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Mubaraq Adewale Razaq

m.razaq@rgu.ac.uk

Robert Gordon University

Taimoor Asim

Robert Gordon University

Okwunna Maryjane Ekechukwu

Robert Gordon University

Khaliq Ur Rahman

Robert Gordon University

Barry Reid

Hydropulsion Ltd

Article

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Posted Date: October 23rd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11267827/v1>

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Additional Declarations: No competing interests reported.

Dynamics of Coherent Vortical Structures Underlying Shape-Shifting Behaviour and Impact Force Fluctuations in Oscillating Jet Nozzles

Mubaraq Adewale Razaq ^{*1}, Taimoor Asim ², Okwunna Maryjane Ekechukwu ³, Khaliq Ur Rahman ⁴ and Barry Reid ⁵

¹⁻⁴ School of Computing, Engineering and Technology, Robert Gordon University, Aberdeen, UK (AB10 7GJ)

⁵ Hydropulsion Ltd., Crombie House, Grandholm Crescent, Aberdeen, UK (AB22 8BD)

* Corresponding author: m.razaq@rgu.ac.uk

Abstract

Oscillating jet nozzles are frequently used in industrial applications for cleaning operations due to their high impact force and larger coverage area. Published studies on oscillating jets severely lack in quantifying the dynamics of coherent vortical structures and their role in the jet's shape-shifting behaviour and impact force fluctuations. This study presents an integrated numerical and experimental approach to evaluate the complex flow physics associated with oscillating jet nozzles. The results obtained reveal that the shape of the oscillating jet periodically shifts between reversed S, reversed C, S and C configurations during an oscillation cycle, driven by the formation, growth, diffusion and dissipation of the vortical structures. The jet impact force peaks at reversed C and C configurations due to straightening of the jet, resulting in 37.3% higher impact force and 4.28 larger coverage area than straight jets. Spatio-temporal analyses of the vortical structures show that the vortex core displacement during the diffusion stage is 83% higher than during the growth stage due to vortex stretching and downstream propagation. The velocity gradients increase by 140% during the growth stage and decrease by 42% during the diffusion stage, eventually resulting in flow reversal during the dissipation stage, indicating weakening vortices. They are most coherent during formation stage and rapidly lose their coherence during growth (76%), diffusion (76%) and dissipation (52%) stages. These findings provide new insights into the mechanics of oscillating jets and establishing the relationship between the dynamics of coherent vortical structures and the jet impact force.

Keywords: Oscillating jet nozzle; Coherent vortical structures; Impact force; Coverage area; Coherence

Nomenclature

u	Velocity field	m/s
v	Y component of flow velocity	m/s
t	Time	s
$\rho_{(m,w,a)}$	Density (mixture, water, air)	kg/m ³
$\alpha_{(m,w,a)}$	Volume fraction (mixture, water, air)	-
$\mu_{(eff,m,t,w,a)}$	Dynamic viscosity (effective, mixture, eddy, water, air)	Pa.s
P	Static pressure	Pa
T_s	Surface tension force	N/m ³
σ	Surface tension coefficient	kg/s ²
κ	Interface curvature	m ⁻¹
k	Turbulent kinetic energy	m ² /s ²
ω	Specific dissipation rate	s ⁻¹
ε	Dissipation rate	m ² /s ³
$\gamma_{(k,\omega)}$	Effective diffusivity of (k, ω)	Pa.s
$P_{(k,\omega)}$	Production of (k, ω)	kg/m.s ³ , kg/m ³ .s ²
$D_{(k,\omega)}$	Dissipation of (k, ω)	kg/m.s ³ , kg/m ³ .s ²
S_ω	Cross-diffusion term	kg/m ³ .s ²
W	Width of the nozzle	m
H	Height of the nozzle	m
T	Thickness of the nozzle	m
w_{in}	Width of nozzle inlet	m
w_{mc}	Width of the mixing chamber	m
w_{fbc}	Width of the feedback channel	m
h_{fbc}	Height of the feedback channel	m
F	Impact force of the jet	N
y^+	Dimensionless wall distance	-
w	Width of the vortical structure	m
h	Height of the vortical structure	m

AR	Aspect ratio of the vortical structure	-
A	Area of the vortical structure	m^2
S	Strain rate tensor	s^{-1}
ξ	Vorticity tensor	s^{-1}
Γ	Circulation of the vortical structure	m^2/s

1.0 Introduction

Cleaning operations are an integral part of many industrial applications such as removal of biofouling in marine aquaculture, descaling of geothermal wells, etc. While marine biofouling on fish-cage nets and buoyant ring collars results in increased weight, drag, wear and corrosion [1-2], scale formation in geothermal wells threatens flow assurance, equipment damage and elevated pressure losses [3-4]. Conventional cleaning methods utilise high-pressure oscillating water jets directed towards the cleaning surfaces as these jets have larger coverage area and high impact/cleaning force [5-6]. For better control of the oscillating jet and maximising its impact force, it is important to understand the underlying complex flow physics and how it affects the fluctuations in the jet impact force. Several studies have been carried out where the oscillating nature of the jet has been characterised, often utilising time and phase averaged analyses and quantifying the frequency of oscillations [7-11]. In comparison with straight jet nozzles where large-scale vortical structures are produced by shear-layer instability and subsequent roll-up [12], oscillating jet nozzles induce additional spatial and temporal variations in the flow fields through internal feedback, wall attachment and self-excited pressure-momentum coupling [13]. This leads to flow fields that are strongly three-dimensional, phase-dependent and highly sensitive to nozzle geometry and operating conditions [14]. Thus, the primary focus in recent literature has not been limited to whether oscillation improves mixing or spreading, but how the internal switching mechanism generates coherent structures, how these structures evolve in the near-field, and which characterisation or decomposition methods are most appropriate for resolving them [15].

Studies that resolved the internal flow structures of fluidic oscillators, rather than treating the oscillator as a black box, have led to major breakthroughs in our understanding of oscillating jet dynamics [13, 16-19]. Bobusch et al. [13] experimentally demonstrated that the oscillation is driven by a growing recirculation bubble between the main jet and the attachment wall, rather than by the pressure-wave mechanism [20-23], by using Particle Image Velocimetry (PIV) and time-resolved pressure measurements with Proper Orthogonal Decomposition (POD) based phase reconstruction. They showed that the flow inside the feedback channel leads to the generation of a separation bubble downstream of the nozzle inlet. This recirculation zone then grows and moves downstream, pushing the attached jet away from the wall and triggering jet oscillation.

This explanation is significant as it shifts the scientific interpretation of oscillation from a purely feedback-momentum depiction to a coupled mechanism involving feedback flow, wall attachment and evolving recirculation structure. The study also showed that the geometry of the inlet and outlet of the mixing chamber strongly influences the oscillation frequency and the jet deflection, further supporting the importance of the internal flow dynamics for the sweeping jet behaviour. A number of studies have characterised the near-field external vortical evolution of sweeping jets emitted from fluidic oscillators [24-29]. Ostermann et al. [24] recreated the three-dimensional, time-resolved velocity field of a sweeping jet in quiescent surroundings using Stereoscopic Particle Image Velocimetry (SPIV) and pressure-based phase correlations. They showed that circular head vortices are generated repetitively when the jet is at maximum deflection, and that the oscillating jet influences the surrounding fluid more dominantly than a steady straight jet, with an entrainment rate larger by a factor of four. They also found that the maximum jet velocity decreased rapidly and the jet depth increased significantly, indicating that the oscillation enhances the momentum transfer mainly by increasing the contact area between the jet and the ambient fluid.

A similar yet distinct geometric configuration that leads to oscillating jets is the fluidic precessing jet nozzle, where the internal separated jet reattaches asymmetrically and then precesses around the chamber [29-31]. Wong et al. [29] gave a clear description of flow in a precessing jet nozzle, resolved in phase. Their measurements showed that the developing jet has an azimuthal velocity component opposite to the precession. At least three different near-field vortex-pair regions were identified, including structures associated with the downstream face of the centre body, shedding from the centre edge and the downstream surface of the exit. This work is particularly important in demonstrating that the external flow is not dominated by a single dominant rotating structure, rather by a hierarchy of interacting vortex-pair regions and smaller vortical blobs embedded in the precessing near-field. Moreover, phase-averaged velocity measurements by Wong et al. [31] identified forward and reverse flow regions inside the chamber, and suggested the presence of large-scale internal recirculation, and thus a physical link between asymmetric reattachment, internal reverse flow and sustained precession. Together, these studies show that precessing nozzles generate a structurally more complex vortical field than is often implied by simplified descriptions of rotating or sweeping jets. Moreover, both the start and robustness of precession were found to be highly dependent on the initial and inlet conditions. In another study of fluidic precessing jet nozzles, Wong et al. [30] reported that inlet conditions associated with non-symmetric shedding boundary layers, such as long pipes or orifice inlets, promoted precession more readily than a smooth contraction inlet. Despite the precession being reliable, there were still minor differences in the mean velocity and turbulence intensity at the exit. This shows that the vortical dynamics in oscillating jets are not only a function of geometry

but also depend on how inlet-generated instability starts internal asymmetry, which then grows into large-scale oscillation or precession.

An equally crucial aspect associated with oscillating jets is the detection and reconstruction of the vortical structures. Simplified mean-flow characteristics do not capture the complex flow physics of oscillating jet nozzles, rather the phase-dependent coherent field analysis is required. The most insightful studies combine PIV with phase conditioning. These studies report that PIV alone is often not sufficient unless combined with some form of phase reconstruction, decomposition or multi-plane acquisition [18, 32-35]. Oberleithner et al. [32] demonstrated an approach to combine POD, phase averaging, assumptions on the azimuthal symmetry, and stability analysis in order to reconstruct three-dimensional coherent structures from two-dimensional PIV snapshots in a strongly swirling jet with vortex breakdown. Their key contribution is the explicit connection between coherent-structure extraction and the triple decomposition of turbulent flow into mean, coherent and random components. Although the study deals with swirling jets rather than oscillating nozzles, but the conceptual framework is highly relevant as the oscillating jets also contain dominant coherent structures embedded in broadband turbulence, and these cannot be adequately interpreted without separating them from incoherent fluctuations.

As far as the flow characteristics of the oscillating jet downstream the nozzle throat are concerned, Kim and Kim [26] expanded the near-field understanding by characterising the three-dimensional structure of a sweeping jet using time-resolved PIV measurements. They found that sweeping frequency increased approximately linearly with Reynolds number, but the switching itself took only a small fraction of the total oscillation period. The time-averaged velocity fields showed the centre-plane flow to be like twin jets, and the cross-sections near the nozzle showed a counter-rotating vortical structure like that of a jet in crossflow. Importantly, they observed that these coherent vortices were quickly dissipating downstream, implying that sweeping jets combine very strong near-field organization with equally rapid loss of coherence as the flow propagates away from the nozzle. This duality helps explain why sweeping jets can produce strong local mixing and spreading without necessarily preserving a single dominant vortical architecture over long downstream distance. A complementary comparison of oscillating and non-oscillating jets was performed by Zeleke et al. [36] who experimentally demonstrated that oscillating jets in the transverse direction exhibited more aggressive breakup of vortical flow structures, larger transverse spreading, increased vorticity and reduced axial velocity as compared to non-oscillating jets. This indicates that the oscillation redistributes momentum from the streamwise to the transverse motion, thus accelerating the breakdown of coherent structures, meanwhile, increasing the dispersion and mixing efficiency. The study is informative as it isolates the contribution of imposed jet oscillation to vorticity growth and structural destabilization from some of the more complex internal features of conventional fluidic oscillators. The

behaviour of oscillating jets becomes considerably more complex when subjected to an external crossflow. In their investigation of a spatially oscillating jet in crossflow, Ostermann et al. [27] demonstrated that the flow field is dominated by streamwise vortices whose dynamics are strongly dependent on Strouhal number. At low Strouhal number, the oscillating jet behaves like a time-dependent vortex-generating jet, with streamwise vortices vary in phase. At high Strouhal number, however, the crossflow is unable to respond sufficiently to the rapid jet motion, and the flow field transition towards quasi-steady, wake-dominated structure. Further analysis revealed that the instantaneous oscillating jet can appear as a vortex generating jet with one dominant vortex and a second weaker vortex, while the asymmetrical exit phases exhibit characteristics consistent with a normal counter-rotating vortex pair. This indicates that the oscillation does not produce a single invariant vortical structure, rather, the observed structure is a result of the interaction between jet sweeping duration and the response timescale of the ambient flow field.

A recent work by Li et al. [37] has stressed upon the importance of nozzle geometry in controlling the formation and evolution of coherent structures. They used Large Eddy Simulation (LES), high-speed visualization and POD to study an oscillating nozzle for enhanced sweeping coverage. The results of their study indicate that increasing the width of the nozzle inlet, mixing chamber, and exit/throat modifies the internal vortex formation, jet attachment, and external deflection angle. Nozzles that are too narrow or too wide may prevent the formation of vortical structures or induce excessive vortex formation, which dissipates the jet momentum and reduces oscillation. The optimised geometric design of the nozzle yielded a deflection angle approaching 89° , and the transient numerical results reproduced its inception, reverse-flow-ring formation, jet deflection, and periodic sweeping. Vortex control by geometric modifications has been demonstrated in non-oscillating jets within the larger scope of investigations on nozzle modifications. Lim et al. [38] investigated coherent structures in V-notched nozzle jets using time-resolved PIV and POD and reported energy redistribution from low-order to higher-order modes, cyclic large-scale structures in symmetric planes, mode pairing and energy cascade from larger to smaller structures. Even though the present study is not directly concerned with a self-excited oscillator, it is conceptually highly relevant as it demonstrates how nozzle-exit shape controls the structure, coherence, and spectral transfer of near-field vortical structures. Flow investigations on inclined and notched elliptic jet nozzles have shown that nozzle modifications can affect the roll-up of ring-vortices, rib structures, streamwise vortices and axis-switching behaviour, which further supports the idea that the dynamics of oscillating jets are most effectively characterised by geometry-dependent instability dynamics rather than conventional turbulent spreading.

A critical review of a number of key and highly relevant studies above highlight the importance of flow structure evolution in oscillating jet nozzles, how different parameters

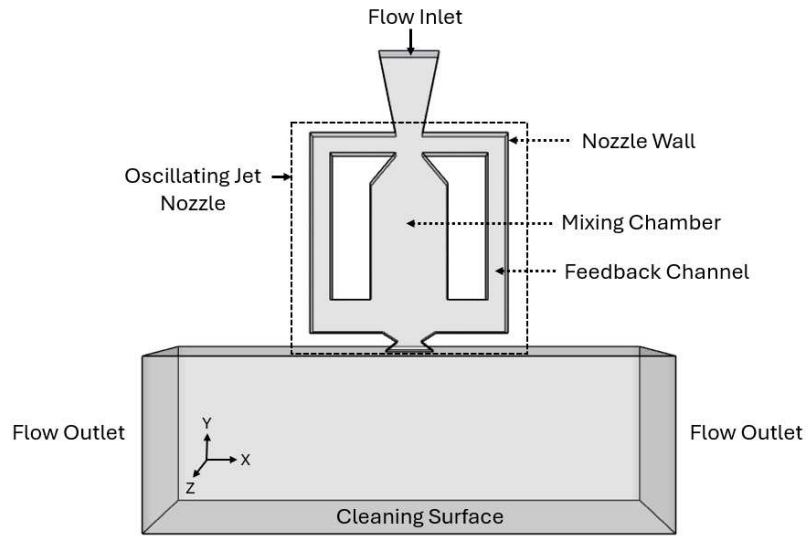
affect it, and what common methodologies are used for analyses. There is however a dearth of knowledge and understanding of the interplay between the dynamics of the coherent vortical structures in the mixing chamber of oscillating jet nozzles, the jet characteristics and its impact force on a surface. The current study has been carried out to bridge this knowledge gap through detailed and systematic investigations on an oscillating jet nozzle, where spatio-temporal analysis of both near-field (in the mixing chamber) and far-field (outside the nozzle) flow evolution has been carried out. Computational Fluid Dynamics (CFD) based numerical modelling and analyses of the oscillating jet nozzle have been conducted, while experimental approach has been employed to validate numerical predictions. The results obtained in this study, for the first time (as far as the authors are aware), establish a clear quantitative relationship between the dynamics of coherent vortical structures, the shape-shifting behaviour of the jet and the fluctuations of the jet impact force. Hence, the findings of this study allow to better strategize flow control in aquaculture and geothermal wells for more efficient biofouling and scale removal, leading to conservation of water and power, and reducing the carbon footprint of cleaning operations.

