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A Versatile Droplet on Demand Generator Based on Active Pressure Control

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Abstract

The development of a novel on demand droplet generator is reported in this paper, based on off-the-shelf electromechanical components. With the ability to produce a large range of droplet sizes, this device was designed to have minimum components without compromising reliability. The generator performance was assessed by producing water droplets for fire dynamics and suppression studies. Droplet formation at the tip of the nozzle was visualised using high speed imaging. Stable and unstable regions can be identified easily though the images. Interchangeable nozzles can be used allowing different droplet sizes. The setting parameters of the device allow accurate control of droplet size and initial speed. The device controls the liquid pressure actively and precisely. The active control of pressure and the ability to have specific droplet ejection parameters ensured the repeatability of droplet conditions. Characterisation of the device is presented in addition to the calibration data which can be collected in an efficient methodology. This data enables the selection of droplet size and speed when required. This system could easily be implemented in other research areas. Hence, the intention to share and highlight the generator features for the use in a range of other scientific applications.

Keywords: Droplet generator, hydraulic, on demand, stream, PID control

I. Introduction

Droplet generators are important instruments used in many fields, including printing, spray processes, surface impact studies [1–3]. Single droplet experiments are commonly conducted to study droplet formation, evolution, stability, evaporation, surface impact, and combustion [4].

Drop on demand techniques promise accurate droplet generation and high repeatability. Challenges arise, however, when an attempt is made to utilise current droplet generation devices in various applications. Difficulties such as satellite droplets, shape distortion, bubbles and trajectory variation are common operation challenges. Therefore, researchers often turn to other experimental approaches where an acceptable compromise is usually adapted.

Repeatable experiments require reliable droplet generation. Existing on-demand droplet generators are highly priced, while most in house manufactured devices are complex and made for a specific application. Several droplet generator novel designs have been proposed for a variety of reasons including construction simplification, enhanced control, disturbance reduction and high extreme working condition ability.

Table I shows recent innovative devices incorporating new ideas and their properties.

Table I. Properties of recently reported droplet generators

Technique	Droplet Size (mm)	Nozzle size (mm) and type	Production rate	Mode	Remarks
Piezoelectric element [6]	0.65-1.32	1.02 mm 3D printed ABS	Every 2 Seconds	On demand	3D printed structure.
Resistive heating of nozzle tip [7]	0.11-2	0.11 - 0.31mm stainless steel syringe tips	Injected by a syringe up to a specific hanging size	Single	Heating the nozzle tip to produce a droplet. Resulted in shape distortion and secondary droplets occasionally.
Mechanical vibration [5]	0.1-1	0.2 heat processed capillary glass	Every oscillation Tested up to 5 kHz	Continuous stream only	Used hard drive actuator arm to vibrate a capillary tube nozzle.
Solenoid impact [8]	0.1-0.3	0.1 - 0.3 Sapphire	1Hz to tens of Hz (as stated)	On demand	Utilised a solenoid as a hammer to provide a pressure pulse.
Piezoelectric Element [9]	0.5-1.4	0.5-1.4 stainless steel	Not tested	On demand	A pump was used to keep a fluid reservoir the same level.
Active Pressure Control	0.9-1.7	0.5 brass nozzle	5 Hz, tested at 0.9mm droplet	On demand & continuous stream	The instrument reported in this paper. Production rate depends on droplet size and nozzle

Other designs implemented thin piezoelectric elements. Unique techniques were presented in order to reduce the power requirements such as low voltage piezoelectric films for portable devices [10]. The technique was used as pump at a maximum rate of 3.6 µl/min . Nonetheless, current designs of piezoelectric require power amplifier and stable pulses, and droplet size has a nonlinear relation with pulse width. Although the head and piezoelectric casing can be relatively inexpensive [9], the required power equipment should also be taken into account. In addition, piezoelectric designs require careful tuning and experimentation to produce the same size droplets and there are known problems encountered in practice such as voltage wave stability and trapped air [11]. They are extremely sensitive to the applied voltage level, frequency and wave shape. Trapped air can deteriorate the system performance completely, and usually, it requires system reassembly and refilling to be in working order again.

