INVESTIGATION AND COMPARISON OF EFFECTIVE PARAMETERS ON EJECTING OF PURE MOLTEN TIN (SN) AND SN-PB ALLOY FROM MAGNETOHYDRODYNAMIC PUMP

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1. Abstract

The conductivity of the molten metal makes it possible to apply force to the melt by using electromagnetic forces without the use of mechanical parts and causes it to be manipulated in any direction. In this research, a distinguished electromagnetic pump to create an intermittent flow of melt to achieve a controllable nozzle in various applications, such as 3D metal printers and equipment for the production of metal powder and granules, has been introduced. In this pump, the production of droplets on demand is based on the discharge of conductive fluid droplets by creating eddy currents and alternating electromagnetic forces inside the melt. This paper aims to investigate effective parameters on the droplet production rate and the effectiveness of the combination of the parameters to achieve an efficient droplet production mechanism. Also, an experimental comparison between pure tin and solder alloy of Sn-Pb is carried out to investigate the effect of the molten metal characteristics (surface tension, electrical conductivity, melting temperature and wettability) on MHD pump.

Keywords: Electromagnetic pump, Drop-on-demand, Metal droplet, Sn

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Introduction

2. Introduction

The fundamental concept of MHD is simple: a unidirectional current is created via an electrically conductive fluid, like seawater [1, 2]. The fluid is then subjected to an intense magnetic field that is perpendicular to the current. An orthogonal magnetic field, an electric field, and the relative motion of ions produce a Lorentz force, which direction is determined by the cross product of the vectors of the magnetic and current fields. The fluid is simply forced, such as being pumped, if the mechanism holding the electromagnet and enclosure is fixed. Newton's second law of motion states that the object will rebound if it is free or encounters little opposition to the motion. The apparatus is here referred to as a pump-jet or thruster. Inlet nozzle, main body, and nozzle dispersion are the three primary structural elements of MHD pumps, as seen in Fig. 1. In the main body, the electrodes and superconducting magnet are positioned so that the magnetic and electric fields are perpendicular. Table 1 summarizes several MHD pumps' benefits and drawbacks in comparison to traditional pumps[3].

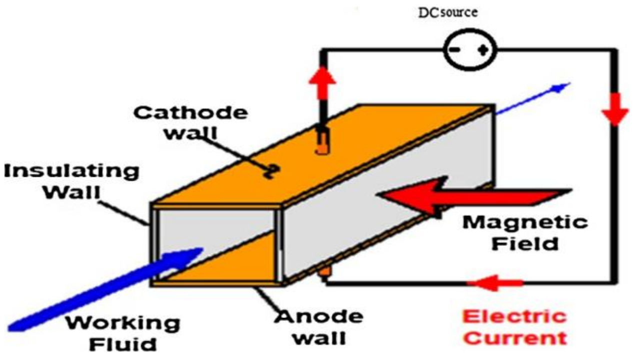
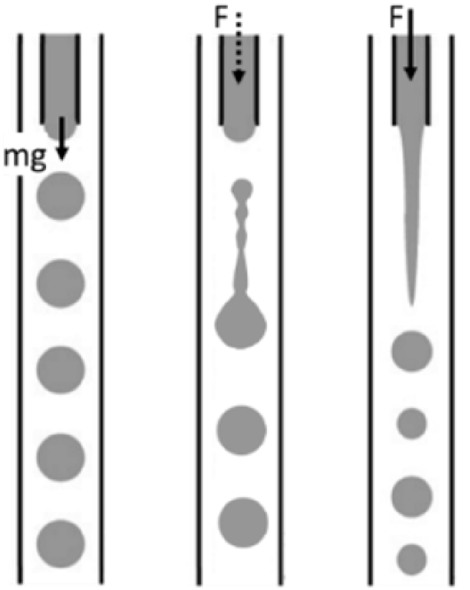


Figure 1: MHD pump elements[3]

Table 1: advantages and disadvantages of MHD pumps[3]

ADVANTAGES	DISADVANTAGES
LOW COMPLICATION	Conductivity limitations
WITHSTANDING HIGH TEMPERATURES	Under some operating conditions, the liquid velocity profile has a non-homogeneous distribution and the flow is could be unstable. (i)
POWER EFFICIENT	
MINIMAL MAINTENANCE	
MICROSCALE APPLICATION	

Electromagnetic pumps are divided into two categories of alternating and direct current, based on the type of the current used to supply the magnetic field, and the type of the electric current applied to the fluid. The conventional method to apply the current is to directly contact the conductive fluid with electrodes. The other method is to apply the current by conducting the current through inducting coils, which apply the magnetic field and also induce the current inside the nozzle. The later method, is mainly used for droplet production due to its control over the duration and intermittent force application. The Drop production methods in different applications, based on the principles of droplet production, can be divided into three categories: (1) dripping, (2) continuous jet, and (3) drop-on-demand. Figure 2 shows the schematics of types of droplet productions.



Droplet production	Dripping	Drop on Demand	Continuous Jet
Droplet production rate	Low	Medium	High
Force of droplet discharge	Gravity	Intermittent pressure	Continuous Pressure

Figure 2: Droplet production mechanism

In the dripping method, droplets of liquid drip through a capillary tube by gravity. The drop production rate in this method is low because it takes a long time (from a few seconds to a few minutes) for each drop to form and reach the required weight, which could be controlled by limited number of influencing parameters such as nozzle material wettability, surface tension of liquid and the nozzle, nozzle geometry and orifice shape and diameter [4, 5]. Therefore, this method is suitable for laboratory devices in which the speed of production and consumption of droplets is less important (such as the device for measuring surface stress or contact angle). The second method of droplet generation is the continuous jet, which occurs when the fluid flow in the capillary tube increases. Under these conditions, the jet continuously turns into separate droplets due to Plateau–Rayleigh instability [6]. With the help of a suitable excitation cycle, a uniform flow of droplets with high speed and frequency can be created. Continuous jet has shown successful performance in inkjet printing processes. However, the production of this type of droplet requires complex control equipment. In the third method, drop-on-demand, a small volume of liquid is transferred due to the pressure of small blows to the liquid's channel and then to the nozzle. Under the accurately calculated conditions, the liquid ejecting the nozzle turns into a drop. This process is an efficient way to generate droplets in micrometer dimensions and deposit them on a surface due to its ease of control by changing the electrical pulse.

In a drop-on-demand magnetohydrodynamic pump, the pulsed voltage applied to both ends of the coil creates an electric current through the coil and eventually a magnetic field through the nozzle. The time-varying magnetic field creates eddy currents inside the conductive fluid, and the coupling of this eddy current and the external magnetic field creates a Lorentz force. Obviously, as the Lorentz force changes, the pressure behind the fluid, forcing the droplet to exit the nozzle and then the characteristics of the droplets produced will change; Because the amount of the induced electric charge in a conducting fluid and the mass distribution in the droplet ejecting the nozzle is highly dependent on the properties of the fluid and the voltage as an influential factor. The nozzle is also designed and constructed so that by applying Lorentz force, the conductive fluid inside the nozzle moves downwards and the nozzle orifice accordingly.

