ON-LINE REAL TIME DIAGNOSTICS OF A SINGLE FLUID ATOMIZATION SYSTEM

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Abstract

A drop tube-Impulse Atomization technique was used to produce copper droplets. In this method, energy is transferred to a liquid by plunger movement resulting in spherical droplets emanating from orifices. A mathematical model of the evolution of droplet velocity and temperature at various heights for different sized droplets was developed. A two-color pyrometer, DPV-2000, and a shadowgraph were used to measure droplets radiant energy, diameter and velocity. The temperature values from the model were used to assess the two color pyrometer assumption over the temperature range of measurement. The DVP 2000 measurements were found to be dependent of droplet size wavelength and position of droplets below the atomizing nozzle. By calibrating the instrument for effective emissivity over the range of measurements, the thermal history of droplets may be recorded using a single color pyrometer approach.

Introduction

The variation of undercooling or cooling rate in solidification provides the possibility to control morphology and size of crystal structures. A number of models have been reported for predicting or estimating the undercooling temperature of droplets in gas, single fluid atomization systems and drop tubes [1-3]. A systematic effort on the investigation of thermal history of falling droplets in-situ during atomization is rare [4]. In addition to the thermal history, in-situ measurement of the droplet diameter, initial velocity and instantaneous velocity is crucial in validating solidification models.

Delshad Khatibi et al. [5] used a two-color pyrometer, DPV-2000, to measure droplets effective radiant energy for different droplet sizes. It was also shown that the acceleration of falling droplets near the melting point is close to gravitational acceleration and as a result the falling droplets do not reach their terminal velocity at their melting point.

The DPV-2000 is a high-speed two colors pyrometer that measures the effective radiant energy of the particles. According to Planck's radiation law, the total energy radiated by a spherical particle can be expressed as:

$$E(\lambda_i) = \frac{C_1 \varepsilon(\lambda_i) \lambda_i^{-5}}{e^{C_2 / \lambda_i T} - 1} \tag{1}$$

where, C_1= 3.74×10^8 W.$\mu m^4/m^2$ and C_2=1.4387×10^4 μm.K [6]. $\varepsilon(\lambda_i)$ is emissivity of the particle at λ_i, wavelength, and T is temperature. In two color pyrometry a measure of the energy radiated from a body is taken at two wavelengths. It is assumed, for a two color pyrometer, that over the measured temperature range the emissivity is not a function of wavelength. In this work, we aim to test this assumption for molten copper droplets atomized into an argon gas atmosphere. Under these conditions, equation (1) would be re-written in the following form for the DVP 2000:

$$Q(\lambda_i) = \frac{C_1\ \alpha(\lambda_i)\, d^2\ \lambda_i^{-5}}{e^{C_2/\lambda_i T} - 1} \tag{2}$$

where $Q(\lambda_i)$ is proportional to $E(\lambda_i)$ and is the quantity measured by the DVP 2000, $\alpha(\lambda_i)$ is proportional to $\varepsilon(\lambda_i)$ and d is the droplet diameter in μm. The DVP 2000 reports measurements of Q at two specific wavelengths designed into the instrument. For these experiments these wavelengths are, λ_1 is 0.787 μm and λ_2 is 0.995 μm. A mathematical model was also utilized to predict the temperature of falling copper droplets at different heights. Thus, for a given measurement of Q for a known droplet size and distance below the nozzle, $\alpha(\lambda_i)$ at each wavelength is the only unknown in Equation (2) and will be compared for values determined at λ_1 and λ_2.

Experimental

Copper with 99.99% purity (Alfa Aesar) was melted in a graphite crucible using a 20kW induction furnace located at the top of a drop tube-impulse atomization (IA) tower. An argon atmosphere of 90ppm oxygen was maintained in the tower during melting and atomization. After melting the copper, it was superheated to 1400°C and the molten metal was atomized through orifices located at the bottom of the crucible, forming ligaments, which spherodized into droplets in the inert argon atmosphere. The falling droplets were cooled in free fall by the argon atmosphere.

