Experimental Study on Dynamics of Cavitation Bubble Off-centred Between Two Convex Solid Boundaries

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Acknowledgements

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Introduction:

The work presented in this report describes the experimental study of cavitation bubble dynamics near curved solid boundaries. Importantly, it focuses on the interaction of a cavitation bubble at an offset from the centre of two convex-shaped boundaries and the type of bubble's collapsing and jetting behaviour by varying the two non-dimensional parameters: $\boldsymbol{W'}$ & $\boldsymbol{s'}$. The dynamics of bubble and jet direction are captured using high-speed imaging techniques.

What are cavitation and cavitation bubbles?

Cavitation in fluid mechanics is a phenomenon where the static pressure inside a liquid falls below its vapour pressure, forming small vapour-filled cavities and generating a bubble. This bubble is known as a cavitation bubble. The formation of these bubbles is affected by pressure, temperature, and surface tension of the surrounding fluid [1]. These are non-equilibrium bubbles with a pressure difference between the bubble and its surroundings, and the inverse is for equilibrium bubbles.

What is a centred and off-centred bubble?

The closest distance between the surfaces of two cylinders is called gap width, denoted by $\boldsymbol{W}$. The distance from the centre of the gap width along the line joining two centres of cylinders at which the spark is generated is called offset distance, denoted by $\boldsymbol{b}$. When the bubble is created at the centre of the gap width, it is called a centred bubble, and the bubble created at an offset distance is called an off-centred bubble (as shown in Fig. 1).

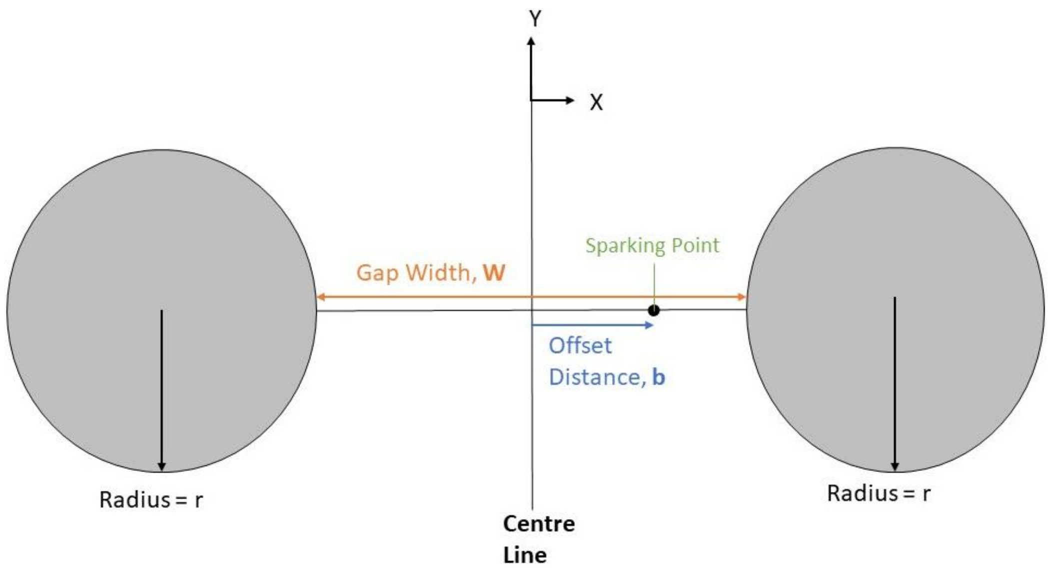

Fig. 1, Diagram of Parameters used

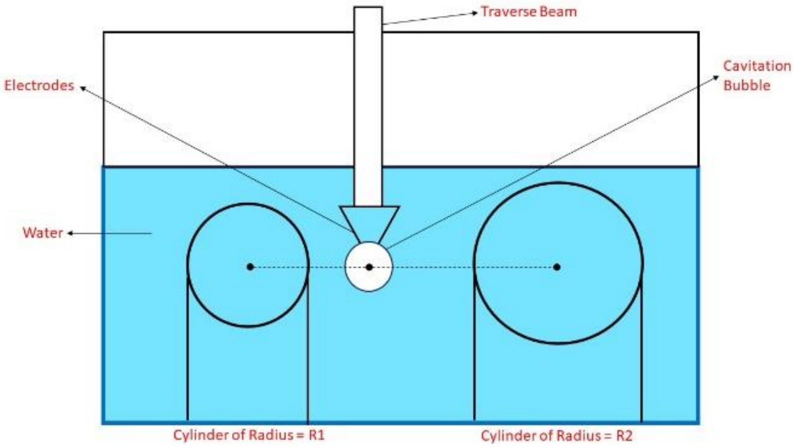

Fig. 2, Front view of setup (as seen by the camera)

Bubble Initiation and generation:

Cavitation bubble initiation can occur in two ways: Homogenous and Heterogenous cavitation.

- **Heterogenous Cavitation**: The formation and collapse of the bubble is at the interface of different phases of the fluid system. It is usually formed at the interface of two immiscible phases.
- **Homogenous Cavitation**: The formation and collapse of the bubble is within the single-phase liquid. The cavity is composed of vapour of the surrounding medium.

The generation of cavitation bubbles can happen in different modes, as described below:

- **Hydrodynamic Cavitation**: A cavitation bubble is generated due to a sudden fluid velocity or pressure change.
- **Acoustic Cavitation**: A cavitation bubble is generated due to the influence of ultrasonic sound waves.
- **Optical Cavitation**: A cavitation bubble is generated due to the sudden discharge of high voltage in the liquid.

Bubble expansion and Collapse behaviour:

When the bubble is formed, the pressure is higher than the surrounding liquid's, creating a pressure difference. This pressure difference leads to the expansion of the bubble.

The bubble collapse can be either inertial or non-inertial:

- **Non-Inertial Cavitation**: The bubble expands and collapses repeatedly in a periodic manner. This usually happens when the pressure difference is low, releasing low energy. Since they oscillate periodically, their timescale ranges between milliseconds.
- **Inertial Cavitation**: The bubble dissipates into the surrounding medium. This usually happens when the pressure difference is very high, releasing much energy. They typically occur for very short timescales, ranging from microseconds to milliseconds. This experiment is based on Inertial Cavitation.

Applications of Cavitation bubbles:

These bubbles collapse rapidly when exposed to higher pressures, creating jet and shock waves, potentially damaging the surface of solid structures inside the liquid by causing surface erosion or fatigue cracks. The most common examples of this type of wear are pumps, propellers, and impellers. When applied judiciously, this phenomenon can be used for positive purposes like breaking down pollutants from water and kidney-stone lithotripsy, drug delivery, and helping design shapes of pumps and propellers to reduce surface erosion. They are also used in ultrasonic cleaning, where a series of bubbles are generated in a narrow gap and force out the dirt through the shearing action of the oscillating bubble and its jet [2].