In the drop-on-demand method, the molten phase is produced in a small volume and stored in a reservoir, firstly. Then the melt is exposed to the intermittent stimulus and forced dropwise out of the nozzle. Various stimuli have been used in various technologies. Among the technologies used, electromagnetic jet [7]and piezoelectric [8] are worth mentioning. The produced droplets lose their temperature in the distance from the nozzle to the surface of the base plate and solidify after colliding with the workpiece (bed surface or previous layers). According to the properties and viscosity of tin[9]at different temperatures, with the conclusion that by increasing the temperature above the melting temperature, the viscosity will decrease and it will be much more difficult to control the drops. So far, this method has been used to print various materials such as wax, lead, tin alloys, and aluminum [10]. This technology is based on several scientific and technological principles, including droplet generation, intermittent flow generation, heat transfer, solidifying, and positioning, which have been studied in this article.

In 2000, Jang et al. [11] studied and simulated the magnetic field applied on molten metal and calculated the governing equations, including the amount of pressure applied, the voltage, and the electric current in the mechanism. The interaction of the magnetic field, and the electric current, creates a force in the perpendicular direction of the two components.

Ahmadi et al[12], has developed a small-scale device to actuate droplets in planar fluids to investigate the parameters such as threshold voltage, the effective channel for the droplet movement and also the effect of surface tension and wettability to indicate the minimum volume of a movable droplet. Using a hydrophobic coating layer could also decrease the resistive forces.

Zhu et al., [13] investigated the influence of wettability and contact angle of aluminum melt with graphite nozzle to produce aluminum droplets. First, by modeling the structure of the nozzle and the aluminum melt and investigating the effect of the contact angle of the aluminum melt with the nozzle and then conducting experimental tests, they have come to the conclusion that by increasing the contact angle of the melt with the surface of the nozzle, they achieve smaller diameter droplets. Also, with the variable wetting coefficient of the nozzle surface in contact with the melt, they cause a change in the path of the drops on the substrate surface. Also, with the increase of the contact angle, the diameter of the aluminum droplets has decreased. White [14], by investigating the effect of temperature on surface tension, found the fact that by increasing the temperature, the surface tension of tin and its alloys with surfaces will decrease.

In order to improve the molten metal ejection performance, Lu et al. investigated the effect of the cone angle of the nozzle without the presence of a plunger (core) and moving parts in a designed micro-jet electromagnetic pump. The effect of the conical angle of the nozzle on the ejection of molten gallium metal was investigated. In this research, it was found that the Lorentz force component parallel to the nozzle that ejects the melt is always greater than its internal friction. Therefore, droplets can be produced with any cone angle but with different kinetic energies. The experimental results show that the mass of the molten droplets, the jet distance, the initial velocity of the ejected droplets and the kinetic energy of the ejected droplets first increase and then decrease. When the angle of the cone is 90 degrees, the mass of the melt drop and the kinetic energy are at their highest. When the angle is 80 degrees, the initial velocity reaches its highest with a calculated value of 0.042 m/s. Moreover, very close and relatively high kinetic energies are obtained at 80◦ and 90◦, indicating that angles between these ranges can provide favorable performance [15].

In another work by Wang et al. [16], who researched the effect of the pulse shape and amplitude of the input current to the coil and the frequency, the results show that compared to the triangular wave and the sine wave, the square pulse wave can produce a drop in Each cycle in the flow produces a constant amplitude and higher droplet formation frequency. Process parameters, such as amplitude, input current frequency, and electronic pulse width have a significant effect on droplet formation. As the pulse frequency increased from 80 Hz to 86 Hz in the input current range of 37 A, the droplet velocity decreased from 0.22 m/s to 0.20 m/s. By increasing the range of the input current from 37 amps to 40 amps, the droplet speed increased from 0.20 m/s to 0.22 m/s at the constant frequency of the input current of 40 amps. Also, by adjusting the pulse width, it is possible to prevent the formation of tail drops (drops that are produced tight at the tail of the desired drops due to improper settings of the device).

The magneto jet process, based on the principles of magnetohydrodynamic (hydro magnetism), involves the study of the dynamics of magnetic fields in electrically conductive fluids. The most widespread application of magnetohydrodynamics is continuous metal casting. The first prototype of the magnetohydrodynamic pump was built in 1907 and has since been used for various applications such as flow control of molten metals, heating, power generation, and magnetic plasma enclosure. Using a magnetohydrodynamic pump, the molten fluid can be drained out of the nozzle at high temperatures, as required.

In 2018, Vader et al. [7] used the magnetohydrodynamic principle in 3D printers and achieved significant results. The process of additive manufacturing method designed and developed in this research is as follows: First, the aluminum filament is fed into the nozzle using the feeding system and melted using a heating system. The electromagnetic coil surrounds the nozzle, and by applying a pulsed voltage to the coil, a magnetic field is formed in the conductive fluid inside the nozzle. Then a vortex flow and a Lorentz force are generated. The nozzle is designed so that the conductive fluid moves towards the inner walls and finally towards the nozzle orifice by applying Lorentz force. The conductive fluid is ejected from the nozzle on demand, dropped onto the base plate, and solidified. By moving the base plate in three directions, three-dimensional metal parts can be created. This study investigates the effect of droplet exit frequency on the correlation of solidified droplets on the base plate. This research found that with increasing the frequency of droplets exiting from the nozzle, the correlation between solidified droplets on the base plate has increased. Also, increasing the temperature of the base plate reduces the thermal gradient in the solidification process of the droplets exiting the nozzle, and the correlation between the droplets has increased [10].

There are uncertainties between droplet size and nozzle diameter. For example, in the article [17], although the diameter of the nozzle is about a few millimeters, the diameter of the drop is about nanometers. The droplet size depends on electrical characteristics, pressure, gravity and surface tension. In [18], which presented the way of droplet formation and its modeling based on a new numerical model, he obtained the parameters affecting droplet production by modeling using the Plackett-Burman design, as well as the output parameters that are used in the way of droplet formation. He considered the droplet diameter, the nozzle exit distance to the ground and the droplet speed to have a significant effect, and among the input parameters affecting the droplet diameter, he named the following 6 parameters: permittivity, the conductivity, the flow rate, the voltage, the viscosity, and the nozzle diameter

3- simplified governing equations

This section offers a condensed mathematical explanation of the ideal MHD pump. Additionally, it introduces some of the fundamental terminologies and ideas. A latest study uncovered various issues that might lower an MHD pump's effectiveness. Any fluid with scalar electrical conductivity s (S/m) at a specific place and velocity vector V (m/s) may be applicable by the equations below. The induced electric current density J (A/m2) is a vector whose magnitude and direction are specified by: if the fluid is subjected to the interaction of the electric field vector E (V/m) and magnetic flux density vector B (T), which then the governing equation will be[3]:

$$J = s(E + V \times B) \qquad \text{Eq. 1}$$

The apparent electric field produced by the cross product (V×B) in equation (1) resembles the back EMF of electric motors, when the motor armature is compared to the flowing fluid. The reverse EMF will be in the direction opposite to the applied electric field when E, V, and B are mutually perpendicular, which is the best scenario. The relative magnitudes of the back EMF and the applied electrical field E determine the current density's amplitude and direction primarily. Depending on the direction of the current density J, the system either operates as a pump or a generator. If the amplitudes and vectors of E, V, and B remain constant throughout the channel, Eq. (1) is simple to apply. This is challenging to do in the real design since Eq. (1) needs to be integrated throughout the full working fluid volume.

