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In-flight thermal control of molten metal droplet streams

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Abstract

Precision droplet manufacturing (PDM) is a process that builds complex 3D parts one nano-liter molten metal droplet at a time from a CAD file without the need for tooling. One method to control the droplet temperature when it arrives at the target is to heat the droplets in-flight. This note describes such a heater that uses helium and nitrogen as the convective heat transfer medium. Heating rates up to 11,000 °C/s are attained. The effect of droplet spacing on the heat transfer coefficient is experimentally detailed and a nascent-turbulent effect is observed to bring the heating rate for nitrogen close to that for helium. In addition, the experimental values are consistent with those from multi-droplet numerical simulations reported in the literature.

Keywords: Droplet heating; Rapid prototyping; Additive manufacturing; Forced convection; Droplet based manufacturing

1. Introduction

The ability to build arbitrary 3D objects directly from CAD data without the need for molds or tools, a process often referred to as rapid prototyping (RP), has been around for a number of years [1]. One of the defining characteristics of RP is that it is generally an additive process and not a subtractive (e.g. CNC) or forming (e.g. forging, injection molding, etc.) process. Without the constraints that tooling or cutter access imposes, additive manufacturing permits greater design freedom since design features such as undercuts and hollow features can be easily realized in most practical circumstances. Precision droplet manufacturing (PDM) is a molten metal droplet based additive RP technique that generates droplets via Rayleigh breakup as illustrated in Fig. 1. The charge tube induces a unique charge to each droplet and the deflection plates then deflect the droplets proportionally at rates up to 20,000 droplets per second. Substrate motion combines with droplet deflection to target droplets anywhere in the build volume. PDM has produced near net-shape metal components with high accuracy, improved material properties (30% increase in strength [2]), fast build times (150 cc/h from a single nozzle), and little warpage. To achieve robust integration of newly deposited droplets with previously deposited material, new droplets should arrive with enough thermal energy to re-melt a thin layer of the previously deposited material. While substrate temperature is an equally important integration parameter, in addition to being much easier to control, other work [3] has shown the importance of being able to control both substrate and droplet arrival temperature. Therefore, a method for manipulating droplet arrival temperature is an important element in successful PDM.

The droplet temperature could be controlled by superheating the reservoir of molten metal but many metal alloys have an optimum "holding" temperature that is not compatible with the temperature that would be required for desired droplet arrival temperature. This "holding" temperature varies for each alloy as a result of the temperature dependent reactivity and solubility of the alloy constituents. Additionally, controlling droplet arrival temperature with this method is sluggish since the temperature of the entire reservoir would need to be controlled.

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Nomenclature

A_s	droplet surface area
Bi	Biot number $(h_{avg}(r/3)/k_d)$
c_p	specific heat
h_{avg}	average convective heat transfer coefficient
k	thermal conductivity
n	droplet spacing parameter
OD	droplet diameter
r	droplet radius
Re	diametric Reynolds number
s_d	ratio of droplet spacing to droplet diameter
t	time
T	temperature
Vol	droplet volume

Greek symbols

α	thermal diffusivity
λ	inter-droplet spacing for full stream
ρ	density
τ_m	molecular diffusion time scale (OD^2/α_a)
τ_t	turbulent time scale (τ_m/Re)

Subscripts

a	atmosphere
d	droplet
in	heater entrance
out	heater exit

Another approach, and the subject of this technical note, is to regulate droplet temperature in-flight after they have been formed. Controlling droplet temperature in-flight effectively decouples holding temperature from droplet arrival temperature and the small volume of material being heated results in rapid response time. As an added advantage, droplet temperature can be controlled closer to impact so cooling effects resulting from variations in droplet flight distance can be managed.