2.0 Numerical Modelling of the Oscillating Jet Nozzle

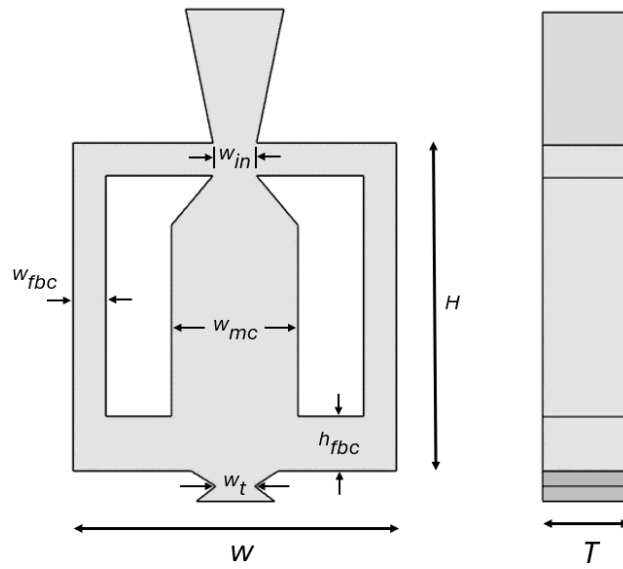
Computational Fluid Dynamics (CFD) based solver called ANSYS FLUENT® has been used in this study to carry out the numerical modelling and analyses of the oscillating jet nozzle. The following sub-sections provide details of the adopted modelling approach.

2.1 Geometric Modelling of the Oscillating Jet Nozzle and the Flow Domain

The geometry of the oscillating jet nozzle considered here is derived from previously published studies [13, 26, 39-40]. The key geometric features of an oscillating jet nozzle are shown in figure 1(a). The nozzle comprises of a central mixing chamber and two feedback channels on either side of it. The exit of the nozzle opens into the cleaning environment, which has been modelled as a rectangular region where the distance between the nozzle's exit and the cleaning surface is 25 mm (~1 inch), a realistic clearance gap between the cleaning tool and the surface in real-world operations. Figure 1(b) shows the oscillating jet nozzle alone with H , W and T as its overall height, width and thickness. The widths of the mixing chamber and the feedback channels are referred to as w_{mc} and w_{fbc} respectively, while w_{in} and w_t are the widths of the nozzle's inlet and its throat. These dimensions are provided in table 1 in relation to the throat width w_t . This is because w_t is one of the two most important geometric dimensions of oscillating jet nozzles, with the other being the width of its inlet w_{in} . As a rule of thumb, in oscillating jet nozzles, $w_t < w_{in}$.



(a)



(b)

Figure 1. Geometric details of the (a) flow domain (b) oscillating jet nozzle.

Table 1. Key dimensions of the oscillating jet nozzle.

Dimension	Value/ w_t
W	7.314
H	8.571
T	2.286
w_{in}	1.143
w_{mc}	3.314
w_{fbc}	0.857
h_{fbc}	1.43

2.2 Flow Governing Equations

The multiphase flow of water and air inside the flow domain is governed by a number of equations that are presented here. For the incompressible, time-dependent flow, the mass conservation is governed by the continuity equation, which can be expressed as: [41]:

$$\nabla \cdot u = 0 \quad (1)$$

where u is the velocity field. For momentum conservation, we employ Unsteady Reynolds-Averaged Navier-Stokes (URANS) equation for the multiphase flow as [41]:

$$\frac{\partial(\rho_m u)}{\partial t} + \nabla \cdot (\rho_m uu) = -\nabla P + \nabla \cdot [\mu_{eff}(\nabla u + \nabla u^T)] + T_s \quad (2)$$

Here, the mixture density (ρ_m) and effective viscosity (μ_{eff}) can be represented as:

$$\rho_m = \alpha_w \rho_w + \alpha_a \rho_a \quad (3)$$

and:

$$\mu_{eff} = \mu_m + \mu_t \quad (4)$$

The effective viscosity is a combination of the mixture viscosity (μ_m) and the eddy viscosity (μ_t) as the flow in the oscillating jet nozzle and the cleaning region is turbulent in real-world conditions. The mixture viscosity, in terms of the two phases considered here, can be represented as:

$$\mu_m = \alpha_w \mu_w + \alpha_a \mu_a \quad (5)$$

where α is the phase volume fraction, while the subscripts w and a refer to water and air. The last term in eq. (2) is the surface tension force (T_s), which originates as a result of the surface tension between water molecules and air, and can be expressed as:

$$T_s = \sigma \kappa \nabla \alpha_w \quad (6)$$

where σ is the surface tension coefficient, specified as 0.074 kg/s² in the current study [42].

For modelling flow turbulence, we have used the eddy viscosity approach, as demonstrated in eq. (4). The eddy viscosity is calculated based on the turbulent kinetic energy (k) and the specific dissipation rate (ω). Thus, we employ a 2-equation turbulence model known as Shear Stress Transport (SST) k - ω model in which the transport equations for k and ω are solved in order to calculate the eddy viscosity. These transport equations can be expressed as [43]:

$$\frac{\partial}{\partial t}(\rho_m k) + \nabla \cdot (\rho_m ku) = \nabla \cdot (\Gamma_k \nabla k) + P_k - D_k \quad (7)$$

and:

$$\frac{\partial}{\partial t}(\rho_m \omega) + \nabla \cdot (\rho_m \omega u) = \nabla \cdot (\gamma_\omega \nabla \omega) + P_\omega - D_\omega + S_\omega \quad (8)$$

The SST k - ω turbulence model uses a cross-diffusion term (S_ω) to transition from the standard k - ω model in the near-wall regions to a k - ε model away from the walls, where ε is the dissipation rate. This approach helps in predicting separated flows and adverse pressure gradients with higher accuracy, both of which are expected in oscillating jet nozzle; separation at the nozzle throat and negative pressure gradient inside the mixing chamber, which are presented in the results section.

For modelling water-air multiphase flow, the Volume of Fluid (VOF) approach has been used in this study. The VOF model helps track the interface between water and air, which is essential for studying oscillating jet nozzles as the interface between the water jet and the surrounding air needs to be resolved accurately. Thus, a phase mass conservation equation is solved, which can be represented as [44]:

$$\frac{\partial \alpha_w}{\partial t} + \nabla \cdot (\alpha_w u) = 0 \quad (9)$$

While eq. (9) solves for the mass conservation of water phase, the volume fraction of air (α_a) can be calculated as:

$$\alpha_a = 1 - \alpha_w \quad (10)$$

2.3 Boundary Conditions and Solver Settings

Initially, the whole flow domain is filled with air. Then, water is injected through the inlet boundary, shown in figure 1(a), at a flowrate of 29 lpm, representing the real-world pumping operation. The density and dynamic viscosity of water considered is 1000 kg/m³ and 0.001 Pa.s respectively. The nozzle walls and the cleaning surface are modelled as stationary walls with no-slip condition, as expected in real-life. The rest of the surfaces of the rectangular domain are modelled as pressure outlet. As this study aims to quantify the dynamics of complex flow structures in the oscillating jet nozzle, the solution is advanced in time based on the Courant number (CFL), which can be expressed as [45-46]:

$$CFL = |u| \frac{\Delta t}{\Delta x} \quad (11)$$

where $|u|$ is the flow velocity magnitude and Δx is the characteristic length of a mesh element. Courant number defines how fast the fluid flows through one mesh element. CFL = 1 has been used in this study to ensure that flow crosses not more than one mesh element in a single time step, which helps in effectively capturing both the oscillating jet's behaviour and its time-dependent impact force on the cleaning surface.

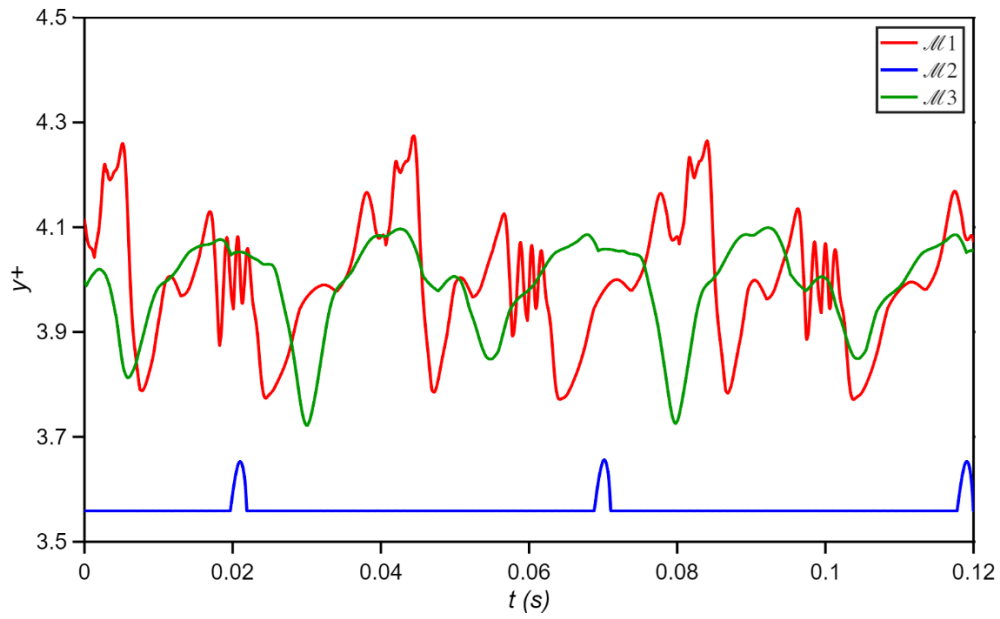
2.4 Spatial Discretisation and Mesh Independence Study

An integral part of CFD based studies is the spatial discretisation of the flow domain i.e. creating the control volumes so that the flow governing equations are applied over them and the fluid transport can be solved across its faces. In turbulent flows, the control volumes (or mesh elements) should be small enough to accurately capture the turbulent eddies [47]. Moreover, in the near-wall region, the mesh elements should be small enough that the boundary layer is effectively captured [48]. This is especially important in case of wall-bounded flows like oscillating jet nozzles. In addition to these requirements, the numerically predicted results should be independent of mesh element size [49]. Considering all these requirements, a thorough mesh independence testing has been carried out in this study.

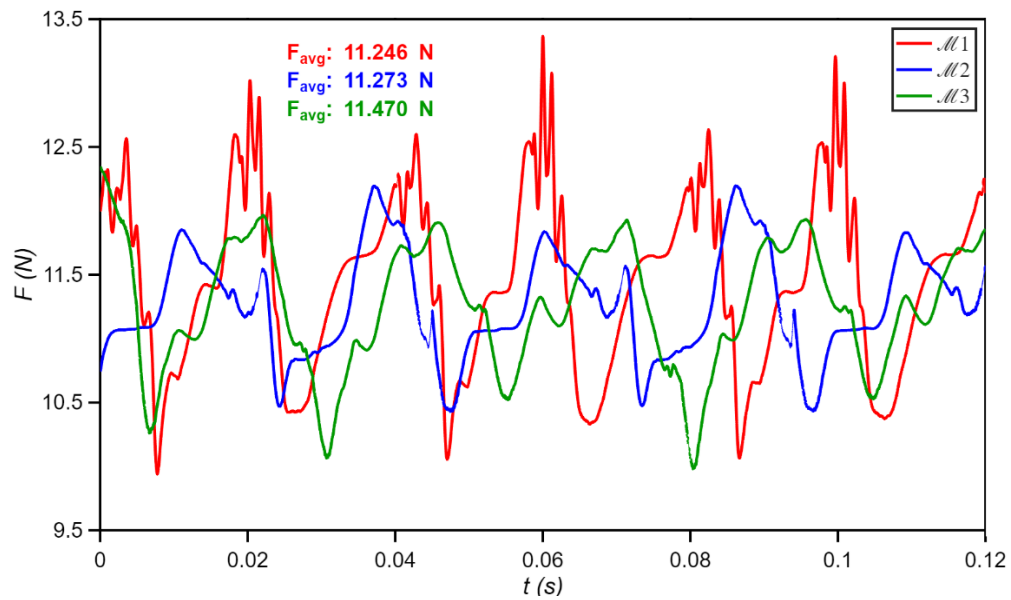
Firstly, considering the flow conditions (29 lpm) and the turbulence modelling (SST $k-\omega$), mesh elements in the near-wall regions are generated to ensure that the first cell lies within the viscous sub-layer i.e. $y^+ < 5$. Then, three different element sizes are selected and the corresponding mesh elements created in the flow domain, which are summarised in table 2. These sizes use 0.5 mm, 0.6 mm and 0.7 mm element size, referred to as fine (**$\mathcal{M}1$**), medium (**$\mathcal{M}2$**) and coarse (**$\mathcal{M}3$**) here. The flow governing equations are solved for these three meshing schemes with the impact force (F) on the cleaning surface as the target parameter. Figure 2 presents the results obtained. It can be seen in figure 2(a) that the y^+ remains below 5 in all three meshing schemes tested. Figure 2(b) shows the temporal variations in the impact force on the cleaning surface. The solution can be clearly seen to have reached statistically steady state and thus, time-averaged impact force has been calculated for the three meshing schemes. It can be seen that the difference in the average impact force between **$\mathcal{M}3$** and **$\mathcal{M}2$** is (i.e. between coarse and medium mesh) is 1.72%, while between **$\mathcal{M}2$** and **$\mathcal{M}1$** (between medium and fine mesh) is 0.24%. Thus, the meshing scheme **$\mathcal{M}2$** has been selected as it provides the optimum balance between the numerical accuracy and the computational cost.

Table 2. Meshing schemes tested.

