Prediction of powder particle size during centrifugal atomisation using a rotating disk

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Received 6 September 2006; received in revised form 25 December 2006; accepted 19 March 2007

Available online 29 May 2007

Abstract

The centrifugal atomisation of metallic melts using a rotating disk is an important process for powder production and spray deposition. The theoretical prediction of powder particle size is desirable for the design of atomisers. In this paper, wave theory was applied to analyse the disintegration of metallic melts in the film disintegration regime during centrifugal atomisation using a rotating disk. A mathematical model was proposed to predict the spray parameters. The governing equation for the fastest-growing wave number was developed and solved numerically. The effect of the variation in film thickness during film extension was taken into account. Film length and powder particle size were calculated and compared with available experimental data in the literature, and a good agreement was achieved. The influence of the break-up parameter was studied, and it is shown that the break-up parameter is not sensitive to the predicted powder particle size. Both simulated results and experimental data showed that fine powders can be produced by increasing disk speed.

Keywords: Powder size; Prediction; Wave theory; Rotating-disk atomisation; Liquid break-up

1. Introduction

Centrifugal atomisation using a rotating disk, originally developed by the Pratt & Whitney Aircraft Group for the production of rapidly solidified Ni-based superalloy powders [1], is currently used for manufacturing powders and near-net-shape preforms of a variety of metals and alloys, which include Sn, Pb, Zn, Cu, Al, Mg, Ni and Ti-based alloys, superalloys and steels [2–5]. The process utilises a rapidly rotating disk to break-up a liquid metal stream into a spray of droplets, which either solidify in flight to form spherical particles with a narrow size distribution or are deposited onto a substrate to form microstructurally refined and chemically homogeneous preforms.

The observations and studies of the centrifugal atomisation of both normal liquids [6] and metallic melts [5,7–9] have shown that liquids/melts break-up according to one of three basic modes. These three basic modes are: (1) direct droplet formation (DDF), (2) ligament disintegration (LD) and (3) film disintegration (FD). Hinze and Milborn [6] studied the transition conditions from DDF to LD and from LD to FD for normal liquids and gave empirical criteria for the transition. Champagne and Angers [7] and Halada et al. [8] successfully applied these criteria to the centrifugal atomisation of metallic melts and developed a centrifugal atomisation map for metallic melts.

Metal powders have been produced by rotating-disk centrifugal atomisation. Cherre and Accary [9] atomised Bi–Sn eutectic alloy and studied the effects of disk diameter, disk rotating speed and atomising gas on median powder particle size. Dogan and Saritas [10] investigated the effects of disk shape, pouring temperature and melt flow rate on the morphology of powder particle size and size distribution of Pb, Al and 8640 steel. Xie et al. [5] observed the morphology of tin powders produced in an LD regime using a rotating disk. Zhao [4] simulated the deposition process on a tilted rotating cylindrical substrate. Li and Tsakiropoulos [11] developed a model to calculate...
powder particle sizes produced in the DDF regime. In this paper, we use wave theory to analyse the disintegration of metallic melts beyond a rotating disk and to predict the powder particle size formed in the FD regime.

2. Mathematical formulation

2.1. Instability of a liquid sheet

When a melt is directed onto the centre of a rotating disk, it spreads radially outward and forms a thin film along the surface of the disk. At high flow rates and high rotating speeds, the film can extend beyond the disk to a certain distance, which is known as the film length, and then disintegrates into droplets, as shown in Fig. 1.

Experiments on the atomisation of both normal liquids [12] and metallic melts [7] showed that waves induced by disturbances on the sheet result in the disintegration of the sheet.

Let us assume that a small periodic disturbance is imposed on the sheet. The amplitude of wave can be expressed by

\[ a = a_0 \exp(\beta_1 \tau), \]  

where \( a_0 \) and \( a \) are the initial amplitude and the amplitude at time \( \tau \) of the disturbance, respectively, and \( \beta_1 \) is the growth rate. If \( \beta_1 \) has a negative value, the disturbance will decay with time and the system is stable. When \( \beta_1 \) is positive, the disturbance will grow, and at a certain time it will reach a critical amplitude and break-up into fragments. In this case the system is unstable.

The studies by previous researchers [11,13–15] have shown that the ratio of the amplitude at break-up to that of the initial disturbance is approximately constant (\( \ln(a^*/a_0) \approx 12 \)). On the basis of this finding, one can calculate the break-up time \( \tau^* \) and the film radial extent (film length) \( x^*_r \) once the growth rate \( \beta_1 \) and radial velocity \( u_r \) of the sheet beyond the disk are known.