In order to provide a solution for combustion experiments and other scientific studies, a novel drop on demand generator was designed using of the shelf components. No component manufacturing was required which resulted in a simple and precise device. The device capability was demonstrated by analysing droplet generation process and its utilisation in experimental work [12]. Single droplets were captured using high-speed imaging. The flow parameters such as pressure were controlled by an electronic circuit module along with a microcontroller development board.

II. System construction

Error! Reference source not found.Fig. 2 Error! Reference source not found. illustrates the device control diagram and hydraulic circuit. The generator consisted of six main components: a liquid reservoir, solenoid valve, nozzle, MPX5100DP pressure sensor, Arduino Uno board, and a peristaltic pump. **Error! Reference source not found.** shows the final assembly of the components. The pump was run by a stepper motor, the pump provided positive displacement airflow to the reservoir. The pump type was peristaltic where a force is essentially applied on a tube to push the flow forward. The components including the pump are widely available. The pressure sensor provided a feedback signal, a voltage corresponded to the air pressure above the liquid level. The signal was acquired by the Arduino development board which is based on the microcontroller ATmega328. The microcontroller sampled the sensor analogue signal and provided an output signal to the pump motor, regulating the pressure of the reservoir. Additionally, the Arduino board provided a precise timing control of the solenoid valve. When the solenoid was energised, the flow passed through the tubing and a droplet was ejected by a copper nozzle. The nozzles employed in the system were also readily available. Overall, these components enabled the creation of a reliable system that can be assembled, programmed, and operated in a short time.