A vector body force per unit volume F (N/m3) acts on an electrically neutral conducting material, when electric current flows through it when a magnetic field is present. F, often known as the Lorentz force, can be calculated as follows:

$$F = J \times B \qquad \text{Eq. 2}$$

conductive fluid in the MHD duct is accelerated by this force. On the other hand, if the direction of J results in the MHD duct becoming a generator, it will cause the liquid to decelerate. Electric power density P (W/m3) is the measure of the total energy supplied to the MHD pump per unit volume. Specifically, it is written as follows for a DC circuit:

$$P = E \times J \qquad \text{Eq. 3}$$

The thrust will use a portion of this power, and the remaining amount will be wasted by heating the MHD channel. The resistive losses for MHD pumps are proportional to the Joule heating power density Pj (W/m3), where,

$$P_j = \frac{J^2}{s} \qquad \text{Eq. 4}$$

The optimum effective propulsion power density Pt (W/m3) is the difference between total power input and Joule heating power losses. The following results from multiplying both sides of Eq. (1) by J:

$$J^2 = J_s(E + V \times B) \qquad \text{Eq. 5}$$

After adjusting Eq. (3) for the power density P and rearrangement, the result of dividing both sides of Eq. (5) by d is as follows:

$$P = VJ \times B + \frac{J^2}{s} \qquad \text{Eq. 6}$$

Consequently, the following is the effective thrust power density:

$$P_t = VF \qquad \text{Eq. 7}$$

An MHD pump consists of the following components:

1- Flow channel
2- Super-conducting magnet or inductive coil
3- Electrodes (any apparatus to apply electrical current)
4- Electrical power supply
5- Main structure

Since the magnetic field is typically not consistent across the channel in real time operation, the flow may not be uniform, especially during transient operation. The solution to Eq. (7) for the total supplied power is involved since J is linked with V and B. In order to approximate the quasi-steady magnetic flux, the following formula is used using Biot-Savart Law:

$$B = C_1 \int\int\int \left(\frac{j_m N_{ab}}{r^2}\right) dv \qquad \text{Eq. 8}$$

where

C1: Magnetic permeability divided by 4

v: Volume of integration

Jm: Current density in magnetic coils

Nab: Unit vector from point a to point b

r: Distance from a to b

Also, Eq. (1) may be used to compute the electric field (E), and the steady-state versions of two of Maxwell's equations are as follows:

$$\nabla \times E = 0 \qquad \text{Eq. 9}$$

$$\nabla . J = 0 \qquad \text{Eq. 10}$$

Given that the magnetic flux density B and the velocity V are known, Eq. (9) suggests the presence of an electric potential that meets the relation:

$$E = (-\nabla \emptyset) \qquad \text{Eq. 11}$$

Using Eq. (11), a second-order partial differential equation in which magnetic flux may be estimated is produced by substituting J from Eq. (1) into Eq. (10).

$$\nabla^2 \emptyset = \nabla . V \times B \qquad \text{Eq. 12}$$

3- method

Knowing that the affecting parameters can be divided into the nozzle side and the pulse side, the investigation on both of the parameters has been conducted. In order to design a nozzle, which doesn't cause an interference with the magnetic field due to its magnetic characteristics, the nozzle was designed and manufactured using stainless steel 316. Also, the design consists of two parts of the shell and the plunger, in order to be able to adjust the channel (duct) of the magnetohydrodynamic pump. By adjusting the width of the duct, the pressure required to eject the droplets out of the nozzle can be achieved, where too wide or too narrow duct can cause the pressure not to be sufficient. Also, the orifice of the shell, where the droplets are ejecting from, is set to be 0.5 mm to have a geometrical control over the droplet size. The nozzle can be seen in figure 3.

Figure 3: Steel nozzle made for the research

Several other factors such as surface tension, contact angle between the molten tin and stainless-steel nozzle, temperature of the molten tin and other factor, are not in the scope of this research and has been set to constant for the conducted tests.

The pulse controlling parameters, such as voltage, pulse on time, duty cycle and pulse frequency are controlling factors which were investigated in this research. By increasing the voltage of the coil which is responsible to induce the eddy current in the molten tin reservoir inside the nozzle and also the magnetic field in the perpendicular vectors, the Lorentz force which is produced orthogonally, is allowed to increase due to the peak of the current in the created pulse. Figure 4 illustrates the relation between the mentioned controlling parameters.

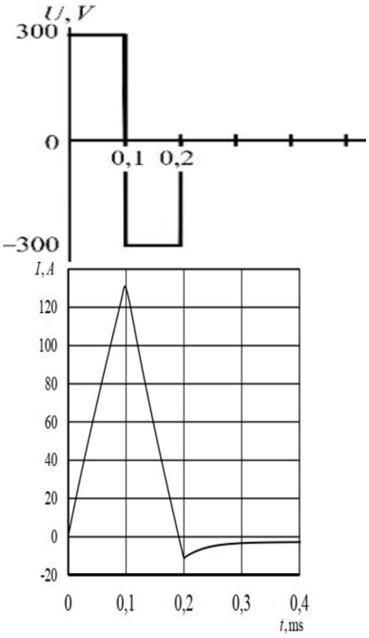


Figure 4: by increasing the voltage in the applied pulse to the coil, the higher peak in the current, and ultimately Lorentz force is achieved.

The same effect can be achieved by increasing the pulse on time, where it should be taken into account the duty cycle should be kept low enough that the melt reservoir wouldn't be turbulent while the next pulse creates the pressure to eject the next droplet. Figure 5 demonstrates the increase in pulse on time and voltage which result in the increase in Lorentz force.

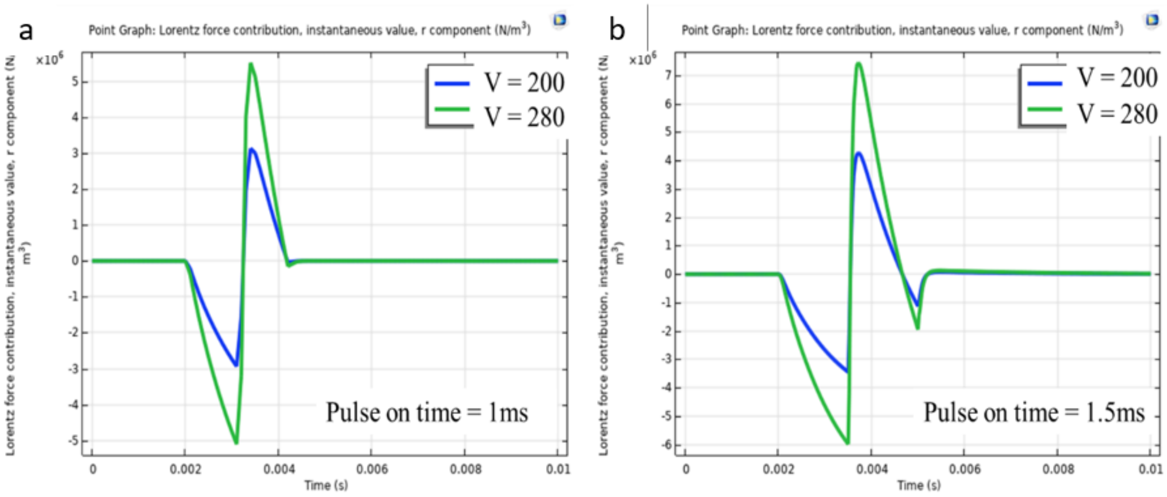


Figure 5: increase in pulse on time and voltage which result in the increase in Lorentz force

Initially, the magnetohydrodynamic drop-on-demand pump is designed and manufactured. This pump consists of a power and control circuit by using of which a pulsed voltage can be applied to the coil. The pump circuit is designed in such a way that the voltage, frequency, and pulse on-time can be altered as desired. The circuit outlet is connected to the electromagnetic coil surrounding the nozzle. Tin is cast into granules and brackets in a nozzle and melted using a heating system. Then, by applying a pulsed voltage, the Lorentz force is formed, and by affecting the molten tin inside the nozzle, it causes the fluid to move towards the nozzle orifice, and the tin melt is ejected out of the nozzle as a drop-on-demand.

