

Table 1: C-nozzle dimensions and process parameters

![Fig. 2: C-nozzle dimensions with MDT (with 2 MM protrusion length)](image)

Table 2 shows boundary conditions applied for C-nozzle for carrying out CFD trials

Figures 3 and 4 shows C-nozzle without and with presence of co-axially fitted MDT where model and mesh were generated using Gambit software of Fluent. MDT boundary was considered as a wall. For plotting Mach number/pressure, an area at nozzle exit was considered with height more than 2 times exit diameter of nozzle (50 mm) and length was taken as 300mm. Hence a chamber like design was considered with PRESSURE-OUTLET boundary condition as ambient pressure (applied atmospheric pressure of 0.1MPa). This was to adopt similar domain condition as that of wind tunnel experiments [16].

A C-nozzle without any parallel portion is termed as nozzle-A and convergent nozzles with 2mm and 6mm parallel portion attached at its end (duct without change in area) are termed as nozzle-B, nozzle-C respectively. These nozzles used for carrying out the CFD trails are shown in Fig. 3 and Fig 4.

![Fig 3: C-nozzle (protrusion length is 0 mm) with mesh and applied boundary conditions](image)

![Fig 4: C-nozzle of protrusion length 2mm (with mesh)](image)

III. TEST CASES CONSIDERED FOR PRESENT ANALYSIS

Different cases considered for conducting experiments on C-nozzle to measure optimum pressure required for gas atomization process as discussed below:

A. Case-1 (Figure: 5)

- A Type nozzle: Protrusion length of 0 mm.
- Inlet pressure applied is 0.3 MPa (0.3 bar)
- Inlet gas temperature is 375K (pre-heated to avoid freezing of gas and melt)

Figure 5 shows pressure distribution plot for C-Nozzle for an inlet pressure of 0.3 MPa. In this case, a pressure of 0.15 MPa was obtained at nozzle exit which was greater than atmospheric pressure. This pressure does not cause flow reversal at the nozzle exit. This is the favorable pressure for gas atomization process.

When protrusion length of MDT is 2 MM and if aspiration pressure may be optimum, which helps in melt...
flowing out of MDT. Therefore, a protrusion length between 2mm and 3mm would be best for atomization process.

Fig. 5: Pressure plot for C – nozzle (Exit pressure is 0.15MPa, protrusion length 0mm)

Similar conditions were observed (keeping protrusion length equal to 2mm) and pressure is varied as shown in figures: Fig 6 - Fig 8.

**B. Case-2**

- B - type nozzle: Protrusion length is 2 mm.
- Inlet pressure applied is 0.3 MPa (3 bar)

1) Refer Figure – 6:

- Here nozzle exit pressure is around 0.136 MPa (1.36 bar)
- This pressure is nearly equal to atmospheric pressure
- This pressure is favorable for gas atomization process

C. **Case-3**

- B-type nozzle: Protrusion length is 2 mm.
- Inlet pressure applied is 0.4 MPa (4 bar)

D. **Case-4**

- B Type nozzle: Protrusion length is 2 mm.
- Inlet pressure applied is 0.5 MPa (5 bar)

Fig 8: Pressure plot when Pi=5 bar (protrusion length is 2mm)

- Here nozzle exit pressure is around 0.135 MPa (1.35 bar)
- This pressure is nearly equal to atmospheric pressure
- This pressure is favorable for gas atomization process

**E. Case-5**

- B Type nozzle: Protrusion length of 2 mm.
- Inlet pressure applied is 0.7MPa (7 bar)

In this condition as shown in fig-9, it can be seen that, for an inlet pressure of 0.7 MPa, the pressure at the outlet of nozzle was found around 0.2 MPa (2.0bar), which is far higher than atmospheric pressure which may not be favorable for gas atomization.

Table: 3 Protrusion length v/s Nozzle exit pressure

As per the table 3, for a protrusion length of 2 mm, for inlet pressure of 0.3 to 0.5 Mpa, the nozzle exit pressure obtained was found to be around 0.135 MPa (1.35 bar) which is favorable for gas atomization process.

