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Investigation of capillary wave formation on water streams with internally propagating ultrasound

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Summary
The present work investigates the formation of capillary waves and subsequent breakup on 10 mm and 15 mm diameter water streams (measured at the nozzle exit) with ultrasound propagating at 135 kHz. Experimental observations of the stream breakup process with a high speed camera are reported. The input signal to the transducer was used to investigate the formation and growth of capillary waves. Lateral spraying of the water stream was observed prior to the formation of surface waves. Once the surface waves are formed, they grow in size leading to a necking zone. Necking can, if sufficiently large, lead to fragmentation of the stream into globules. The capillary wavelength, lateral spraying velocity and water stream breakup length are measured and presented in an attempt to understand the nature of the breakup process.

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1. Introduction

This paper deals with the study and characterization of capillary wave formation on cylindrically flowing water streams, with a pressure release boundary condition, when ultrasound is passing thorough them. In the present study both 10 mm and 15 mm diameter nozzles (inside diameter at the exit) were used for flowing water. It was observed that, when the ultrasonic signal is passing through, the water stream begins to exhibit surface oscillations (instead of flowing as a tapered cylindrical column). These oscillations grew in size and, after propagating some distance along the length of the stream, cause it to disintegrate into smaller and larger globules. Once the stream breaks up into these globules, the ultrasound cannot pass further, i.e., beyond the discontinuity, because of the acoustic impedance mismatch at the air-water interface. This limits the range to which the ultrasound can be propagated in the water stream.

It is well understood that a liquid stream emerging into another fluid (in this case, air) is unstable [1]. This breakup process of the stream can be controlled either by an external disturbance [1] or is related to the hydrodynamic instability of the flow [2, 3]. The globules thus formed after the stream breaks up are classified into major and satellite globules (the use of the terms major and satellite droplets is also quite common in the literture [3]). The formation of these major and satellite globules is either important or undesirable, depending on the application. The breakup process of the liquid stream is studied and used in many applications such as ink jets [4] or electrospraying [4]. Oscillations excited on the surface of the liquid streams by vibrating the nozzle induces capillary waves that break the stream at a specific distance from the excitation point [2]. Atomization of micrometer sized liquid streams (1 to 5 μm) to a form fine mist or fine spray with the use of ultrasound [4], or with the help of high velocity air flow over the nozzle [4], are common applications.

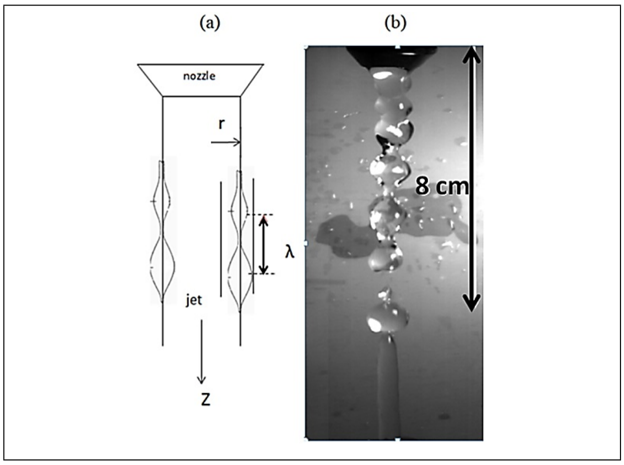

Figure 1. The coordinate system used in the present paper with the axes and a snapshot of the breakup process on a 15 mm exit diameter of the water stream (measured as the inner diameter at the nozzle) under the action of 134.9 kHz ultrasound.

Much of the research into the instability of micrometer streams [5] stems from the pioneering work of Lord Rayleigh. He approached the phenomenon by considering the fastest growing wavenumber on a non-viscous liquid stream [6]. Works on the instability generally developed in two broad directions, one path concentrating on the mathematical analysis of the breakup process using non-linear capillary instability studies [4, 7, 8, 9], the second path concentrating on experimental studies using imposed disturbances on the nozzle or in the stream [1, 4, 10]. Studies of the response of streams to internal modulated ultrasound [2, 11], and investigations into controlling the breakup by using electrically charged streams [4], have been linked to the various industrial applications to which these instability dynamics are germane.

The breakup process (presented in this paper), and the surface oscillations demonstrated by the stream, are shown in Figure 1. Part (a) of Figure 1 shows the co-ordinate system that is used in the present study, and indicates the variables that are here used to parametrize the stream and its oscillations. Part (b) shows a snapshot of the surface oscillations formed on a 15 mm diameter stream (the diameter of the stream is the measure of inside diameter of the nozzle). Water flow rate was 2.8 litre.min^{-1} and the input signal was 134.9 kHz sinusoidal and continuous ultrasound signal (220 V$_{RMS}$ supplied across the terminals of the transducer). This image was captured using a Phantom v5.1c high speed camera. The surface waves, the breakup length and globule formation can be noted.

