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Effect of Nozzle Tip Geometry on Drop Diameter Falling Down String

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Abstract

The creation of sequential droplets that fall through a vertical string at a specific period without any clash and maintaining the same pace is an ideal condition for any heat/mass transfer calculation as the entire system can be deemed stagnant. The available investigations to create those sequential droplets on vertical string mainly focus on flow rate and nozzle diameter. Contrary to prior studies, this investigation focuses on the effect of the nozzle tip geometry on droplet generation along vertical string while keeping constant flow rate and nozzle diameter. The nozzle tip geometry has been modified to form different droplet diameters while considering the fundamentals of droplet generation. The changes in droplet diameters, which flow down the vertical string for each specific nozzle tip geometry, were investigated experimentally. All results and findings have been presented in this paper.

Key words

Droplet generation, Nozzle tip geometry, Flow down string, Drop weight method

1. INTRODUCTION

Due to interfacial dynamics, thin film flows falling down on a vertically oriented highly curved surface cannot maintain their film form. While that thin film falls, traveling wave patterns appear initially, and subsequently those wave patterns evolve to droplets. Even though same mass flow rate, droplets generated by dynamic interfacial effects have larger surface area in specific volume. The increased surface area helps heat and mass transfer processes substantially.

Researchers are interested in the concept of free-falling flow over vertical string in a variety of industrial applications, including humidification-dehumidification, desalination, water vapor capturing [1], CO_2 capturing [2,3,4], thermal heat recovery [5,6], and other heat/mass transfer applications. Because of the advantages provided by these systems, such as highly efficient heat and mass transfer [1], low pressure drop values [7], researchers are still interested in this topic.

Due to highly curved small diameter string, surface tension, inertia and viscous diffusion, liquid shapes itself as drops which flow down string. This complex flow character has been investigated by multiple researchers. Early papers we can reach, written by Lord Rayleigh [8], describes parameters of wave formation on infinite cylinder. Lately, Trifonov et al. [9] used the integral method to determine wavy nonlinear regimes of falling liquid film on vertical wires.

This type of specific droplet pattern forms itself while falling down to string, but it is mostly instable since droplets form different diameters collide and merge during flow. Kliakhandler et al. [10] has identified three different flow regimes; a) Rayleigh-Plateau regime, in which waves move periodically at constant speed b) Convective regime, in which waves are irregular that clash each other during flow c) isolated droplet regime, in which waves are unbalanced and there is a big distance between them. Sadeghpour [1] shows that stability, Rayleigh-Plateau regime, and instability, convective regime, situation with his experimental investigation. Figure 1 shows data taken from his experimental setup; section A is stability situation where droplet diameters and distance between them are equal. On the other hand, section B is unstable, convective regime, where diameters of droplets are not same, during fall though string they crash and merge.

