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EFFECTS OF NOZZLE DIAMETER AND DUTY CYCLE ON DROPLET FORMATION IN DROP-ON-DEMAND ADDITIVE MANUFACTURING

Liquid metal drop-on-demand (DOD) additive manufacturing enables precise control of individual droplet deposition. A critical bottleneck in this manufacturing process is achieving continuous, uniform droplet ejection, which is influenced by several parameters, including nozzle diameter and pressure-pulse actuation mechanism. To address this challenge, this study investigated droplet formation using the Volume of Fluid (VOF) method, as it conserves liquid volume, incorporates free surface tracking and interface evolution during droplet formation. The effects of nozzle diameter and duty cycle on droplet size, detachment time, detachment distance, ligament stability and satellite formation were investigated. The results revealed that the droplet diameter scales linearly with nozzle diameter. The gas pressure required for single droplet ejection decreased with increasing nozzle diameter, while the resulting droplet velocity also decreased. The DOE revealed different flow regimes. Droplets with diameters between 0.55 mm and 0.95 mm were produced at 100 Hz, as the duty cycle was varied from 10% to 50% for a 0.3 mm diameter nozzle. Higher duty cycles resulted in larger droplet diameters, droplet overlap and formation of satellite droplets, which led to unstable ejections. Parameter sets were identified for efficient droplet generation, which provide preliminary insights into nozzle diameter and pressure-pulse design for DOD metal additive manufacturing.

1. INTRODUCTION

Drop-on-Demand (DOD) droplet 3D printing is a technique in additive manufacturing (AM) where precise individual droplets are produced only when triggered. This enables controlled deposition of molten metal to 3D parts layer by layer [1]. In metal DOD systems, actuation mechanisms create a pulsed driving force that overcomes capillary forces at the nozzle to eject discrete molten droplets. There are various techniques for achieving pulsed driving force, such as pneumatic actuation, piezoelectric actuation, impact-driven, electrostatic, electrohydrodynamic (EHD), magnetohydrodynamic (MHD) ejection, or droplet generation by application of a high-power laser [2, 3]. Pneumatic DOD uses controlled compressed gas pulses to pressurise a molten metal reservoir and force molten metal through

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a nozzle on demand. It synchronises droplet ejection with motion for geometric control[4]. Pneumatic DOD systems are particularly advantageous for metals with high melting temperatures, because the pneumatic actuation mechanism avoids internal moving parts in the melt. This reduces thermal stress on actuation components and enables higher operating temperatures than some other actuation mechanisms [1].

DOD 3D printing has demonstrated its usefulness across many industries, such as the aerospace industry, microelectronics printing & flexible circuits [5, 6], and complex parts manufacturing [7]. DOD systems possess the capacity to produce complex parts with high precision, minimal material wastage and good surface quality at a low cost. The versatility of the process has been demonstrated by utilising different materials, such as copper. [6, 8], aluminium, and tin-lead alloys [9]. Despite these advantages, the widespread adoption of DOD metal printing is still limited by difficulties in high-temperature operation, such as nozzle clogging, erosion, and chemical interactions between the molten metal and nozzle material, as well as oxidation effects [10]. Small changes in nozzle diameter, applied pressure, frequency, actuation timing and temperature can induce transitions from a stable single-droplet regime to satellites, undesirable off-axis ejection, droplet coalescence, dripping or jetting modes [11]. Instabilities during droplet formation can lead to different droplet sizes, delayed or premature detachment and satellite droplet formation, all of which negatively affect deposition accuracy and part quality [12].

Zhong et al. [13] developed a mechanism for generating droplets smaller than the nozzle hole diameter. They investigated the effects of structure parameters on aluminium droplet formation. The results showed that the aspect ratio and the distance between the inlet hole and nozzle hole had significant effects on droplet size, while the inlet hole diameter had little effect on droplet size. Chao and Hao [14] investigated the influence of jet pressure, pulse width, and duty ratio in the droplet pneumatic drop-on-demand spraying process using gallium indium alloy (GaIn24.5). They found that large pulse width and duty cycle result in a longer liquid metal jet, and the breakup process occurs in multiple locations. They were able to produce a single uniform liquid metal droplet (diameter 1080 μm) under 1.5 kPa jet pressure, 100 ms pulse width, and 50% duty ratio with a 280 μm nozzle diameter. Zhong et al. [12] demonstrated that supply pressure and electronic pulse width have a significant effect on pressure variation and droplet formation. Single copper droplets were obtained under supply pressure 60 kPa – 100 kPa and pulse width 550 µs – 1550 µs at 1200 °C. Seo et al. [15] demonstrated that nozzle geometry strongly controls meniscus damping and thus droplet stability in high-frequency liquid metal jetting.

