Effect of a rotating magnetic field on the decay of a free-falling metal jet

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Additive manufacturing enables the production of individualized high-grade components. Established techniques can use metal powder as its basic material. The generated product is often limited by the particle size distribution, particle shapes, and its composition. The metal powder manufacturing process needs to be understood and improved to enhance the quality of the fabricated products. In this work, numerical simulations are performed to describe the flow processes of powder production using the method of free-falling gas atomization. Furthermore, the use and influence of a rotating magnetic field is adapted to the atomization process and investigated by varying the influencing parameters like magnetic field strength and rotational frequency.

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1 Introduction

Additive manufacturing (AM) revolutionizes upcoming technologies by a pointwise production in layers. This reduces the material use and leads to an optimized product in functionality and flexibility. Established techniques for AM such as metal laser sintering and selective laser melting use metal powder as their basic material. The final product is restricted significantly by powder characteristics e.g. particle size distribution, shapes, and composition [1, 2]. Gas atomization processes can be used to produce metal powder. Their working principle is transferring kinetic energy from a directed high-speed pressurized gas jet onto a liquid metal stream [3]. The following research is focused on the primary breakup of a free-falling gas atomization process, specifically, before the gas jet collides with the melt after a short free-falling distance underneath the nozzle outlet. Computational fluid dynamics helps to understand the high-complexity phenomena and reveals information that is not experimentally accessible. Furthermore, a rotating magnetic field (RMF) is developed in the numerical model to provoke a rotational flow and an increasing flow velocity to form a helix surface or a hollow-cone jet shape and a faster disintegration for smaller particles.

2 Numerical model

The numerical approach describes a 3D-flow of a turbulent free falling metal melt jet flowing out of a nozzle into a static gaseous atmosphere with laminar flow conditions. The continuity and momentum (Navier-Stokes Eq.) equations are assumed as incompressible and isothermal with constant material parameters:

\[ \nabla \cdot \vec{u} = 0, \]

\[ \rho \left( \frac{\partial \vec{u}}{\partial t} + \nabla \cdot (\vec{u} \vec{u}) \right) = -\nabla \rho + \rho \vec{g} + \eta \nabla \cdot (\nabla \vec{u} + \nabla \vec{u}^T) + \tau_{SGS}^{\alpha} + F_{surf} + F_L, \]

\[ F_L = 0.5 \rho B_0^2 \omega R. \]

where \( \vec{u}, \rho, \) and \( \vec{g} \) are velocity, pressure, and gravity acceleration, respectively. \( \eta \) denotes dynamic viscosity and \( \tau_{SGS}^{\alpha} \) implies the subgrid scale stress tensor. For the Lorentz force which drives the melt in accordance to the RMF:

\[ \nabla \cdot (\vec{u} \times \vec{B}) = \frac{1}{\sigma} \nabla \cdot \vec{E}, \]

\[ \nabla \cdot \vec{E} = \frac{1}{\sigma} \rho \omega \vec{B}. \]

\[ \frac{\partial \alpha}{\partial t} + \nabla \cdot (\vec{u} \alpha) = 0, \quad \text{with} \quad \alpha = \begin{cases} 1 & \text{steel}, \\ 0 & \text{gas}, \\ 0 < \alpha < 1 & \end{cases} \]

and \( \vec{E} = \vec{E}_{surf} \) is included in Eq. (2) which is based on the surface tension force method [5]. The conservation of the volume fraction is described by:

\[ \frac{\partial \alpha}{\partial t} + \nabla \cdot (\vec{u} \alpha) + \nabla \cdot (\vec{u} \alpha (1 - \alpha)) = 0, \]

\[ \text{with} \quad \alpha = \begin{cases} 1 & \text{steel}, \\ 0 < \alpha < 1 & \text{interface between gas and steel}, \\ 0 & \text{gas}, \end{cases} \]

with its dependencies for the material properties of density and viscosity.

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3 Results

Many theoretical models study the primary breakup of liquid steel to gain uniform metal powder [3]. The results from this study show that a flow rotation can improve particle production. Therefore, the primary breakup influenced by a RMF is investigated by varying influencing parameters like magnetic field strength $B_0$ or rotational frequency $f$, see Figure 1.

![Jet formation length from nozzle exit](image1)

Fig. 1: Free-falling steel melt jet influenced by a RMF with a contour plot of the jet ($\alpha = 0.5$) at $t = 0.5$ s. Left: Comparison of different magnetic field strengths $B_0$ for $f = 50$ Hz with the gas velocity in the background. Right: Comparison of different rotational frequencies for $B_0 = 0.75$ T.

In order to compare the influencing factors, a free-falling melt jet without a RMF is presented in 1. By increasing $B_0$, the formation of a helix-structured surface up to a hollow-cone jet shape can be seen, see result 2 and 3. Moreover, a faster jet disintegration in the primary breakup regime occurs. The background gas velocity gets accelerated due to the rotational outflow and promotes atomization. The arising velocities lead to an increasing Reynolds number up to $5.5 \times 10^4$ for $B_0 = 0.75$ T and $f = 50$ Hz.

By intensifying the rotational frequency, the jet develops flat, twisted sheets with surface waves, see Figure 1 results 4 to 6. Additionally, a breakup into spanwise ligaments and droplets occur faster at higher frequencies. The jet spreading and the formation of a hollow-cone appears also quicker. This is visible for the disintegrated formation length of the free-falling jet. For example, the so-called widening length can be scaled with 41 mm for $f = 10$ Hz and 13 mm for $f = 50$ Hz (with $B_0 = 0.75$ T).

4 Conclusion

The results of the simulation provide an insight into the complex flow phenomena of a free-falling gas atomization process and its primary breakup procedure. Furthermore, the developed numerical model enhanced by a RMF is able to track its influence with different adjustments. It shows that a RMF generates a faster primary breakup and the frequency influences the process by gaining more and smaller particles than an increasing magnetic field strength. In the interest of advancing understanding on this matter, future research of applying the model with a supplemented gas stream to optimize experimental parameter settings is considered.

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