Mesh level	Element size (mm)	Number of elements ($\times 10^5$)
$\mathcal{M}1$ (Fine)	0.5	7.7
$\mathcal{M}2$ (Medium)	0.6	4.7
$\mathcal{M}3$ (Coarse)	0.7	3.1



(a)



(b)

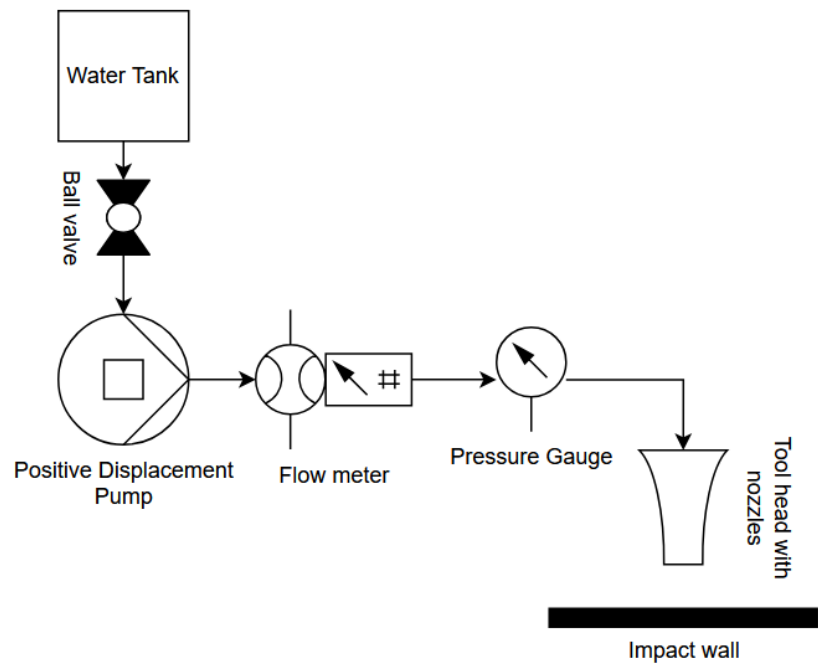
Figure 2. Time-dependent variations in the (a) y^+ values on the walls of the oscillating jet nozzle (b) impact force on the cleaning surface.

3.0 Experimental Setup

In order to validate the results obtained from the numerical solver, an experimental facility has been developed to quantify the hydrodynamic performance of the oscillating jet nozzle under controlled conditions. Figure 3 shows the different aspects of this facility i.e. the piping and instrumentation diagram (P&ID), different components of the facility, schematic of the test setup and its components. It can be seen that a large tank acts as

the water supply and is fitted with a ball valve. A 1-inch hose pipe connects the water tank to a LOWARA positive displacement pump model 15SVH 17F150T/D which can deliver upto $24 \text{ m}^3/\text{hr}$ of flow at a maximum operating pressure of 45 bar. The pump is controlled by an IP55 protected 15 kW motor which has a power supply of 50 Hz and rotor speed of upto 2950 rpm. At pump's outlet, a FLOWQUIP 200 Series turbine flow meter is installed which can measure flowrates from 25-250 lpm. A heavy-duty hose pipe that can sustain upto 6090 psi working pressure delivery the flow to the test section.

The test section has been specifically designed to carry out controlled experiments under a range of different operating conditions. There are several components of the test section. The key component is a 2-tier stand made of stainless-steel plates and a guiding pipe. The purpose of the guiding pipe is to keep the hose pipe in place and doesn't allow any movement or excessive vibrations. The hose pipe itself is connected to the tool head, which contains the nozzle. A platform-type load cell Model 1260 from SENSOR TECHNIQUES LTD is attached on the base of the stand's upper tier. The aluminium built load cell has a capacity and accuracy of 500 kg and 0.02% respectively. The load cell is pre-calibrated and is connected to an amplifier from the same supplier (model DAD 141.1) which has a sampling rate of 600 Hz. The amplifier is connected to a PC with the DOP 4 software to record the impact force readings. The clearance gap between the nozzle's exit and the load cell is kept constant at 20 mm (~ 1 inch). The whole stand resides inside 1 m^3 intermediate bulk container (IBC) whose top has been cut as shown in the figure. The IBC is used to contain the water coming out of the tool/nozzle and is safely drained into a sump. A protective clear PVC sheet is placed on top of the IBC to block the water spray coming out of the IBC. A 5-inch clear acrylic pipe can also be seen in the setup, but it was not used in this study, rather for a future study to mimic submerged cleaning conditions. Hence, a cut-out hole on the side of the acrylic pipe can be seen in the figure to allow water to drain into the IBC. The stand was painted in a corrosion resistant paint. During the experiments, a 50 kg weight was placed on the base of stand to stop any unwanted vibrations which might affect the load cell readings, as per the recommendation of the load cell supplier.



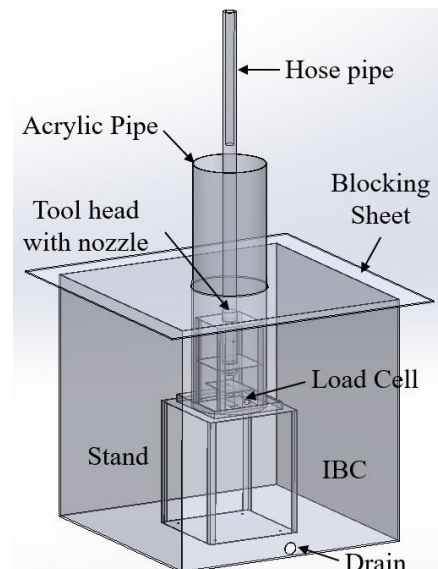
P&ID



Water tank



Pump, flow meter and hose pipe



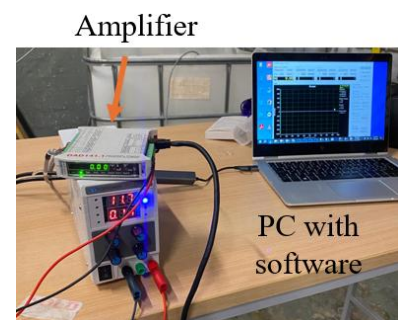
Schematic illustration of the test setup



Test setup



Stand



Amplifier and PC

Figure 3. Details of the test setup and its components.

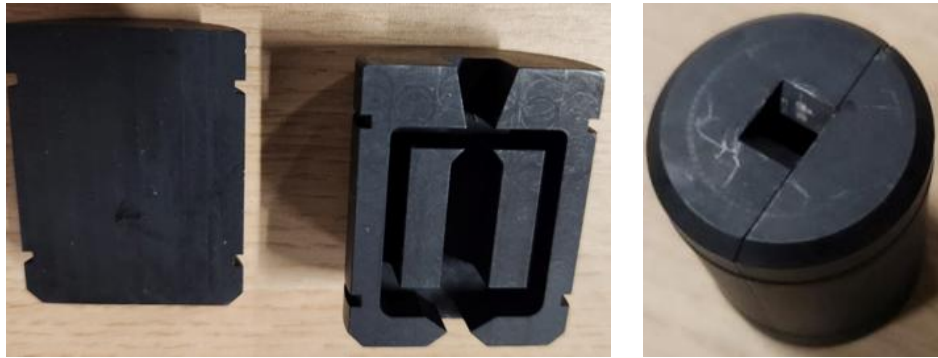
3.1 Experimental Procedure

The hydraulic circuit has been fully primed and stabilised before data is acquired. Motor current was adjusted to attain a flowrate of 29 lpm passing through the flow meter. Every effort was made to ensure that the flowrate remained constant throughout the testing procedure. The software displayed instantaneous load cell readings. Data was recorded for 30 s and then time averaged as per:

$$\bar{F} = \left(\frac{1}{T}\right) \int_0^T F(t) dt \quad (12)$$

to get the average impact force ($\bar{F}$) value, which is then used for validation purposes in section 4.2.

Two nozzles were tested i.e. the oscillating jet nozzle, shown in figure 4(a), and an equi-sized straight jet nozzle. The comparative analysis between the two allows for evaluating/ascertaining the superiority of oscillating jet nozzle's cleaning performance over the straight jet nozzle. Thus, both the nozzles were individually inserted into the same tool head, shown in figure 4(b).



(a)



(b)

Figure 4. (a) Oscillating jet nozzle (b) Tool head.

4.0 Results and Discussions

The numerically predicted results obtained in this study have been presented and discussed in this section. For the purpose of meaningful analysis, one complete oscillation of the jet in the cleaning region has been divided into eight segments, where the first four segments are shown in figure 5. Starting with the far-right position of the jet in the cleaning region, the jet moves left towards its far-right position and then returns to its initial position. The time it takes to complete one complete oscillation is equal to non-dimensional time of 2λ . The initial position of the jet is thus 0λ . When the jet reaches the middle position, the non-dimensional time is $\frac{1}{2}\lambda$, and when it reaches the far-left position, time is 1λ . Similarly, on the return journey, when the jet reaches the middle position, the time is $\frac{3}{2}\lambda$, and finally when it reaches its initial position, time is 2λ . The analysis presented in the following sub-sections will refer to this non-dimensional time.

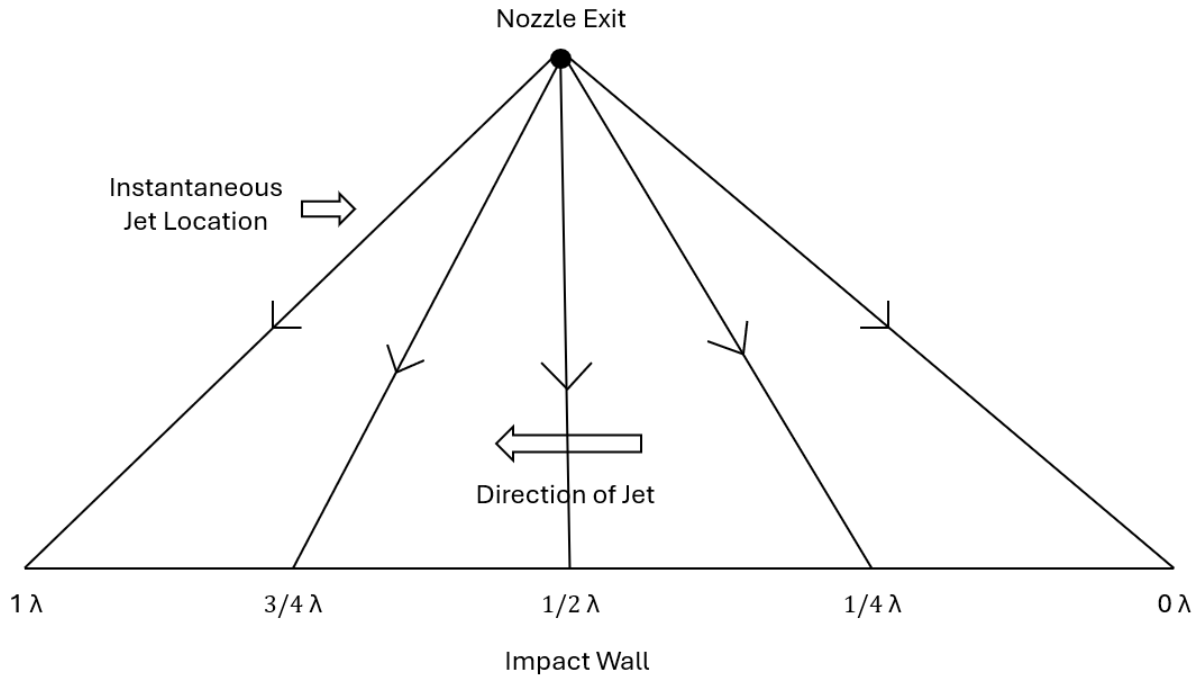
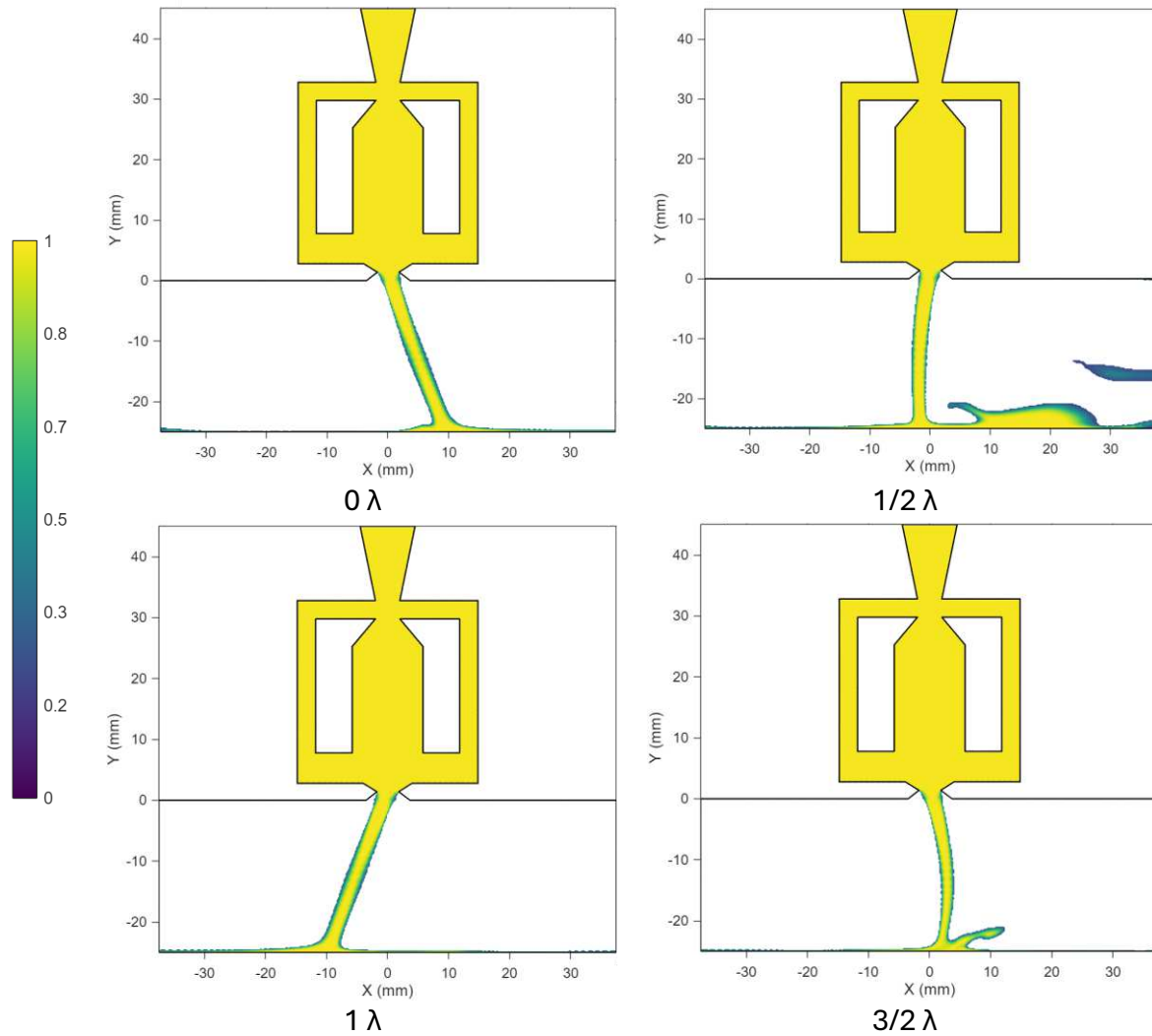


Figure 5. Schematic of the jet location on the impact wall at different time stamps during half oscillation.

The following sub-sections are arranged such that we start with the global flow analysis of the oscillating jet nozzle (section 4.1), leading to the validation of the numerically predicted results (section 4.2). This is followed by the dynamics of the coherent vortical structures in the mixing chamber of the nozzle that drive the jet's shape-shifting phenomenon and its impact force fluctuations (section 4.3).