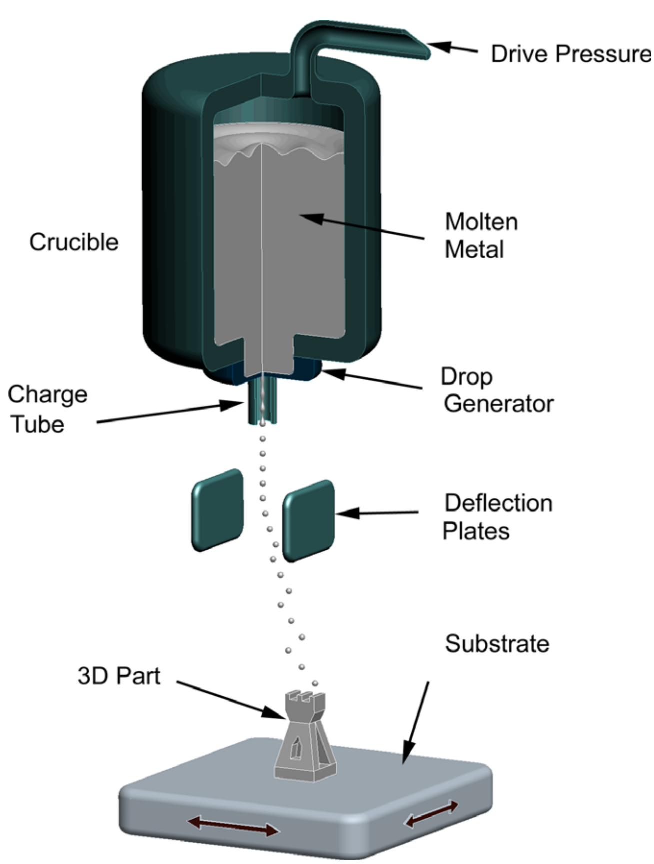

Fig. 1. Schematic of PDM apparatus.

Each drop in PDM experiences a unique cooling history because droplets are deflected along different paths. In addition, heating and cooling rates of a solitary droplet can vary substantially from the rates when the droplet resides in a tight stream. This "caravan" effect, where the wake of preceding droplets modifies the local surroundings of trailing droplets has been documented experimentally and theoretically in the literature for vaporizing droplets [4]. In the case of molten metal droplets, the stream configuration affects the local heat transfer coefficient and can yield temperature variability. Since PDM requires variable droplet spacing, quantifying the caravan effect is important if the droplet temperature at arrival is to be controlled. Hence, for an in-flight droplet heater to be useful for PDM, the heat transfer differences associated with varied droplet spacing need to yield a droplet arrival temperature range that is appropriate for effective droplet integration.

2. In-flight droplet heater

Convective heating of a mono-disperse droplet stream is accomplished by locally heating the gas in the droplet stream flight path. A nitrogen atmosphere is generally used for our PDM apparatus but nitrogen has relatively poor thermal conductivity ($k_a = 0.04580$ W/(m K)) and diffusivity ($\alpha_a = 0.7486 \times 10^{-4}$ m^2/s). Thus, another gas with superior heat transfer properties might improve the effectiveness of an in-flight convective droplet heating apparatus. Helium was chosen because of its high thermal conductivity ($k_a = 0.225$ W/(m K)) and thermal diffusivity ($\alpha_a = 5.215 \times 10^{-4}$ m^2/s). The results were compared with a nitrogen-based heater system. Our heater design consists of a resistance heater, gas supply, and diffuser. To focus the heating on the droplet stream and minimize gas loss, the droplet heater is encased in a heavily insulated ceramic fiber package with small slots for droplet stream entry and exit. The convective heater design is shown in Fig. 2. Inert gas (helium or nitrogen) is supplied at a constant rate and a diffuser screen minimizes crosscurrents that could divert