The designed device to achieve the drop producing mechanism is illustrated in figure 6.

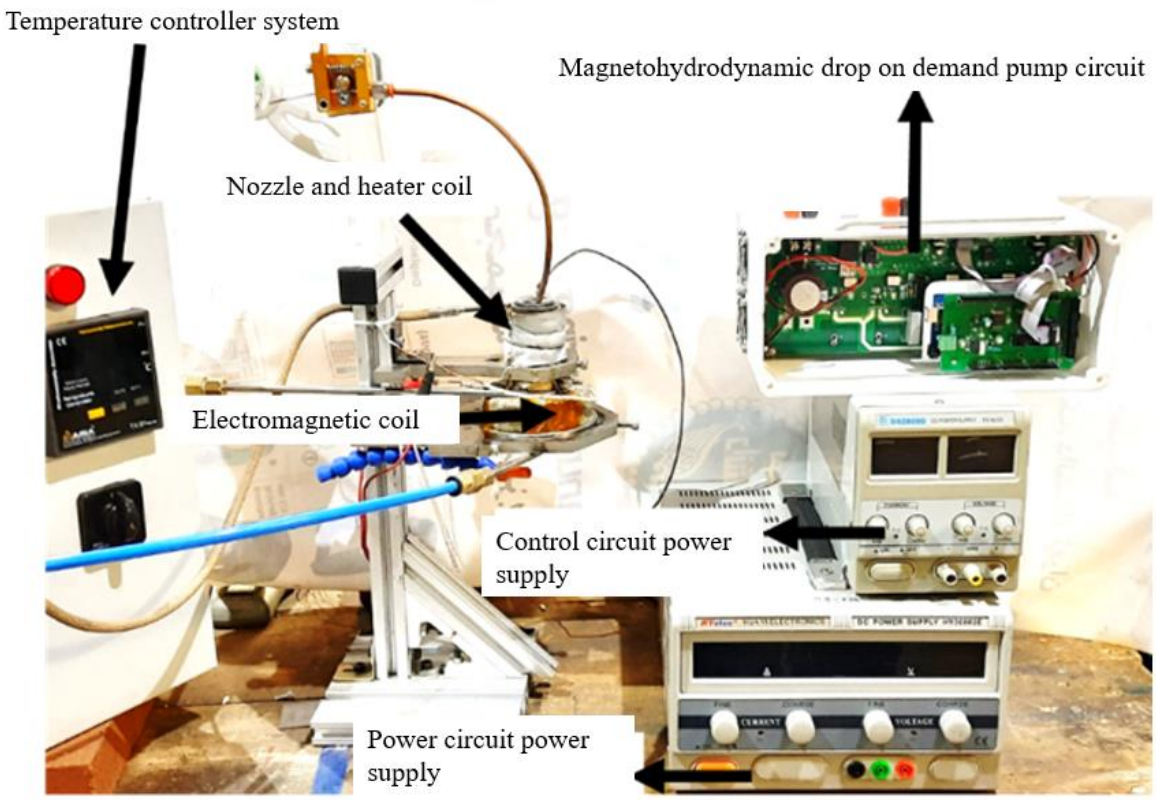


Figure 6: General view of the designed device as the test bench of this research

According to the studies performed to create the intermittent flow of molten tin metal, the appropriate frequency range between 5 and 20 Hz will be considered. Voltage can also be varied in the range between 200 and 300 volts. According to the research results another important parameter in creating the desired current is the pulse on-time, which was selected as 1 and 1.5 milliseconds in the mentioned experiments. Finally, by designing a suitable experiment in the mentioned ranges, the results and the droplet output will be analyzed, and the best possible state will be obtained to produce smaller sized droplets with the highest frequency possible. The shape of the drops is also very important in the experiments, and this feature also determines the quality of the produced droplets.

In this study, to perform the experiments according to the test design table, the frequency was set in three levels and the pulse on-time was set in two levels. Changing the frequency and the pulse on-time requires changing the code installed on the control circuit. The power circuit is also used to change the applied voltage to both ends of the coil. According to the test design table, six different codes are installed on the control circuit and the tests performed by each of these codes are performed in two voltages of 200 and 280 volts. The code is developed in Arduino software and uploaded to the Arduino board.

4. Results and discussions

4.1- Investigation of the effect of voltage, frequency and pulse on-time of drop-on-demand magnetohydrodynamic pump on the number of pure tin droplets exiting the nozzle at 320 ° C

First, the effect of frequency, voltage and pulse on-time of the drop-on-demand magnetohydrodynamic pump on the number of the droplets exiting the nozzle with pure tin at 320 ° C is investigated.

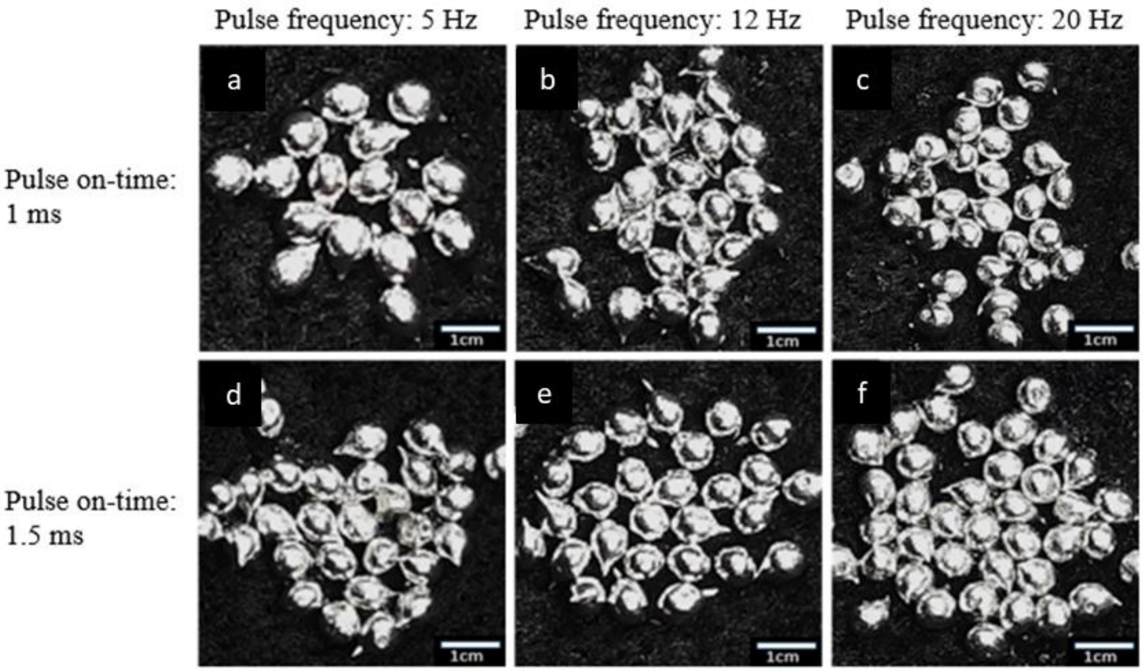


Figure 7: Results of frequency change and pulse on-time on pure tin droplets at 200 volts and 320 ° C