The break-up time can be calculated from

\[ \tau^* = \frac{1}{\beta_1} \ln\left(\frac{a^*}{a_0}\right), \]  

and the film length at break-up is given by

\[ x^*_r = \int_0^{\tau^*} u_r \, d\tau. \]  

2.2. Growth rate and fastest-growing wave number

The instability of a thin sheet moving into a surrounding gas has been studied by many researchers. Squire [16] analysed the instability of a two-dimensional inviscid sheet of uniform thickness in an inviscid gas. Hagerty and Shea [17] performed a similar analysis for a two-sided inviscid sheet. Dombrowski and Johns [18] extended Squire’s and Hagerty and Shea’s research by examining a more realistic case where the liquid viscosity and variation of sheet thickness as the sheet moves away from an orifice were taken into account. Li and Tankin [19] gave a detailed analysis of the instability of a two-dimensional inviscid sheet moving into an inviscid gas medium. More recently, Senecal et al. [13] summarised the wave theories of sheet disintegration and carried out a more practicable analysis.

In centrifugal atomisation using a rotating disk, metallic melt is delivered onto the centre of a disk. The melt flows on the disk and beyond the disk are axially symmetric, thus, the break-up of the extended sheet beyond the disk is also axially symmetric. Hence, in the study of the instability of the sheet we mainly need to consider the break-up in the radial direction. In this paper, Senecal et al.’s modified dispersion equation will be used to analyse the disintegration of metallic melts beyond a rotating disk.

Consider a two-dimensional thin film of melt of density \( \rho_1 \), viscosity \( \mu_1 \) and surface tension \( \sigma \) moving with a velocity \( v \) through a stationary gas of density \( \rho_2 \); see Fig. 1.

The growth rate of the disturbance as a function of the wave number, which is known as the dispersion relation, is given by [13]

\[ \beta^2 \left[ \tanh(kh/2) + \frac{\rho_2}{\rho_1} \right] + \beta \left[ \frac{4}{\rho_1} \frac{\mu_1}{k^2} \tanh(kh/2) \right. \]
\[ + 2i \frac{\rho_2}{k \rho_1} \left[ \frac{4}{\rho_1} \left( \frac{\mu_1}{k^2} \right)^{2/3} \tanh(kh/2) \right. \]
\[ - 4 \left( \frac{\mu_1}{\rho_1} \right)^{2/3} \left[ k^2 + \frac{\beta \rho_1}{\mu_1} \right]^{0.5} \tanh \left[ \left( k^2 + \frac{\beta \rho_1}{\mu_1} \right)^{0.5} h/2 \right] \]
\[ - v^2 k^2 \frac{\rho_2}{\rho_1} + \frac{\sigma k^3}{\rho_1} = 0, \]  

where \( \beta \) is the complex growth rate and can be further written as \( \beta = \beta_1 + i\beta_1 \); \( h \) is the thickness of the film and \( k \) is the wave number. Eq. (4) has a solution:

\[ \beta_1 = -\frac{2(\mu_1/\rho_1)k^2 \tanh(kh/2)}{\tanh(kh/2) + \rho_2/\rho_1} \]
\[ \frac{4(\mu_1/\rho_1)^2 k^4 \tanh^2(kh/2) - (\rho_2/\rho_1)^2 v^2 k^2}{1 - [\tanh(kh/2) + \rho_2/\rho_1] \left( (\rho_2/\rho_1)v^2 k^2 + \sigma k^3/\rho_1 \right) \tanh(kh/2) + \rho_2/\rho_1} \]  

When \( \rho_2/\rho_1 \ll kh \), Eq. (5) reduces to

\[ \beta_1 = -\frac{2(\mu_1/\rho_1)k^2}{\rho_1} + \sqrt{\frac{(\mu_1/\rho_1)^2}{k^4} + \frac{2\rho_2v^2 k^2}{\rho_1 h} - \frac{2\sigma k^5}{\rho_1 h}}. \]
It can be seen from Eq. (6) that the growth rate is function of the film thickness, film velocity and wave number, and depends on the physical properties of the melt and gas. When the properties of the melt and gas and the film thickness are kept constant, the growth rate depends only on the wave number. At some wave number, the growth rate reaches a maximum (see Fig. 2). The wave number corresponding to the maximum growth rate can be found by differentiating the growth rate with respect to the wave number and equating it to zero.

