Oral presentation | Industrial applications
Industrial applications-I
Mon. Jul 15, 2024 4:30 PM - 6:30 PM Room B

[3-B-03] Influence of Vortical Structures on Liquid Metal Breakup in Atomization Process

*Seunghan Lee[1], Jinyul Hwang[1] (1. Pusan National University)

Keywords: Computational Fluid Dynamics, Vortical Structure, Two Phase Flow, Primary Breakup

Influence of Vortical Structures on Liquid Metal Breakup in Atomization Process

Seunghan Lee* and Jinyul Hwang*
Corresponding author: jhwang@pusan.ac.kr
* School of Mechanical Engineering, Pusan National University, Busan, Korea

Abstract: High-pressure gas atomization is crucial for producing high-quality metal powders with desired properties. This study explores the influence of vortical structures on the primary breakup of molten aluminum in an annular-slit close-coupled gas atomizer, with the atomizing gas as nitrogen. The numerical simulation is performed using the volume of fluid model in OpenFOAM. We extract individual liquid metal objects in instantaneous flow fields and track these identified objects temporally to examine their breakup process. We also simultaneously detect the surrounding vortical structures. It is found that vortical structures play a critical role in the fragmentation of the liquid metal into ligaments and droplets. The droplet size distribution follows a log-normal pattern, and in particular, finer droplets are generated close to the metal nozzle after the formation of liquid film on the nozzle surface. We observe that the liquid film on the metal nozzle surface is induced by the vortical motions, and at the tip of the liquid film, spherical liquid droplets are generated. These findings provide insights into optimizing gas atomization processes by understanding turbulence effects.

Keywords: Computational Fluid Dynamics, Vortical Structure, Two Phase Flow, Primary Breakup.

1 Introduction

The development of additive manufacturing technologies has led to an increased demand for high-quality metal powders. Among many powder manufacturing methods, high-pressure gas atomization stands out due to its high sphericity, adjustable particle size, low oxygen content, and cost efficiency. For the advanced development of this process, precise measurement and analysis are essential; however, due to the limitations of experimental methods, research using simulation is necessary.

In the high-pressure gas atomizer process, high-speed gas jets are utilized to atomize the molten metal or alloy into fine particles. This process encompasses intricate flow dynamics, including the atomization of molten metal. The atomization is generally composed of two stages, i.e., primary and secondary breakup. The molten material breaks up into ligaments and droplets during primary atomization. This is succeeded by secondary atomization, where these droplets are further disintegrated into smaller droplets. A comprehensive understanding of the atomization mechanism is crucial for obtaining high-quality metal powder.

To comprehend the atomization process, it is essential to simulate the molten metal and gas flow concurrently [1]. Given that turbulent gas flow is composed of a wide range of vortical structures, these structures are presumed to play a significant role in the primary breakup. Therefore, this study aims to explore the influence of vortical structures on the breakup process of molten metal in the gas atomizer process using numerical simulation.

2 Numerical Details

The geometry and simulation setup for the gas atomizer are the same as those in [2]. Nitrogen was chosen as the atomizing gas, with aluminum serving as the molten metal, and the atomization process was conducted using an annular-slit, close-coupled gas atomizer. Both the gas and the molten metal were assumed to be incompressible fluids for this simulation. We conducted the simulation using

OpenFOAM multiphase flow solver, where the primary breakup of liquid metal in the gas atomizer was specifically simulated using the Volume of Fluid (VOF) model. This simulation approach allowed for a detailed capture of the interactions between metal and gas, as well as the formation of ligaments and droplets, on a three-dimensional scale. The computational domain was defined by a 90-degree wedge geometry, leading to the implementation of two independent symmetric boundary conditions. To optimize the observation of the primary breakup process and reduce computational demands, a 20mm column of molten metal from the inlet was designated as the initial field. We used large-eddy simulation with the Smagorinsky-Lilly subgrid-scale model.

3 Result and Discussion

Figure 1 shows the instantaneous flow field at an early stage of the entire simulation. The orange iso-surfaces represent the VOF value of 0.1 for the melt, while the black and white contours denote the gas velocity magnitude. The primary breakup process, characterized by the fragmentation of the main column into ligaments and large droplets due to the action of high-speed gas, is clearly observable. To further explore the interaction between the metal and the vortical structures, we employed a method similar to that used in our previous work [3] for extracting individual objects in the instantaneous flow field. The droplet size distribution range of the droplets extracted this way was found to be consistent with previous studies and was verified to follow a log-normal distribution. Continuing our exploration, we analyzed the interaction between breakup processes and surrounding vortical structures, focusing on the time evolution of melt as it deforms and breaks up [4, 5]. Figure 2(a) shows the melt at a moment when the breakup process is actively occurring. Figure 2(b–e) indicates the process where a ligament detaches from the main column and eventually breaks off as a droplet over time, influenced by the surrounding vortical structures. In the figure, the blue iso-surfaces represent vortical structures, identified by Q-criterion. To nondimensionalize time, we employ the inertial time scale of drop, given by $t_d = (d^2/\varepsilon)^{1/3}$, a time scale used for analyzing a single drop in homogeneous isotropic turbulence [6]. Here, d represents the diameter of a single spherical diameter and ε denotes the dissipation rate. In this study, we define d as the length of a ligament. In figure 2(c,d), the ligament is stretched by the surrounding vortical structures. The ligament gradually becomes thinner and breaks up as a droplet in figure 2(e). The time required for such a ligament to breakup into a droplet is $2.46t_d$. This result implies that the length of the ligament is affected by turbulent velocity fluctuations, indicating a connection with turbulence.