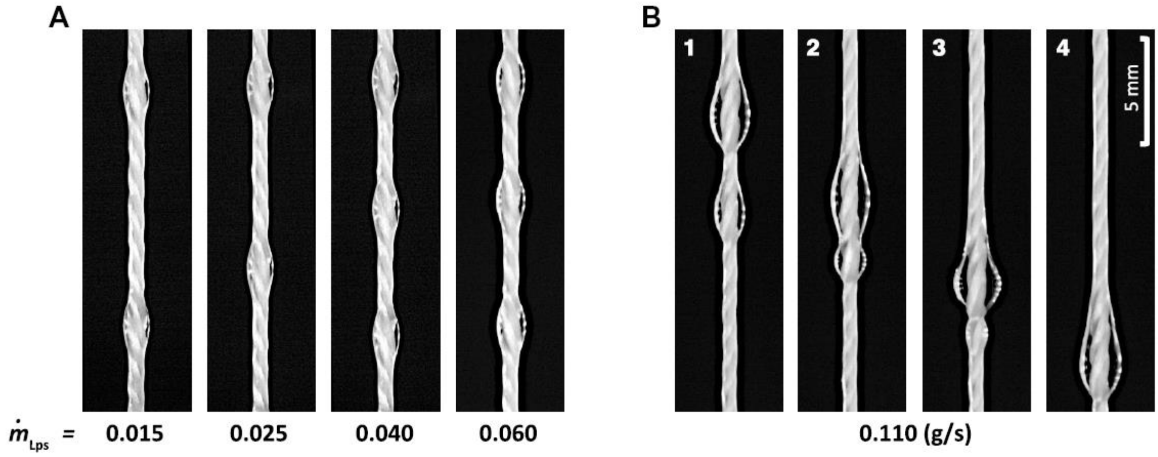

Figure 1. Sadeghpour's experimental results on Rayleigh-Plateau regime (A) and convective regime (B).

Due to the instability of falling droplets, heat and mass transfer calculations are not practical. However, that situation is completely different under the Rayleigh Plateau regime, where the flow is stable. Drop diameters and speed are constant in the Rayleigh-Plateau regime, on highly curved surfaces like string droplets formed periodically and flow at a constant rate. This resembles the flow of a "pearl necklace" image. As a result of the uniformity of the flow and the formation of droplets, calculations become simple and precise.

Sadeghpour [12] approached this topic from different angles and studied experimentally on nozzle geometry effect on falling film flows down vertical fiber. By using different string diameters and nozzle diameters he identified effect on drop diameters and speed while falling through string. Later on, Ji [13] studied on analytical model of nozzle diameters effect. She achieved good agreement with developed and experimental results. Both Sadeghpour and Ji used silicon oil V50 falling down through polymeric fiber, as that oil well wetting character on polymeric string.

While investigating droplet flow across highly curved vertical surfaces, we must also consider drop generation at the nozzle. When it comes to drop formation, Tate's [14] drop weight strategy comes to mind. Tate uses the force balance on the nozzle tip to calculate the weight of a pendant or detached drop, which is a function of surface tension and nozzle diameter. This is known as Tate Law;

$$\sigma = \frac{mg}{2\pi r} \tag{1}$$

Following Tate's investigation, commit corrective factors to have a better correlation with real-world conditions. When a pendant drop detaches, some liquid remains on the nozzle side; as a result, Harkins and Brown [15] proposed adding a correction factor since the surface tension coefficient is overestimated. That correction factor is called F, and it is less than one, so that when it is calculated, it balances the weight of the drop and does not calculate surface tension incorrectly. The following is Tate's formulation with Harkins and Brown's adjustment factor;

$$\sigma = \frac{mgF}{2\pi r} \tag{2}$$

In following years, Hauser et al [16], Hartland and Srinivasan [17] proposed various correction factors for their experimental results. In their detailed review, Boon-Beng and Pogaku [18] discuss all of these developments on correction factors.

Scheele and Meister [19] extend the drop weight method to achieve correlation for low velocity systems. They use experimental data and the force balance of drop formation to create their correlation.

Here, we report our experimental study nozzle tip effect on droplet diameter and speed through highly curved surfaces. While previous researches look into flow dynamics based on nozzle diameter, mass flow, and string diameter, in this study, we concentrate on nozzle tip effects on free falling flow through vertical string to investigate how nozzle tip affects drop formation and drop diameters experimentally on Rayleigh-Plateau regime.

The liquid selected for this experiment is water which is one of the most common fluids used in the process industry. Water is high-surface energy and low viscosity fluid, cotton string has been paired with it while common practice on this kind of experimental studies use low-surface energy and high viscosity fluids such as silicon oil with nylon string. Water is well wetting liquid of cotton thread. Furthermore, in this study, we employed a 2,0m long cotton thread to control speed changes long range, whereas previous studies used a 0,5m thread.