DPV-2000 (Tecnar Automation Ltée) was used to measure effective radiant energy, $Q(\lambda_1)$ and $Q(\lambda_2)$, and a shadowgraph (Sizing Master Shadow from LaVision GmbH in Gottingen, Germany) was used to measure velocity and droplet size of the falling copper droplets. These sensors were installed on a translation stage inside the drop tube that was capable of moving in all three directions. DPV-2000 is an optical sensing device based on a patented technology developed by the National Research Council of Canada. DPV-2000 uses a dual slit optical sensor that can measure the effective radiant energy of up to 800 droplets per second with the depth of field of 1.9 mm, and it can measure radiant energy of droplets at two different wavelengths [7]. Sizing Master Shadow from LaVision uses the backlighting technique to visualize droplets for image analysis. A light source, in this case a pulsed laser combined with diffuser optics, illuminates in-flight droplets 5 times per second. Backlight of droplets inside the measurement volume of 6×6×6 mm is captured by a high resolution high-speed imaging system. It is possible to investigate droplet sizes down to 5μm using the shadowgraph device.

The focal point of both shadowgraph and DPV-2000 was set to an imaginary vertical line going through the center of the bottom of the crucible; therefore, any unfocused droplets would be rejected by the criteria set by the operator in the respective software of each instrument. Particle size distribution of falling droplets (D50 and D90), velocity and effective radiant energy were measured at three distances of 10, 30 and 50 cm from the orifices.

Modeling

A mathematical model was developed to calculate droplet velocity and temperature for different sized copper droplets at different heights.

Droplets begin their downward trajectory with an initial velocity. The subsequent trajectory of the droplets depends on this initial velocity, and the forces of gravity, buoyancy and drag as shown schematically in Figure 1.

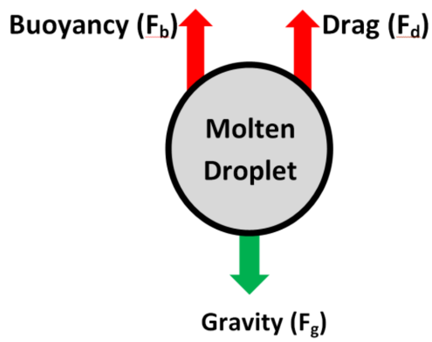

Figure 1. Schematic of the forces acting on a falling droplet.

Applying Newton's Second Law on the droplet, the instantaneous acceleration can be found as follows [8]:

$$\frac{dv}{dt} = g - \frac{3}{4}\frac{\rho_g}{\rho_p}\frac{c_d}{d}.v^2 \tag{3}$$

where v is the relative velocity between the droplet and the atomization gas, (which in the case of IA v_{gas}=0) and ρ_p and ρ_g are the densities of the droplet and atomization gas, respectively. The gravitational acceleration is given by g and d is the droplet diameter. The discharge coefficient, C_d, for droplets in laminar flow is given by [9]:

$$C_d = \frac{18.5}{Re^{0.6}} \tag{4}$$

The Reynolds number, *Re*, in Equation (4) is given by:

$$Re = \frac{\rho_g.v.d}{\mu_g} \tag{5}$$

where μ_g is the gas viscosity.

To calculate the thermal history of a falling droplet, the heat energy loss from the surface of the droplet to the surrounding gas is given by:

$$q = h_{eff}A(T_m - T_0) \tag{6}$$

where h_{eff} is the effective heat transfer and consisting of the additive contribution of convection, conduction and radiation heat transfer mechanisms, A is the surface area of the droplet, T_m is the droplet surface temperature and T_0 is the gas temperature. It is assumed that the surface temperature of the droplet represents the entire droplet temperature, since the internal temperature gradient within the droplets are negligible (Biot <0.1) [10]. It is also assumed that the temperature increase due to surface oxidation is negligible [5]. The effective heat transfer was calculated using the modified Whitaker correlation introduced by Wiskel et al. [10], as shown in Equation 7.