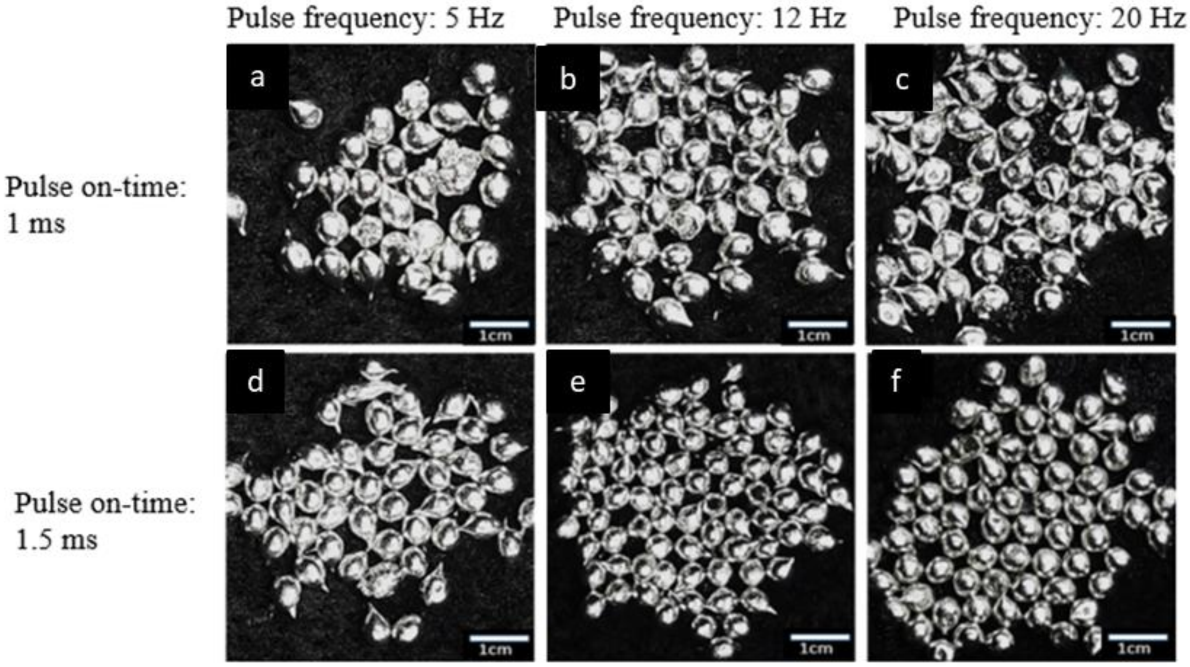


Figure 8: Results of change in frequency and pulse on-time on pure tin droplets at 280 volts and 320 ° C

4.2- Investigation of the effect of frequency and pulse on-time at 320 ° C on the number of tin droplets exiting the drop-on-demand magnetohydrodynamic pump nozzle at constant voltages of 200 and 280 volts

According to the research conducted by Lee et al. [19] and figures 7a and 7b the effect of increasing the pulse on-time and frequency on the number of droplets ejected from the nozzle of the drop-on-demand magnetohydrodynamic pump at constant voltage of 200 and 280 is shown, respectively. Increasing the voltage from 200 volts to 280 volts has increased the number of droplets being ejected the nozzle in a constant time of one minute. According to the results of previous experiments, with increasing frequency and pulse on-time, the number of droplets exiting the nozzle at 200 and 280 volts in a constant time of one-minute increases. In this section, the pulse on-time is investigated as an effective factor at two levels of one and one a half millisecond. Due to the utilization of a coil with 200 turns, the inductance of the coil is considered as a significant parameter in pulse on-time, which are in order of milliseconds and microseconds. Therefore, the coil does not saturate the desired current in 1.5 milliseconds. By applying pulsed voltage, the amount of current passing through the coil increases. Increasing the current passing through the coil increases the eddy current formed in the conductive molten tin and increasing the eddy current, increases the Lorentz force. Therefore, it can be concluded that the time of applying pressure behind the fluid to create a drop positively affects the number the droplets. That is, the number of drops produced in experiments with a pulse on-time of 1.5 milliseconds is more than the number of drops produced with a pulse on-time of 1 millisecond.

Also, Figures 9c and 9d show that the frequency effect is greater than the pulse on-time, and the direction of the effect of the pulse frequency and pulse on-time on the droplets leaving the nozzle is in one direction. With increasing frequency and pulse on-time, the number of droplets exiting the drop-on-demand magnetohydrodynamic pump nozzle has increased.

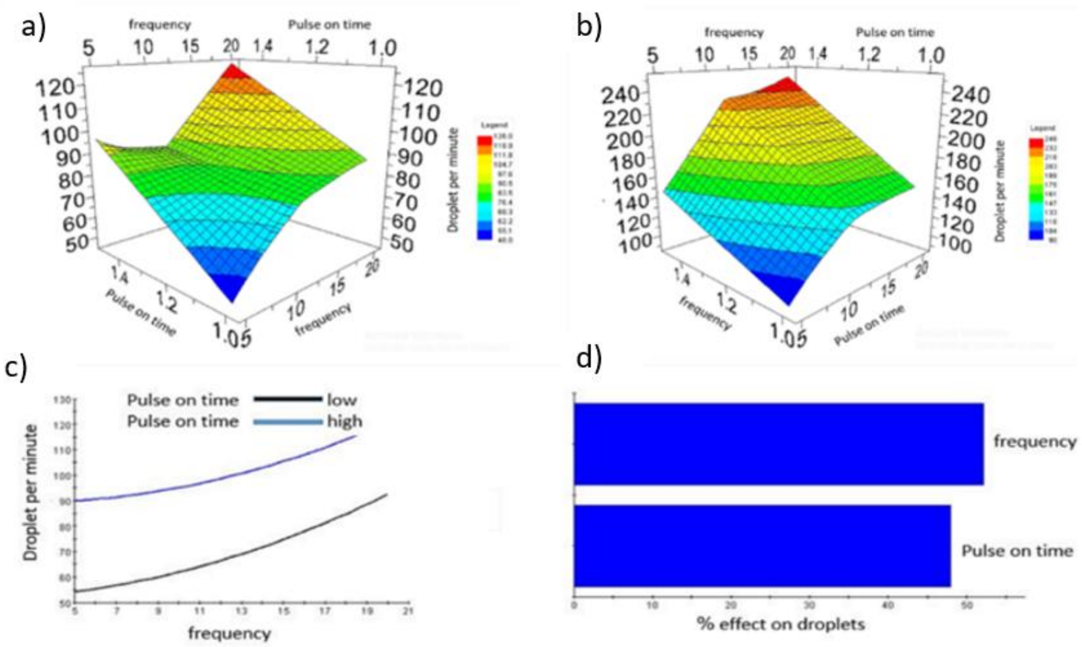


Figure 9: Number of pure tin droplets at 320 ° C ejected from the nozzle at 200 and 280 volts, respectively.