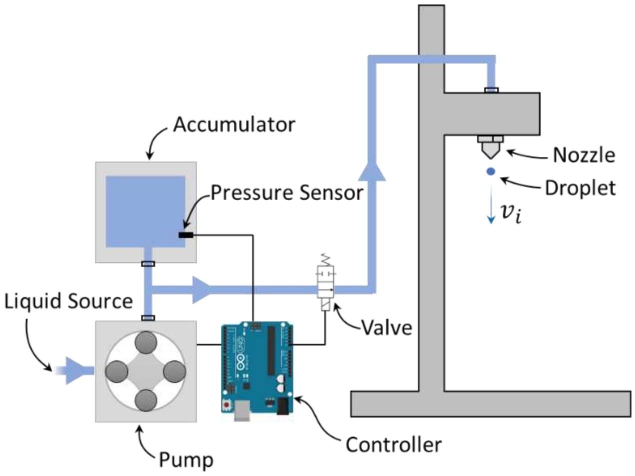

Fig. 1. Components of the device

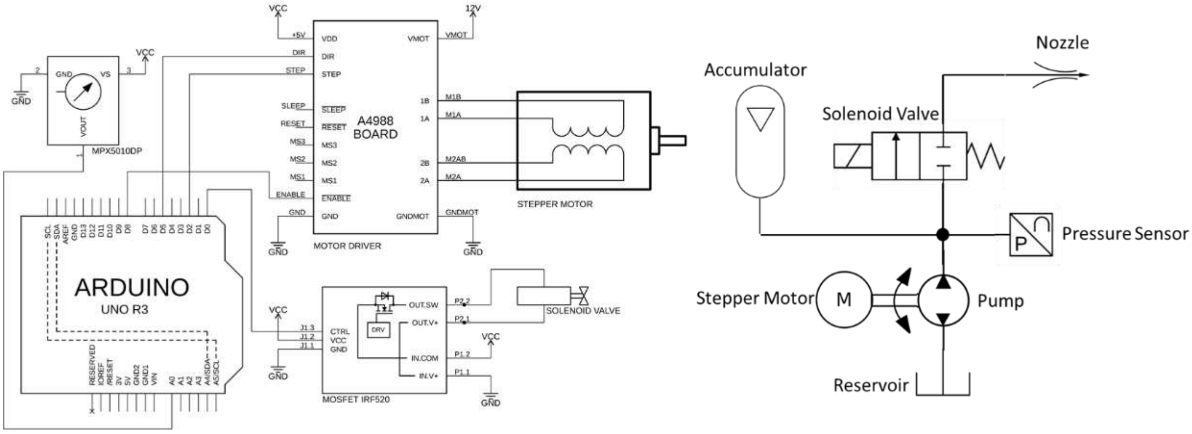

Fig. 2. Electrical and hydraulic circuits of the device

Reservoir pressure was controlled electronically, and two methods were employed. First, an ON-OFF controller was implemented. Although this method is considered elementary, the system reliability was shown to be satisfactory. However, this method should be used when slow response and lower accuracy are acceptable. The bang-bang method operates by switching a controlled element when a feedback signal crosses the acceptable error bounds on both sides of a set point. Practically, the microcontroller drove the pump to increase the accumulator pressure up to a setpoint. At that point, the pump was switched off. If the pressure decreased and passed the lower error limit, the pump would be operated again. This method was implemented in a loop, repeating the process maintained the pressure approximately at the set point. Furthermore, the second control strategy involved a PID controller. The second method provided responsive pressure compensation. Compared to the ON-OFF method basic implementation, the PID controller resulted in considerable improvement in the time required to achieve a stable output. The PID manual tuning proved essential for stable operation.

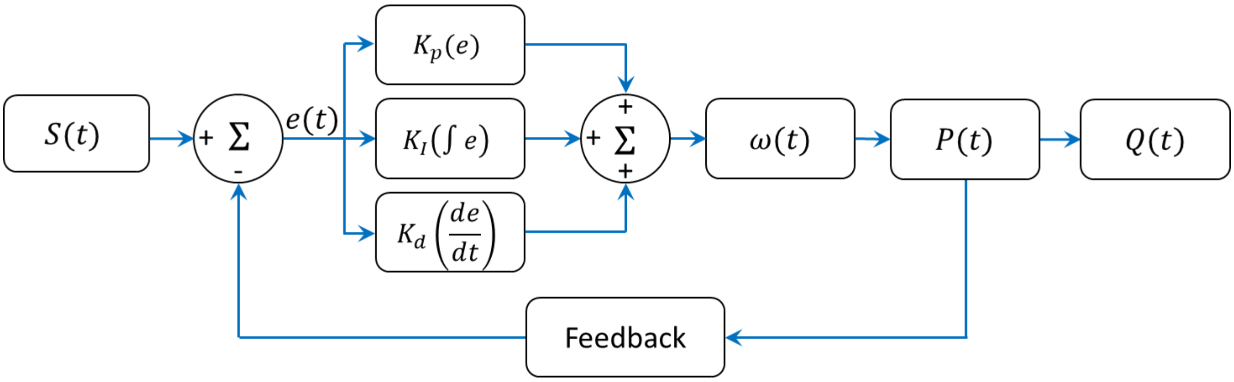

Fig. 3. Block diagram of active pressure control implemented in the controller

Fig. 3 shows the mathematical representation of the active pressure control implemented in the controller. $S(t)$ represents the pressure setpoint, while $e(t)$ is the difference between the setpoint and the actual pressure $P(t)$. The three parameters K_p, K_I, and K_d are the PID tuneable constants. $\omega(t)$ represents the stepper motor and pump rotational speed. $Q(t)$ represent the flow rate of the system when the valve is operated.