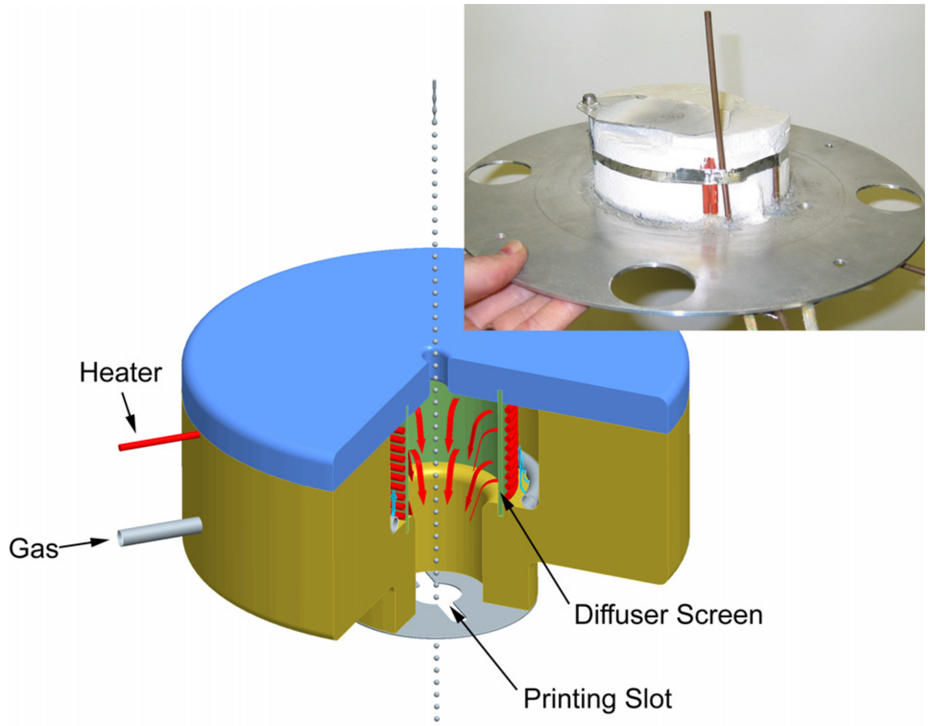

Fig. 2. Convective droplet heater design.

droplet trajectories or produce a heterogeneous temperature distribution within the heater.

2.1. Droplet heater experiments

To quantify the performance of the convective in-flight droplet heater a stream of near eutectic solder (60Sn40Pb) droplets ($OD = 173.6 \pm 1.8\ \mu m$, $k_d = 25\ W/(m\ K)$, $\rho_d = 8218\ kg/m^3$, $c_{p\_d} = 238\ J/(kg\ K)$) is jetted through the droplet heater to generate a continuous stream of droplets at 12 kHz. Droplet residence time in the heater is 13 ms and droplet temperature is measured with a fine-wire 127 μm (0.005 in.) diameter type T thermocouple at the entrance (T_{in}) and exit (T_{out}) of the heater section after a steady-state thermal condition has been achieved. The heater was tested with a core temperature of $T_a = 700$ K (800 °F) and all gas properties are taken at the film temperature of 600 K (620 °F). The Re, based on droplet velocity (5.8 ± 0.08 m/s) and diameter, is 2.7 for helium and 19.5 for nitrogen. The caravan effect is explored by varying the droplet spacing (s_d) and measuring the temperature difference that results. The parameter s_d is defined as the ratio of inter-droplet spacing (λ) to droplet diameter (OD). The droplet spacing options are limited by the minimum spacing for a full stream ($s_d = 2.778$). Other s_d spacing can be realized by selectively charging and extracting droplets from the full stream with extracted droplets being collected before they reach the heater. With this method, s_d values of 2.778, 5.560, 8.340, 11.120, and 13.899 are investigated. For our chosen heater core temperature, a maximum heating rate of 11,000 °C/s was achieved.