Many studies have investigated the effect of various process parameters of DOD systems using various metals, especially metals with low melting points. However, limited studies have investigated droplet formation in stainless steel 316 (SS 316), despite its widespread use in the manufacturing industry due to its excellent mechanical properties and superior corrosion resistance. This work presents a systematic numerical investigation of molten stainless steel (SS 316) droplet formation using the Volume of Fluid (VOF) method. The VOF method enables accurate tracking of free-surface evolution, necking behaviour, droplet regimes, droplet diameter, droplet velocity, droplet stability, formation time and detachment behaviour. This study provides insight into how nozzle diameter and actuation parameters affect droplet generation regimes in high-temperature metal DOD systems. Also, the outcomes contribute to improving nozzle design guidelines, optimised operating windows, and enhanced stability for future metal DOD AM technologies.

2. NUMERICAL METHOD

A series of simulations was conducted under different conditions in order to study the influence of nozzle diameter and duty cycle on droplet formation. At 100 Hz, a pulsed inlet pressure ranging from 120 to 160 kPa (absolute) was applied, while the suction was maintained at atmospheric pressure (101 kPa). The max temperature was set at 1500 ℃. The duty cycle was varied from 10 % to 50 %, and the nozzle diameter was varied from 0.3 mm to 0.9 mm, as shown in Tables 2 and 3. Liquid metal droplet generation was assumed to be an isothermal and incompressible flow process [12, 13]. The temperature variations during the short ejection timescale were assumed to be negligible; hence, the physical properties of the molten metal, such as density, surface tension, and kinematic viscosity, were assumed to be constant throughout the jetting process. Equations (1) and (2) for mass conservation and momentum were taken as governing equations.

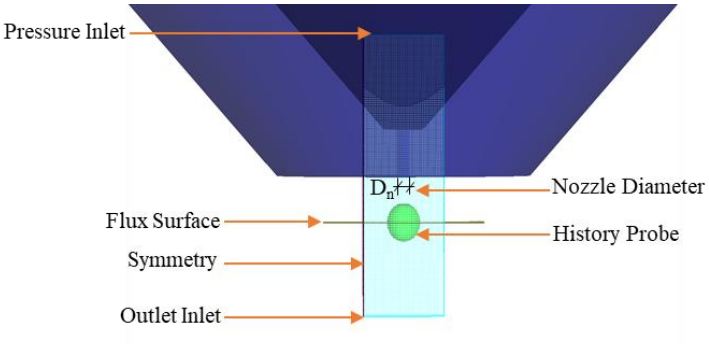

Fig. 1 Simulation setup and boundary conditions

Flow-3D 12.0.2.5 was used to develop the numerical model. To examine the droplet formation process, a three-dimensional simulation model was created using the Volume of Fluid (VOF) method. As illustrated in Fig. 1, the model consists of a nozzle; measuring tools such as a history probe and flux surface were placed 1 mm from the nozzle tip. History probes are point data recorders. Flux surfaces are surfaces with a fixed porosity equal to 1, which means they are completely open to flow. They are special objects that are used to measure the flow of quantities through them. The computational domain considered here is an enclosed region around the nozzle tip and the outer region through which the droplets travel. The boundary conditions of the computational model were set as an inlet pressure boundary for Y_max and as an outlet pressure boundary for Y_min. This represents the vertical axis of the domain, which corresponds with the inlet and outlet of the domain; other boundaries were set as symmetry. As shown in Fig. 1, a Cartesian mesh system was used to discretise the computational domain. A mesh independence study was performed with mesh sizes 72 µm, 48 µm and 32 µm. The difference in the droplet diameter between the two finest meshes was below 3%; the monitored output parameter for the convergence analysis was the detached droplet diameter measured at 1mm below the nozzle tip. Thus, the 48 µm mesh was selected as a compromise between accuracy and computational cost. Similarly, the time-step sensitivity analysis showed negligible variation in droplet formation behaviour for smaller time increments. The material properties for SS 316 used in this work are given in Table 1.

$$\nabla . V = 0 \tag{1}$$

$$\rho \frac{\partial V}{\partial t} + (V . \nabla)V = \rho g + \mathsf{F}_{vol} - \nabla . \mathrm{p} + \mu \nabla^2 V \tag{2}$$

Here, V represents the velocity vector, ρ the density, g the gravitational vector, F_{vol}, represents the effect of surface tension, p the pressure, μ denotes the viscosity, and t denotes time [13].