4.3- Investigation of the effect of voltage and pulse on-time at 320 ° C on the number of tin droplets exiting the drop-on-demand magnetohydrodynamic pump nozzle at constant frequencies of 5, 12 and 20 Hz

At constant frequency, by increasing voltage and increasing pulse on-time, the number of droplets exiting the nozzle increases at a constant time of one minute. Also, it is observed that the effect of the voltage as a parameter is greater than the pulse on-time. The pump's frequency actually indicates the number of times the Lawrence force is applied or the number of effective pressure peaks applied per second. In this study, three frequencies of 5, 12, and 20 Hz have been studied. By increasing the number of effective pressures on the conductive molten tin inside the nozzle, the number of droplets per minute leaving the nozzle increase, while keeping other effective factors under control. Figures 10a, 10b, and 10c show the changes in the number of droplets being ejected of the nozzle at constant frequencies of 5, 12 and 20 Hz, respectively.

Then, the effects of voltage and pulse on-time of the drop-on-demand magnetohydrodynamic pump on the number of pure tin droplets leaving the nozzle at 320 ° C was also studied. Increasing the voltage increases the magnetic field and, naturally increases the eddy current produced through the conductive molten tin inside the nozzle. The Lorentz force depends on the presence of magnetic field and the eddy current. Therefore, by increasing eddy current and magnetic field, the Lorentz force increases and, in fact, the pressure affecting the droplets ejecting from the nozzle of the drop-on-demand magnetohydrodynamic pump increases. Figures 7d and 7e demonstrate that the effect of increasing the pulse voltage is greater than the effect of increasing the pulse on-time, for the desired outcome of increasing the number of leaving drops from the nozzle and the direction of these two parameters is the same. Therefore, by increasing voltage and pulse on-time at a constant frequency, the number of the droplets leaving the nozzle increases.

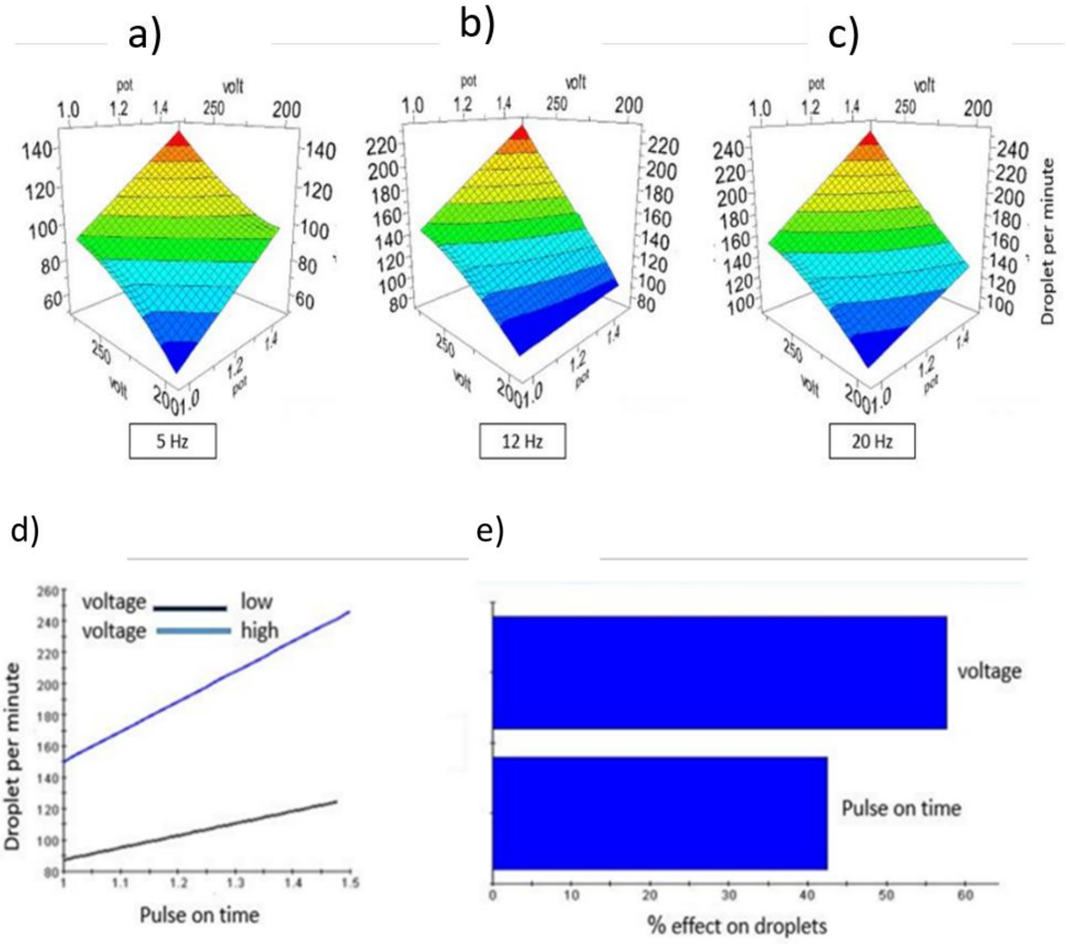


Figure 10: a,b,c) Effect of voltage and pulse on-time (pot) on the number of pure tin droplets exiting the nozzle at 320 ° C

e,d) the effectiveness and direction of voltage and pulse on-time

4.4- Investigation of the effect of voltage and frequency at 320 ° C on the number of the droplets of pure tin exiting the drop-on-demand magnetohydrodynamic pump nozzle at constant pulse on-times of 1 ms and 1.5 ms.

The frequency of the drop-on-demand magnetohydrodynamic pump indicates the number of pulsed voltages applied per second to the electromagnetic coil. As the number of pulses applied is increased, the number of Lorentz forces and the number of pressures acting on the conductive molten tin inside the nozzle increase. The results of this study show that by increasing pump frequency, the number of droplets exiting the nozzle increases. The reason is that the number of force peaks applied to the melt inside the nozzle increases and the process of droplet formation occurs in less time. As shown in figures 11a and 11b, as the voltage and frequency increase, the number of droplets being ejected from the nozzle increases, and the voltage is more effective than the frequency.