2.1.1. Analysis

The measured temperature response is used to calculate the heat transfer coefficients using a lumped capacitance since the Biot numbers ($Bi = h_{avg}(r/3)/k_d$) for the droplets are less than 0.005. Balancing the rate of internal temperature change with the rate of heat loss from the droplet surface yields [5]

$$\rho_d c_{p\_d} \mathrm{Vol} \frac{dT}{dt} = -h_{avg} A_s (T - T_a) \tag{1}$$

Integrating Eq. (1) yields

$$h_{avg} = -\ln\left(\frac{T_{out} - T_a}{T_{in} - T_a}\right) \frac{c_p \rho_d \mathrm{Vol}}{A_s T} \tag{2}$$

and h_{avg} is plotted in Figs. 3 and 4 for helium and nitrogen, respectively. Entrance effects are not significant since the molecular diffusion timescale for droplets of this size is less than 3% of the time the droplets spend in-flight through the heater. Fig. 3 shows that the helium convective heater exhibits a clear relationship between droplet spacing and heat transfer coefficient. As droplet spacing increases, the heat transfer coefficient increases asymptotically to the heat transfer coefficient predicted for a convectively heated, isolated sphere [5]. To estimate an expected lower bound, the theoretical heat transfer coefficient for conduction of an infinite cylinder is also plotted. For helium there is excellent agreement with previous numerical and theoretical work.

The nitrogen heater, however, did not behave as expected. The heat transfer coefficient appears to be insensitive to droplet spacing and, most notably, the heat transfer coefficients are similar in magnitude to those in the

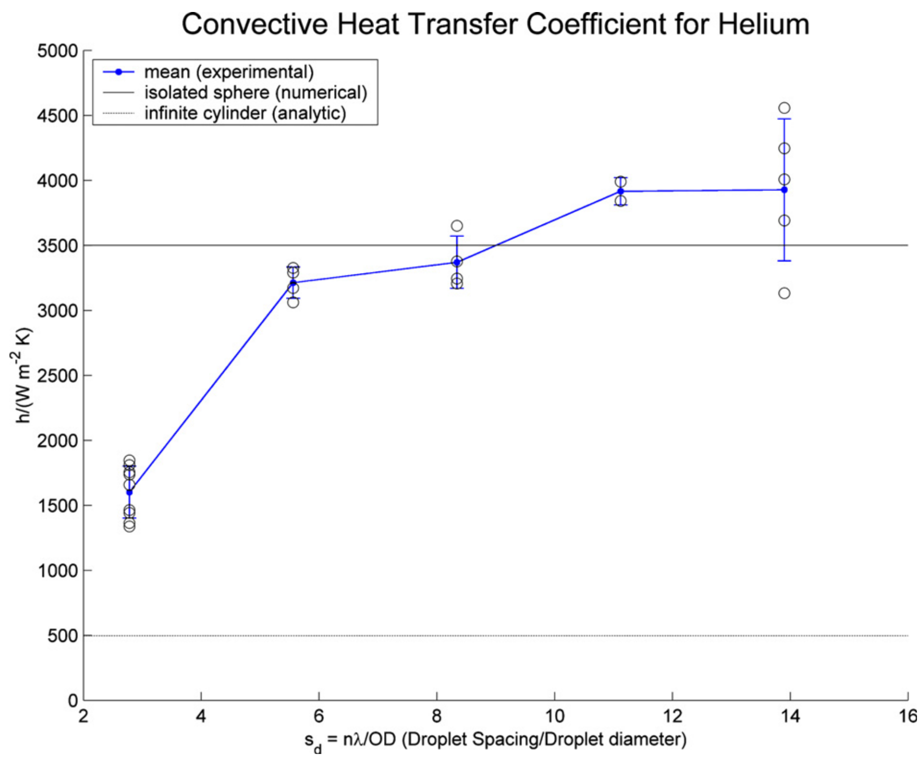

Fig. 3. Average heat transfer coefficient for helium.