Table 1. Properties of Steel SS 316

Material	Density $\rho.(\boldsymbol{kg/m^3})$	Surface Tension $\sigma\,(\boldsymbol{N/m})$	Kinematic Viscosity ν (Pa.s)	Melting Point $\boldsymbol{T_m}$(°C)
Stainless steel SS 316	7249.2	1.8	0.007	1424

3. RESULTS AND DISCUSSION

In this simulation study, the droplets exhibit different breakup modes depending on the nozzle diameter, duty cycle, and gas pressures. There are several important stages, such as the no droplet formation stage, single droplet formation stage, satellite formation stage and the jetting stage. At low gas pressures below the capillary pressure, surface tension dominates, and the molten metal remains stable at the nozzle tip, hence no droplet formation. As the pressure increases, a single droplet grows at the tip, elongates, and a thin liquid neck forms between the droplet and the nozzle. The neck progressively thins until it reaches a critical radius and pinches off, producing a single primary droplet. With a further increase in pressure, the necking process became more rapid and unstable, which led to secondary pinch-off resulting in the formation of smaller satellite droplets. Further increase in pressure eventually accelerated the molten metal out of the nozzle, which led to a continuous jet of molten metal. This is because the liquid metal didn't have sufficient time to accumulate at the nozzle tip, grow into a droplet, undergo necking and pinch-off, as shown in Fig. 2a–2g.

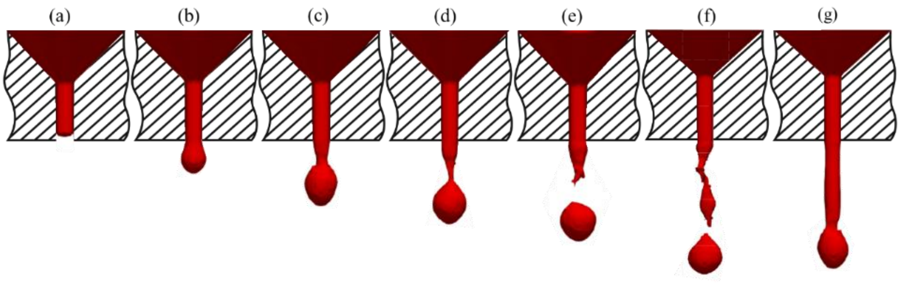

Fig. 2 Droplet formation stages

3.1. EFFECT OF NOZZLE DIAMETER

For this simulation, the gas pressure levels shown in Table 2 were applied to nozzle diameters 0.3 mm, 0.5 mm, 0.7 mm and 0.9 mm, at 10% duty cycle. During the simulation, four phenomena were observed: no droplet, single droplets, satellite droplets and jetting; as shown in Fig. 4

Table 2. DOE factors and levels for nozzle diameter investigation

Factor	Unit	Level 1	Level 2	Level 3	Level 4	Level 5
Nozzle Diameter, $\boldsymbol{D_n}$	mm	0.3	0.5	0.7	0.9	–
Pressure, $\boldsymbol{P}$	kPa	120	130	140	150	160

Controlled Parameter: Duty cycle, $DC = 10$ %

3.1.1. EFFECT OF NOZZLE DIAMETER ON DROPLET PARAMETERS

As the nozzle diameter increased from 0.3 mm to 0.9 mm, droplet parameters such as the droplet diameter, velocity, and detachment time were investigated. Fig. 3a shows a linear relationship between nozzle diameter and droplet diameter. As the nozzle diameter increased, the droplet diameter also increased as described in Equation (3). A similar linear relationship was reported by Tang et al [16], Luo et al [17].