4.1 Global Flow Characterisation of the Oscillating Jet Nozzle

Global flow characteristics associated with an oscillating jet nozzle are presented and analysed here on a plane passing through the centre of the flow domain i.e. at $Z=0$. Figure 6 depicts variations in the volume fraction of water at this plane, at time stamps 0λ (far-right), $\frac{1}{2}\lambda$ (centre), 1λ (far-left), $\frac{3}{2}\lambda$ (centre while on return journey) and 2λ (far-right). The oscillatory nature of the jet is evident from the figure. The nozzle is completely filled with water. The area in the cleaning region that is dominated by air has been masked to clearly visualise the water jet. It can be seen that at the throat of the nozzle, the jet gets separated from the nozzle wall, leaving space for air to fill-in. An important observation made is that the jet is straight only at the extreme positions (far-left and far-right). As the jet starts to move from one extreme position towards the other extreme position, it gets slightly curved in the direction of motion. This will be later seen in this section to have implications for the instantaneous force exerted by the jet on the impact wall.



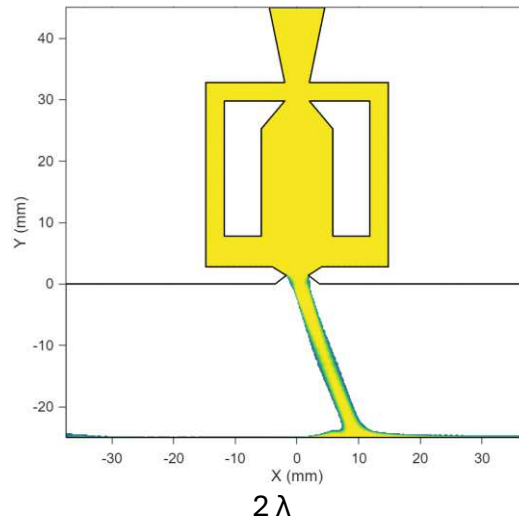


Figure 6. Variations in the volume fraction of water in the flow domain at $Z=0$ plane.

Figure 6 provides useful information on the sweeping action of the oscillating jet and its instantaneous position in the cleaning region however; it is not clear what is happening inside the nozzle as it is fully occupied by water. In order to visualise and understand the flow dynamics inside the oscillating jet nozzle, figure 7 shows the variations in the $-Y$ flow velocity. Negative (or reversed) Y velocity has been considered to show the velocity values as positive (based on the coordinate system shown in figure 1(a)). Just like in case of figure 6, the area in the cleaning region where the velocity is very low (air occupied region) has been masked to clearly visualise the water jet. Overall, the high velocity jet can be seen within the mixing chamber of the oscillating jet nozzle however, depending on the location of the jet in the cleaning region, the structure of the jet in the mixing chamber changes. A time 0λ , when the jet is at its far-right position, the jet in the mixing chamber can be seen to form a reversed S shape (2). At time $\frac{1}{2}\lambda$ when the jet reaches its central position, the jet inside the mixing chamber changes its shape from reversed S to a reversed C ($\complement$). At time 1λ when the jet reaches its far-left position, its shape in the mixing chamber changes to a normal S. Then at $\frac{3}{2}\lambda$, its shape is normal C, and eventually, its shape changes back to reversed S (2) as the oscillation completes. Thus, whatever the shape of the jet in the mixing chamber is during half the oscillation, it reverses during the other half. The reason for these variations in the shape of the jet inside the mixing chamber of the oscillating jet nozzle will be discussed in detail in section 4.3.

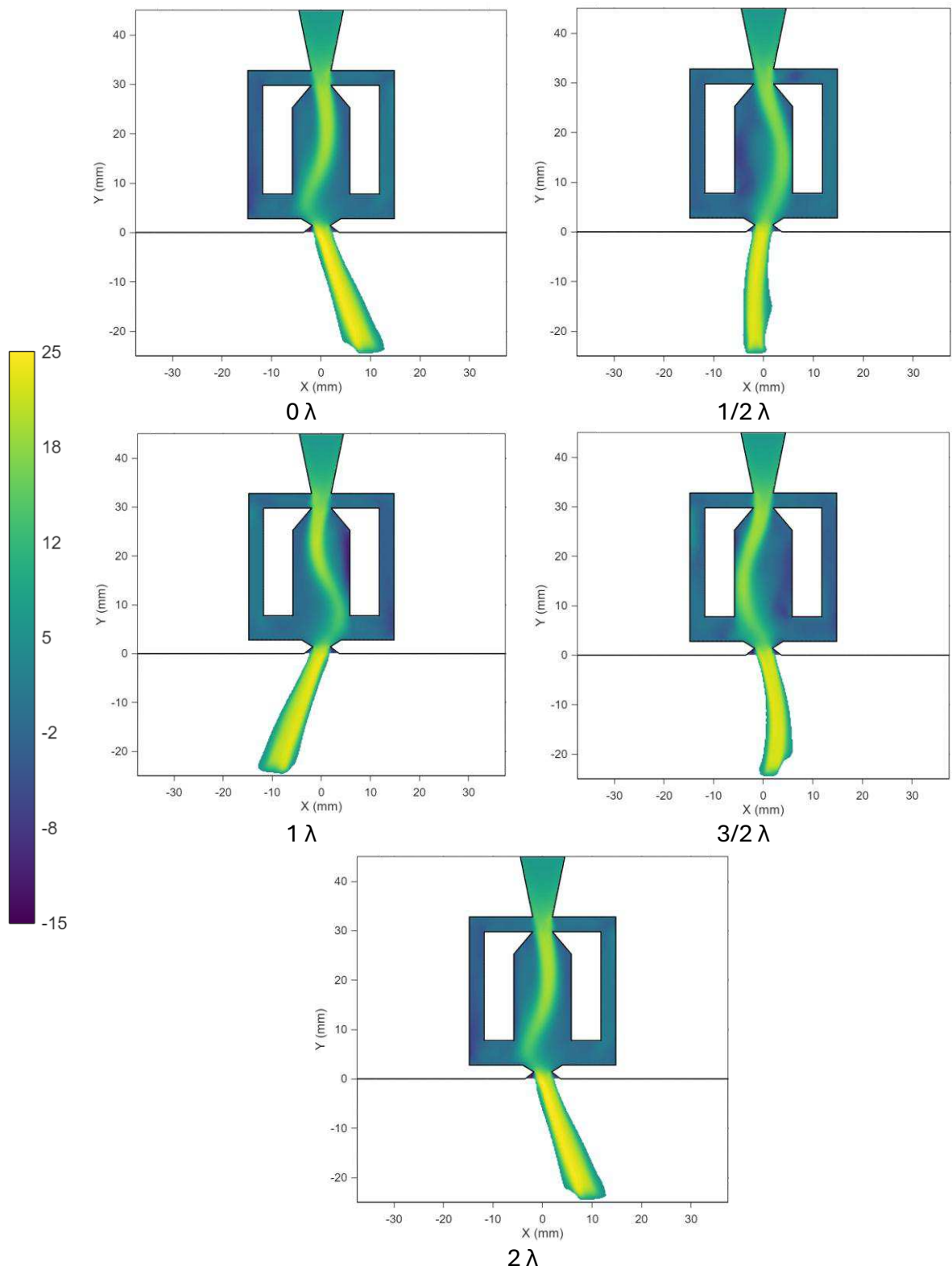


Figure 7. Variations in the reversed Y velocity in the flow domain at Z=0 plane.

Although the jet velocity in the cleaning region seems to be roughly the same, it is still important to quantify this as it dictates the jet momentum and thus, the force exerted by the jet on the impact wall, which is directly related to the cleaning performance of the oscillating jet nozzle [50]. For this purpose, reversed Y velocity profiles have been drawn

on a line 5 mm above the impact wall (to avoid the effects of jet splash) and going from -15 mm to +15 mm in X direction. The velocity profiles are shown in figure 8, where the reversed Y velocity ($-v$) has been normalised against the flow velocity magnitude at the inlet of the oscillating jet nozzle ($|U_{in}|$ at $Y = 32$ mm). Thus:

$$U^* = -\frac{v}{|U_{in}|} \quad (13)$$

It can be clearly seen that the velocity of the jet as it approaches the impact wall is at least 50% higher than the flow velocity at the inlet of the nozzle, suggesting that the impact force of the oscillating jet on the cleaning surface is expected to be higher than the impact force of the jet emerging from an equivalent sized straight jet nozzle. This will be discussed in more detail in the validation sub-section (section 4.2). It can be further observed in figure 8 that the jet velocity is slightly higher when it is at its extreme locations (far-right or far-left), while it decreases (slightly) when the jet is in the middle. This can be attributed to the curvature of the jet when it leaves its extreme positions, as shown in Figure 2 at time stamps $\frac{1}{2}\lambda$ and $\frac{3}{2}\lambda$, and can be explained as loss of momentum due to change in its direction. One last observation for the black curve in the plot representing $\frac{1}{2}\lambda$ is increase in jet velocity from $X = 2$ mm to 15 mm, which is due to the jet splash, which can be seen in figure 6.

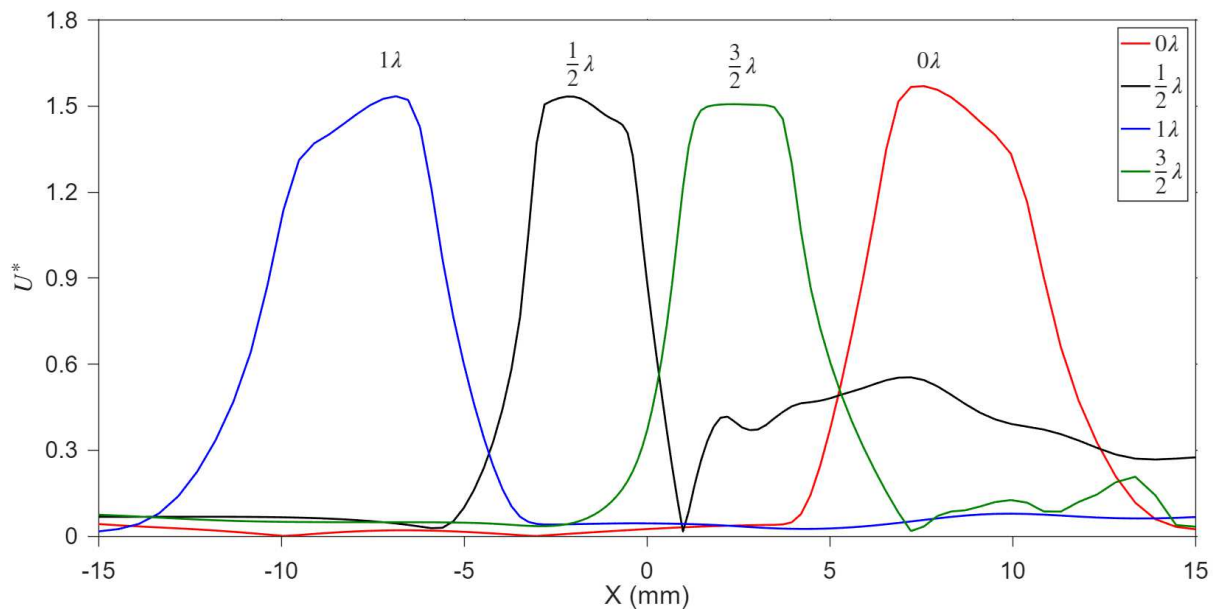
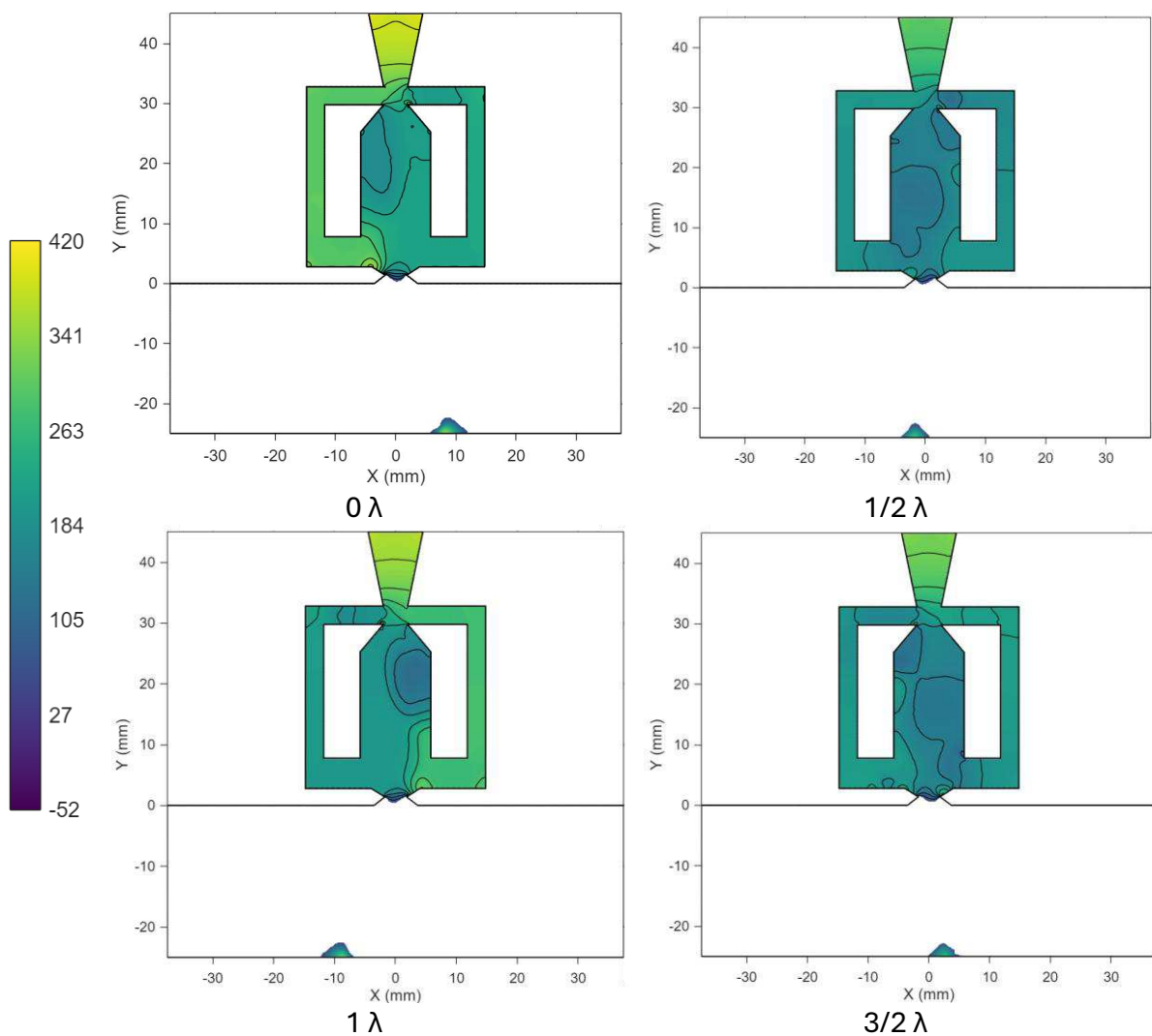


Figure 8. U^* profiles of the jet just above the impact wall at different jet locations during one complete oscillation.