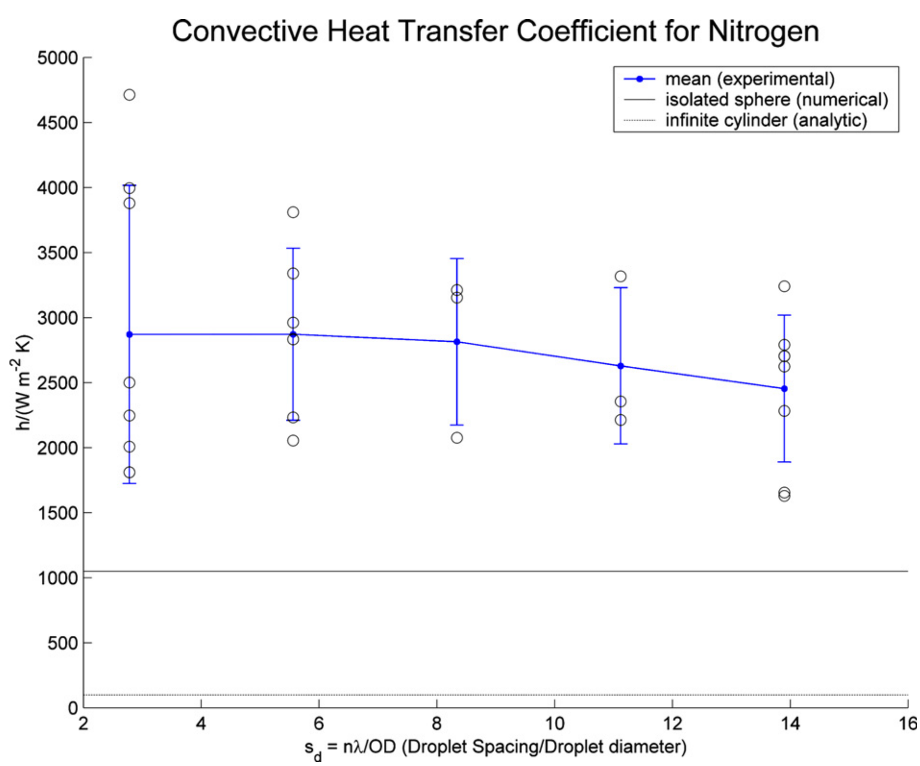

Fig. 4. Average heat transfer coefficient for nitrogen.

helium results. Thus, even though nitrogen has much lower thermal conductivity and diffusivity than helium, it yields comparable thermal performance for the flow of interest. The reason appears to be the different fluid dynamics for the two cases. The time scale for molecular diffusion is approximately $\tau_m = \frac{OD^2}{\alpha_a}$. This yields a molecular diffusion time scale of 58 μs for helium and 410 μs for nitrogen. However, any turbulent convective component means that the time scale for turbulent diffusion should also be considered. The ratio of the time scales for molecular and turbulent diffusion corresponds roughly to the Reynolds number [6]. Thus, the turbulent time scale can be expressed as

$$\tau_t = \frac{\tau_m}{Re} \tag{3}$$

For the current droplet stream, this yields a turbulent time scale (τ_t) of 22 μs for helium and 21 μs for nitrogen. Thus, the higher Reynolds number associated with the nitrogen ($10\times$) balances its relatively poor thermal diffusivity ($0.10\times$). Since the droplet stream system resides at the unique *Re* number regime where helium and nitrogen have similar convective heat transfer coefficients, similar heating rates are observed. This phenomenon is rarely observed in macro-scale systems because their far higher *Re* numbers will not counterbalance molecular effects as in our system. Previous work detailing unsteady wake interaction in droplet streams lends support to this supposition [7–9]. In addition, the high standard deviation for nitrogen is further indication that chaotic/turbulent flow is participating in the process.

3. Conclusions

In the context of PDM, a heater must be able to reliably heat droplets to the required integration temperature. The convective heater designed and tested can generate high heating rates and the required droplet arrival temperature using either helium or nitrogen since they have similar heat transfer coefficients. The caravan effect on droplet heating is clearly demonstrated with helium, but less obvious with nitrogen because of the nascent turbulence in the droplet wake. This latter effect is interesting and may warrant further study in the heat transfer of interacting droplets near $Re = 20$.

Acknowledgements

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