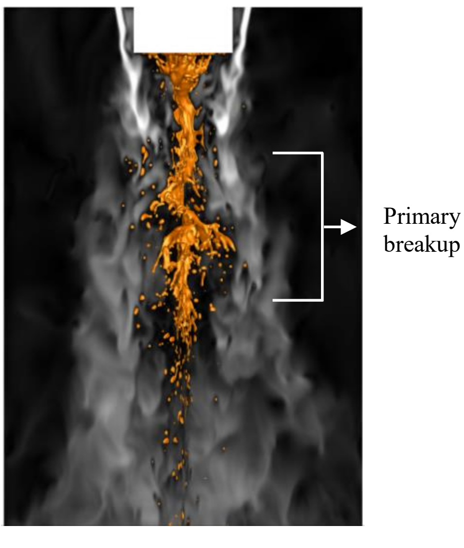

Figure 2: Primary breakup of a 3-D melt under a gas pressure of 2.5 MPa.

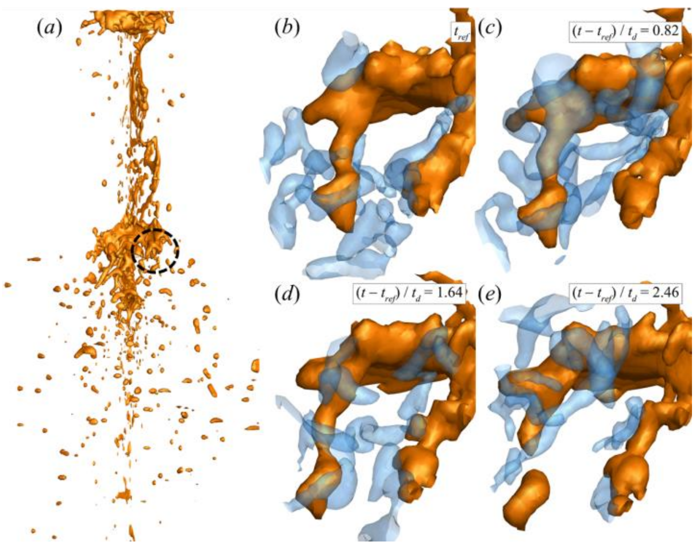

Figure 1: Temporal evolution of melt deformation and breakup with surrounding vortical structures identified by the Q-criterion.

Another significant flow phenomenon observed in a gas atomizer is the recirculation zone. When the obliquely ejected gas jet encounters liquid metal or gas in the opposite direction, it creates a rotating recirculation region at the front of the nozzle. The recirculating gases push the liquid metal against the melt nozzle surface, forming a film. This swirling motion induces the formation of a liquid film on the melt nozzle surface [7]. The formation of this film is the main factor influencing the production of small, spherical, high-quality powders. Figure 3(a) shows the recirculation zone and the film formed at the front of the nozzle. Spherical droplets are observed breaking up at the edge of the film. Here, D is the diameter of the melt nozzle. The gas flow field can be divided into near-field and far-field. The downstream region of the melt nozzle, approximately 3-4D in length, is referred to as the near field. The gas jet in the near field is characterized by high kinetic energy, resulting in substantial atomization in this region. The region further downstream is referred to as the far field.

In this study, the identified droplets were classified into three categories using aspect ratio (= d_{max}/d_{min}) and sphericity (= $(3V/4\pi)^{-1/3}/d_{max}$) [8]. Here, d_{min} and d_{max} indicates the minimum and maximum diameter of the droplets, respectivley, and V is the volume of the droplet. According to these morphological parameters, the droplets are classified into three groups: fibers, spheres, and ligaments. Those with sphericity below 0.4 and aspect ratio above 3 are fibers; with sphericity above 0.4 and aspect ratio below 3 are spheroids; and with both sphericity and aspect ratio above 0.4 and 3, respectively, are ligaments [9]. Figure 3(b) shows the distribution of droplets with respect to the aspect ratio and the sphericity in the near and far regions. Here, the colors blue, red, and yellow represent fibers, spheres, and ligaments, respecitvley. In the far-field region, the proportion of fibers is the highest, and the proportion of spherical droplets is the lowest. On the other hand, in the near region, the proportion of fibers decreases, and the proportion of spherical droplets becomes the majority. This is expected because, in the near-field region, the melt forms a thin film and is pushed toward the high kinetic energy gas jet. Figure 3(c) shows a histogram of the radial position of these spherical droplets when break-up occurs. It can be seen that most spherical droplets occur at the edges of the film, with the proportion increasing closer to the edge. These results suggest the importance of controlling the flow in the near-field region to obtain spherical, high-quality powders in the gas atomizer.