Before moving on to the quest to find the reason behind the shape shifting jet profile in the mixing chamber of the oscillating jet nozzle, the global flow characterisation is completed here through the spatio-temporal analysis of the static gauge pressure in the flow domain at $Z=0$ plane, as shown in figure 9. As earlier, the area representing air has been masked, and most of the jet in the cleaning region has also been masked (threshold set at -52 kPa). This has been purposefully done in order to clearly visualise different

levels of pressure contours inside the mixing chamber. The part of the jet in the cleaning region that has static pressure higher than -52 kPa can also be seen immediately next to the impact wall; this will be discussed after figure 9. Focusing on the pressure variations in the mixing chamber, it can be seen that at 0λ , the lowest pressure region in the mixing chamber is located at top left of the chamber. Then at time $\frac{1}{2}\lambda$, this low-pressure region can be seen to increase in size and moves down in the mixing chamber. At these times in figure 7, we saw reversed S and reversed C jet profiles. During the next two time stamps (1λ and $\frac{3}{2}\lambda$), the same phenomenon occurs on the opposite side of the mixing chamber, and we saw normal S and C profiles respectively in figure 7. Interestingly, both the velocity and pressure are low in these regions at the same time. Thus, these regions warrant further investigations, which are presented in section 4.3.



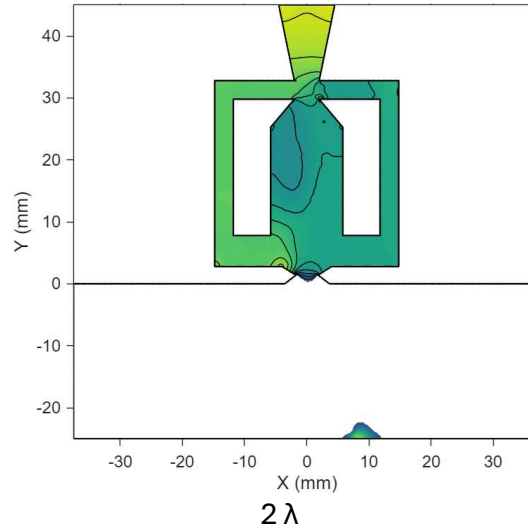
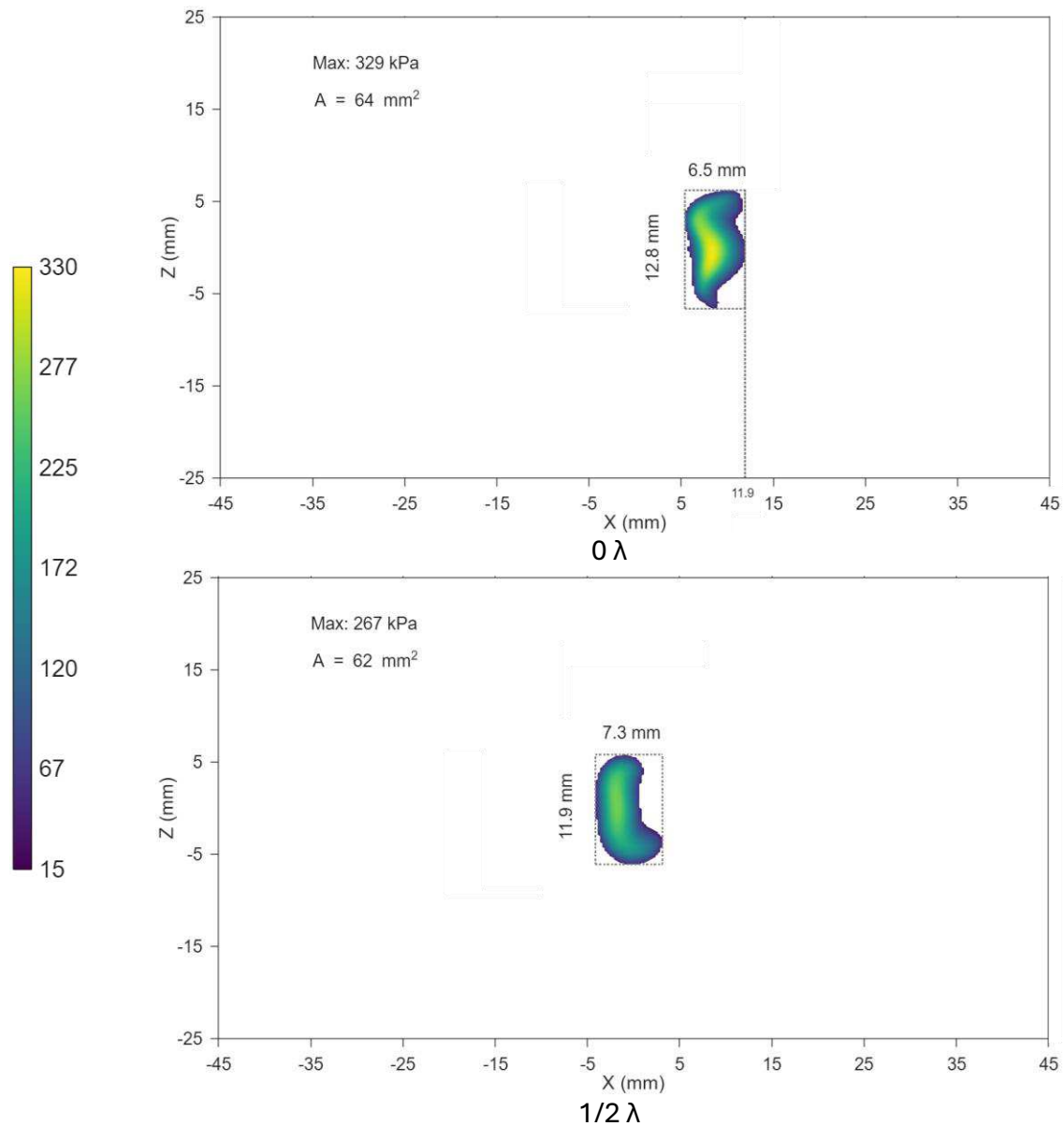


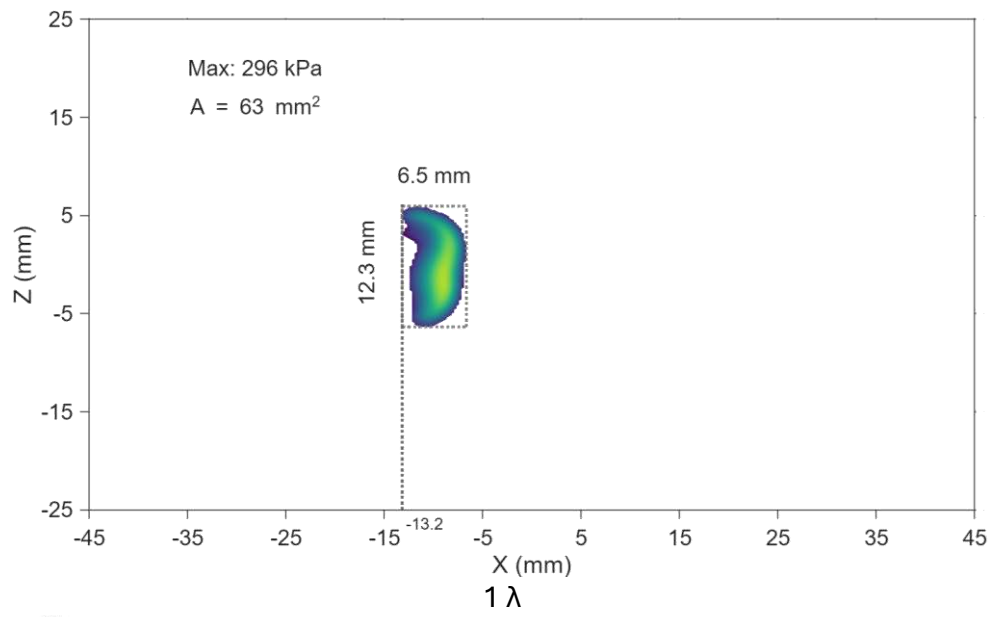
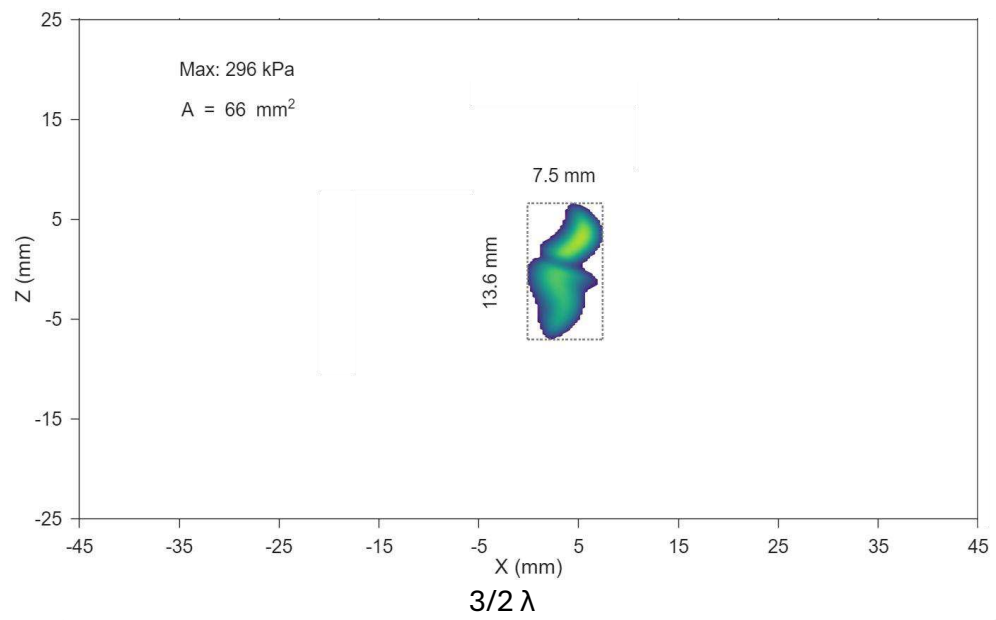
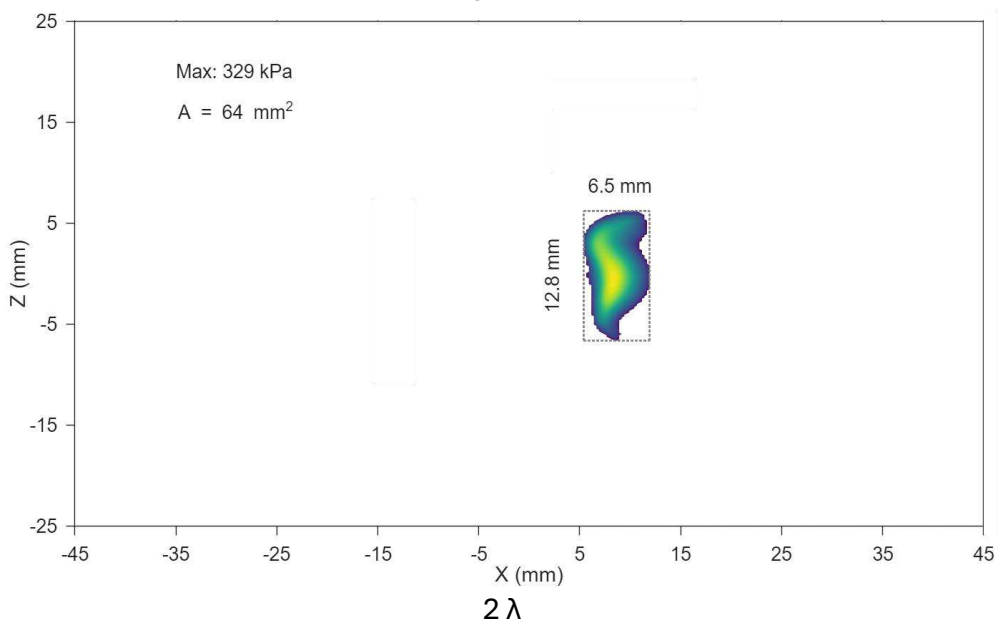
Figure 9. Variations in the reversed Y velocity in the flow domain at $Z=0$ plane.

Now we analyse the static pressure variations of the jet on the impact wall in figure 10 for one complete oscillation, while capping the lower limit at 15 kPa to clearly visualise the impacted area on the wall. This is important as the pressure exerted by the jet on the impact wall leads to the calculation of the impact force ($F=PA$) which is one of the two most important performance metrics of hydro-blasting nozzles used for well intervention [51]. The other parameter is the cleaning surface area. At the start of the oscillation (0λ), the maximum pressure exerted by the jet on the impact wall is 320 kPa. In terms of the size of the impact area, it can be seen that the jet is contained in a 6.5 mm x 12.8 mm region. It is worth re-mentioning that the thickness of the oscillating jet nozzle (T) is 2.286 times its throat width (w_t), as summarised in table 1, and thus we see the thickness of the impact area about twice its width. The impact area has been calculated to be 64 mm². In comparison, the impact area of a straight jet nozzle has been calculated to be 58 mm², which is also shown in this figure at the end. Note that we carried out numerical investigations on an equivalent sized straight jet nozzle as well (i.e. bore cross-sectional area the same as the throat cross-sectional area of the oscillating jet nozzle). For effective comparison, we ensured that the flowrate of water passing through the straight jet nozzle is the same as for the oscillating jet nozzle. The dimensions of the cleaning region and all other relevant solver settings are also the same. Another observation from this figure is that the far-right end of the impact area is at $X = 11.9$ mm. This will help calculate the sweep length of the oscillating jet i.e. far-right to far-left position of the jet on the impact wall.

At time $\frac{1}{2} \lambda$, the impact area is in the centre of the impact wall. As the jet is moving towards left in the figure, we see it bulging towards its direction of motion. The impact area remains roughly the same i.e. 62 mm², while the maximum static pressure has decreased to 267 kPa, suggesting a decrease in the impact force (due to jet curvature seen in Figure 2). At time 1λ when the jet reaches its far-left position and completes its half oscillation, the impact area is almost the mirror image of impact area at 0λ . The far-

left end of the impact area is at $X = -13.2$ mm. Thus, the sweep length of the oscillating jet is 25.1 mm. At $3/2 \lambda$, the shape of the impact area seems a bit distorted, which can be associated to jet splash at this very location, as seen in Figure 3. Overall, for the oscillating jet nozzle, the impact area ranges between 62-64 mm² and maximum pressure ranges between 267-329 kPa, so there are more variations in the pressure exerted by the jet on the impact wall ($\sim 23\%$) than its impact area. For the straight jet nozzle, the circular impact area is 58 mm², while the maximum pressure is 154 kPa which is significantly lower than the oscillating jet nozzle.