As depicted in Fig. 3b, the droplet velocity decreased as the nozzle diameter increased. This is consistent with reports by Tang et al [16]. Droplet velocity plays a significant role in wetting and bonding on the substrate; high droplet velocity improves wetting and bonding. Fig. 3a shows that detachment time increased as the nozzle diameter increased; it shows that larger droplets require a longer time to accumulate sufficient volume and weight before detachment. It also indicates a transition towards dripping behaviour at larger nozzle diameters, where the effects of gravity and inertial forces increase relative to surface tension.

$$D_d = 1.38D_n + 0.142 \tag{3}$$

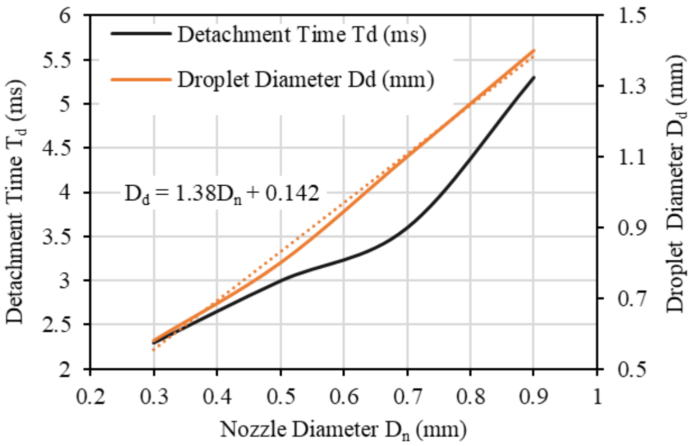

Fig. 3a. Effect of nozzle diameter on droplet diameter and detachment time

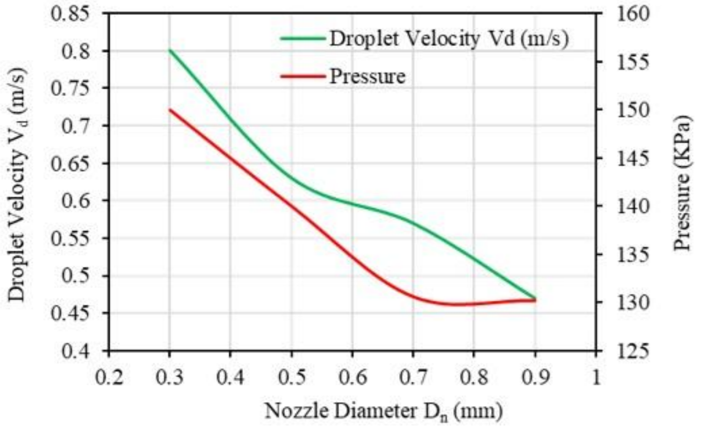

Fig. 3b. Effect of nozzle diameter on droplet velocity and gas pressure

3.1.2. EFFECT OF NOZZLE DIAMETER ON DROPLET FORMATION MODES

For a 0.3 mm nozzle diameter, gas pressures between 120 kPa and 140 kPa, no droplet was produced; the gas pressure was not sufficient to overcome the capillary pressure to eject a droplet from the nozzle. Single droplets were produced at 150 kPa; as the pressure increased to 160 kPa, satellite droplets began to form. For a nozzle diameter of 0.5 mm, no droplet was formed at 120 kPa. Single droplets began to form at 130 kPa as the pressure increased to 150 kPa; the droplets transitioned to satellites. At 160 kPa, jetting (continuous flow) of the molten metal was observed. For a nozzle diameter of 0.7 mm, no droplet was formed at 120 kPa. Single droplets were formed at 130 kPa. As the pressure increased to 140 kPa, satellite droplets formed; higher gas pressures resulted in the jetting of the liquid metal. For a nozzle diameter of 0.9 mm, no droplets were formed at 120 kPa. Single droplets formed at 130 kPa, as the pressure increased to 140 kPa, satellite droplets formed, while gas pressures of 150 kPa and 160 kPa resulted in jetting of the liquid metal.