Substituting Eq. (10) into Eq. (9) gives the film thickness as

$$h = \frac{Q}{\pi (d + 2x_t) u_r},$$

where $Q$ is the flow rate of the melt, $d$ is the disk diameter, $x_t$ is the radial position of the extended film from the edge of the disk and $u_r$ is the radial velocity of the extended film, which can be calculated from [14]

$$u_r = \frac{1}{(d + 2x_t)} \sqrt{v^2(d + 2x_t)^2 - d^2(v^2 - u_m^2)}.$$  

Substituting Eq. (10) into Eq. (9) gives the film thickness

$$h = \frac{Q}{2\pi v \sqrt{(d^2u_m^2/4v^2 + x_t d + x_t^2)}},$$

where $v$ and $u_m$ are the velocity of the film and its radial component at the edge of a disk, respectively, which can be determined from [8,14]

$$v = \sqrt{(\omega R)^2 + u_m^2},$$

$$u_m = \frac{1}{(2\pi^2\mu_1 R)} \sqrt{\frac{\rho_1 \omega^2 Q^2}{12\pi^2\mu_1 R}}.$$  

2.3. Film thickness during film extension

Assuming that the radial velocity of the film after the melt leaves the edge of a rotating disk is $u_r$, the film thickness can be found by applying mass conservation and is given by

$$h = \frac{Q}{\pi (d + 2x_t) u_r},$$

where $Q$ is the flow rate of the melt, $d$ is the disk diameter, $x_t$ is the radial position of the extended film from the edge of the disk and $u_r$ is the radial velocity of the extended film, which can be calculated from [14]

$$u_r = \frac{1}{(d + 2x_t)} \sqrt{v^2(d + 2x_t)^2 - d^2(v^2 - u_m^2)}.$$  

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Because of the dependence of the film thickness on the position in the extended film and the complexity of Eq. (7), an iteration method was used to numerically calculate the fastest-growing wave number and the maximum growth

Fig. 2. The relation between the wave number and the growth rate for Bi–Sn alloy atomised using a disk of diameter 0.03 m.
rate at different positions of the film and the film length at break-up.

2.4. Calculation of powder particle size

Dombrowski and Hooper [15] have proposed a model to calculate the droplet size from a fan-shaped spray nozzle. In their model, the wave on a sheet continues to grow until the wave reaches the critical amplitude and the crests are nipped off, thus breaking the sheet into fragments with half the wavelength. These fragments rapidly contract into ligaments, which in turn break-up into droplets, as shown in Fig. 1. Using this model and Weber theory on the disintegration of a cylindrical jet, the droplet size can be calculated.

The diameter of the ligaments formed from the fragments of half wavelength and one-sheet thickness can be calculated from the conservation of mass and is given by [15]

\[
d_l = \frac{2}{k_{\text{opt}}} \sqrt{4h_n}, \tag{15}
\]

where \( h_n \) and \( k_{\text{opt}} \) are the film thickness and the fastest-growing wave number at the break-up of the film, respectively, and can be calculated from Eqs. (11) and (7), respectively.

The droplet size produced from the break-up of a ligament can be obtained from Weber theory [11]:

\[
d_p = \frac{3}{2} \lambda_{\text{opt}} d_l, \tag{16}
\]

where \( \lambda_{\text{opt}} \) is the optimal wavelength of the wave on the ligament and is given by

\[
\lambda_{\text{opt}} = \sqrt{2\pi d_l \left[ 1 + \frac{3\mu_1}{\rho_1 \sigma d_l} \right]}, \tag{17}
\]

After solidification, the mean powder particle size can be calculated using mass conservation and is given by

\[
d_s = d_p \sqrt{\frac{\rho_1}{\rho_s}}, \tag{18}
\]

where \( \rho_s \) is the density of the powder.

2.5. Solution method

The above model can be used to calculate the film length and powder particle size. A computer program has been written to perform the calculation. The programme flow chart is shown in Fig. 3.

First, the related data, which include the physical properties of the metallic melt and gas medium, disk diameter, disk speed, the flow rate of the melt, and control parameters are input to a computer. After checking the break-up mode, a film length is assumed and used for the initial evaluation. Then the film thickness, the fastest-growing wave number and the maximum growth rate at the different positions of the extended film are calculated. Once the break-up time is obtained, the film length can be calculated and compared with the assumed
value. When the difference between the two values is less than the preset error, the iteration ends. Finally, the powder particle size can be found after the film thickness and the fast-growing wave number at the break-up are obtained.

3. Results and discussion

3.1. Comparison of calculated and experimental film lengths

Kamiya and Kayano [20] atomised aqueous millet jelly solutions by the rotating-disk method and studied in detail the effects of atomising conditions on spray parameters. Fig. 4 shows the film length predicted by our model compared with the experimental data for two kinds of aqueous solutions of millet jelly under different operating conditions. The physical properties of the two solutions are given in Table 1 [20].

It can be seen from Fig. 4 that with increasing disk speed, the calculated film lengths for the two solutions decrease and are in reasonable agreement with the experimental results. For Solution I, our calculation underestimates the film length. For Solution II, the predicted film lengths are higher than the experimental values. A possible reason is the difference in the physical properties between two solutions.