$$Nu = \frac{h_{eff} d}{k_g} = 2\frac{C}{k_s(m+1)} \cdot \frac{\left(T_s^{m+1} - T_g^{m+1}\right)}{\left(T_s - T_g\right)} + \left(0.4\,\mathrm{Re}^{1/2} + 0.06\,\mathrm{Re}^{2/3}\right)\mathrm{Pr}^{0/4}\left(\frac{\mu_g}{\mu_s}\right) \quad (7)$$

In Equation 7, Nu is the Nusselt Number, Pr is the Prandtl number and d is the droplet diameter. k_g and k_s are conductivity of gas and droplet, respectively while μ_g and μ_s are viscosity of gas and the droplet, respectively. From the variation of gas conductivity with temperature ($k_g = C\times T^m$) for argon $C = 1.86\times10^{-4}$ and $m = 0.7915$ [4], the model was able to closely predict the range of time and distance in which the droplets completely solidified under the condition that k_s be evaluated at the metal droplet surface temperature and the *Re* and *Pr* numbers evaluated at the free stream gas temperature. Table 1 lists the properties of pure copper and argon which were used in the model.

Table I. Thermophysical properties of copper and argon at 1400°C and 40°C, respectively [11]

	Temperature (°C)	**Thermal conductivity (W/K.m)**	**Specific heat (J/kg.K)**	**Density (kg/m^3)**	**Viscosity (m^2/s)**
Copper	1400	325	532	7722	-
Argon	40	0.01853	20.80	0.287	0.021

Results and Discussion

During atomization, the shadowgraph was continuously collecting droplet size and velocity data at 5Hz frequency. A total number of 6100 droplets were measured during the entire atomization time of two minutes. Using the shadowgraph, D10=456 µm and D50=565 µm were measured. These two particles sizes will be used as examples to show the process of droplet temperature calculations.

In our previous work [5], it was shown that the particles exit the orifices with an average initial velocity of 1 m/s. Using this initial average velocity, the temperature of droplets with diameters of 456 and 565 µm was determined using the model described above and the results are plotted as a function of distance from the nozzle plate (Figure 2). These predicted temperatures will be used below to estimate values for $\alpha(\lambda_1)$ and $\alpha(\lambda_2)$.

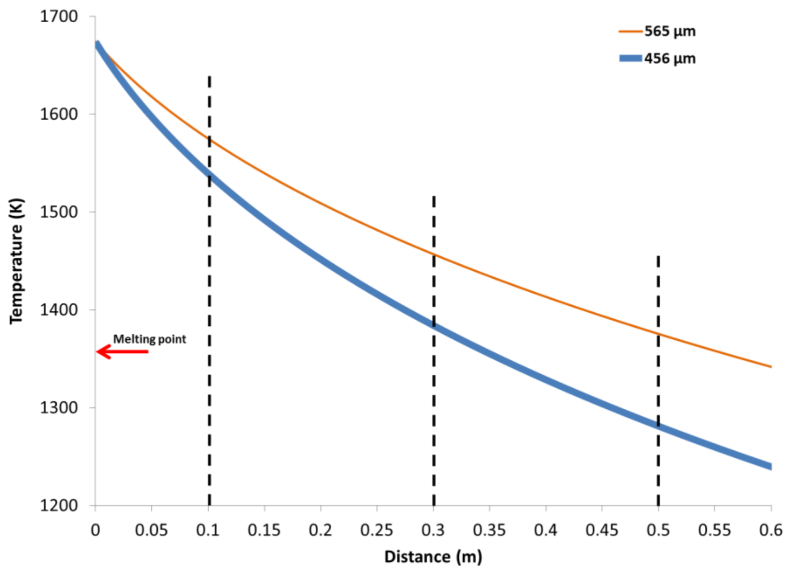

Figure 2. Temperature vs. distance from nozzle plate (plotted using the model) for two different particle sizes. Dashed line shows distance from the nozzle plate.

While the shadowgraph was collecting the velocity and diameter of falling droplets at the center of the spray, the DPV-2000 was measuring the effective radiant energy of the droplets from the same location. Figure 3(a) shows the signal counts of each droplet that DPV-2000 measured at two wavelengths. The area under the curves shown in Figure 3(a) represents the effective radiant energy and as such it is a dimensionless value. The effective radiant energies measured for different droplet sizes at two different wavelengths are shown in Figure 3(b). The measurement shown in Figure 3 was done at 10cm below the nozzle plate. It can be seen that larger droplets have higher effective radiant energy. The same trend was also observed when measurements were performed at 30 and 50cm distances from the nozzle plate.

