Chemical Engineering Science 66 (2011) 6498–6504

Contents lists available at SciVerse ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

CFD modeling of primary breakup during metal powder atomization

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ARTICLE INFO

Article history:
Received 22 June 2011
Received in revised form
1 September 2011
Accepted 7 September 2011
Available online 22 September 2011

Keywords:
CFD
Metal powder
Gas atomization
Primary break-up
VOF
Modeling

ABSTRACT

Powder metals are the basis of powder metallurgy with a large variety of applications, including sintering and thermal spray coatings. The Gas atomization process has been widely employed as an effective method to produce fine spherical metal powders. New applications and emerging surface technologies demand high quality powders with a very narrow particle size distribution. A computational fluid dynamics (CFD) approach is developed to examine complex fluids during atomization from different nozzle designs, using the volume of fluid (VOF) method and the Reynolds Stress Model (RSM). The modeling results show that the swirling gas atomizer is not beneficial to the atomization process while the inner-jet atomizer can improve the powder generation processing.

1. Introduction

Powder metals are the basis of powder metallurgy with a large variety of applications, including sintering and thermal spray coatings. New applications and emerging surface technologies demand high quality powders with a very narrow particle size distribution. Two good examples include the dye-sensitized solar cell (Grätzel, 2003) and bioactive prosthetic implants with anti-bacterial components (Bai et al., 2010). Powder shape is also often a prerequisite, which may be spherical, flake like, hollow or irregular. Despite the rapid development of surface technology over the last decade, the methods of producing metal powders have not changed significantly and are divided into three main categories: chemical, mechanical and physical (Neikov et al., 2007).

This investigation is targeted towards the physical atomization of a liquid melt by a high speed gas jet. The gas–melt atomization process has been widely employed as an effective method to produce fine spherical metal powders (Berndt and Lenling, 2004). The principle of high pressure gas atomization is to transfer kinetic energy from a high-speed gas jet to a liquid metal stream. The liquid metal stream in turn becomes unstable and breaks into ligaments that are successively atomized (Lawley, 1978). The particles produced in this process then undergo in-flight solidification and are collected as metal powder. The most widely employed processes in industrial practice to produce metal powders are close-coupled and free-fall atomization. The underlying difference between these two technologies is the location of gas–melt interaction. Fig. 1 highlights the main characteristics of the two systems, showing that the gas exit is confined to the melt delivery tube in close-coupled atomization while in the free-fall atomization a distance varying from 10 cm to 30 cm is maintained between the exit of melt feeding tube and the gas exit. This distance allows the melt to flow downward in quiescent air before the high velocity gas interacts with the melt. Close-coupled atomization is able to produce finer powders despite the drawbacks of backflow and freeze-off that normally do not occur during free-fall atomization. This study focuses on the close-coupled atomization technology due to the overwhelming demand from industry on high quality fine powders.

The design of the gas nozzle is critical in order to achieve a gas energy that is high enough to destabilize the melt. Up to now, two different gas nozzles are widely used for the close-coupled atomization, namely the annular-slit and the discrete-jet nozzle. The annular-slit nozzle is an annular slot surrounding the melt feeding tube while the discrete-jet nozzle is made of a number of discrete holes. The annular-slit nozzles are more widely used by industry due to their superior performance in comparison with the discrete-jet nozzles, and therefore are used as the basis of this investigation.

Thompson (1948) performed the earliest detailed study of Aluminum close coupled atomization. He analyzed the influence of the process parameters, such as gas pressure, metal temperature

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doi:10.1016/j.ces.2011.09.014

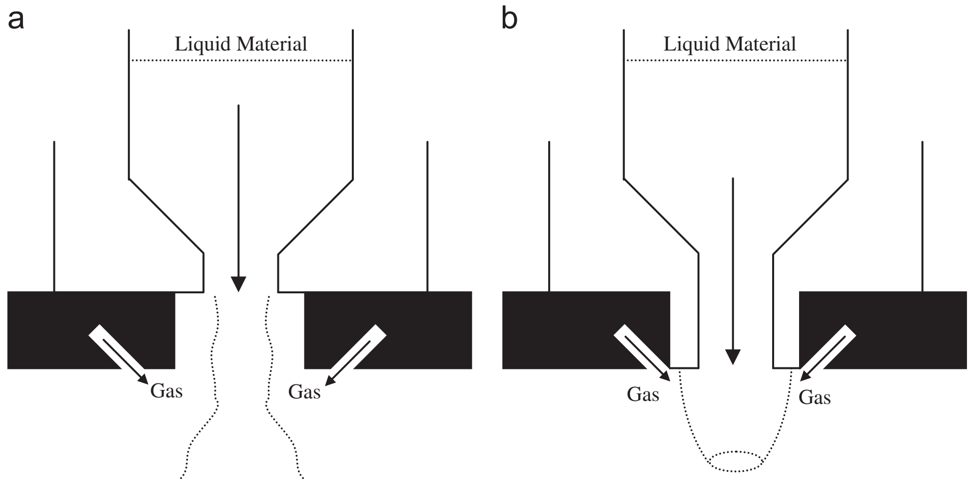

Fig. 1. Schematic diagram of free-fall gas atomization (a) and close-coupled gas atomization (b).