2. EXPERIMENTAL METHODOLOGY

2.1. Experimental Setup

The experimental setup used in this study is presented in Fig. 2. This setup includes; inlet tank, various nozzles, high speed camera, outlet tank and weight scale. All equipment mentioned below are placed inside of a hanger system which is made by metal sigma profiles so that it allows components to move or be replaced easily.

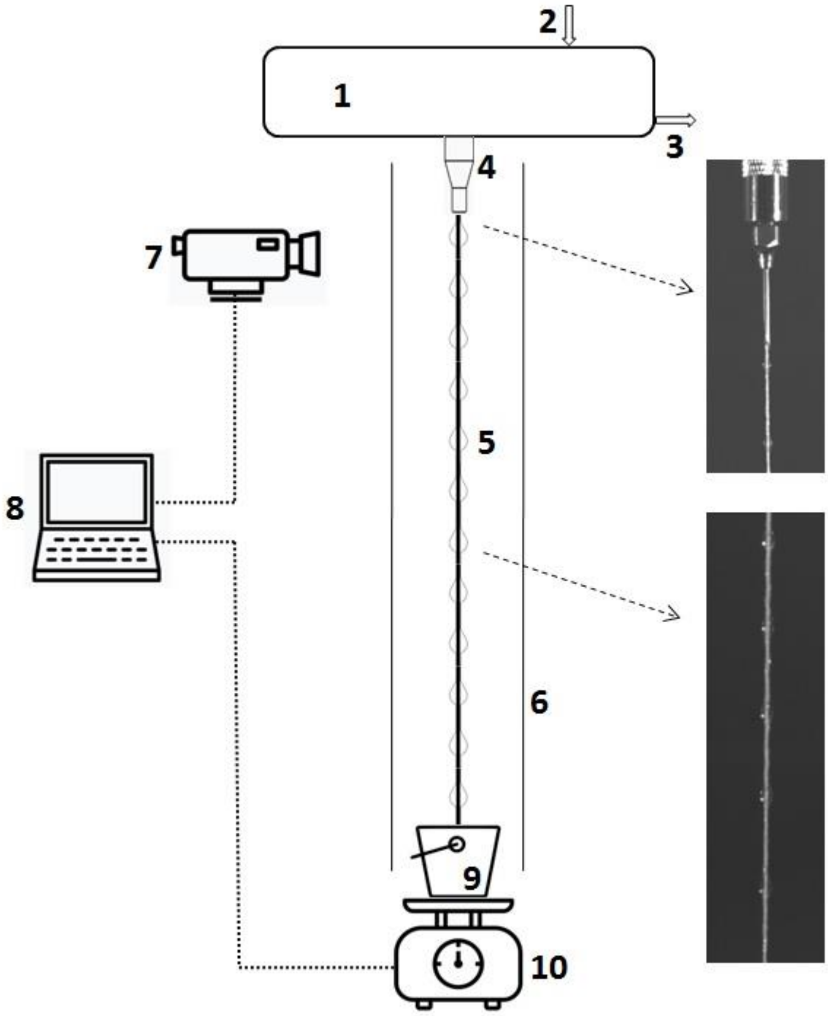

Figure 2. Schematic of the experimental system.

- Item 1 is an inlet tank that is used to deliver and store water for our experiment. To keep the flow rate constant, we keep our inlet tank large enough so that during flow our total water height will not change and keep flow rate as constant as possible. Also, inlet tank has vertically placed multiple outlet ports to adjust flow rates with opening and closing those ports. Inlet tank is connected nozzles with luer lock system to ensure sealing as we will use multiple nozzles and change for each experiment. The tank is made of plexiglass material.