Table 1

| Physical properties of aqueous solutions of millet jelly |
|--------------------------------------------------------|
| Density (Kg m\(^{-3}\)) | Surface tension (N m\(^{-1}\)) | Viscosity (Ns m\(^{-2}\)) |
|--------------------------|-------------------------------|---------------------------|
| Solution I               | 890                           | 0.0364                    | 0.134                     |
| Solution II              | 1310                          | 0.087                     | 0.197                     |

3.2. Comparison of calculated and experimental powder sizes

Cherre and Accary [9] atomised Bi–Sn alloy in a 5% H\(_2\)–Ar atmosphere using a disk of 0.03 m at the flow rate of 3.5 \times 10\(^{-6}\) m\(^3\)/s and studied the effect of disk rotating speed on the powder size. The physical properties of the Bi–Sn alloy used in our calculation are given in Table 3 [21].

Fig. 5 shows the calculated and experimental mean powder sizes as a function of disk rotating speed.

It can be seen from Fig. 5 that the general trend of the calculated powder particle size matches the experimental data well and shows that wave theory can be used to predict the powder particle size resulting from centrifugal atomisation using the rotating-disk method reasonably well. It can also be seen that the calculated and experimental powder particle sizes decrease with increasing disk speed. Therefore, fine powders can be produced by increasing the disk speed.
3.3. Effect of break-up parameters

One important assumption in our model is that melts break-up when the ratio of the amplitude of waves at the break-up to the initial amplitude reaches a constant \( \ln \left( \frac{a^*}{a_0} \right) = 12 \). Although the assumption is based on the findings of experiments by previous researchers, we still examine the influence of the parameter on our predicted results. Fig. 6 shows the dependence of the calculated powder particle size on the parameter.

It can be seen that the predicted powder particle size is not very sensitive to the break-up parameter. A larger break-up parameter implies that the film travels a longer distance before it breaks up. Far from the disk, the film becomes thinner and this leads to smaller powder particles.

4. Conclusions

Melt break-up in the film disintegration regime during centrifugal atomisation using a rotating disk has been analysed using wave theory. A mathematical model was proposed to predict the spray parameters. The calculated film length and powder particle size as a function of disk speed show reasonable agreement with the limited experimental data in the literature. Fine powders can be produced by increasing disk speed.

Notation

- \( a \): amplitude of wave
- \( a^* \): amplitude of wave at break-up
- \( a_0 \): initial amplitude of wave
- \( d \): diameter of disk
- \( d_l \): diameter of ligament
- \( d_p \): mean droplet size
- \( d_s \): mean powder particle size
- \( h \): thickness of film
- \( h_0 \): film thickness at the edge of a disk
- \( h^* \): film thickness at the break-up
- \( k \): wave number
- \( k_{opt} \): fastest-growing wave number
- \( k^{*}_{opt} \): fastest-growing wave number at the break-up
- \( Q \): melt flow rate
- \( R \): radius of disk
- \( Re \): Reynolds number, \( Re = \omega \rho_1 R^2 / \mu_1 \)
- \( u_0 \): mean radial velocity of the film at the edge of a disk
- \( u_r \): radial velocity of extended film
- \( v \): velocity of the film
- \( v_t \): tangential velocity of the film
- \( We \): Weber number, \( We = \rho_1 \omega^2 R^3 / \sigma \)
- \( x_r \): radial film position
- \( x_r^e \): calculated radial film length at the break-up
- \( x_r^e \): initial estimate of radial film length at the break-up

Greek symbols

- \( \beta_r \): real growth rate
- \( \beta_m \): mean maximum growth rate
- \( \beta_{max} \): maximum growth rate
- \( \xi_k \): control precision for the fast-growing wave number
- \( \xi_x \): control precision for film length
- \( \lambda_{opt} \): optimal wavelength of ligament
- \( \mu_1 \): viscosity of melt
- \( \mu_2 \): viscosity of surrounding gas
- \( \rho_1 \): density of melt
- \( \rho_2 \): density of surrounding gas
- \( \rho_s \): density of powder
- \( \sigma \): surface tension of melt

Table 3

| Property       | Value | Density at 298 K (Kg m\(^{-3}\)) |
|----------------|-------|----------------------------------|
|                |       | Surface tension (N m\(^{-1}\))   |
|                |       | Viscosity (m Ns m\(^{-2}\))      |
|                |       | Density (Kg m\(^{-3}\))         |
| Value          | 8560  | 0.38                             |
|                | 1.82  | 8375                             |

Fig. 5. Comparison of the calculated and experimental powder sizes of Bi–Sn eutectic alloy.

Fig. 6. Influence of break-up parameter on predicted powder size.
\( \tau \)  time
\( \tau^* \)  break-up time
\( \omega \)  disk rotating speed

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