and metal flow rate, on the powder sizes. However, it was not until the 1980s, due to the driven interest in powder microstructure, this research activity grew. Further research followed in order to investigate the effects of different operating conditions on the atomization process, including the operational gas pressure by Couper and Singer (1984); gas type, gas–melt flow ratio and the melt temperature Unal (1987); and the preheated gas temperature by Strauss (1999). The best yielding gas stagnation pressure for the production of the finest powder was found to be one, which minimizes the static pressure at the melt exit orifice. Helium was found to produce the finest powder while the most coarse powder was obtained by Argon.

Alongside these investigations, several design tests have also been carried out in order to optimize the atomization process. Miller et al. (1997) made a comparison between axisymmetric and non-axisymmetric nozzle geometries. The results showed that the yield of fine powder is improved by the use of a non-axisymmetric configuration. Mates et al. (2000) investigated four different converging nozzle geometries, three with discrete number of nozzles and one with annular slit. The process showed that droplet breakup is driven by the dynamic pressure but it is not confined to the nozzle tip region. In fact the atomization continues far from the melt exit. Hence, the distance over which the dynamic pressure is kept high plays an important role, and a long supersonic jet improves the interaction between melt and gas, producing finer droplets. Pressure profiles demonstrated that the increase in gas operating pressure corresponded to a longer supersonic plume due to the higher momentum of the gas flow. The annular nozzle produced a longer supersonic jet with higher dynamic pressure over the examined pressure range. A comprehensive overview on close coupled gas atomization was published by (Mates and Settles (2005a, 2005b). They analyzed the characteristics of gas only flow and related performance during metal atomization for both converging and converging diverging nozzles. According to their results, the jet plume was almost the same for the two configurations. The microsecond exposure Schlieren images clearly identify primary break-up close to the nozzle tip and secondary break-up up to 10 nozzle diameters from melt exit. Large un-atomized droplets were visible downstream in the jet core, while fine particles exist in the outer region at the same distance. The strength of gas core is weakened by the mass loading of the carried particles, causing reduction in the amount of melt atomization. Similar yielding was achievable with different nozzle geometries when stagnation pressure and gas–melt flow ratio are approximately the same. With the aim of maintaining a narrow particle size range Lagutkin et al. (2004) proposed a pressurized centrifugal nozzle for melt where liquid metal leaves the nozzle as a hollow cone; in this way the melt prefilming is ensured and the primary breakup is more efficient. The concept of isentropic plug nozzles for gas atomization is proposed by Zeoli and Gu (2008) to reduce the shocks and maximize kinetic energy being transferred from the gas to instablize the melt stream while a 2d model was developed for the gas flow and droplet breakup.

This paper is a numerical simulation based investigation whereby the volume of fluid (VOF) computational fluid dynamics (CFD) approach is utilized. The purpose of the investigation is to aid the development of the gas atomization process for metal powder production. Hence, the unsteady features of a liquid melt are captured close to the nozzle exit for three different geometries, namely, the annular-slit atomizer, the gas-swirl atomizer and the inner gas jet atomizer, in order to evaluate their performance.

2. Numerical methods

The computational domains for the annular-slit atomizer, the gas swirl atomizer and the inner gas jet atomizer are depicted in Fig. 2, and a sketch of each nozzle is given in Fig. 3. For the gas swirl atomizer, gas enters the atomization nozzle from inlet 1 and inlet 2 faces and leaves the atomization nozzle after the expansion over a 15° conical plug. The grid for each computational domain is made of 1.2 million structured computational cells, apart from the head of the gas swirl atomizer, which is unstructured. The nitrogen operating pressure is 12 atm and the inlets are assumed to be directly connected to the reservoir.

For all scenarios the grid is refined at the plug nozzle wall in order to capture the boundary layer features. The boundary conditions are pressure inlet for the entering gas and pressure outlet at the chamber interface. Nitrogen is modeled as a perfect gas and the metal stream as a liquid with the properties listed in Table 1. A pressure based solver with second order implicit time discretization is used for the solution of the flow equations. The semi-implicit method for pressure linked equations (SIMPLE) algorithm (Patankar, 1980) is applied to determine the pressure correction term. Second order space discretization requires the use of low under-relaxation factors to avoid solution divergence. The volume of fluid (VOF) method together with the Reynolds Stress Model (RSM) is applied to capture the unsteady, turbulent solution of the two phase flow field. The simulations were