III. System Characterisation

The device performance was evaluated using pressure response data and droplet dynamics. **Fig. 4** is the time evolution of droplets with increasing injection time. On the figure, the horizontal axis shows the nozzle and ejected droplet resulted from various injection times. Evolution of droplets in time is shown from top to bottom as indicated on the vertical axis. If the injection time is short as indicated at 6ms of the actual time, a small amount of liquid is observed at the nozzle but retracts soon after and no droplet is ejected. Injection times starting from 2ms shows droplet formations. The droplets attain a larger size because the ejected stream accumulate when the valve is open. The images at the actual time of 12ms show that droplets are ejected with increasing initial velocity when injection time is longer. Both actual times of 12ms and 18ms indicate that larger droplets can exhibit instability. This is due to the inertial forces competing with surface tension. In a later stage, this is dissipated by the viscous forces. Although a droplet might be considered unstable initially, the droplet can reach a stable state if it travels sufficient distance after ejection.

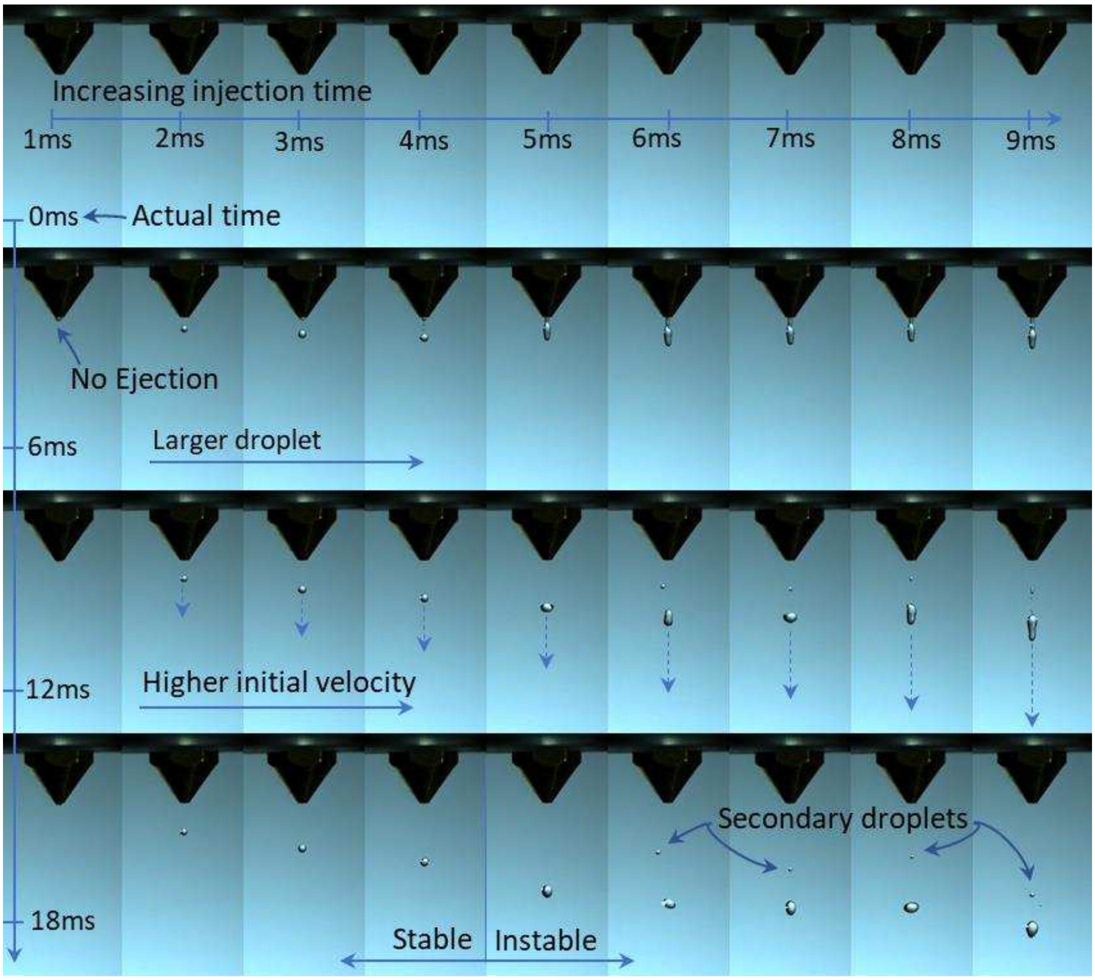

Fig. 4. Evolution of droplets with increasing injection time.