Previous work:

Researchers have recently investigated confinement's effect on oscillating bubbles' dynamics. Quah et al. studied the bubble dynamics for a bubble created precisely at the centre with respect to mid-planes between two solid flat plate boundaries. The presence of these boundaries affects the jetting behaviour of the bubble. Two types of collapse behaviour were observed: a) Central Collapse, where the bubble collapses towards the centre of the bubble, and b) Split Collapse, where the bubble collapses towards the solid walls [1,2,3]. Prince et al. experimentally studied a combination of flat-plate and curved boundaries. For these cases, the bubble was generated only at the centre with respect to the mid-plane between two solid boundaries, where they found four different types of collapse behaviour: spherical collapse, split collapse, split after the first collapse, and central collapse for different non-dimensional gap widths. Bimal-Narayan et al. experimentally studied the dynamics of a cavitation bubble generated between two convex perspex cylinders of the same and different radii of curvature. They also found four types of collapse behaviour by bubble, as in Prince's work, for different non-dimensional gap widths.

Problem statement:

In continuation of Bimal-Narayan's work, I aim to study experimentally the dynamics and jetting behaviour of cavitation bubbles initially off-centred in the mid-plane between two convex perspex cylinders of the same radii of curvature. This offset can be termed a horizontal offset from the centre of the gap width between two cylinders. At the same time, the vertical symmetry is still maintained.

Experimental Setup:

Low-voltage spark circuit:

All the experiments are completed using a modified version of the Goh et al. [4] spark circuit, which generates a cavitation bubble. The circuit is divided into four main sections: charging, storing, discharging, and sparking. These circuits are connected to relays and a MOSFET and controlled by a LabVIEW® program on a NI-DAQ (model USB-6008). It has two capacitors connected in parallel (with the equivalent capacitance of 6900 µF); the charging circuit is connected to a DC supply of

180V. This is then short-circuited using a pair of electrodes of 0.1 mm diameter copper wires. During experiments, one-point contact is maintained between them by crossing with each other. When capacitors discharge, spark and vapour bubbles are generated at this point of contact.

Explanation of Setup:

The setup contains a 450mm × 450mm × 450mm Perspex tank filled with 75% water, three Perspex cylinders of 25mm, 40mm, and 50mm diameter and 50mm long, a low-voltage discharge system, copper electrodes, a multimeter, a high-speed camera (Photron Fastcam SA-Z), a light-emitting source, a diffuser, a 3D microcontroller, a computer as shown below.

The low-voltage spark circuit is connected to the charging circuit, and synchronised charging, discharging, and sparking are done using the synchroniser BNC Pulse Generator (Model-577), operated using LabVIEW®. The sparking circuit is connected to another 10V DC supply. Three DC supplies, each of 60V, are connected in series, after which the net input voltage of the charging circuit becomes 180V, although a cavitation bubble is generated at 120V.

The high-speed camera captures the generated bubbles at 30,000 frames/second, a shutter speed of 1/40000, and a 412 × 500 pixels resolution, operated using Photron-Fastcam-Viewer-4 (PFV4). Only the first 151 frames are considered for experimental results for each captured video, and the final video is saved at 10 frames/second. The diffuser evenly spreads light from the emitter from the background, as shown in Fig. 3.

The position of electrodes is controlled using a 3D microcontroller, operated using Micro-Motion software. Further, data analysis is done using software tools like Python, ImageJ, and Microsoft Excel.

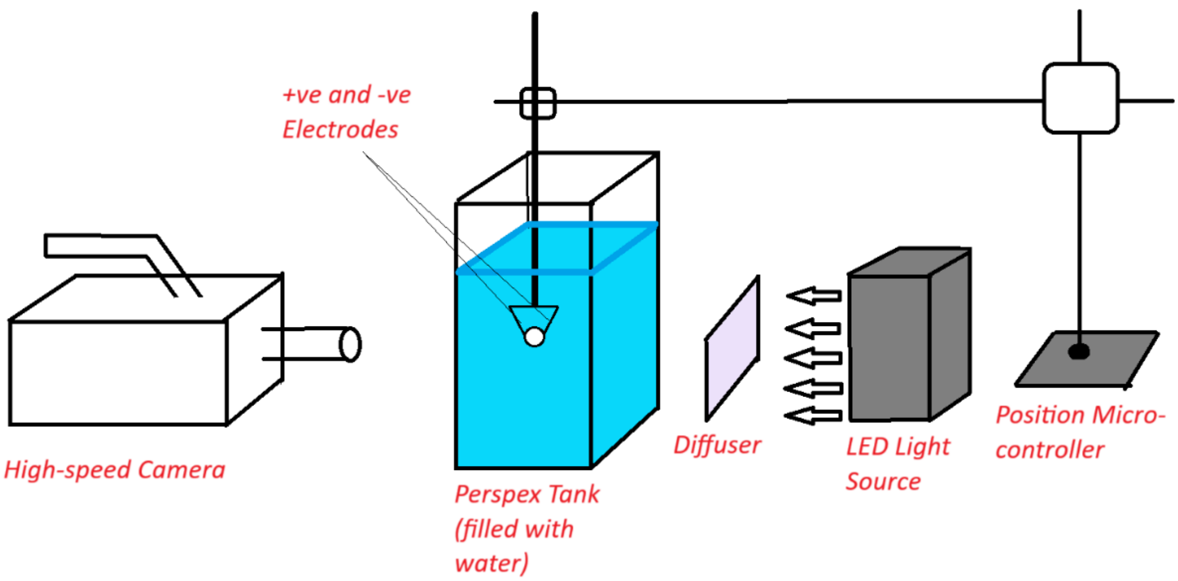

Fig. 3, Experimental Setup

Flow of Experiments:

- First, the Perspex tank is filled with 75% water (as shown in Fig. 3), and cylinders are placed parallel at a given gap width.
- Copper Electrodes are attached to the microcontroller, and a one-point contact is made between them.
- The offset position is calculated using the PFV-4, and electrodes are placed at this offset using the Micro-Motion software.
- The charging circuit is switched ON, and the capacitors are charged till 120V, then a spark is generated. After sparking, the circuit is discharged, and electrodes are taken from the tank.
- This phenomenon is recorded using a high-speed camera, and the captured video is saved at given parameters on the disk.
- The screenshot of the setup and scale at the given focus is taken at the end to calibrate distances and calculate the bubble's radius.
- For each case, with all parameters being fixed, the same experiment is repeated 3 times.

Non-Dimensional Parameters:

The cavitation bubble is generated at a precise offset from the centre between two cylinders, and its dynamics are studied. To study the collapse behaviour, two parameters are made: $\boldsymbol{W'}$ and $\boldsymbol{s}'$

- $\boldsymbol{W'}$**:** This is the non-dimensional gap-width between two cylinders defined by

$$\boldsymbol{W'} = \frac{Gap\ Width}{Max.Radius\ of\ Bubble} = \frac{\boldsymbol{W}}{\boldsymbol{R_{max}}}$$

  This parameter physically signifies the confinement of a bubble between cylinders. A smaller gap width relative to the bubble's size means high confinement, significantly affecting the bubble's collapse or jetting behaviour due to increased interactions with the surface. The value of $\boldsymbol{W'}$ varies from 0.045 to 10.941.