In this paper it is assumed that the air around the water stream is inviscid and stationary. The stream axis coincides with the Z axis, and water is flowing along the positive Z direction, the instantaneous radius parameter is r, the wavelength of the surface oscillation λ, ρ is the density of water, a is the mean radius of the cylindrical water stream measured at the nozzle tip, and τ is the surface tension at the air-water interface.

The driving force for the breakup in the present case is the energy provided via the ultrasonic transducer propagating through the stream (while the restoring force is the surface tension force at the air water interface). For acoustic propagation, a water stream exiting a 15 mm diameter nozzle operating on pressure release boundary condition (at sound speed c_0 of 1450 m.s^{-1}) has cut off frequency [12] of 73.88 kHz.

The capillary waves so formed (for small amplitude oscillations of the meniscus about its mean position i.e., measured close the nozzle tip and away from the breakup zone) can be characterized using the wavelength of the capillary wave λ and the time period of the waves (which is the inverse of capillary frequency f_1 of the waves). These variables are related by the Kelvin's equation[13]:

$$\lambda = \sqrt[3]{\frac{2\pi\tau}{\rho f_1^2}}. \tag{1}$$

Equation 1 is used to calculate the capillary frequency f_1 of the surface waves formed on the stream, by measuring the capillary wavelength. From Rayleigh's linear theory of instability (working far from the discontinuity point), the instability wavelength on a stream exiting a 10 mm diameter nozzle corresponds to a very low capillary frequency of 9 to 15 Hz (with the maximum instability at 12 Hz) and a for a water stream exiting a 15 mm diameter nozzle has an unstable capillary frequency in the range 12-17 Hz (with a maximum instability at 14 Hz).

2. Experimental Setup

The experimental setup used for observing the formation of surface waves on the stream surface is presented in Figure 2. The nozzle has either a 10 mm or 15 mm exit diameter (2a). A 134.9 kHz transducer is glued to the other end of the nozzle on a polycarbonate sheet. The other end of the nozzle has provisions for water inlet and a bleed valve (to remove the excess air in the flow). Water is circulated in a closed loop using a Hailea HX-8815F pump. A water heater/reservoir system was used for measuring and controlling the liquid temperature. A GEMS FT-110 turbine type flow meter and flow control valve are placed in the water path to control the flow rate. Deionized (DI) water was used in all the experiments. The setup was placed in an observation glass tank. A settlement tube was used in the immediately after the pump to reduce any flow variations introduced via the pump or to remove any bubbles that may have been entrained by the pump.

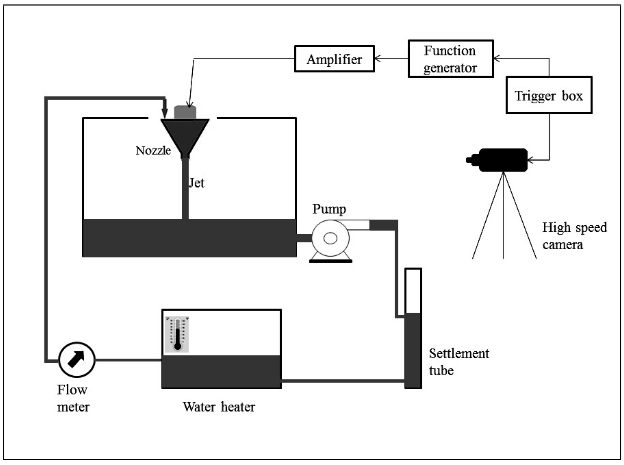

Figure 2. Experimental setup used for observing the surface oscillations formed on the surface of stream with ultrasound propagating through it.

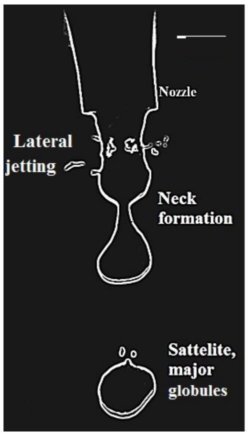

Figure 3. An edge detection technique used to observe the breakup of a water stream exiting a 10 mm inner diameter nozzle activated by 134.9 kHz continuous ultrasound signal.

A Phantom v5.1C high speed camera, used in conjunction with Phantom 663 software, captured the instability formation on the stream surface at 600 to 3100 frames per second (fps). A TGA 1244 Arbitrary waveform generator was used to generate continuous sinusoidal ultrasound signal at 134.9 kHz. An EIN model 2100L RF power amplifier was used at a fixed 50 dB amplification and the amplified signal is supplied to the transducer (the voltage across the terminals of the transducer is maintained at 220 V_{RMS}).