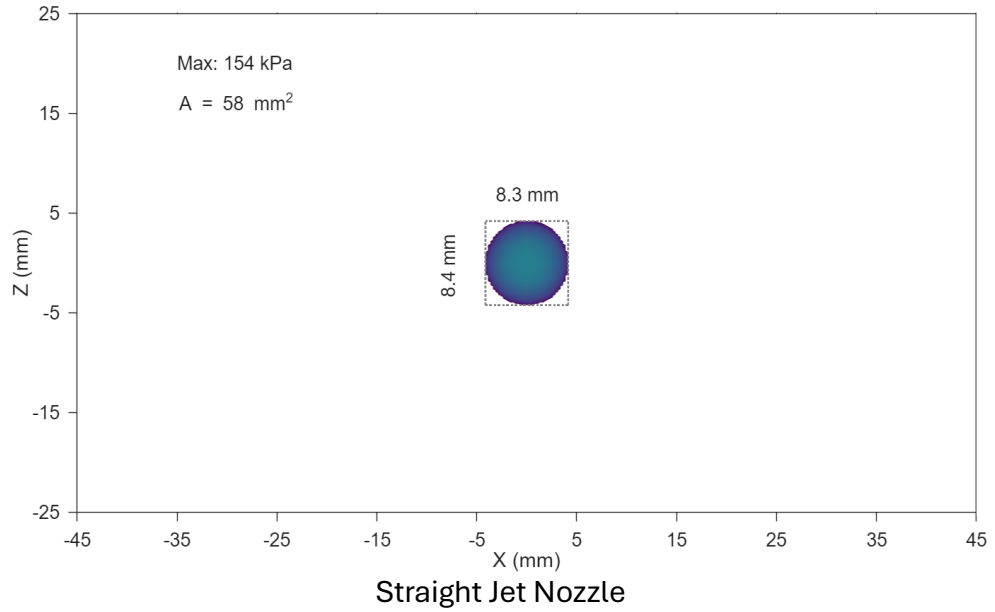


Figure 10. Variations in the impact area's shape, size and static pressure at different positions of the oscillating jet, and comparison with the straight jet.

The pressure variations translate into the impact force. For oscillating jets, these variations are periodic in nature, repeating every oscillation. The impact force variations during one complete oscillation are shown in figure 11. The impact force of the straight jet nozzle is also shown for comparison. It can be seen that the force exerted by the oscillating jet on the impact wall (F) is high when the jet is at its far-right (0λ and 2λ) and far-left (1λ) positions in the cleaning region. These are the time stamps when the jet is straight (figures 6 and 7), and it exerts high pressure on the impact wall (figure 10). When the jet is in the central position (at $\frac{1}{2}\lambda$ and $\frac{3}{2}\lambda$), it is curved (figures 6 and 7), its pressure on the impact wall is comparatively lower (figure 10) and thus, the impact force is lowest. The oscillation average impact force of the oscillating jet (F_{avg}) has been calculated to be 11.26 N, while for the straight jet, the impact force is 8.2 N. Moreover, while the straight jet cleans $8.33\text{ mm} \times 8.4\text{ mm} = 70\text{ mm}^2$ area, the oscillating jet cleans at-least $12\text{ mm} \times 25.1\text{ mm} = 300\text{ mm}^2$ area, which is 4.28 times the cleaning area of the straight jet. Thus, the oscillating jet nozzle not only cleans more area due to its sweeping action, but it also demonstrates superior cleaning performance due to 37.3% higher impact force, in comparison with a straight jet nozzle of equivalent size and at the same flowrate.

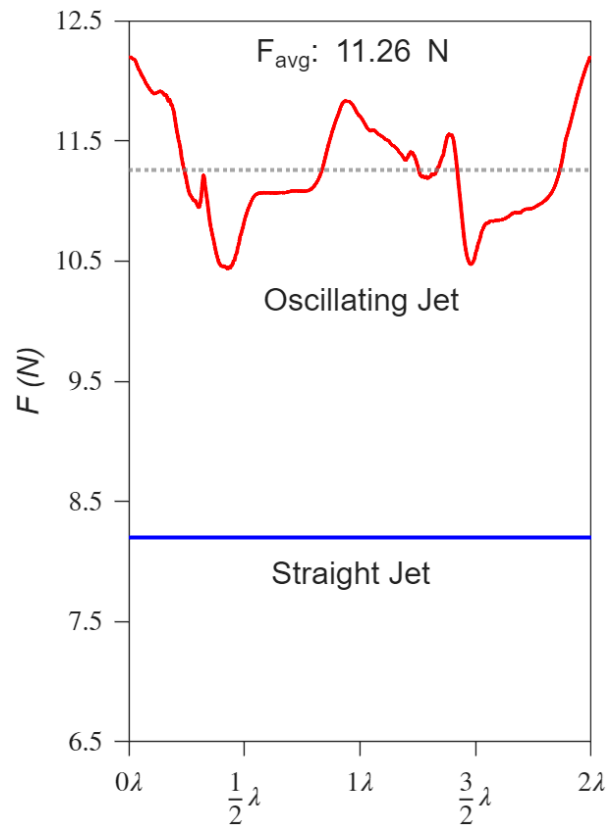


Figure 11. Impact force comparison between the oscillating and straight jet.

Concluding this section, table 3 summarises the key characteristics of the oscillating and straight jet nozzles. Apart from the impact force, sweep length and area which have already been discussed in detail, time taken for the oscillating jet to go from 0λ to 1λ positions (which is equal to one sweep) has been calculated to be 0.0246 s, which results in an oscillating frequency of 20 Hz. Thus, the oscillating jet cleans (sweeps) 300 mm^2 area on the cleaning surface 40 times in a second.

Table 3. Key characteristics of oscillating and straight jets.

Jet characteristics	Oscillating jet	Straight jet
Impact force (F)	Max: 12.2 N Min: 10.4 N	8.2 N
Sweep length	25.1 mm	8.3 mm
Sweep area	300 mm^2	70 mm^2
Time for one sweep	0.0246 s	-
Oscillating frequency	$\sim 20\text{ Hz}$	-

4.2 Validation of the Numerical Results

To gain confidence in the accuracy of the numerically predicted results presented in the previous sub-section (and following sub-sections), it is imperative to ensure that they can be reproduced in the real-world [52]. The experimental methodology adopted has already been presented in detail in section 3. Figure 12 shows the comparison between the numerically predicted results and the experimentally obtained data for the impact force and the static pressure measured at the inlet of both the oscillating jet and the straight jet nozzles. It can be seen that experimentally measured impact force of the oscillating jet is 11.5 N, which is 2% higher than numerically predicted impact force. Similarly, the experimentally recorded static pressure at the inlet of the oscillating jet nozzle is 379 kPa, while numerically predicted pressure is 369 kPa, which is 2.6% lower than experimentally measured pressure. For the straight jet nozzle, the difference between experimental and numerically predicted impact force is 2.4%, while for the pressure measurements, it is 6%. These minor differences between experimental and numerical results can be attributed to the flowrate measurements during the experiments. Although every effort was made to keep it constant during the experiments, but some minor variations were unavoidable, while in numerical modelling, as flowrate has been used as a boundary conditions, it remains constant at 29 lpm.

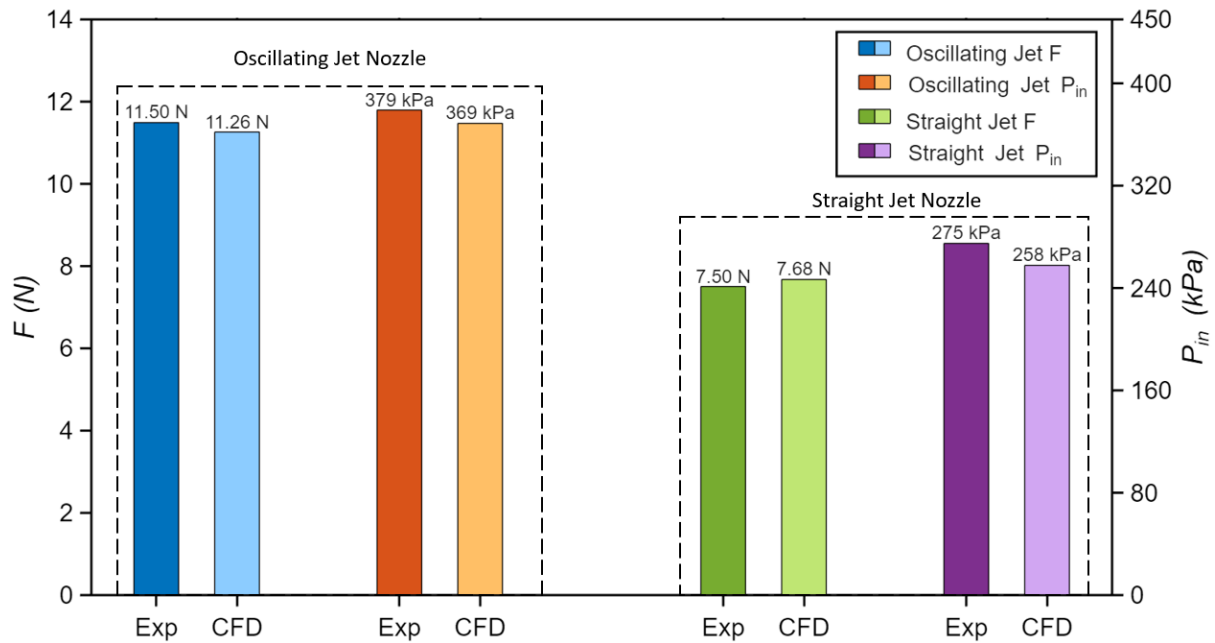


Figure 12. Comparison between experimentally obtained and numerically predicted jet impact force and static pressure at the inlet of the oscillating and straight jet nozzles.

4.3 *Dynamics of the Coherent Vortical Structures in the Mixing Chamber*

The oscillating nature of the jet in the cleaning region is a direct consequence of shape-shifting jet phenomena observed in the mixing chamber of the oscillating jet nozzle (figure 7). Thus, in order to better control the oscillating jet for enhanced cleaning purposes, an in-depth understanding of spatio-temporal variations of complex flow physics in the mixing chamber of the jet is needed. This is the objective of this section, and it has been achieved through detailed vortex dynamics utilising a range of different flow parameters. Firstly, we release massless particles from the right half of the nozzle inlet and track their pathlines on $Z=0$ in order to visually identify the coherent vortical structures. As seen previously that the flow features in the mixing chamber depict an alternating trend i.e. whatever happens in the right half of the mixing chamber during the first sweep (half oscillation), mirrors in the left half of the chamber during the second sweep (figure 7). Thus, the focus of following investigations is only the right half of the nozzle, and that's why the particles are released from only the right half of the nozzle inlet.

It can be seen in figure 13 that at time 0λ when the jet in the cleaning region is at its far-right position, the pathlines originating from the inlet propagate downstream the mixing chamber in a curved path due to the shape of the jet at this instance, and thus the jet depicts a reversed S shape (2). Some of the pathlines can be seen to enter the feedback channel. At time $\frac{1}{2}\lambda$ when the jet is at its central position in the cleaning region, the reversed C shape of the jet ($\complement$) in the mixing chamber is evident, as was previously seen in figure 7. While analysing the static pressure in figure 9, a low-pressure region was observed on the top right corner of the mixing chamber. Now it can be seen that a vortical structure forms at this location. Advancing in time to 1λ when the jet completes one sweep (half oscillation), this vortical structure has increased substantially in size, and can be seen to push the jet outwards in the mixing chamber. This leads to change in the shape of the jet to a normal S. At time $\frac{3}{2}\lambda$, the vortical structure can be seen to have grown in size further. Meanwhile, it has shifted its position and has moved down the mixing chamber. It has pushed the jet further to the left and now no part of the jet is touching the right wall of the mixing chamber. This leads to a further change in the shape of the jet in the mixing chamber to a normal C. Finally, at the end of the oscillation at time 2λ , the vortical structure can be seen to have completely dissipated.

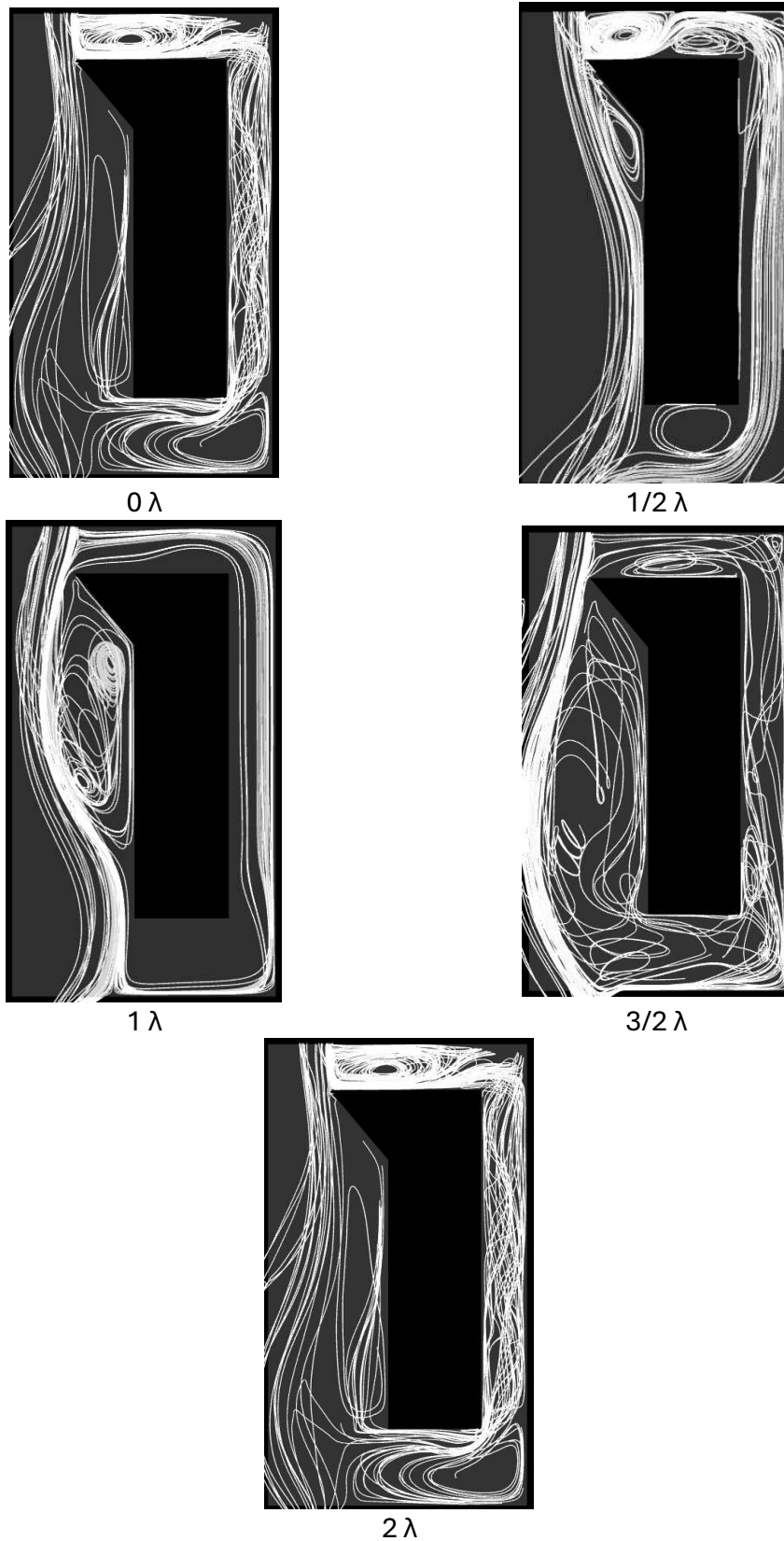


Figure 13. Flow pathlines in the right half of the oscillating jet nozzle during one complete oscillation.