- $\boldsymbol{s}'$: This is the non-dimensional offset distance defined by

$$\boldsymbol{s}' = \frac{Offset\ Distance}{Radius\ of\ Cylinder} = \frac{\boldsymbol{b}}{\boldsymbol{r}}\ \ where\ \boldsymbol{b} < \frac{\boldsymbol{W}}{2}$$

  This parameter signifies the relative position of the bubble from the centre between two cylinders. A larger offset distance leads to an increase in asymmetry with respect to the centre point. The value of $\boldsymbol{s}'$ varies from 0.007 to 1.374.

Results and Discussion:

Based on 320+ experiments, the cavitation bubble collapse behaviour is divided into Jetting or Collapse. Jetting behaviour can be jetting towards a nearer wall or jetting away from a nearer wall. Further collapsing can be centre collapse, spherical collapse, split collapse, and split after collapse. The details about them are as follows:

Jetting Towards Nearer Wall:

In this type of jetting, as an example in Fig. 4, the bubble initially expands between two curve boundaries from t = 0 s to its maximum radius of 7.128 mm at t = 2.03 ms. During the collapse period, the region nearer to the curved boundary shrinks faster than that of the opposite side, due to which the bubble loses its spherical shape at t = 2.46 ms. The shape of the bubble nearly becomes oval with a narrower part towards the curved boundary, by t = 2.63 ms. The formation of the jet is observed towards the curved boundary by t = 2.76 ms, and the jet strikes the nearer curved boundary at t = 3.43 ms.

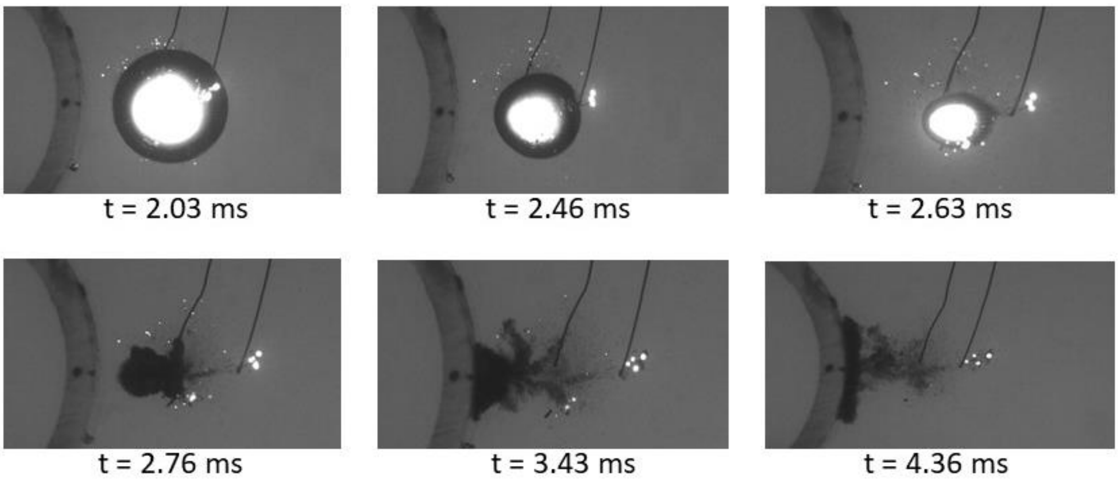

Fig. 4, Jetting Towards Nearer Wall at $\boldsymbol{R_{max}} = 7.128\ mm$, $\boldsymbol{W'} = 5.960$, $\boldsymbol{s'} = 0.531$

The relation of this behaviour with different parameters is shown below:

$$\boldsymbol{Jetting\ Towards} \propto Radius\ of\ Cylinder\ (\boldsymbol{r}) \propto Offset\ Distance\ (\boldsymbol{b})$$

$$\boldsymbol{Jetting\ Towards} \propto \frac{1}{Gap\ Width\ (\boldsymbol{W})} \propto Max.Radius\ of\ Bubble\ (\boldsymbol{R_{max}})$$

This behaviour is the result of the force of attraction by the curved boundary of the cylinder, hence the offset distance, $\boldsymbol{b}$ plays a crucial role in observing this behaviour. This is why it is observed for nearly all $\boldsymbol{W'}$> 1.5. For $\boldsymbol{W'} \in (1.5, 3)$, this behaviour is observed for $\boldsymbol{s'}$ > 0.14, and minimum value of $\boldsymbol{s'}$ decreases to 0.02 for $\boldsymbol{W'}$ = 3. For $\boldsymbol{W'}$ > 3, this behaviour is observed for $\boldsymbol{s'}$ > 0.02, which also increases as $\boldsymbol{W'}$ increases, as shown in Fig. 5.

Range of W'	Range of s' for behaviour to occur	Trend for minimum s'
$W' \in (1.5, 3)$	s' > 0.14 at W' = 1.5	Decreases as W' increases
$W' > 3$	s' > 0.04 at W' = 3	Increases as W' increases

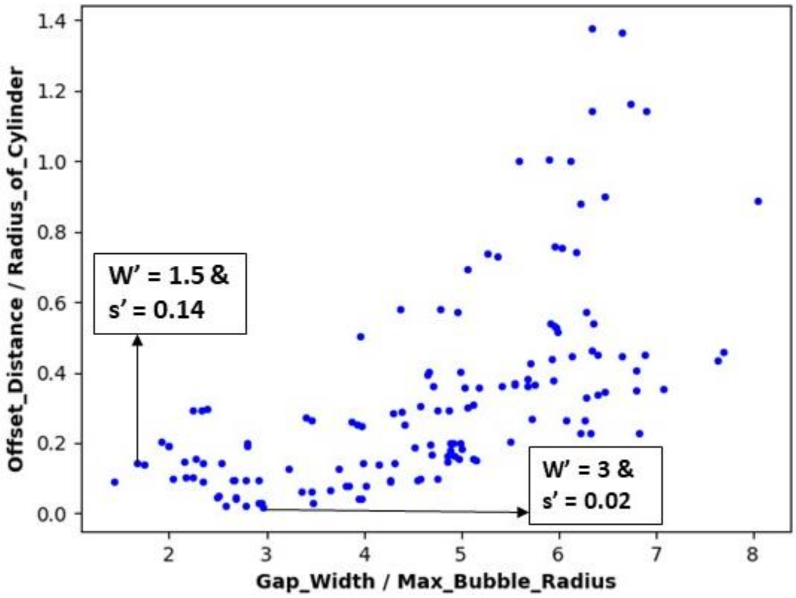

Fig. 5, Plot of W' vs s' for Jetting Towards Nearer Wall

Jetting Away From Nearer Wall:

In this type of jetting, as an example in Fig. 6, the bubble initially expands between two curve boundaries from t = 0 to reach its maximum radius of 8.101 mm at t = 1.73 ms. After the bubble reaches its maximum radius, it experiences the higher effect of the wall away from it, and from t = 2.30 ms, it starts to form a jet away from its closer wall. From t = 2.50 ms to t = 2.56 ms, it moves away from the closer wall, and finally, at t = 2.63 ms, it strikes the wall away from the point of generation.