3. Results

Using the high-speed camera, the evolution of capillary waves on the free surface of the stream was initially recorded at 600 fps (Figure 1). It was observed that, the stream instability begins with the lateral spraying or lateral jetting (see Figure 3). Subsequently the surface waves are formed and associated necking is observed. The instabilities then grew very rapidly, after the orifice, such that they attained steady state within one two cycles of the capillary wave (i.e. within 2 to 3 cm from the nozzle). This precluded any detailed measurement of the growth rate even at higher frame rates (in contrast to the exponential growth being described in references |1, 3-10|). The necking formation might reduce the passage of ultrasound beyond the narrowed stream thus formed [2]. The disturbance (surface oscillations) then convect with the flow and breaks up the stream further down, disintegrating into globules. This cycle repeats again as fresh liquid issues from the nozzle. The measured values of capillary wavelength (measured close to the nozzle tip) and the calculated capillary frequency (evaluated using equation 1) are summarized in table I, along with the standard deviations for the measurement of capillary waves. The capillary frequency calculated, matched the unstable frequencies predicted

Table I. Measurements of capillary wavelength & corresponding capillary frequencies (from high-speed recordings and using equation 1) of surface oscillations of liquid stream. The standard deviation of measurements is presented the parenthesis.

$15mm$	$15mm$	$10mm$	$10mm$
Capillary Wavelength (mm)	Capillary Frequency (Hz)	Capillary Wavelength (mm)	Capillary Frequency (Hz)
14.2(±0.1)	12.2	16.2(±0.1)	9.5

by the non-viscous stream breakup theory established by Lord Rayleigh [5].

The ejection velocity of lateral jetting of the stream was measured to be 1.1 m.sec^{-1} (±65 mm.sec^{-1}) using a high-speed recordings at 1200 fps. This lateral jetting action causes a loss of fluid and the formation necking zone is accelerated as an effect. A Laplacian type edge detection technique (available with the Phantom 663 software) was used to observe the formation of lateral jets on the water stream. Figure 3 shows a snapshot of one such image, processed with the edge detection routine demonstrating the formation of capillary waves, lateral jetting, neck/globule formation and the breakup. The breakup length of the water stream exiting the 10 mm inner diameter nozzle (under this instability regime) was measured and found to be varying between 55-70 mm, and the breakup length of the water stream exiting the 15 mm diameter inner diameter nozzle was observed to be 70-85 mm.

4. Conclusions

The breakup process of a cylindrical water stream under the action of internally propagating ultrasound was presented in this paper. Observations and measurements were made for the surface undulations from the mean position using recordings from high-speed camera. These surface oscillations were observed to form along the length of the stream, grow in amplitude and forming a necking zone. This subsequently leads to the breaking up the stream and disintegration into large and small globules.

Lateral jetting was also observed. The lateral jetting velocity (1.1 m.sec^{-1}) and capillary wavelength (14.2 mm for 10 mm inner diameter nozzle) were measured and reported. The capillary frequency calculated was found to be related to the nozzle exit diameter (using Rayleigh's theory). Future work will concentrate on changing the system parameters flow rate, viscosity and surface tension in an attempt to control this breakup process.

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References

[1] Cline H. E. and Anthony T. R.: The effect of harmonics on the capillary instability of liquid jets. Journal of Applied Physics **49** (1978) 3203-3208.

[2] Lonzaga Joel B., Osterhoudt Curtis F., Thiessen David B., and Marston Philip L.: Liquid jet response to internal modulated ultrasonic radiation pressure and stimulated drop production. Acoustical society of America **121** (2007) 3323- 3330.

[3] S.P. Lin, R.D. Reitz: Drop and spray formation from a liquid jet. Annual review of fluid mechanics **30** (1998) 85-105.

[4] Jens E. and V. Emmanuel: Physics of liquid jets. Reports on Progress in Physics 2008.

[5] Lord Rayleigh: On the instability of liquid jets. Proceedings of London Mathematical Society **10** (1878) 4-13.

[6] Joseph B. Keller, S.I. Rubinow, and Y.O. Tu: Spatial instability of jets. The physics of fluids **16(12)** (1973) 2052- 2055.

[7] Yuen M. C.: Non-linear capillary instability of a liquid jet. Journal of Fluid Mechanics (1968) 151-163.

[8] J. Leib and M.E. Goldstein: The generation of capillary instabilities on a liquid jet. Journal of fluid mechanics. **18** (1986) 479-500.

[9] Chaudhary K. C. and L. G. Redekopp: The nonlinear capillary instability of a liquid jet part 1: Theory. Journal of Fluid Mechanics (1980) 257-274.

[10] Donnelly R. J. and W. Glaberson: Experiments on the capillary instability of a liquid jet. Proceedings of the Royal Society of London Series, A Mathematical and Physical Sciences (1966) 547-556.

[11] Lonzaga Joel B., Thiessen David B., and Marston Philip L.: Uniformly valid solution for acoustic propagation in weakly tapered circular waveguides: Liquid jet example. Acoustical society of America **124** (2008) 151-160.

[12] William. J. Jacobi: Propagation of sound waves along liquid cylinders. The journal of acoustical society of America **21(2)** (March 1949) 122-127.

[13] J.W.S. Rayleigh: The theory of sound. **353(2)**, Dover edition, NewYork, 1945.