The quest to characterise the oscillating jet has reached a critical point now. It has been established that the reason behind the oscillation of the jet in the cleaning region is the shape-shifting jet in the mixing chamber, and the reason behind shape-shifting characteristics of the jet is the dynamics of the coherent vortical structures that appear alternately on either sides of the mixing chamber during one complete oscillation of the jet. The next logical step is to analyse the dynamic nature of this coherent vortical structure. We start this by analysing the variations in its static pressure, masking everything else for clear visualisation. In figure 9, we saw the formation of a low-pressure region at the top right corner of the mixing chamber (at time $\frac{1}{2}\lambda$), thus we start from this point onwards. In figure 14, at time $\frac{1}{2}\lambda$, the formation of the vortical structure is evident at the top right corner of the mixing chamber. The static pressure is fairly constant in most parts of it at 90 kPa and can be seen to increase to 191 kPa towards its bottom end. At time 1λ , the vortical structure has been stretched downwards substantially, while it has moved slightly away from the vertical wall of the mixing chamber. The upper and lower portions of the vortical structure demonstrate higher pressure compared to its centre where the pressure is 121 kPa. At time $\frac{3}{2}\lambda$, the vortical structure has expanded laterally and has propagated both downwards and away from the vertical wall of the mixing chamber. Now, it is no longer touching any wall. Its static pressure is almost constant throughout and ranges between 136 kPa and 154 kPa. At the end of the oscillation (2λ), the vortical structure has shrunk in size and has moved further downwards in the mixing chamber. Its static pressure is almost constant at 205 kPa. Thus, the minimum static pressure keeps increasing from 90 kPa to 205 kPa, while pressure fluctuations keep decreasing from 100 kPa to almost 0 kPa. Increasing minimum pressure is an indication of weakening centrifugal forces [53], leading to pressure recovery and dissipation of the vortical structure. Decreasing pressure fluctuations indicate weakening of velocity gradients and local acceleration [54]. Thus, the vortical structure can be said to transition from formation at $\frac{1}{2}\lambda$ to growth at 1λ , to diffusion at $\frac{3}{2}\lambda$ and finally dissipation at 2λ , as sketched in figure 15.

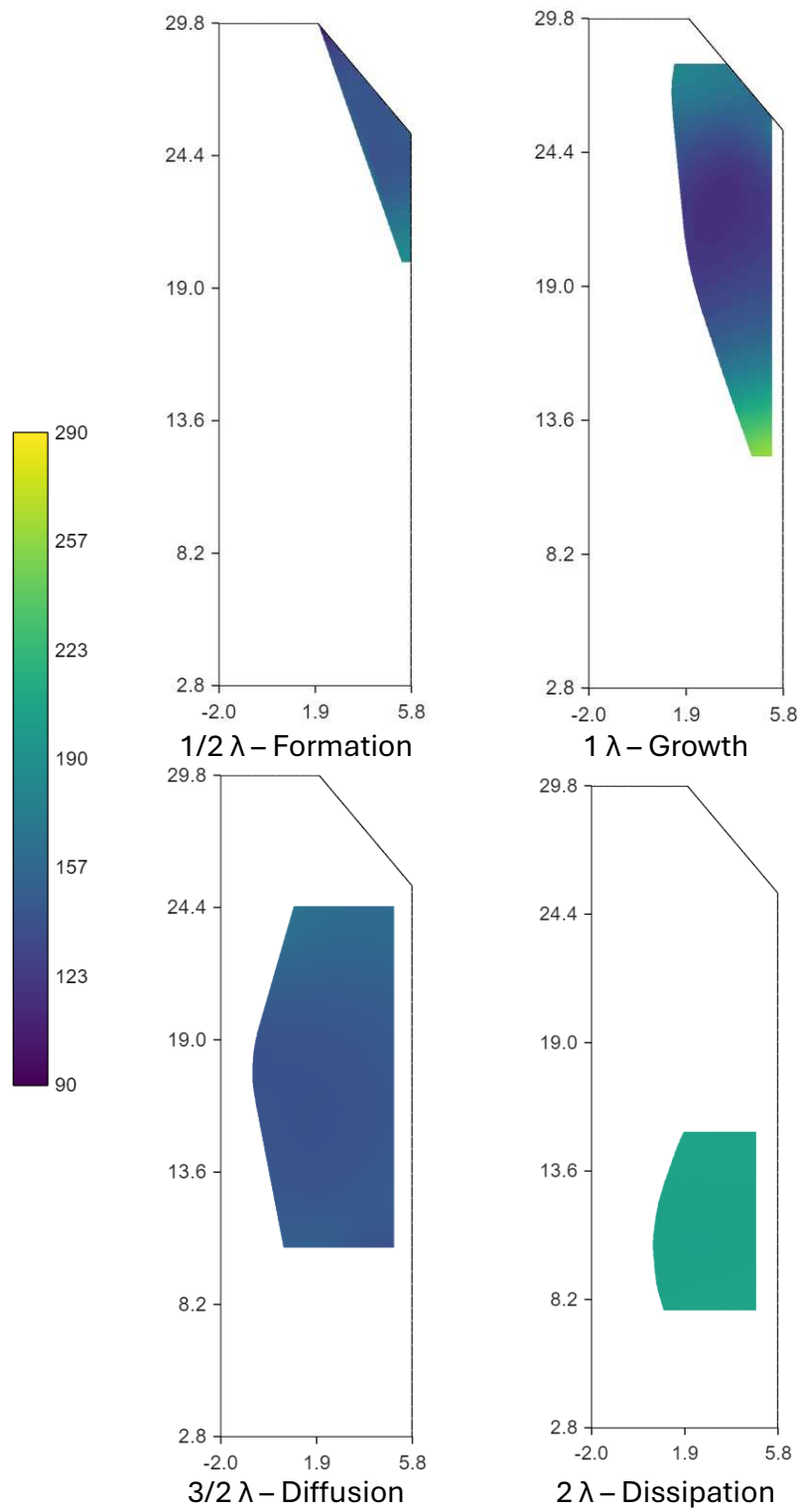


Figure 14. Static pressure variations in the vortical structure, appearing in the right half of the mixing chamber, during its evolutionary journey.

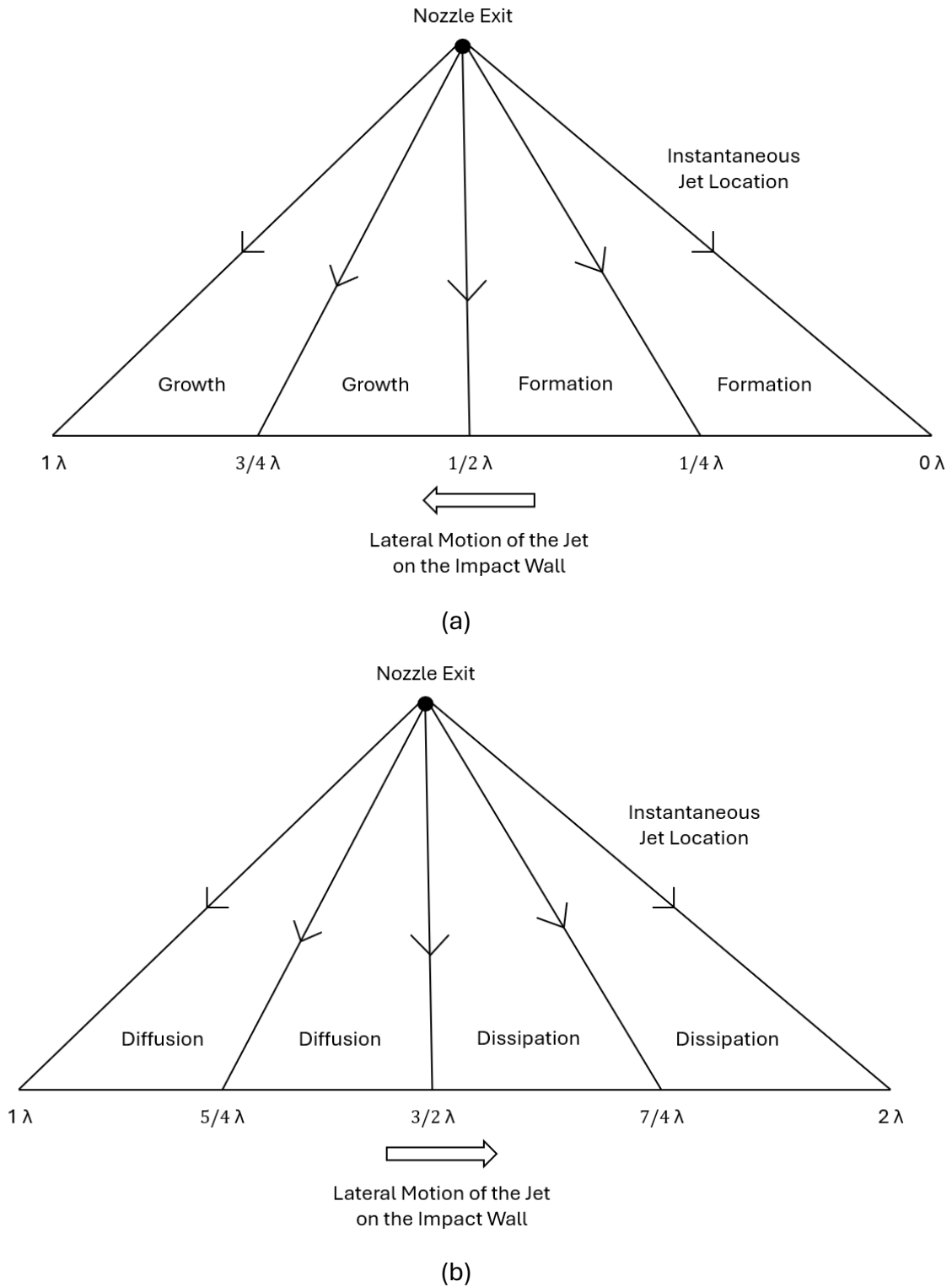


Figure 15. Stages of evolution of the vortical structure in the mixing chamber of the oscillating jet nozzle while the jet is laterally propagating (a) left and (b) right in the cleaning region.

Whether the lifespan of the vortical structure can be categorised according to the four identified stages, need further analyses to confirm this, which have been carried out hereafter. The coordinates of the vortical structure's core have been identified at each

time stamp shown in figure 14, corresponding to the identified stages. The core of the vortical structure is the point where the static pressure is minimum. The core of the vortical structure is located at (4.63 mm, 24.2 mm) at time stamp $\frac{1}{2} \lambda$, while it moves to (3.4 mm, 21.2 mm) at time 1λ , resulting in a displacement magnitude of 3.24 mm from $\frac{1}{2} \lambda$ to 1λ . From figure 14 we know that this displacement in core's position is not due to the motion of the vortical structure, rather due to its stretching/growth. At time stamp $\frac{3}{2} \lambda$, where we saw in figure 14 the vortical structure getting detached from the mixing chamber walls and propagating downwards, its core is located at (2.05 mm, 15.4 mm). The core's displacement magnitude is 5.95 mm, which is 83% higher than core's displacement from $\frac{1}{2} \lambda$ to 1λ . This further confirms weakening velocity gradients and local acceleration of the vortical structure due to advection by the bulk flow in the mixing chamber during the diffusion stage. At time 2λ , the core is at (2.97 mm, 11.1 mm), which is equal to a displacement magnitude of 4.4 mm from the previous location of the core. Significant shrinking of the vortical structure at 2λ (figure 14), and lower displacement of its core compared to during the growth stage, clearly indicate its decay, loss of momentum and strength, and its viscous dissipation into the bulk flow.

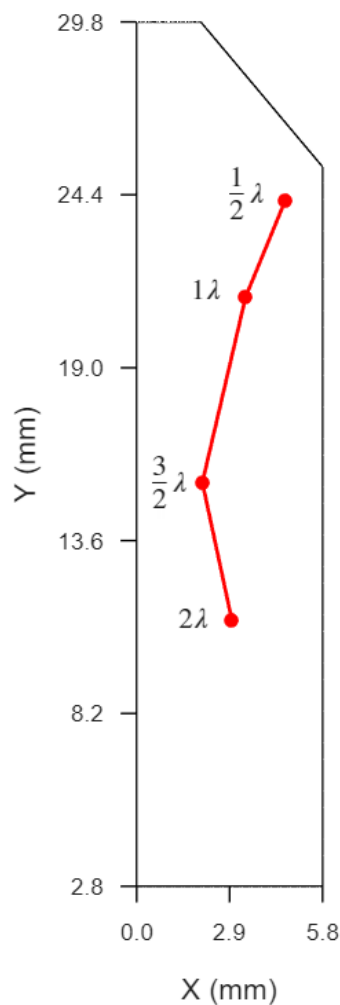


Figure 16. Movement of the vortical structure's core in the mixing chamber from its formation to dissipation.

Reference to velocity gradients have been made several times while explaining the dynamics of the vortical structure, and thus, figure 17 depicts variations in the Y velocity during these stages inside the vortical structure. The core of the vortical structure can be seen to have been positioned at (0,0), while velocity vectors have been superimposed to visually analyse flow direction. Y velocity is always maximum and positive on the right boundary of the vortical structure i.e. closest to the mixing chamber wall. On the other side of the vortical structure i.e. on the left boundary, Y velocity is always minimum and negative. Thus, the direction of flow is upwards on the right boundary, and downwards on the left boundary of the vortical structure, resulting in anti-clockwise rotation. At the formation stage ($1/2 \lambda$), the maximum and minimum Y velocities are (3.95 m/s, -3 m/s) i.e. the upwards flow velocity on the right boundary is 3.95 m/s and downwards flow velocity on the left boundary is 3 m/s. Thus, the Y velocity difference across the width of vortical structure is 6.95 m/s. This velocity difference leads to strong velocity gradients and shear across the vortical structure and results in its growth. At the growth stage, the maximum and minimum velocities are (10.71 m/s, -5.92 m/s), thus, the difference in the Y velocities is 16.63 m/s, which is 140% more than during the formation stage. This is conclusive evidence of vortical structure's growth. It is noteworthy at this point that the maximum X direction flow velocity in the vortical structure at formation stage is 2.22 m/s, while at growth stage is 4.86 m/s. At the diffusion stage ($3/2 \lambda$), the maximum and minimum Y velocities are (5.8 m/s, -3.78 m/s), resulting in Y velocity difference of 9.6 m/s, which is 42% less than at the growth stage. The maximum X velocity has also decreased to 1.73 m/s. Thus, the velocity gradients are weakening and the vortical structure is diffusing its energy into the bulk flow. At dissipation stage (2λ), the maximum and minimum Y velocities are (1.64 m/s, -1.85 m/s). It is clear that the velocity difference across the vortical structure has considerably decreased, and it's the first time that -Y velocity is more than +Y velocity. With almost constant pressure throughout the vortical structure (figure 14), and diminishing velocity gradients, the vortical structure is fast dissipating into the bulk flow.