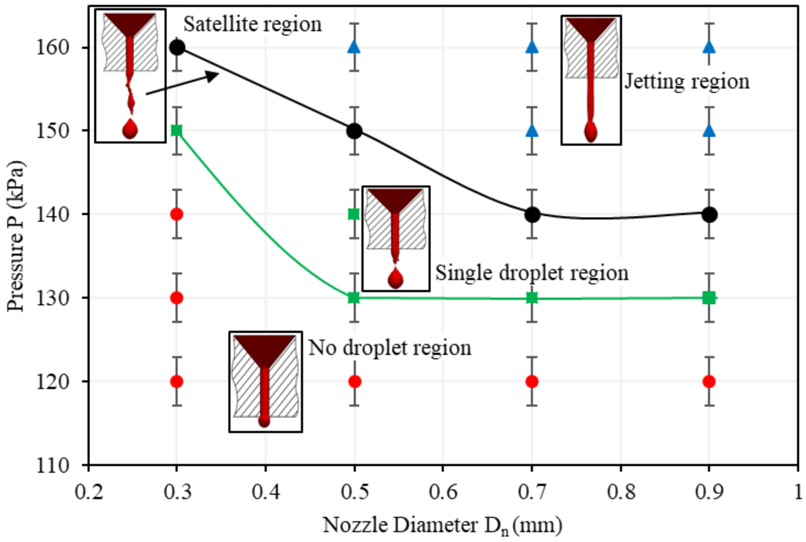

Fig. 4. Effect of nozzle diameter on droplet formation mode

In Fig. 4, the region bounded by red markers represents the region where no ejection occurred, while the region bounded by green and black markers depicts the region within which droplet formation can be achieved. The black markers indicate the region where satellites are formed. Satellite droplets were formed due to the oscillations generated by the breakup of the main droplet; as a result, a lower pressure should be selected to prevent the formation of satellites. The region bounded by blue markers shows the region of continuous jetting of the liquid metal.

3.2. EFFECT OF DUTY CYCLE

To investigate the effect of duty cycle on droplet formation, a nozzle diameter of 0.3 mm was used for the simulations, because it produced the smallest droplet diameter among the cases studied. Smaller droplet diameters are desirable because they improve the spatial resolution and dimensional accuracy of fabricated parts.

3.2.1. EFFECT OF DUTY CYCLE ON DROPLET PARAMETERS

During the simulation, the duty cycle was varied from 10% to 50% at 100 Hz and 0.3 mm nozzle outlet diameter, see Table 3.

Table 3. DOE factors and levels for duty cycle investigation

Factor	Unit	Level 1	Level 2	Level 3	Level 4	Level 5
Duty Cycle, $\boldsymbol{DC}$	%	10	20	30	40	50
Pressure, $\boldsymbol{P}$	kPa	120	130	140	150	160

Controlled Parameter: Nozzle diameter, $D_n = 0.3$

Figure 6a shows that an increase in duty cycle results in an increase in droplet diameter, from 0.55 mm to 0.9 mm, which is consistent with results obtained by Chao et al [11] and Gao et al [4].

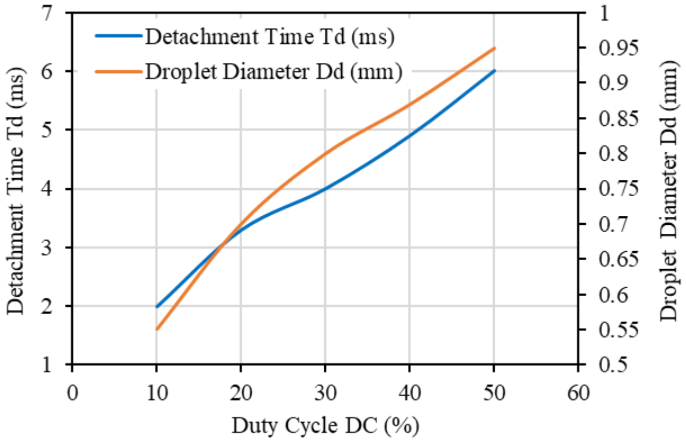

Fig. 6a. Effect of duty cycle on droplet diameter and detachment time

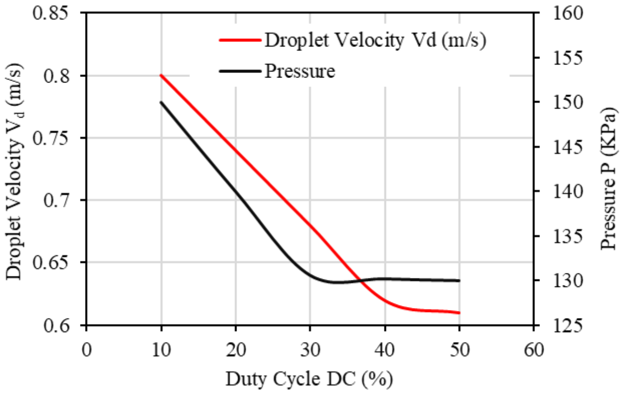

Fig 6b. Effect of duty cycle on droplet velocity and gas pressure

This trend shows that longer actuation duration enables greater volumetric accumulation before pinch-off, which leads to the formation of larger droplets. Droplet detachment time increased significantly with duty cycle from 2 ms to 6 ms. The increase shows the prolonged droplet growth phase associated with extended actuation time, in which the droplet remains attached to the nozzle until the capillary pressure of the molten metal is overcome.