- Item 2 and 3 are our water balance system. Water is feed to keep the height of the water in tank stable to have constant mass flow through nozzle while an adjustable outlet port allows extra water to leave the system.
- Item 4 is our nozzle which forms water drops also center string. All inlet nozzles are with inner diameter 1,00mm and an outer diameter 1,40mm made of steel with specific tip points. As our inlet nozzles are the essential part of our experiment, details will be explained separately.
- Item 5 is our string where formed water drops flow through. In experiments we used two different diameters of string; cotton thread with outer diameter 0,35mm and 0,5 mm length is over 2m. 50g metal weight is added at bottom of that string to keep it tight while diameter of the string did not change. Another metal wire is placed next to our string to use as a reference point while processing data shot by high-speed camera. The metal wire is kept dry and same distance to the camera, its diameter is calibrated to 0,5mm.
- Item 6 is a basic cover made by plexiglass to prevent any airwave to distribute our flow while allowing the camera to record.
- Item 7 is our high-speed camera, Phantom Miro eX4. It is adjusted to shoot 600 frames per second with 180mm lens. A special lighting system has been placed to illuminate drops to capture clear visuals. Camera has fixed on a frame to prevent any shake/movement.
- Item 8 is our PC where our devices are connected to transfer data. Also, same PC used to post process data send by camera with dedicated software, Phantom Camera Control Application V3.5.
- Item 9 is outlet tank, which is basic container to collect water fall through the cotton thread. It is placed on a weight scale.
- Item 10 is our weight scale, Metter Toledo PB 4002-S/FACT. It has been used to measure mass flow through string. Its precession rate is 0,01g.

2.2. Inlet Nozzle Design

Just keeping the basics of drop formation, with Tate's Law, we can change the weight/diameter of the droplet by updating surface tension between droplet and nozzle or nozzle diameter. Used nozzles are made of steel with ID: 1,00mm and OD: 1,40mm. the length of the nozzles is 30mm. Nozzles are assembled to inlet tank with luer locking system to prevent any leakage.

Three main changes are made on tip of nozzles:

- The first change we implemented on nozzles is adding a surfactant to reduce surface tension between nozzle and water around tip area. Aim to lower adhesion force between water drop and nozzle tip. For that purpose, we have used surfactant with surface tension 0,035 Nm, which has been represented with blue lines on Figure 3 (1c, 2c, 3c, 4c, 5c).
- The second point we worked on is to change the contact surface area between water and nozzle tip. As our nozzles ID and OD is similar, to implement that we added a chamfer around our nozzle tip, so our contact area has been reduced as small as a circle. Added chamfers can be seen on Figure 3 (1b, 2b, 3b, 4b, 5c).
- The third modification is to cut our nozzle tip diagonally with various angles. Tips are cut diagonally with angles 15º, 25º, 45º, 60º, 90º, while nozzles have sharper tip points, outlet of the get wider. Figure 3 (1a, 2a, 3a, 4a, 5a).

With all those updates we had total of 15 pieces of nozzle to be tested in our system to identify nozzle effects. Figure 3 shows all those changes. Figure 4 is a photo of the some samples of used nozzle on the experimental setup.

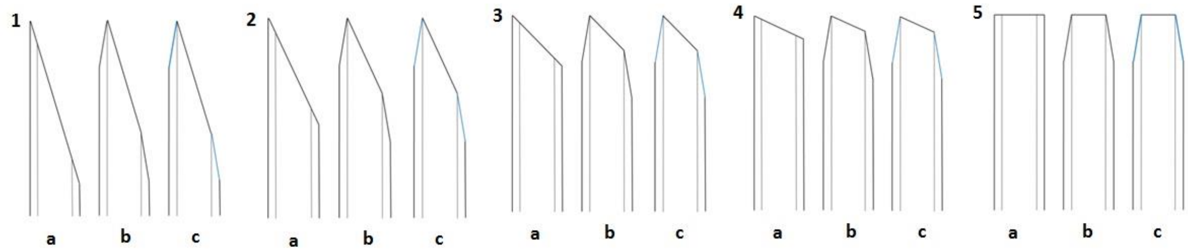

Figure 3. Inlet Nozzle Types. (a) Diagonal cut, (b) Diagonal cut with chamfer, (c) Diagonal cut, chamfer and surfactant. (1) Diagonal cut 15º, (2) Diagonal cut 25º, (3) Diagonal cut 45º, (4) Diagonal cut 60º, (5) Diagonal cut 90º.