Figure 10 shows C-nozzle with mesh and applied boundary conditions with protrusion length of 6mm. The other parameters remain unchanged (like boundary conditions and inlet parameters).
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(IJSRD/Vol. 3/Issue 1/2016/086)

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Fig. 10: C-nozzle with protrusion length of 6 mm (nozzle with mesh)

Figures 11, 12 and 13 shows that when protrusion length increases from 2mm to 6mm, aspiration pressure also increases and this pressure (0.18 MPa [1.8 bar] – more than atmospheric pressure) may not be favorable for gas atomization process.

F. Case-6

1) C Type nozzle: Protrusion length of 6 mm
2) Inlet pressure applied is 0.3 MPa (3 bar)
   – Here the nozzle exit pressure was found to be around 0.18 MPa (1.80 bar).
   – This nozzle exit pressure is more for gas atomization with protrusion length of 6 mm.
   – When protrusion length increases from 2mm to 6mm, aspiration pressure also increases and this pressure may not be favorable for gas atomization process.

Fig. 11: Pressure plot when Pi=3 bar (protrusion length is 6 mm)

Table 4: Protrusion length v/s Nozzle exit pressure (PL = 6mm)

<table>
<thead>
<tr>
<th>Nozzle Type</th>
<th>Protrusion Length (mm)</th>
<th>Nozzle Inlet Pressure (MPa)</th>
<th>Nozzle Exit Pressure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>6</td>
<td>0.3</td>
<td>0.18</td>
</tr>
<tr>
<td>C</td>
<td>6</td>
<td>0.5</td>
<td>0.22</td>
</tr>
<tr>
<td>C</td>
<td>6</td>
<td>0.7</td>
<td>0.28</td>
</tr>
</tbody>
</table>

As shown in figure 13, (both experimentation and numerical), as atomization pressure increases, aspiration pressure also increases [1].

Fig. 12: Pressure plot when Pi=7 bar (Protrusion length is 6 mm)

G. Case-7

1) C Type nozzle: Protrusion length is 6 mm.
2) Inlet pressure applied is 0.5 MPa (5 bar)
   – Here the nozzle exit pressure was found to be around 0.22 MPa (2.20 bar).
   – This nozzle exit pressure is more for gas atomization with protrusion length of 6 mm.

Fig 11: Pressure plot when Pi=5 bar (protrusion length is 6 mm)

H. Case-8

1) C-type nozzle: Protrusion length is 6 mm.
2) Inlet pressure applied is 0.7 MPa (7 bar)

Both modeling and experimental results also show that as applied gas pressure increases, aspiration pressure also increases. Cui et al. (2003) have carried out pressure measurements for the gas jet exiting at an angle of 15° from the vertical axis, which is close to the set-up used in the present investigation. They also observed that aspiration pressure decreases with increase in protrusion length from 0 to 6mm, and aspiration pressure increased with increase in atomization pressure from 5 bar to 7 bar [1,11].

It is also observed that, with increase in applied gas pressure, magnitudes of minimum and maximum pressure change but their locations do not change. The effect of protrusion length can be deduced by comparing the pressure profiles at a fixed applied gas pressure. It can be seen that by increasing the protrusion length from 0mm to 2mm the stagnation point shifts to a shorter distance and stagnation pressure increases for all the applied gas pressures. However, the location of minimum pressure does not change with protrusion length; it remains between 2mm and 3mm for...
nozzle-A, -B and -C. The minimum pressure increases with increase in protrusion length. However, pressure which is important for atomization is aspiration pressure, i.e., the pressure existing at the tip of MDT. If aspiration pressure is low, it helps in melt flowing out of the delivery tube. Therefore, a protrusion length between 2mm and 3mm would be the best for the atomization as the tip of the melt delivery tube will coincide with the location of minimum pressure [12].

Fig. 14: Aspiration pressure in terms of gauge pressure at the tip of the melt delivery tube obtained from experiment and modeling for various protrusion lengths and applied gas pressures

Both modeling and experimental results shows that when the applied gas pressure increases, from 0.3 0.7 MPa, aspiration pressure also increases [12].

IV. CONCLUSION

The minimum pressure increases with increase in protrusion length. However, pressure which is important for atomization is aspiration pressure, i.e., the pressure existing at the tip of MDT. If aspiration pressure is low, it helps in melt flowing out of the delivery tube. Therefore, a protrusion length between 2mm and 3mm would be the best for the atomization as the tip of MDT will coincide with the location of minimum pressure.

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