The present study demonstrates the relationship between vortical structures and the breakup of melt in the atomization process, suggesting that turbulence structures have an influence on primary atomization. We have shown that the recirculation zone and the induced pre-filming phenomenon are crucial for producing small, spherical, high-quality powders. The swirling motion of the recirculating gases creates a thin film on the metal nozzle surface, leading to the detachment of spherical droplets at the film's edge. In this talk, we will analyze the geometrical features of each identified droplet with surrounding vortical structures. We will also focus on analyzing the size distribution of droplets and the characteristic time scale of the associated breakup process, considering the strength of the surrounding vortical structures. Figure 3(c) demonstrates that most spherical droplets originate at the edges of the film, with their proportion increasing closer to the edge, suggesting the importance of controlling the flow in the near-field region to achieve high-quality powder production. Our research provides insights into controlling gas atomizer processes by manipulating vortical structures and flow characteristics in the near-field region. Understanding these dynamics can lead to improved efficiency and quality in the production of metal powders.

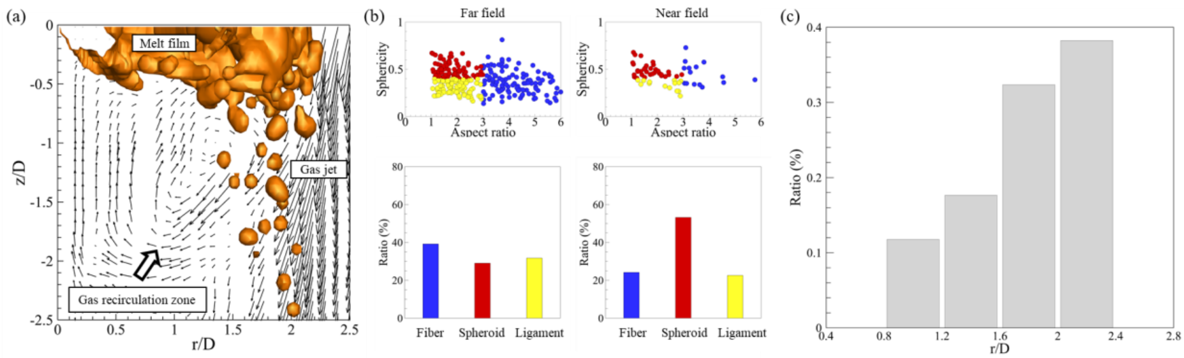

Figure 3: Droplet statistics in the near field. (a) Iso-contour of the melt showing the liquid film formation on the melt nozzle surface and the breakup of droplets at the film tip. (b) Scatter plot of the droplets' aspect ratio and sphericity in far field and the near field, along with the ratio among three droplet morphologies. (c) Histogram of the initial radial position of the spherical droplets' primary branch.

Acknowledgments

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (Grant No. RS-2023-00211896 and Grant No. 2022M3H4A3095288).

References

[1] Zeoli, N., et al. CFD modeling of primary breakup during metal powder atomization. Chem. Eng. Sci. 66**:** 6498-6504, 2011

[2] Arachchilage, K. H., et al. Numerical simulation of high-pressure gas atomization of two-phase flow: Effect of gas pressure on droplet size distribution. Adv. Powder Technol. 30**:** 2726-2732, 2019

[3] Hwang, J. and H. J. Sung Wall-attached clusters for the logarithmic velocity law in turbulent pipe flow. Phys. Fluids. 31, 2019

[4] Hwang, J. and H. J. Sung Wall-attached structures of velocity fluctuations in a turbulent boundary layer. J. Fluid Mech. 856: 958-983, 2018

[5] Yang, J., et al. Influence of wall-attached structures on the boundary of the quiescent core region in turbulent pipe flow. Phys. Rev. Fluids. 4: 114606, 2019

[6] Vela-Martín, A. and M. Avila Deformation of drops by outer eddies in turbulence. J. Fluid Mech. 929**:** A38, 2021

[7] Ouyang, H.-W., et al. Influence of melt superheat on breakup process of close-coupled gas atomization. Trans. Nonferrous Met. Soc. China. 17: 967-973, 2007

[8] Han, S., et al. Morphological classification of disintegration behavior of viscoelastic simulant gel propellant in coaxial streams. J. Vis. 23: 287-298, 2020

[9] Luo, S., et al. 3D numerical modeling of gas atomization process for powder preparation based on similarity theory. Powder Technol. 433: 119244, 2024