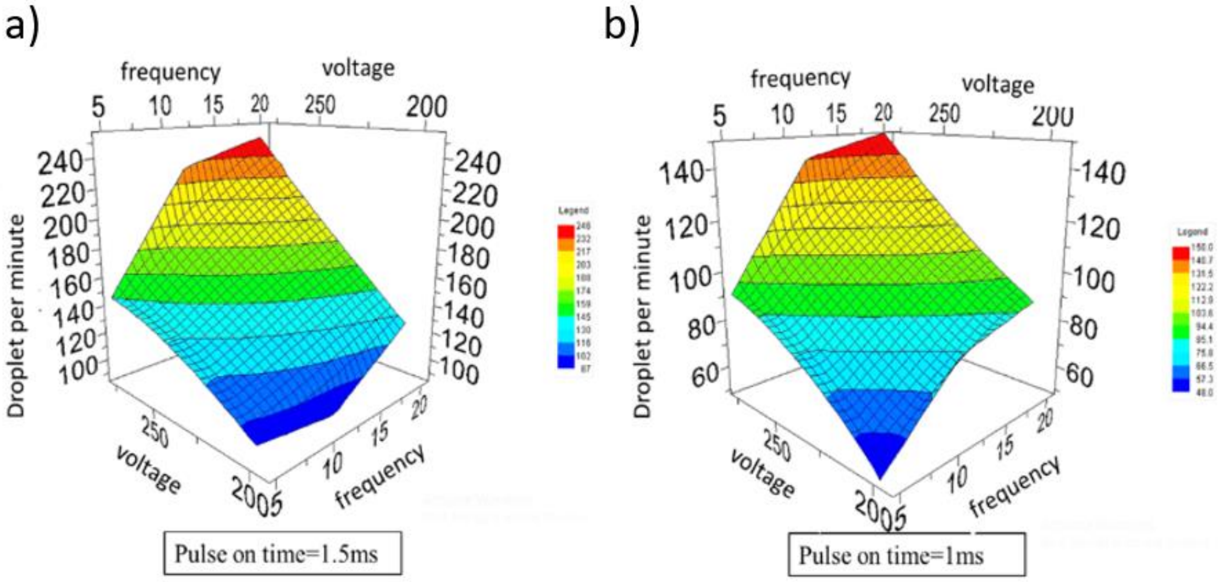


Figure 11: Effect of voltage and frequency on the number of droplets of pure tin at 320 ° C

4.5- Investigation of the effect of voltage, frequency, and pulse on-time on drop-on-demand magnetohydrodynamic pump on the number of pure tin droplets ejecting the nozzle at a temperature of 250 ° C

Effects of frequency, voltage and pulse on-time of drop-on-demand magnetohydrodynamic pump on the number of ejected pure tin melt at 250 ° C from the nozzles in another part of the experiments was performed and shown in figures 12 and 13. In these experiments, first the process voltage was set at 200 volts (figure 9) and then 280 volts (figure 13).

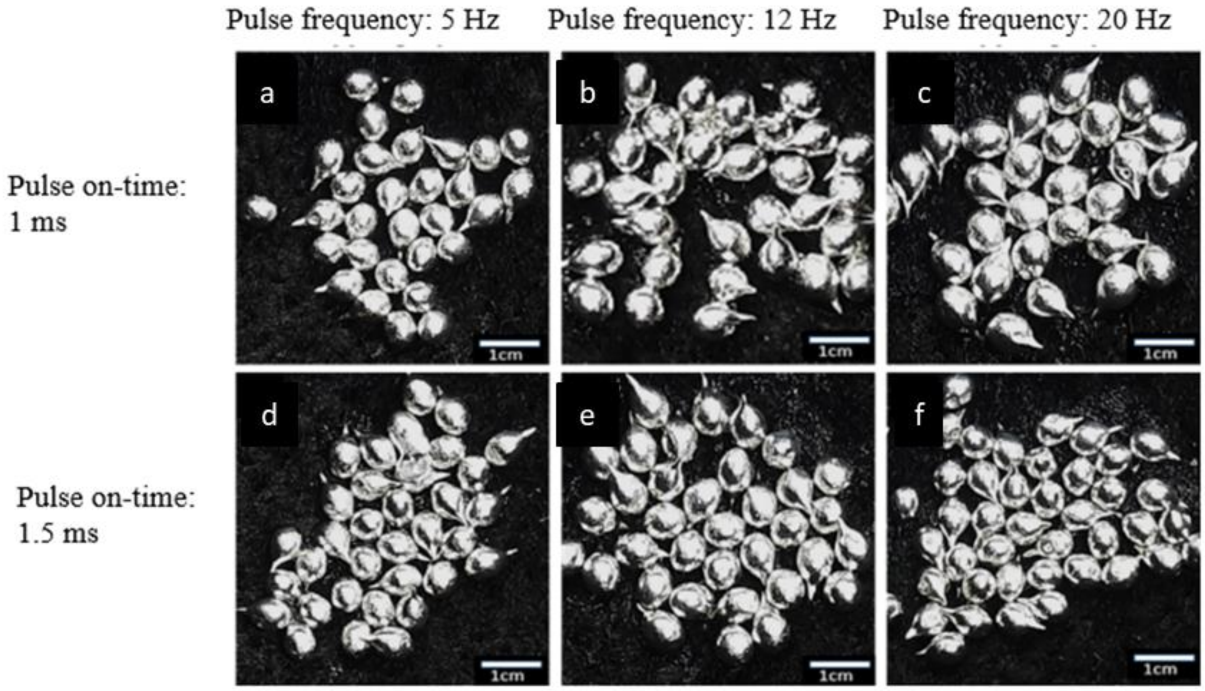


Figure 12: Results of change of frequency and on-time of pure tin pulse at 200 volts and at a temperature of 250 degrees Celsius

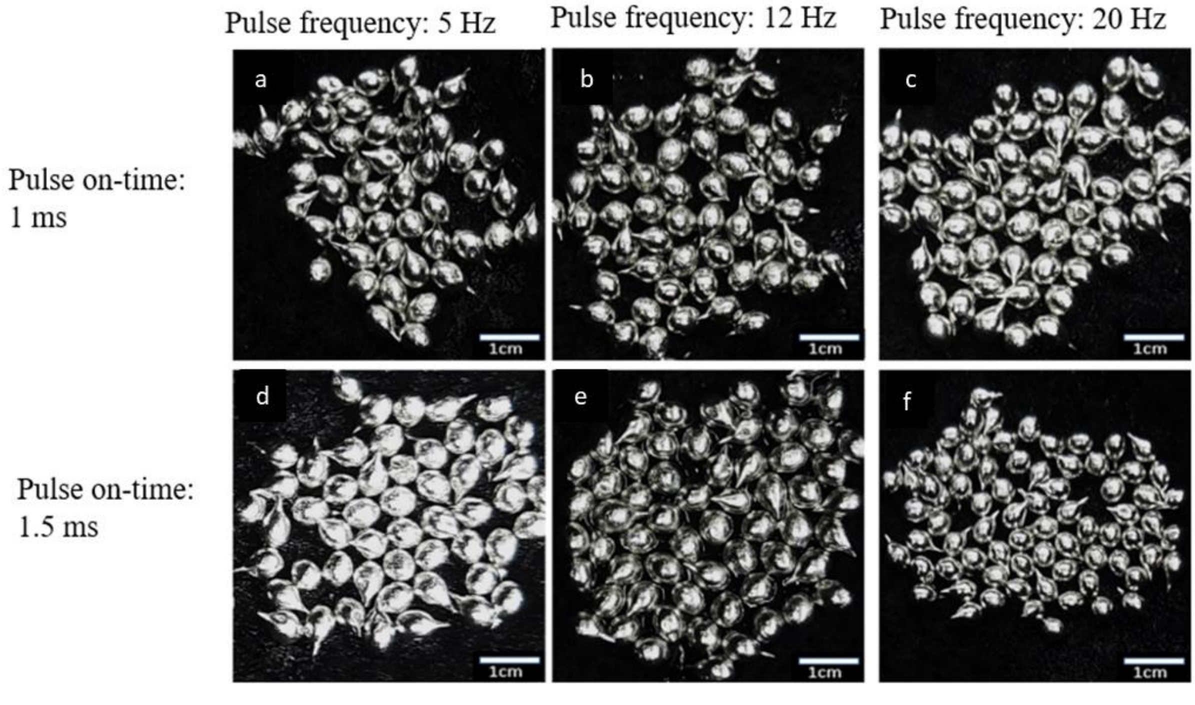


Figure 13: Results of frequency change and pulse on-time on the droplets of pure tin at 280 volts and 250 ° C

4.6- Comparison of droplet weight of pure tin and solder alloy (Sn 60-Pb40) in different settings to investigate of the effect of surface tension, viscosity and temperature of the material on the ejection of the droplets

In the first test, the electromagnetic pump has been calibrated to observe the effect of increasing the pulse on time. This test was performed for two tin metals and tin-lead alloy at two different temperatures and at a frequency of 20 Hz with a voltage range of 200 V. In this experiment, it was observed that the weight of the produced droplets increases with the increase in the pulse on time. In the figure 14, it can be seen that in addition to the fact that the temperature affects the weight of the droplets, the weight of the metal drops also increases with the increase in the duration of the voltage pulses.