Fig. 5 shows the dependence of droplet size with injection time. Given that the setpoint pressure is constant, the increasing injection time allows the liquid flow to produce a larger droplet. In addition, increasing pressure setting results in faster flow and therefore a larger droplet provided the injection time stays constant. The relation can easily be fit with a polynomial at each pressure and can then be used to determine the required injection time for specific droplet size. Droplet diameter is not the only parameter that changes with injection time but also the initial speed of droplets

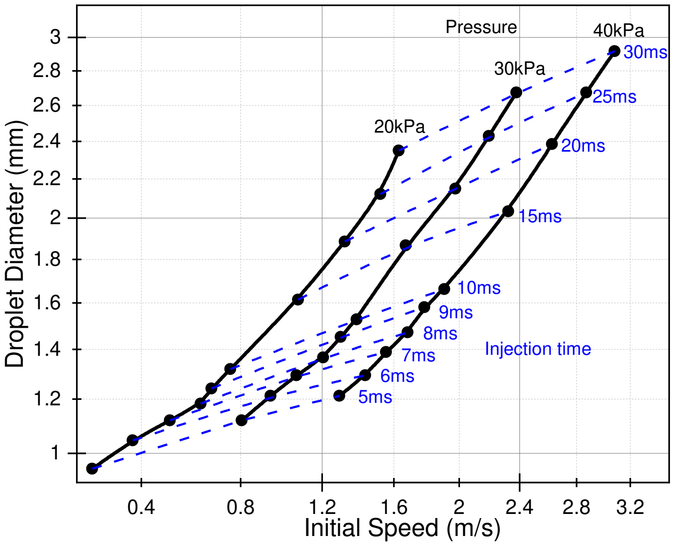

Fig. 5. Droplet size and initial speed increase with injection time at different pressure settings

Fig. 5Error! Reference source not found. also presents the relation of droplet initial speed with injection time. When the valve is opened, the momentum of the injected flow out of the nozzle is transferred to the generated droplet. The droplet acquires a higher initial speed with increasing injection time. For example, if the nozzle is pointed downwards towards a target surface at a distance of 0.2 m from the nozzle, the impact velocity is higher for larger droplets as shown in Fig. 6. One way to achieve constant impact velocity is to vary the distance between the nozzle and a target surface.