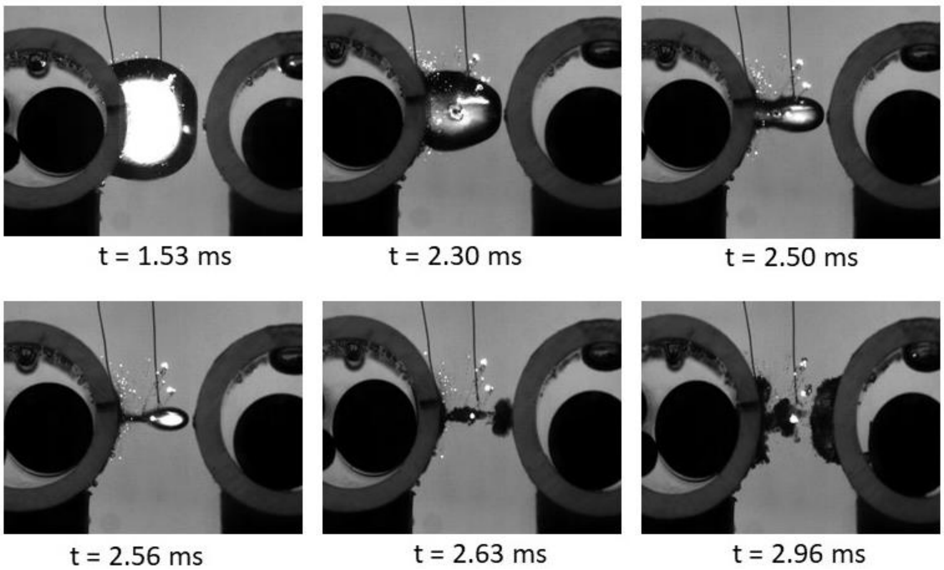

Fig. 6, Jetting Away From Nearer Wall at $R_{max} = 8.101\ mm$, $W' = 1.266$, $s' = 0.205$

This type of jetting behaviour is observed when the bubble touches the closer wall and the gap width: $\boldsymbol{W}$ is very small compared to the size of a free-field bubble. In this type of jetting behaviour, the force of attraction from the farther wall dominates over the force of attraction from the closer wall, due to which the jet moves towards the farther wall. It is observed for $\boldsymbol{W'}$ < 1.3. For $\boldsymbol{W'}$ = 1.3, it is observed for $\boldsymbol{s'}$ < 0.2, and as $\boldsymbol{W'}$ decreases the maximum value up to which this behaviour is observed also decreases, $\boldsymbol{s'}$ becomes 0.011 for $\boldsymbol{W'}$ = 0.522, as shown in Fig. 7.

Range of W'	Range of s' for behaviour to occur	Trend for maximum s'
$\boldsymbol{W'} < 1.3$	$\boldsymbol{s'}$ < 0.2 at $\boldsymbol{W'}$ = 1.3	Decreases as $\boldsymbol{W'}$ decreases

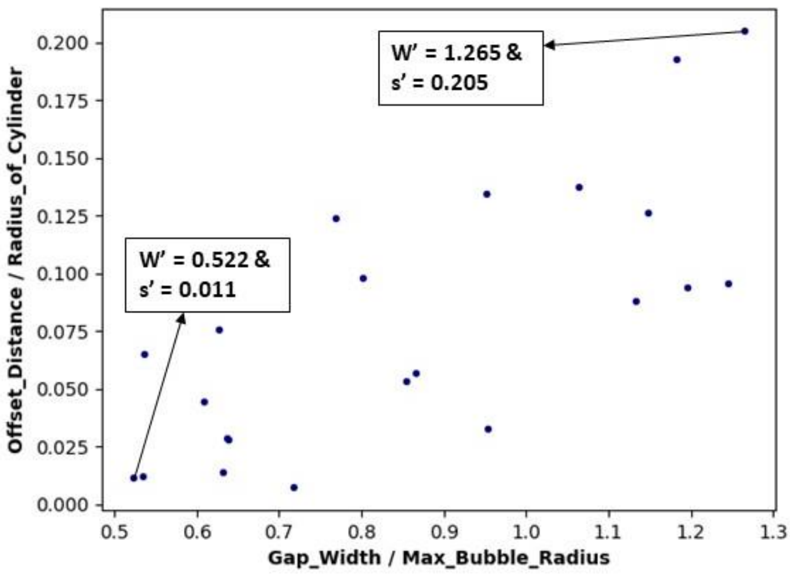

Fig. 7, Plot of $\boldsymbol{W'}$ vs $\boldsymbol{s'}$ for Jetting Away From Nearer Wall

Spherical Collapse:

In this type of collapse, as an example in Fig. 8, the bubble initially expands between two curve boundaries from t = 0 s to reach its maximum radius of 4.906 mm at t = 1.83 ms. During its collapse period, the bubble always maintains its spherical shape, and at t = 2.63 ms, it collapses in the centre of the bubble (i.e., where the bubble was generated). After its collapse at the centre, small jets are observed in all directions at t = 2.83 ms. This indicates that the curved boundaries on both sides don't affect this collapse behaviour.

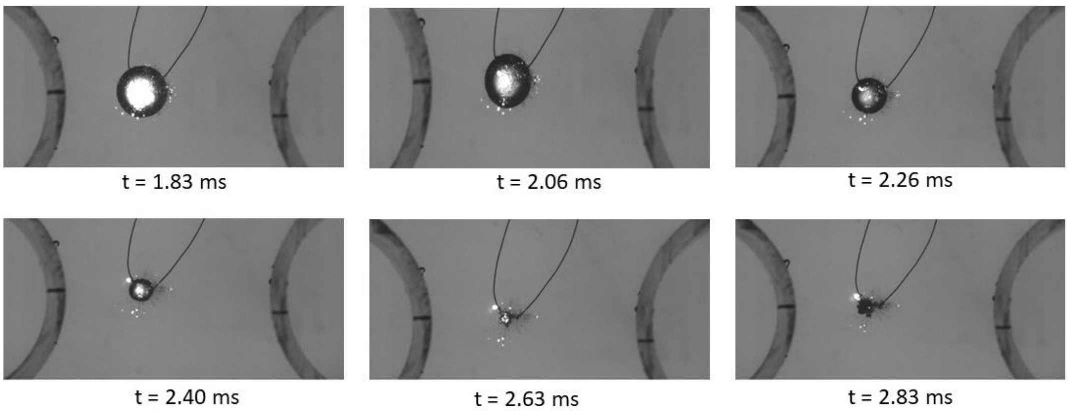

Fig. 8, Spherical Collapse at $\boldsymbol{R_{max}} = 4.906\ mm$, $\boldsymbol{W'} = 7.897$ $\boldsymbol{b'} = 0.193$

The relation of this behaviour with different parameters is shown below:

$$\boldsymbol{Spherical\ Collapse} \propto \frac{1}{Radius\ of\ Cylinder\ (\boldsymbol{r})} \propto \frac{1}{Offset\ Distance\ (\boldsymbol{b})}$$

$$\boldsymbol{Spherical\ Collapse} \propto Gap\ Width\ (\boldsymbol{W}) \propto \frac{1}{Max.Radius\ of\ Bubble\ (\boldsymbol{R_{max}})}$$

If the bubble shows spherical collapse, it is like a bubble generated in a free field with no wall (of any shape) around it. Hence, for this behaviour, the gap width: $\boldsymbol{W}$, and offset distance: $\boldsymbol{b}$ are both crucial. For $\boldsymbol{W'}$ > 4, it is observed for $\boldsymbol{s'}$ < 0.125. As the value of $\boldsymbol{W'}$ increases, the maximum value of $\boldsymbol{s'}$ up to which this behaviour is observed also increases, as shown in Fig. 9.