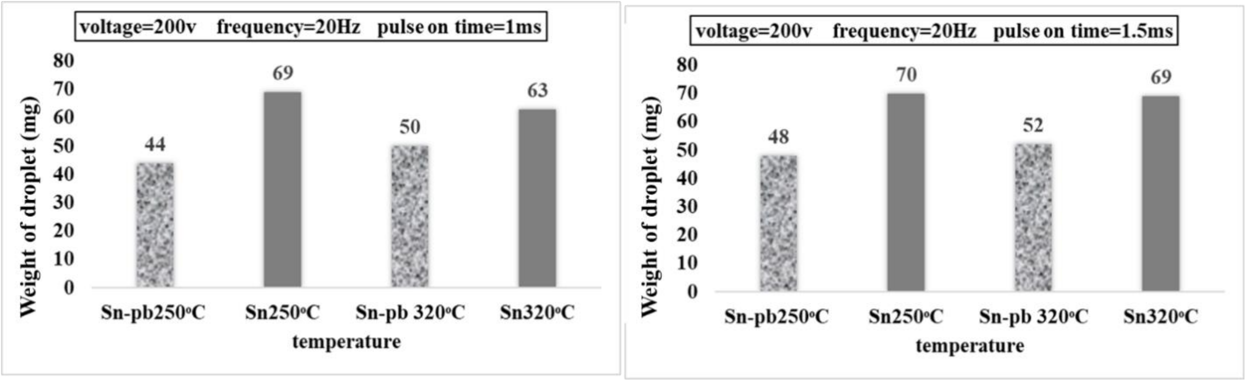


figure 14: investigating the droplet weight of pure tin and tin-lead alloy by changing the temperature of the nozzle and the pulse on time, frequency at 20Hz, voltage at 200V

The weight of the pure tin droplets is higher in the identical settings, due to their lower viscosity and higher contact angle compared with the Sn-Pb alloy, which confirms the effects of the surface tension being a reason for less resistant over droplet formation. Also, by increasing the temperature to over the 20 percent of the melting point, would cause lower control over the droplet formation and higher droplet weight.

4.7- Comparison of droplet weight of pure tin and solder alloy (Sn60-Pb40) by increasing the applied voltage of the pulse

Another experiment has been done to observe the effect of the voltage range of the generated pulses in the power circuit that is given to the coil. In this experiment, other parameters such as the frequency of voltage pulses and the pulse on time have been kept constant. The only parameter that has changed in this test is the voltage range. In three cases of these tests, the weight of the drops increased with the increase of the voltage range, and in only one case, the weight decreased with the increase of the voltage, which can be an error in the practical test due to the environmental conditions. This test was done in the same way at two different temperatures. The effect of temperature in this experiment shows that with the increase in the temperature of the molten fluid, the weight of the produced droplets increases.

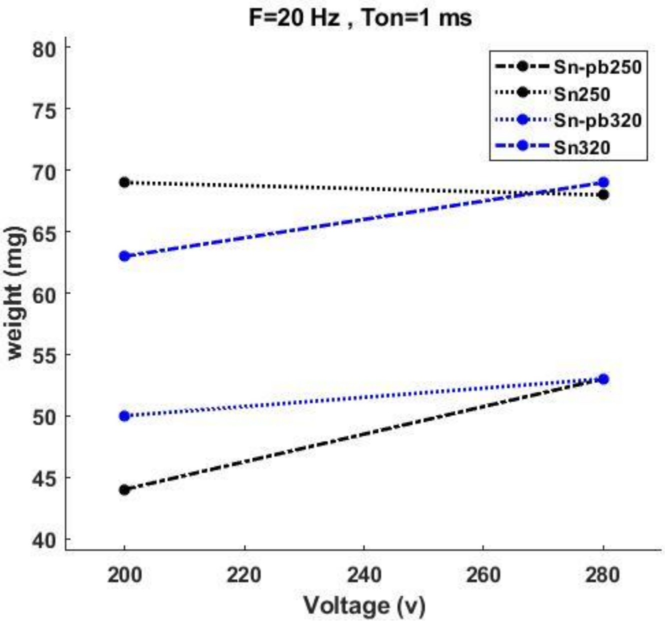


Figure 15: Investigating the drop weight of pure tin and tin-lead with alloy voltage change

Conclusion

Based on the results obtained by changing the effective parameters at different levels, in general, increasing the voltage, frequency and pulse on-time leads to an increase in the number of droplets ejecting from the nozzle of the drop-on-demand magnetohydrodynamic pump. Increasing the voltage from 200 volts to 280 volts increases the Lorentz force, and thus increases the pressure acting on the conductive fluid inside the nozzle, with a constant 1.5 milliseconds for the pulse on-time and 20 Hz for the frequency in a constant time of one minute. The resulting effect was increase in the number of drops exiting the nozzle from 126 to 246 drops. Also, at a pulse on-time of 1.0 millisecond and a frequency of 5 Hz in one minute, with increasing voltage from 200 to 280 volts, the number of drops exiting the nozzle has increased from 48 to 90 drops.

Increasing the pulse on-time from 1.0 milliseconds to 1.5 milliseconds increases the number of droplets exiting the nozzle at a fixed time because as the pulse on-time increases, the duration of force and also the effective pressure on the conductive fluid inside the nozzle increase. At a voltage of 280 volts and a frequency of 20 Hz, the number of droplets getting ejected out of the nozzle has increased from 150 to 246 drops by increasing the pulse on-time from 1.0 to 1.5 milliseconds. Increasing the frequency of the drop-on-demand magnetohydrodynamic pump has increased the number of droplets exiting the nozzle at a fixed time. At 280 volts and a pulse on-time of 1.5 milliseconds, the number of droplets leaving the nozzle has increased from 144 to 246 drops by increasing the frequency from 5 to 20 Hz. Also, at a voltage of 200 volts and a pulse on-time of 1.0 millisecond, the number of droplets leaving the nozzle has increased from 48 to 87 drops by increasing the frequency from 5 to 20 Hz. Increasing the temperature from 250 ° C to 320 ° C has the greatest effect on changing the parameters of the drop-on-demand magnetohydrodynamic pump regarding the number of droplets being ejected the nozzle at a constant time, respectively, in comparison with voltage, frequency and pulse on-time. The reason for the phenomenon is that by decreasing the surface tension through high temperature, the melt is drawn out of the orifice and the droplets are to be ejected with less resistivity due to the orifice friction.

Also, by comparing the weight of the pure tin droplets and Sn-Pb alloys, it is confirmed that tdue to the higher surface tension of the pure tin and lower viscosity, the weight of the droplets are higher than the Sn-Pb droplets.

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