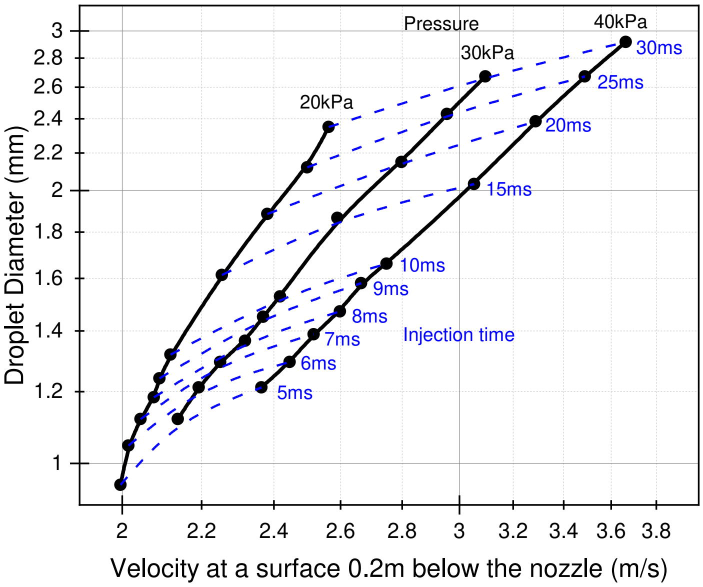

Fig. 6. Droplet velocity at a distance of 0.2m below the nozzle

Fig. 7 indicates the distance between the nozzle and a surface to attain the same impact velocity with increasing droplet diameter. Because larger droplets are ejected with higher initial speed, then the distance should be reduced between the nozzle and the surface. Therefore, the acceleration due to gravity will be limited by the distance available. Note that this is only true if the droplet does not reach its terminal velocity.

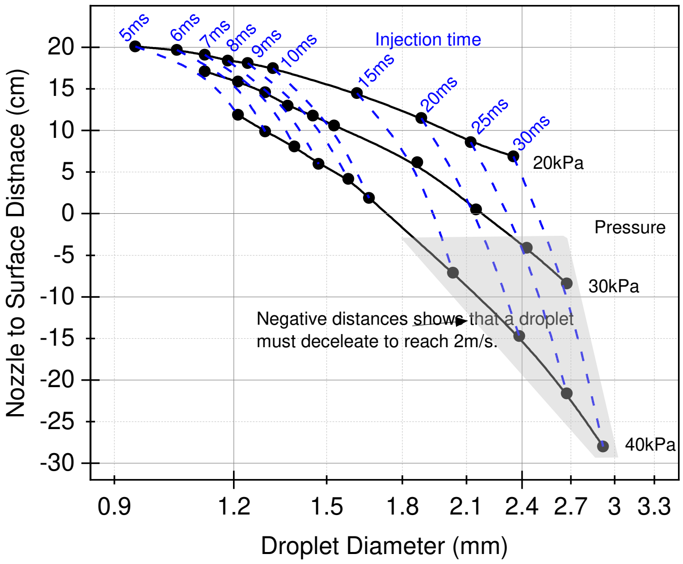

Fig. 7. Required distance from the nozzle to a target to achieve a constant velocity with different droplet sizes

IV. Variability

In order to study the variability of the droplet generation process, droplet ejection was repeated five times at the same conditions with pressure setpoint of 20 KPa. Table II lists the injection time tested and the equivalent average droplet diameter. It also shows the percentage deviation in droplet diameter and initial speed. Droplet diameter was measured using images scaled to an object of a known size. The initial speed was obtained using a series of droplet images after detachment from the nozzle, using the speed $v = d/t$ formula, where d is the distance travelled and t is the time duration between images.

Table II shows that smaller droplets have higher error percentages. Instabilities can affect the measurement as in the case of 1.67mm diameter where the deviation was high. Error percentages of the initial speed values are considerably lower than error percentages of the diameter values.

Table II. Droplet diameter and initial speed deviation at setpoint pressure of 20kPa

Injection time (ms)	Average diameter (mm)	Max. deviation from average diameter (mm)	Diameter error percentage	Average initial speed (m/s)	Max. deviation from average initial speed (m/s)	Initial speed error percentage
6	0.93	0.10	10.75%	0.742	0.024	3.19%
8	1.28	0.06	4.69%	0.861	0.019	2.17%
10	1.43	0.07	4.90%	0.981	0.011	1.15%
12	1.54	0.07	4.77%	1.060	0.012	1.13%
14	1.67	0.16	9.58%	1.196	0.007	0.56%
15	1.76	0.07	4.17%	1.206	0.019	1.60%

V. Control Response

The results presented in **Fig. 8** show the response of pressure control using a PID Controller. The PID performed better than the ON-OFF controller which suffered from fluctuations at the setpoint. The PID method produced a rapid response when changing pressure setpoint. These values were dependant on the parameter tuning in the microcontroller code, sensor capability, and setpoint pressure.