3.2.2. EFFECT OF DUTY CYCLE ON DROPLET FORMATION MODES

Four phenomena were observed: no droplet, single droplets, satellites and jetting modes; Fig. 7 shows the region for each mode. For a duty cycle of 10 %, gas pressure between 120 kPa and 140 kPa was not sufficient to overcome the capillary pressure at the nozzle; hence, the system was unable to eject a droplet as shown in Fig. 7.

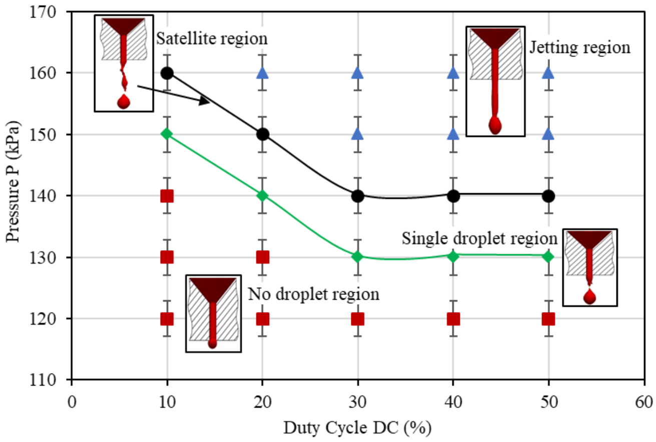

Fig. 7. Effect of duty cycle on droplet formation mode

Single droplets were produced at 150 kPa. As the pressure increased to 160 kPa, satellite droplets began to form. This suggests that droplet formation is highly sensitive to small variations in applied pressure at low duty cycle. At 20 % duty cycle, no droplets formed between 120 kPa and 130 kPa; single droplets began to form as pressure increased to 140 kPa. At 150 kPa, satellite droplets began to form. 160 kPa led to jetting of the liquid metal. No droplets formed at 120 kPa gas pressure for 30 % duty cycle, single droplets formed at 130 kPa and transitioned into satellites as the pressure increased to 140 kPa. From 150 kPa, it transitioned into jetting mode. For 40 % duty cycle, single droplets formed at 130 kPa. Satellite droplets began to form as the gas pressure was increased to 140 kPa. As the pressure was further increased to 150 kPa, the flow transitioned into jetting mode. At 50 % duty cycle, a similar flow pattern to that observed at 40 % duty cycle was obtained, although at 50 % duty cycle, droplets with a bigger diameter were observed.

4. CONCLUSION

This study presented a systematic numerical investigation of SS 316 droplet formation. The results showed that droplet formation is strongly influenced by nozzle diameter, gas pressure and duty cycle. Four distinct flow regimes were identified: no droplet formation, single droplet formation, satellite formation and continuous jetting.

For all nozzle diameters investigated (0.3-0.9 mm), as the pressure increased, the breakup mode transitioned from stable single droplet formation to satellite formation and eventually to continuous jetting. Larger nozzle diameters required lower pressures for droplet initiation and produced larger droplets. A linear relationship was observed between nozzle diameter and droplet diameter, which confirmed that nozzle diameter is a primary factor that influences droplet size.

An increase in duty cycle led to extended actuation time, which enables greater molten metal accumulation before necking and pinch-off. Hence, droplet diameter and detachment time increased with duty cycle.

Overall, stable droplet generation was observed within a limited operational window defined by moderate pressure and duty cycle values. Outside this window, the process transitioned to either no droplet formation, satellite formation or continuous jetting, which are undesirable outcomes.

Due to the simplified isothermal modelling assumptions and the lack of experimental validation, the results presented in this work should be considered preliminary and indicative of general trends rather than definitive predictive guidelines. Future work should focus on optimising the pressure and duty cycle to achieve stable single droplet formation while minimising satellite generation, particularly for high melting point metals such as SS 316. Experimental validation is needed to confirm the numerical results, and future models should incorporate thermal effects such as temperature gradients and solidification for realistic results. Further studies on nozzle aspect ratio and high frequency operation area are also recommended to enhance droplet stability, repeatability and overall process control.

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