Range of W'	Range of s' for behaviour to occur	Trend for maximum s'
$\boldsymbol{W'} > 4$	$\boldsymbol{s'} < 0.125$ at $\boldsymbol{W'}$ = 4	Increases as $\boldsymbol{W'}$ increases

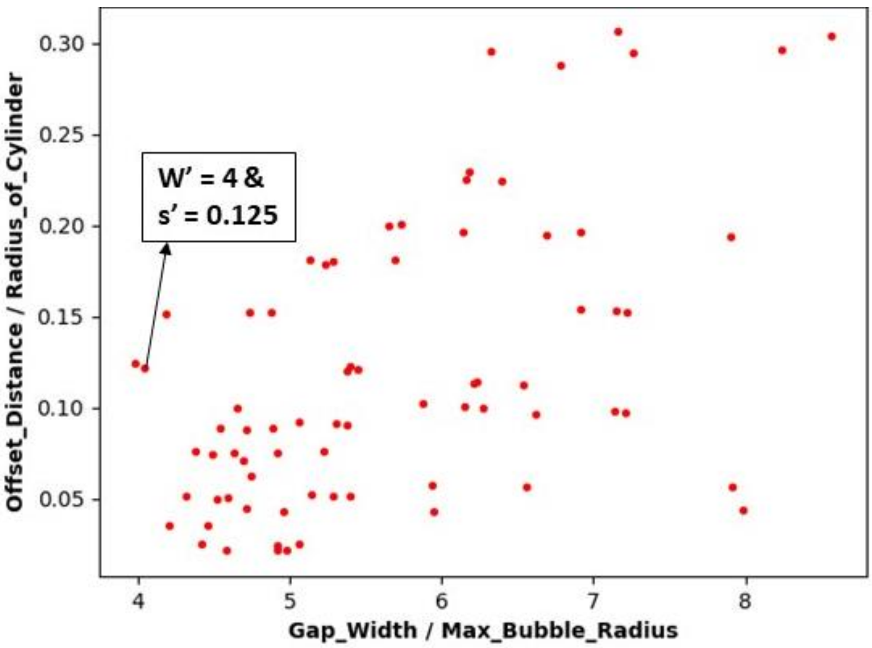

Fig. 9, Plot of $\boldsymbol{W'}$ vs $\boldsymbol{s'}$ for Spherical Collapse

Split Collapse:

In this type of collapse, as an example in Fig. 10, the bubble initially expands between two curve boundaries from t = 0 s to reach its maximum radius of 7.195 mm at t = 1.56 ms. The bubble collapses normally from t = 1.56 ms to t = 2.43 ms. From t= 2.5 ms, the bubble starts splitting into two equal halves (not necessarily half in all cases) till t = 2.57 ms; the splitting becomes clear. By t = 2.64 ms, each half moves towards the nearer wall, and by t = 2.96 ms, each half strikes the wall near it.

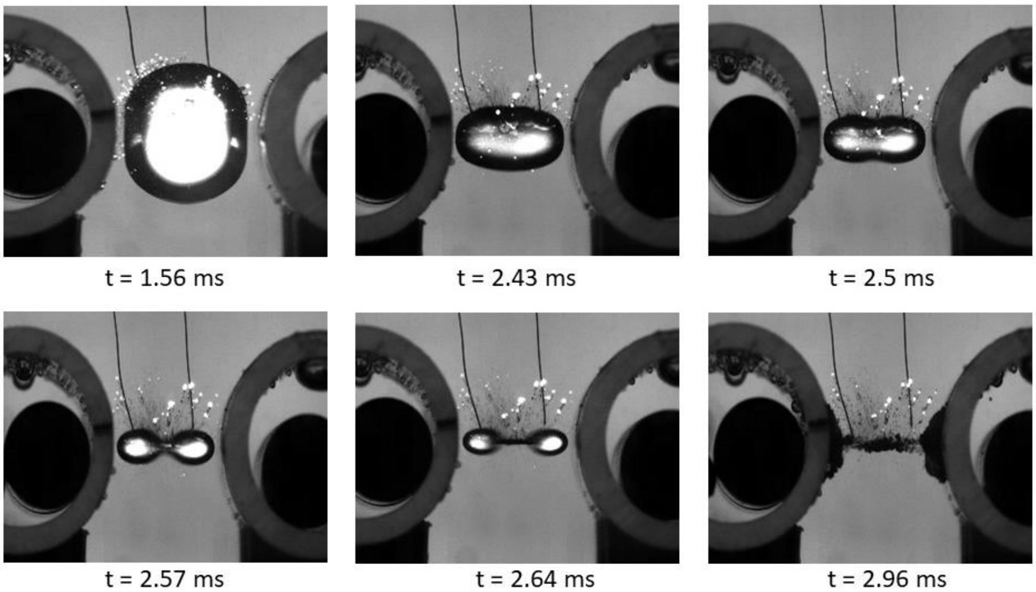

Fig. 10, Split Collapse at $\boldsymbol{R_{max}} = 7.195\ mm$, $\boldsymbol{W'} = 1.966$, $\boldsymbol{b'} = 0.035$

The relation of this behaviour with different parameters is shown below:

$$\boldsymbol{Split\ Collapse} \propto Radius\ of\ Cylinder\ (\boldsymbol{r}) \propto \frac{1}{Offset\ Distance\ (\boldsymbol{b})}$$

$$\boldsymbol{Split\ Collapse} \propto \frac{1}{Gap\ Width\ (\boldsymbol{W})} \propto Max.Radius\ of\ Bubble\ (\boldsymbol{R_{max}})$$

This indicates that the curved boundaries on both sides affect this collapse behaviour. Both the walls attract bubbles towards them, due to which the bubble splits into two halves. Splitting can be equal or unequal, depending upon offset distance, $\boldsymbol{b}$. As the $\boldsymbol{b}$ increases, splitting will become unequal, in which larger volume will be towards the nearer wall and smaller volume will be towards the farther wall. This behaviour comes into effect from $\boldsymbol{W'}$ = 0.923. For $\boldsymbol{W'} \in (0.9, 1.4)$, it is observed for $\boldsymbol{s'}$ < 0.07, and the maximum value of $\boldsymbol{s'}$ increases to 0.121 at $\boldsymbol{W'}$ = 1.385. For $\boldsymbol{W'} \in (1.4, 2.6)$, the maximum value of $\boldsymbol{s'}$ up to which this behaviour is observed decreases to 0.022.