Figure 4. Nozzle sample used in the experimental setup.

2.3. Experiment Phase

All components have been placed on 2,5m long metal hanger system as shown in Fig 1. Nozzles have been numbered and changed for each measurement. Cotton threads have been pre-wetted with water and centralized on nozzles. To ensure the Rayleigh-Plateau regime on our cotton thread, water flow has been fixed, 0,05g/s, by adjusting inlet and outlet on water tank. This value has been cascaded from paper of Sadeghpour [1] and their experimental investigations.

High speed camera with 180mm lens has been placed on an adjustable tripod, to collect data from the nozzle tip. High speed camera needs strong light to make a visible recording of water drop, as it is transparent to prevent shining of water matte black background added.

Calibrated metal wire has been placed close and parallel to cotton thread to be used as a reference diameter. That wire has been used to asses pixel size in our camera's software which needs reference diameter for post processing. Images captured during test and reference scale can be obtained with an error of ±1 pixels or ±0,01mm. Camera's timer has been used as chronometer during post processing. Since frame rate of the camera was 600fps, timing uncertainty is 1,66ms. By using this dimension and time errors, error of speed can be reached which is 0,00001mm/s level.

After the system started to flow, cotton thread surrounded with plexiglass covers to prevent any airflow which can disturb our flow.

With 15 different nozzles, 2 different diameter cotton threads, data has been collected from 10 different heights of thread. Then all data post processed with Phantom Camera Control Application V3.5.

3. RESULTS AND DISCUSSION

The experimental setup run with two different cotton thread diameters, 0,35mm and 0,5mm, with a fixed mass flow rate 0,05 g/s room temperature water. All fifteen different nozzles tested vertically placed on experimental setup with these two different cotton threads.

Our nozzles have been formed different drop diameters;

- We have identified that when cotton thread diameter gets smaller, drop sizes get bigger. A gap between thread and inner diameter of nozzle is bigger at 0,35mm compare to 0,5mm.

- Chamfering of nozzle tip also helps to change drop diameters. As surface area between nozzle and droplet reduces, adhesion force reduces then droplet detaches with lower weight or another smaller diameter. This can be easily seen with Tate's law.
- When we add surfactant to reduce surface tension that significantly changes our drop diameter. As adding surfactant lowers adhesion force, droplet detaches before diameter gets bigger. This can be also identified with Tate's Law.
- Although our diagonal cut increases surface area, we have visualized significant change in drop diameter inversely. When we reduce diagonal cut angle, nozzle tip gets sharper tip point, drop diameter reduces. It can be seen it is contradicting Tate's law, however we have found out there is another physical mechanism in there. While drop begin to form itself it begins to accelerate parallel to our diagonal cut with help of the gravity. That move leads our drop to sharp tip point of the nozzle where surface area is really reduced. Also, with the dynamic characteristic of moving drop detach from nozzle tip before it grows. That leads us smaller drop diameter on our cotton threads.

Figure 5. is a snapshot from our experimental setup to show differences occur when nozzle tip changes. Figure 5. A is nozzle number 2c which is diagonally cut 25º, with chamfering and surfactant while B is nozzle 2a which is only diagonally cut 25º. As both nozzle feed by water with 0,05g/s mass flow, nozzle 2c form smaller droplets in higher frequency compare to nozzle 2a.

All experimental data can be found in Figure 6. Also, trendlines have been generated to show change of the drop diameters due to nozzle tip angle, cotton thread diameter and other changes done on nozzle tip.