It is evident in **Fig. 8** that the actual signal takes more time to stabilise when the difference between two consecutive setpoints is larger. For example, the controller took two seconds approximately to raise the pressure from 3 to 5 kPa, in contrast, it took three seconds to increase the pressure from 5 to 8 kPa.

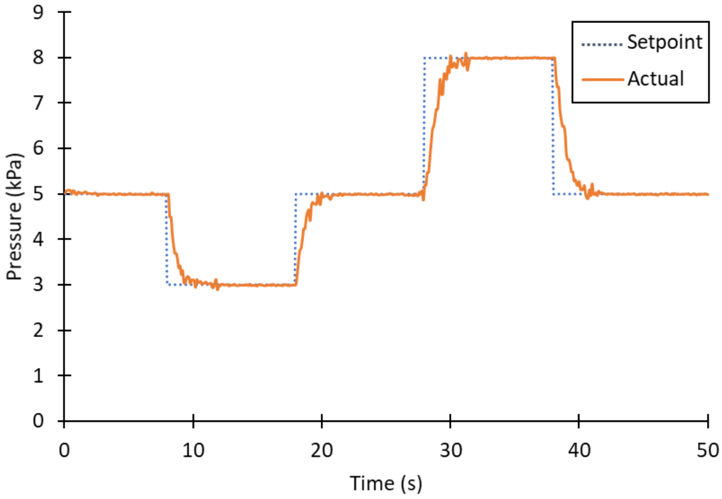

Fig. 8 Setpoint signal and pressure response

5.1. Pressure setpoint control and tuning

PID control method was tested for different setpoint profiles. Profiles were implemented in the microcontroller code. This test presented the importance of correct PID tuning. The response could be made faster by removing the differential component of the controller, implementing a PI controller with slight overshoot being tolerated.

Flexibility was an advantage in terms of the pressure control strategy. The control method can be chosen to fit other application as required. This feature is not limited to the droplet generator mechanism implemented in this system but can be integrated into other droplet generation techniques. Ultimately, the pressure control pump is suitable for other applications where a certain fluid needs to be maintained at specific conditions.

5.2. Pressure sensor calibration and acquisition

The pressure sensor used was MPX5100DP, a gauge sensor with two inlets. One inlet was by design against fluids as stated in the datasheet. This inlet was connected to the accumulator. The other inlet was left open to the atmosphere. The sensor required no calibration because the additional pressure above atmospheric pressure was measured.

The pressure sensor output was an analogue signal, hence, analogue reader or at least an analogue to digital converter was required. The signal was acquired by the microcontroller ATmega328 on the Arduino Uno development board. The advantage of this microcontroller is the ability to read analogue signals with 10-bit resolution. In fact, it has five analogue inputs and only one pin was required in the current system. The sensor value was measured every 100 milliseconds and was used as an input to the control algorithm. The same pressure values were sent in real-time to a computer using the serial interface and USB port available on the board.

5.3. Control application

The current droplet generator functions can be significantly enhanced by developing an interface. An application can be developed to control the droplet generation process. The application should allow a fast generation procedure by having a user interface. Parameters such as pressure setpoint can be directly changed when needed, and a custom delay time allows a user to set a specific time to produce a certain droplet size. Droplet stream function can also be integrated to give the ability to eject several droplets with a defined delay between consecutive droplets. Pressure monitoring will allow live monitoring of both the setpoint and the actual measured pressure. In addition, the relation between device settings can be mapped against the ejected droplet properties, hence, enabling the selection of the required size and initial speed of the ejected droplet.

VI. Conclusion

The droplet generator presented in this paper provides an exceptional tool for researches and can be used in a wide range of applications requiring pressure regulated stream and repeatable droplet ejection conditions. This generator offers a user-friendly alternative to other systems which usually require power amplifiers and lengthy tuning. High-speed images were taken of the generated droplets at different conditions. The relation between control parameters and ejected droplets was presented. A control system was implemented to compensate for lost pressure actively.

Availability of data:

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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