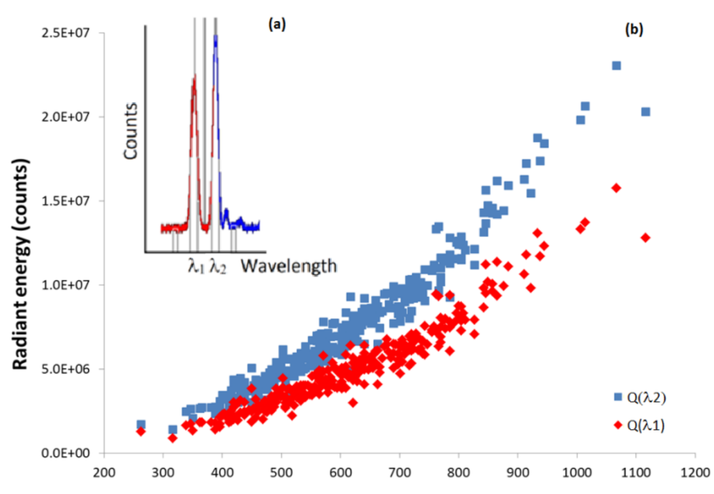

Figure 3. (a) The signal counts measured at two different wavelengths for a single droplet, (b) Radiant energy vs. droplet diameter measured by DPV-2000 at 10cm below the nozzle plate.

From Figure 3, the effective radiant intensity values for the particles with diameters of 456 and 565 µm were averaged and were plotted at three different distances in Figure 4. The error bars in this figure represent the standard deviation from the averaged radiant energy measured for each particle size. The lines connecting the data points of same distances are only for better visualization of the results.

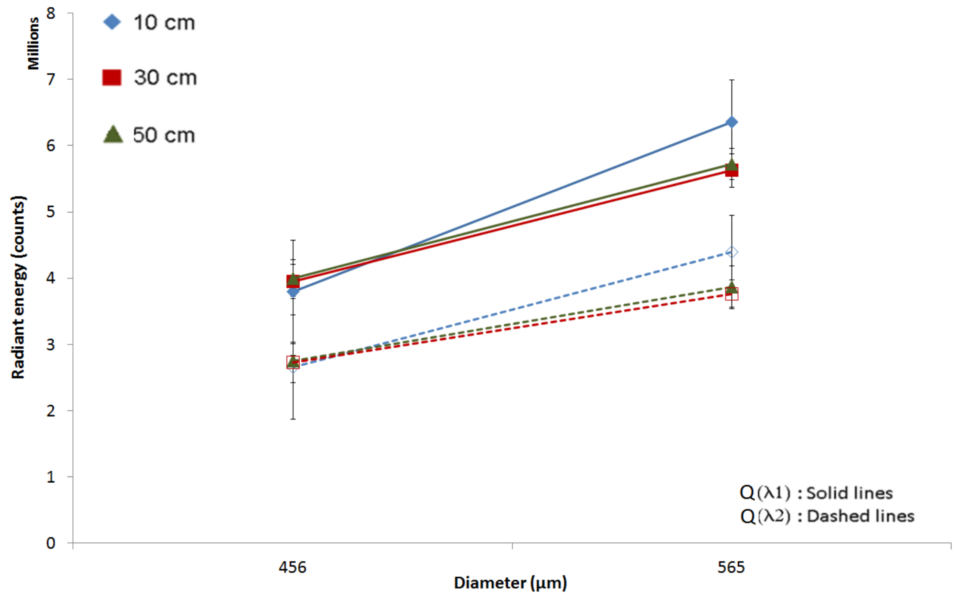

Figure 4. The radiant energies measured by DPV-2000 for 456 and 565 µm particle sizes at three different distances from the nozzle plate.