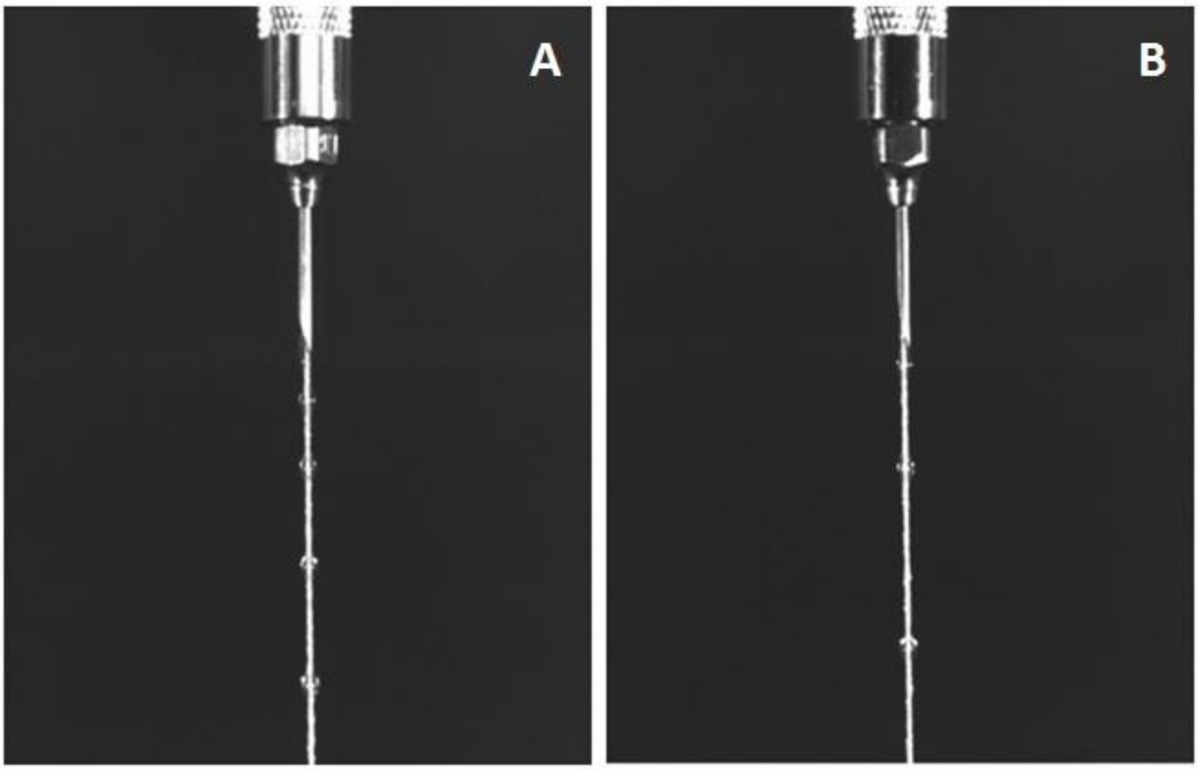

Figure 5. Change of diameter and distance between two nozzles on different tips, A) Nozzle 2c, B) Nozzle 2a.