Range of W'	Range of s' for behaviour to occur	Trend for maximum s'
$\boldsymbol{W'} \in (0.9, 1.4)$	$\boldsymbol{s'} < 0.07$ at $\boldsymbol{W'}$ = 0.923 & $\boldsymbol{s'}$ < 0.121 at $\boldsymbol{W'}$ = 1.385	Increases as $\boldsymbol{W'}$ increases
$\boldsymbol{W'} \in (1.4, 2.6)$	$\boldsymbol{s'} < 0.022$	Decreases as $\boldsymbol{W'}$ increases

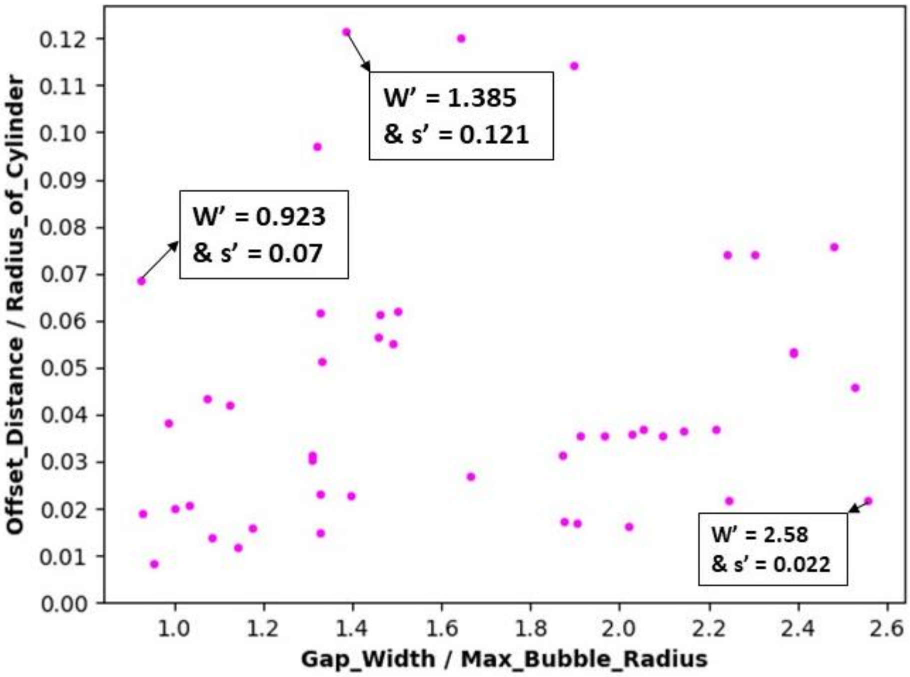

Fig. 11, Plot of W' vs s' for Split Collapse

Split After Collapse:

In this type of collapse, as an example in Fig. 12, the bubble initially expands from t = 0 s to reach its maximum radius of 5.50 mm at t = 1.83 ms. It maintains its spherical shape from t = 1.83 ms to t = 2.90 ms during its collapse period. After its first collapse at the generation point, from t = 2.96 ms, the jet splits into two halves along the y-axis, and each half moves towards the nearer surface till t = 3.33 ms.

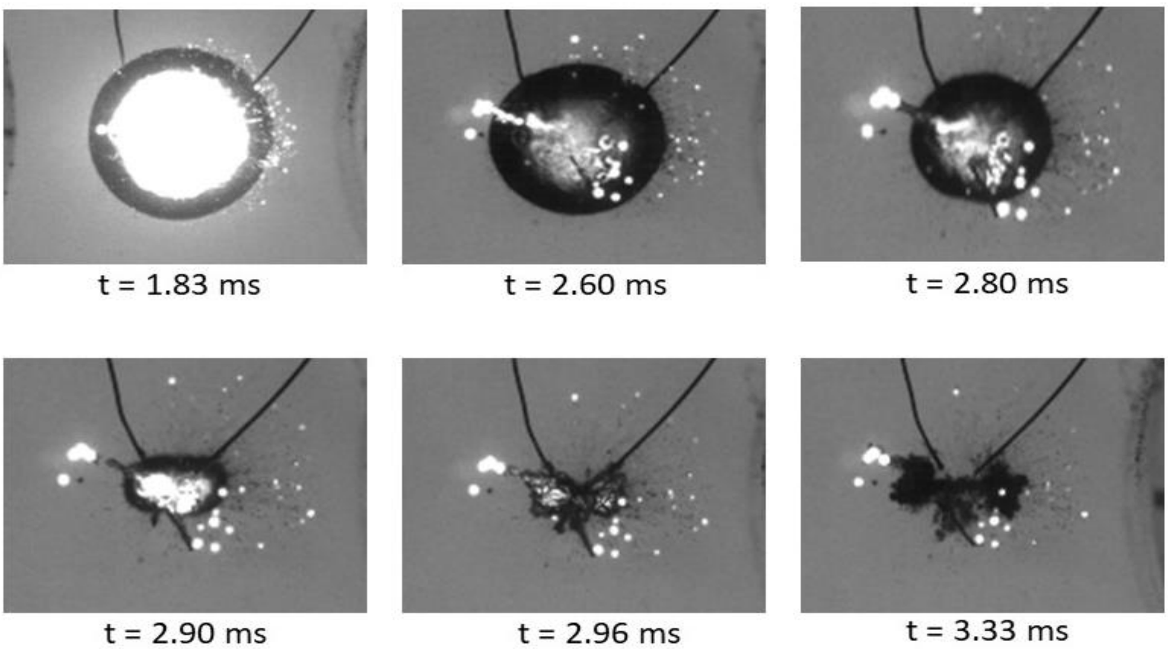

Fig. 12, Split After Collapse at $R_{max} = 5.50\ mm$, $W' = 3.713$, $b' = 0.016$

The relation of this behaviour with different parameters is shown below:

$$\boldsymbol{Split\ After\ Collapse} \propto Radius\ of\ Cylinder\ (\boldsymbol{r}) \propto \frac{1}{Offset\ Distance\ (\boldsymbol{b})}$$

$$\boldsymbol{Split\ After\ Collapse} \propto \frac{1}{Gap\ Width\ (\boldsymbol{W})} \propto \frac{1}{Max.Radius\ of\ Bubble\ (\boldsymbol{R_{max}})}$$

This collapse is similar to Split Collapse, but the splitting happens after the bubble collapses for the first time at the point of generation. It was observed in those cases of split collapse where the bubble generation was abnormal. When sufficient energy is not imparted in the bubble, the bubble's size decreases, so instead of a Split Collapse, the bubble shows a Split After Collapse. Hence, this type of collapse has very little probability to occur. It is observed for $\boldsymbol{W'}$ ranging from 2.5 to 4, and $\boldsymbol{s'}$ < 0.07, as shown in Fig. 13. It can be concluded that these were the cases for 1 < $\boldsymbol{W'}$ < 2, but due to the small radius of the bubble, $\boldsymbol{W'}$ increased.