From Figure 4, it is evident that larger particles have emitted higher effective radiant energies at each wavelength.

To find effective emissivity, $\alpha(\lambda_1)$ and $\alpha(\lambda_2)$, values at λ_1 and λ_2 for different particle sizes at different heights, the effective radiant energies shown in Figure 4 and the respective temperatures from Figure 2 were used in Equation 2. The results are shown in Figure 5.

From Figure 5 it can be seen that there is a difference between $\alpha(\lambda_1)$ and $\alpha(\lambda_2)$ and by extension, $\varepsilon(\lambda_1)$ and $\varepsilon(\lambda_2)$ over the temperature range of interest in these experiments. This difference decreases with increasing temperature. Based on the two-color pyrometer's theory, it is assumed that the wavelengths are chosen so close that the change in emissivity as a result of wavelength change is insignificant. This assumption may be more precise at high temperatures where the radiant energy as a function of wavelength does not significantly change, above 1600K in Figure 5 for copper. However, below 1600K for copper, having the effective emissivity values as a function of temperature for each wavelength will allow the calibration of DPV-2000 as a one-color pyrometer. Further work is required to determine if the values of $\alpha(\lambda_1)$ and $\alpha(\lambda_2)$ are a function of material and to test this approach over a wider range of droplet sizes and temperatures.

Summary

Diameter, velocity and radiant energy of falling droplets of copper were measured using a shadowgraph and a two-color pyrometer, DPV-2000. The measurements were performed at 10, 30 and 50 cm from the nozzle. DPV-2000 measured radiant energy at two different wavelengths on atomized copper droplets. A mathematical model of droplet cooling was developed and used to predict the particle temperatures at different heights. The temperature values from the model were used with the measured values of effective radiance intensity to estimate values of $\alpha(\lambda_1)$ and $\alpha(\lambda_2)$. Both of these values are proportional to the respective emissivities. It was found that the values of α were a function of temperature and wavelength. Using these values it is feasible to calibrate the DVP instrument and use it as a single color pyrometer.

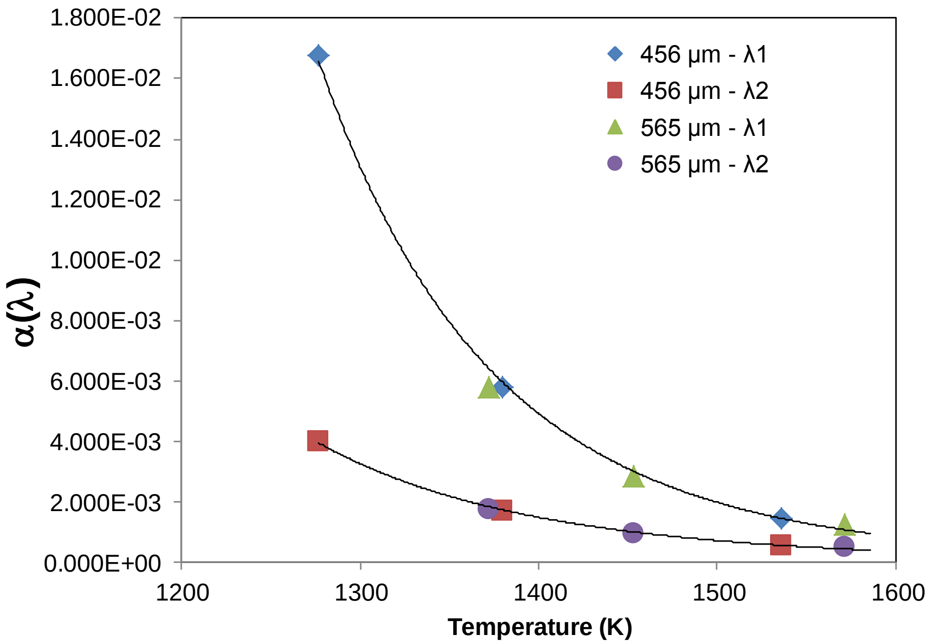

Figure 5. Effective emissivity, $\alpha(\lambda)$ as a function of temperature

Acknowledgments

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