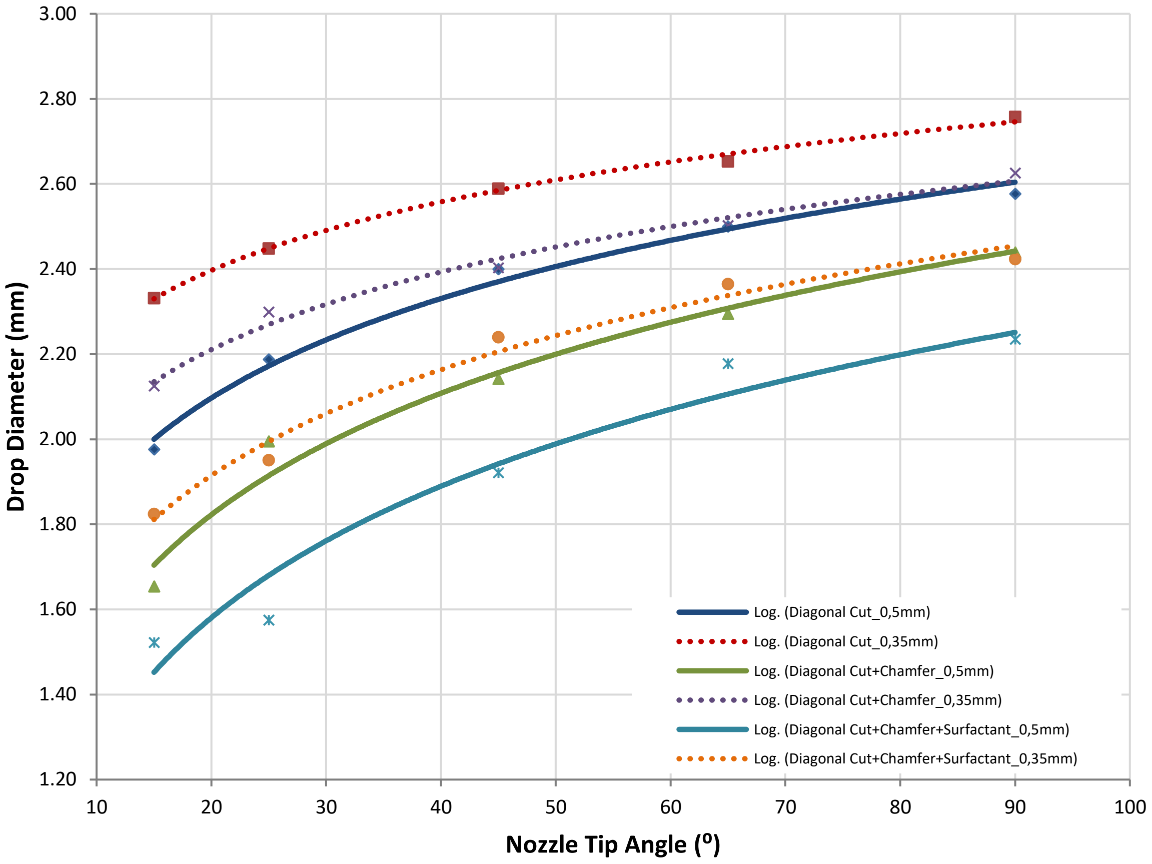

Figure 6. Drop diameter change with different nozzle configurations.

4. SUMMARY AND CONCLUSION

In this study, series of experiments has been done to understand how the nozzle tip geometrical change effect droplet diameter falling through vertical thread. With implemented geometrical modifications on nozzle tip, differentiation of the droplet diameters achieved while keeping other parameters such as mass flow, nozzle internal and outer diameter.

We have found out that change of the nozzle tip effects droplet diameters directly. As the mass flow is constant, with change of the droplet diameter that also changes frequency of droplet generation. So that frequency of the droplets can be also controlled by nozzle tip.

We can summarize our findings below,

- Adding a chamfer on nozzle and modifying tip geometry effects droplet diameters. The chamfer added nozzle generates smaller diameter compare to the one which is not added.
- The cutting nozzle tip angularly also effects droplet diameters generated on nozzle tip. Although the surface area on the nozzle tip enlarges, droplet size gets bigger cut angle get bigger (nozzle tip gets sharper). We have visualized through our experiments that, due to angularity liquid begins to accelerate towards to nozzle tip, where is pointy. That pointy edge and acceleration pushes droplet to fall earlier before it gets bigger. So, we can say that, when nozzle tip gets sharper, droplet diameter gets smaller.
- As mass flow is same, different diameters of droplets generated effects frequency of the droplets fall through the thread. When droplets get smaller frequency is increase.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests of personal relationships that could have appeared to influence the work reported in this paper.

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