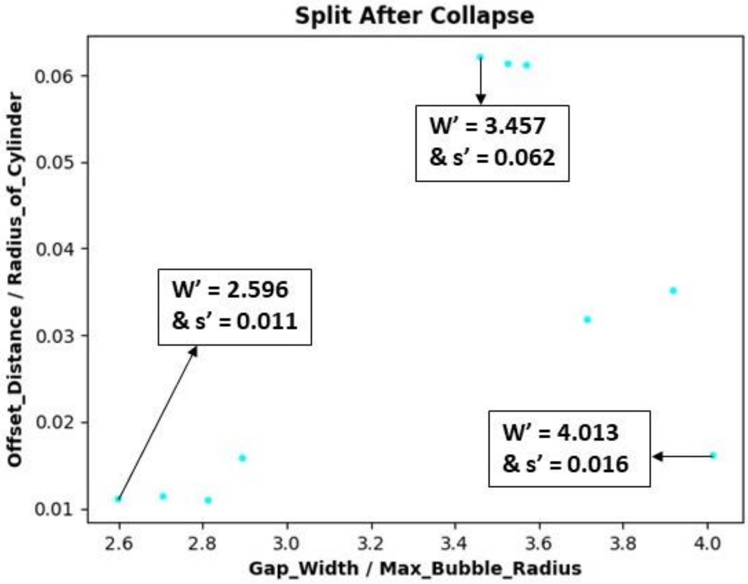

Fig. 13, Plot of $\boldsymbol{W'}$ vs $\boldsymbol{s'}$ for Split After Collapse

Centre Collapse:

In this type of collapse, as an example in Fig. 14, the bubble initially expands from t = 0 to reach its maximum radius of 7.322 mm at t = 1.73 ms, touching the cylinders' walls on both sides. From t = 2.33 ms, it collapses on the point of generation till t = 2.70 ms and at t = 2.80 ms, the jet strikes the walls on both sides.

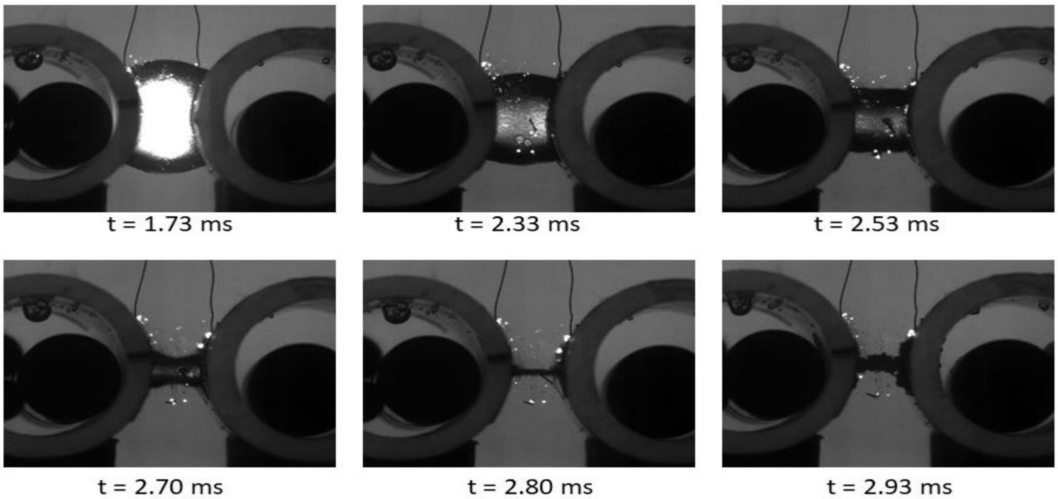

Fig. 14, Centre Collapse at $\boldsymbol{R_{max}} = 7.322$, $\boldsymbol{W'} = 0.870, \boldsymbol{b} = 0.032$

For this collapse to occur, the gap width has to be very small; in our case, it is observed only for $\boldsymbol{W}$ = 5 mm, which also means the value of $\boldsymbol{b}$ is very small. This type of collapse is observed for $\boldsymbol{W'}$ < 1.1, and $\boldsymbol{s'}$ < 0.055. As the $\boldsymbol{W'}$ decreases, the maximum value of $\boldsymbol{s'}$ up to which this collapse is observed also decreases. For $\boldsymbol{W'}$ = 0.5, it is observed for $\boldsymbol{s'}$ < 0.03, which further reduces to $\boldsymbol{s'}$ = 0.013 for $\boldsymbol{W'}$ < 0.5, as shown in Fig. 15.

Range of W'	**Range of s' for behaviour to occur**	**Trend for maximum s'**
$\boldsymbol{W'} < 1.1$	$\boldsymbol{s'} < 0.055$ at $\boldsymbol{W'}$ = 1.1	Decreases as $\boldsymbol{W'}$ decreases
$\boldsymbol{W'} < 0.5$	$\boldsymbol{s'} < 0.03$ at $\boldsymbol{W'}$ = 0.5	Decreases as $\boldsymbol{W'}$ decreases

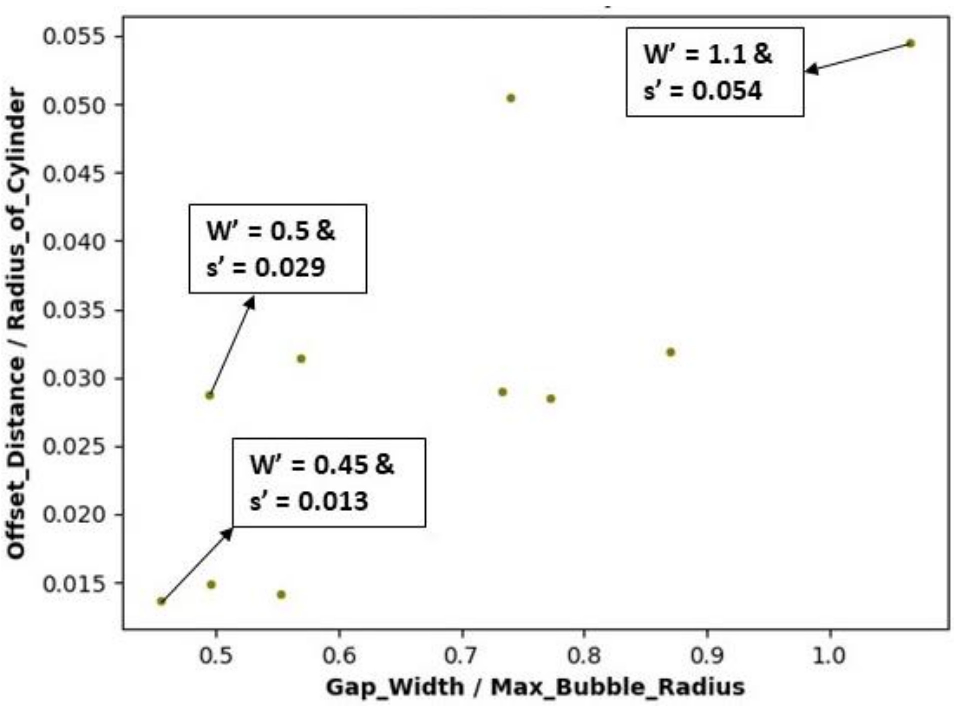

Fig. 15, Plot of $\boldsymbol{W'}$ vs $\boldsymbol{s'}$ for Centre Collapse

Conclusions:

The gap width $\boldsymbol{W}$ notably influences the behaviour of cavitation bubbles between convex surfaces. This study highlights the intricate dynamics that occur as the bubble interacts with its surrounding boundaries. The results clearly indicate that as the gap width decreases, the maximum size of the cavitation bubble increases. This trend is evidenced by the comparative measurements of the mean bubble radius: r_{mean} at various gap widths.

From Fig. 16, for r_{mean} = 6.55 mm at $\boldsymbol{W}$ = 20 mm, and r_{mean} = 7 mm at $\boldsymbol{W} = 15\ mm\ \approx 2 * \boldsymbol{r}$. Further, when $\boldsymbol{W}$ = 10 mm, r_{mean} increases to 7.45 mm. For $\boldsymbol{W}$ = 5 mm, standard deviation of r_{mean} = ± 2.303 mm. This large standard deviation indicates that the bubble's size varies widely due to the significant influence of the closely spaced convex surfaces. This behaviour is likely due to the increased pressure and confinement effects exerted by the convex boundaries on the bubble, which, in turn, enhance the bubble's growth before the collapse.

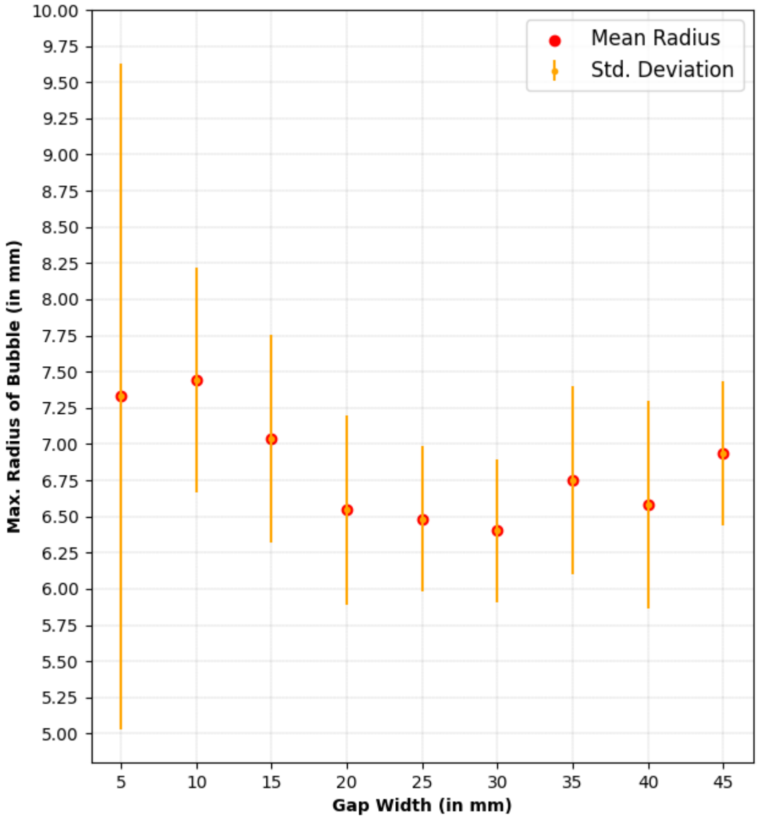

Fig. 16, Mean & Std. Deviation of Bubble's Max. Radius for different $\boldsymbol{W}$

Fig. 17 gives a clear idea of each type of bubble's behaviour, where the onset and ending points for different behaviours can be estimated using the two non-dimensional parameters $\boldsymbol{W'}$ and $\boldsymbol{s'}$. The Jetting towards behaviour was observed for nearly all $\boldsymbol{W'}$ > 1.5, i.e., $\boldsymbol{W}\ \geq 25\ mm$, further depending on $\boldsymbol{s'}$, it can be converted to Spherical Collapse. For the same range of $\boldsymbol{s'}$ on decreasing $\boldsymbol{W'}$ it can be converted into Split or Split After Collapse. For $\boldsymbol{W'}$ < 1.5, Jetting towards behaviour is converted into Jetting away from the nearer wall, and Split Collapse is replaced by Centre Collapse.

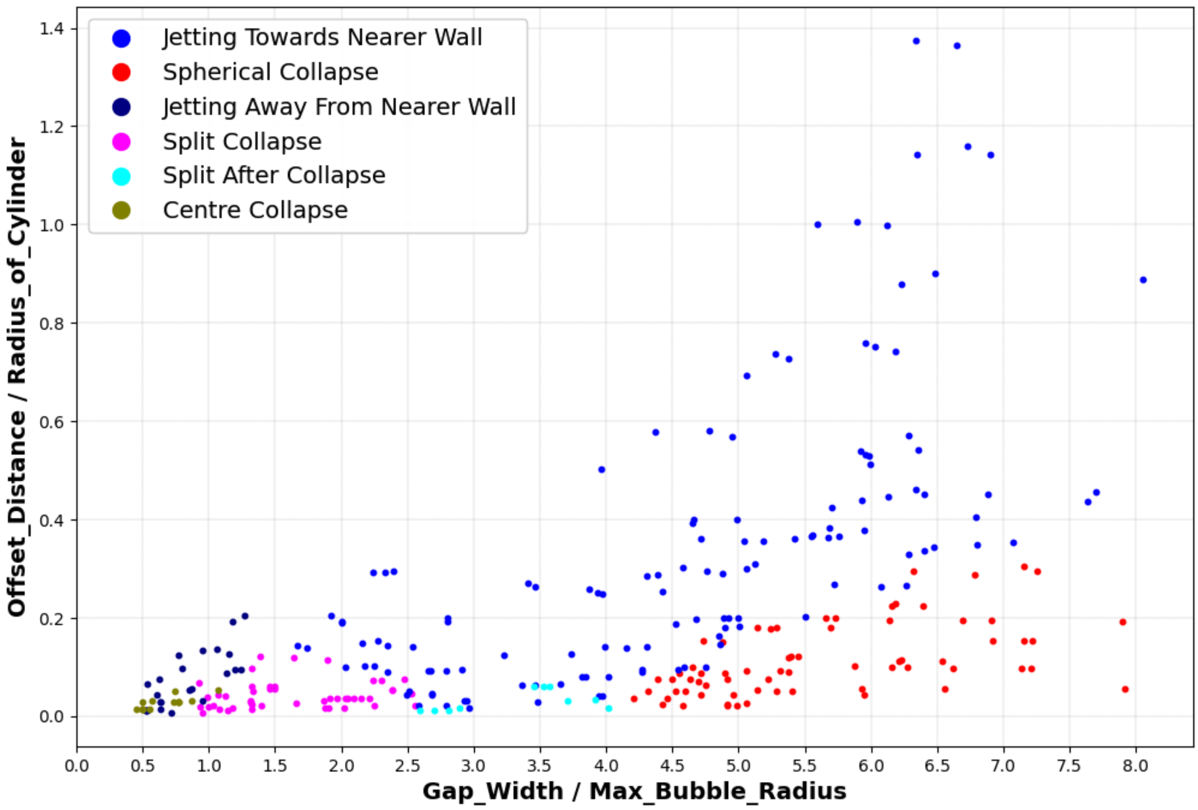

Fig. 17, Plot of W' vs s' for different Jetting and Collapsing behaviour

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** All the analysis can be viewed ***here***.