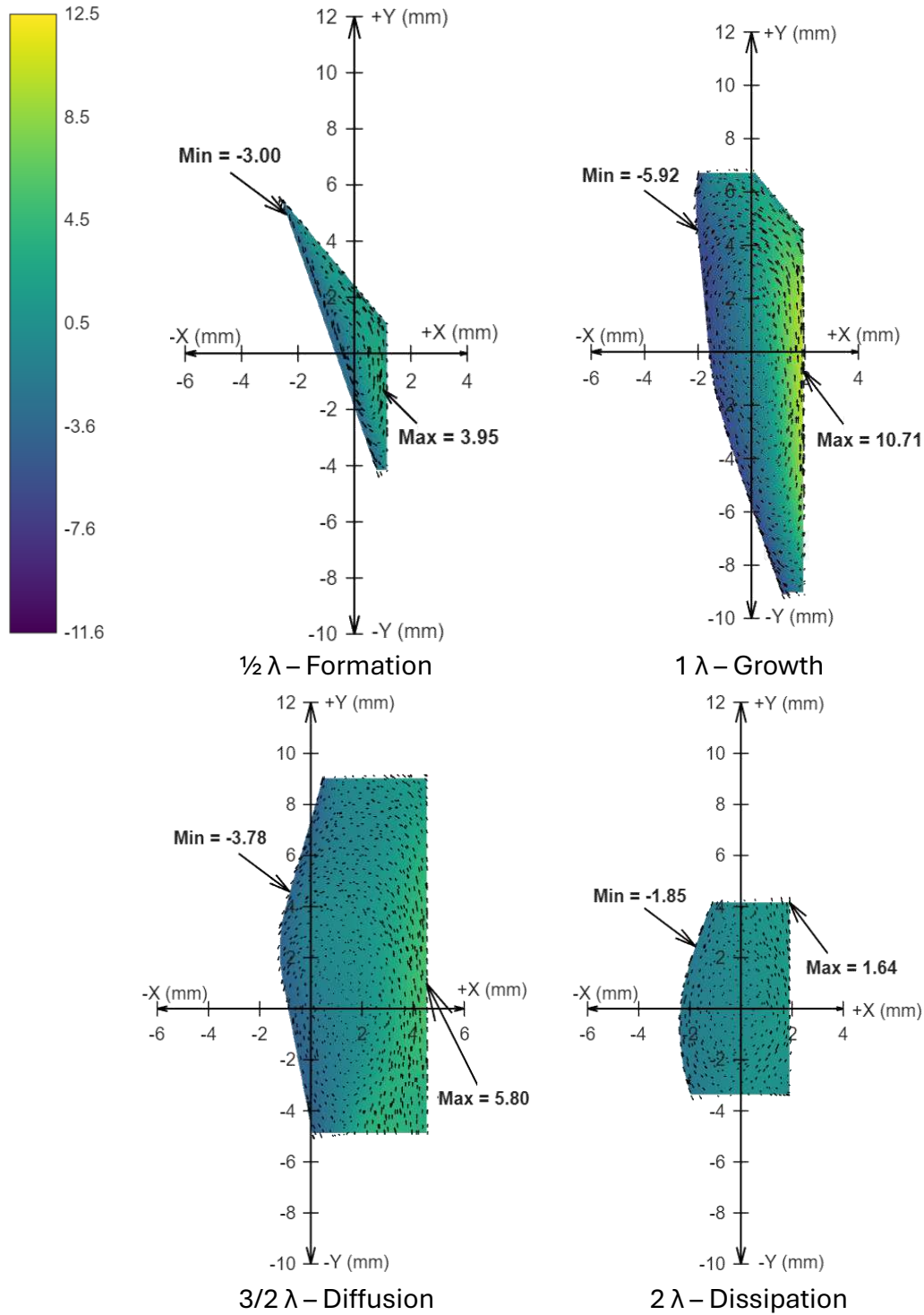


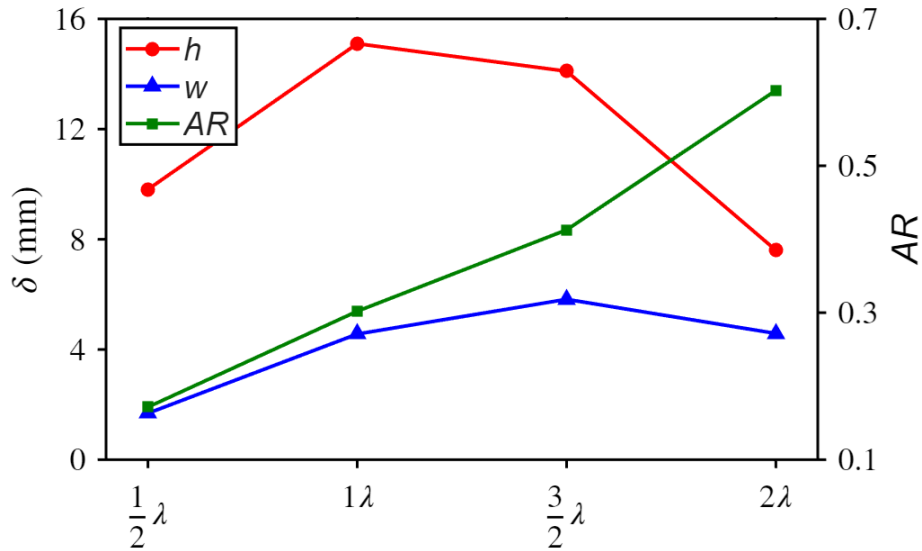
Figure 17. Y velocity variations in the vortical structure during different stages of its evolution.

Qualitative characterisation of the vortical structure's dynamics have been presented above. For quantitative analysis, variations in its size, shape and strength are depicted in figure 18. For accurately quantifying the dynamics of the vortical structure, it is imperative to explain and analyse them as processes rather than considering them as individual states. Thus, $\frac{1}{2} \lambda$ to 1λ is the growth stage, 1λ to $\frac{3}{2} \lambda$ is the diffusion stage, and $\frac{3}{2} \lambda$ to 2λ is the dissipation stage. Similarly, 0λ to $\frac{1}{2} \lambda$ (or 2λ to $\frac{1}{2} \lambda$) is the formation stage during

which the vortical structure forms. In figure 18, the primary focus is on the growth, diffusion and dissipation stages. It can be seen that during the growth stage, the height, width, aspect ratio and circulation of the vortical structure all increase. Aspect ratio (AR) is defined here as the ratio of width (w) to height (h) of the vortical structure. Circulation (Γ) is defined here as the line integral of the velocity field (u) around a closed curvature such as a vortical structure. It can be mathematically expressed as [55]:

$$\Gamma = \oint_C u \cdot dl \quad (14)$$

Circulation is a representation of the net rotational fluid motion in the vortical structure. Thus, increase in the circulation during the growth stage is an indication of strengthening of the vortical structure through accumulation of rotational motion and vorticity from the bulk flow in the mixing chamber. During the diffusion stage, while the width, area and aspect ratio of the vortical structure increase, its height and circulation decreases. Increase in area and width, and decrease in height is evident from figure 17, resulting in increase in the aspect ratio. As for the decrease in its circulation during diffusion stage, we calculated earlier that between 1λ and $3/2\lambda$, the difference in the Y velocity across the width of the vortical structure decreased by 42%, thus, this decrease results in lower circulation as the velocity shear in the vortical structure decreases. During the dissipation stage ($3/2\lambda$ to 2λ), all parameters under consideration except the aspect ratio decrease, indicating decay and eventual complete viscous dissipation of the vortical structure in the bulk flow. The aspect ratio still increases because the decrease in the height of the vortical structure (46%) is more pronounced than decrease in its width (21%).



(a)

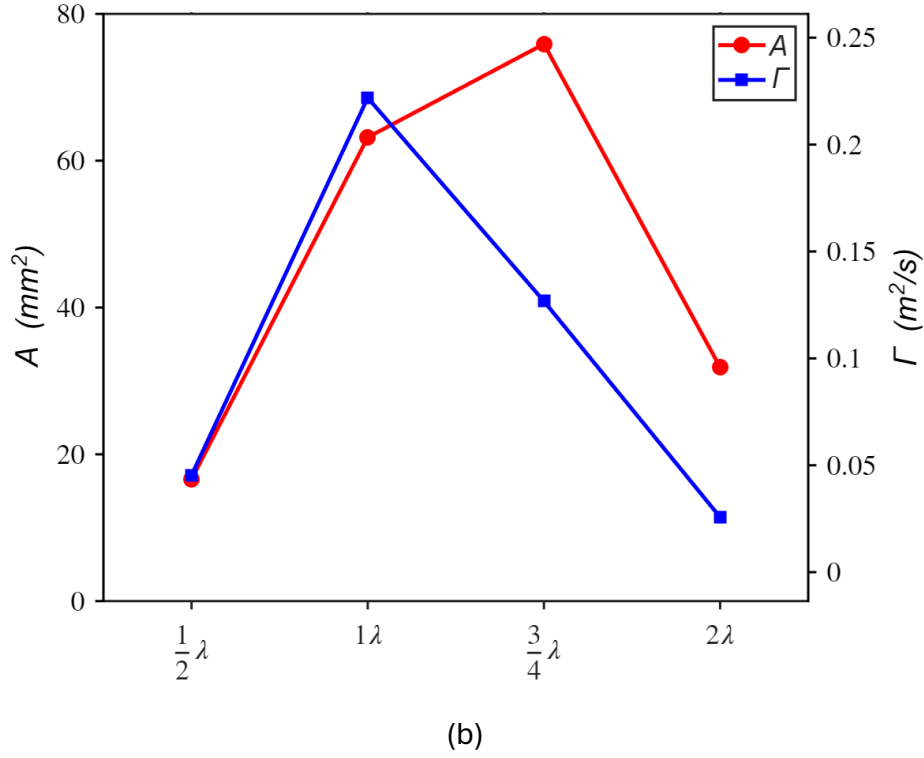


Figure 18. Quantification of the vortical structure in the mixing chamber during its life cycle through its (a) height, width and aspect ratio, and (b) area and circulation.

Further analysing the dynamics of the vortical structure, variations in its coherence have been computed. Coherence is representation of spatio-temporal organisation of a flow feature i.e. how well it maintains its shape and size [56]. Hence, coherence analysis of the vortical structure can reveal its dynamic behaviour. A strongly coherent vortical structure would maintain its structural integrity, while a weakly coherent one would show clear signs of disintegration [57]. In the present study, we use λ_2 criteria to quantify the vortical structure's coherence. It is a widely used vortex identification method that defines the core of a vortical structure as a connected region when the 2nd eigenvalue of the tensor $S^2 + \xi^2$ is negative i.e. $\lambda_2 < 0$ [58]. Here, S is the strain rate tensor and ξ is the vorticity tensor. Thus, λ_2 is negative when rotation dominates over shear in the coherent flow structure. Figure 19 shows negative λ_2 region/s inside the vortical structure during its different evolutionary stages. At time stamp $\frac{1}{2}\lambda$ (formation), it can be seen that the vortical structure is strongly coherent in its central region. At time 1λ (growth), negative λ_2 values can be seen in a much larger area compared to the previous, clearly showing growth of the coherent vortical structure. At time $\frac{3}{2}\lambda$ (diffusion), λ_2 values are less negative and a small portion is disconnected from the main coherent vortical structure. This indicates that the vortical structure has started losing coherence and the rotational flow feature is no longer behaving as a single core. At time 2λ (dissipation), λ_2 values are again much higher and several chunks of the vortical structure can be seen to break-off from the main core region, indicating dissipation of the vortical structure into the bulk flow.

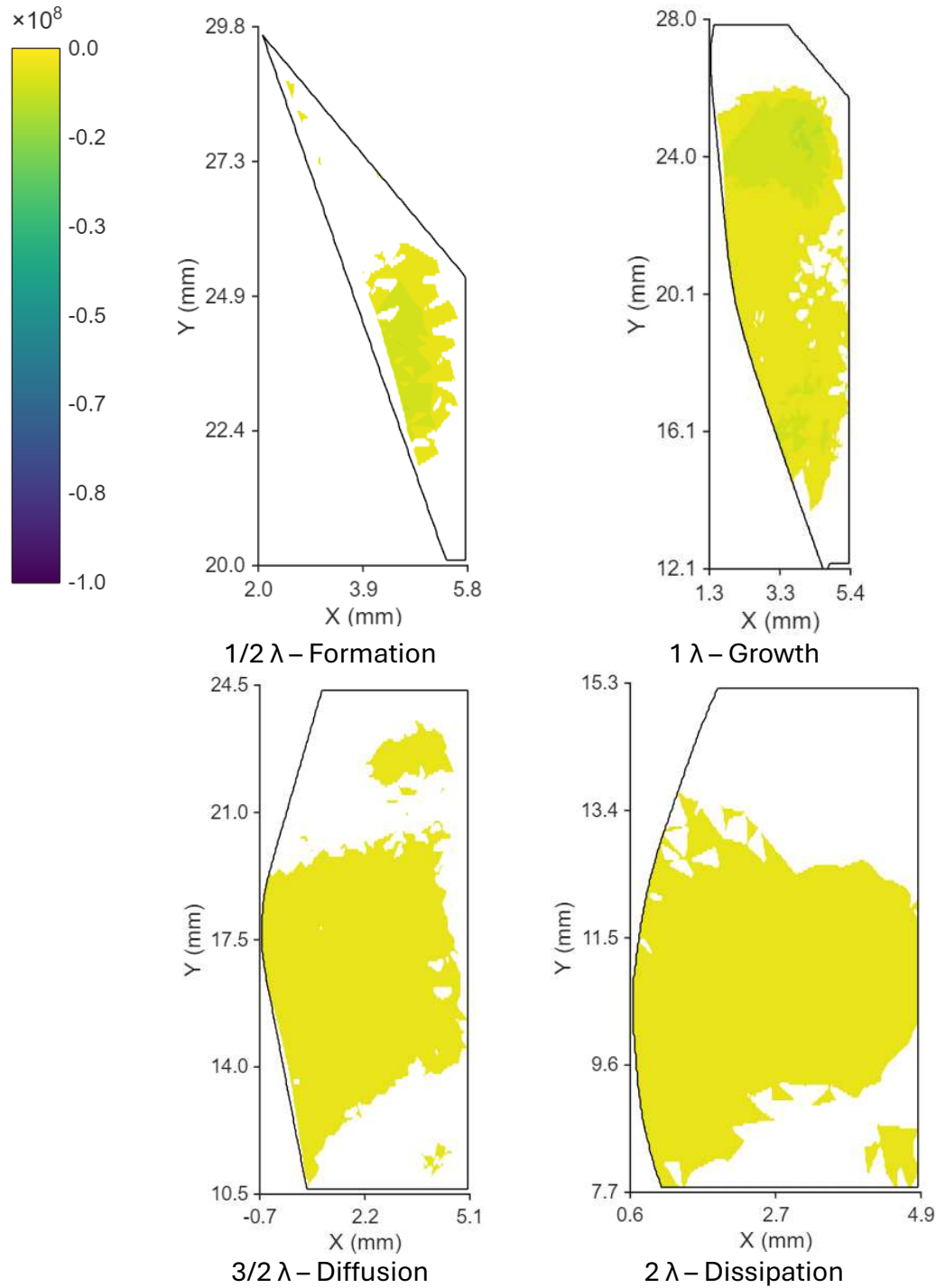


Figure 19. λ_2 variations of the vortical structure during different stages of its evolution.

Although λ_2 variations seen in figure 19 clearly highlight regions of high coherence, the scale of these variations is quite large, which makes it difficult to effectively gauge differences between the stages, especially between diffusion and dissipation. For this purpose, the lowest value of λ_2 at each time stamp has been plotted in figure 20, showing the variations clearly in growth, diffusion and dissipation stages. It can be seen that during the growth of the vortical structure ($1/2 \lambda$ to 1λ), it loses its coherence by 76%, though it is still quite high at 1λ . During the diffusion stage (1λ to $3/2 \lambda$), the vortical structure further loses its coherence by 76%, indicating weakening rotational dominance

and increasing strain effects. During the dissipation stage ($3/2 \lambda$ to 2λ), the vortical structure further loses its coherence by 52%, which is lower than during previous stages because the vortical structure has already lost most of its coherence during those stages.

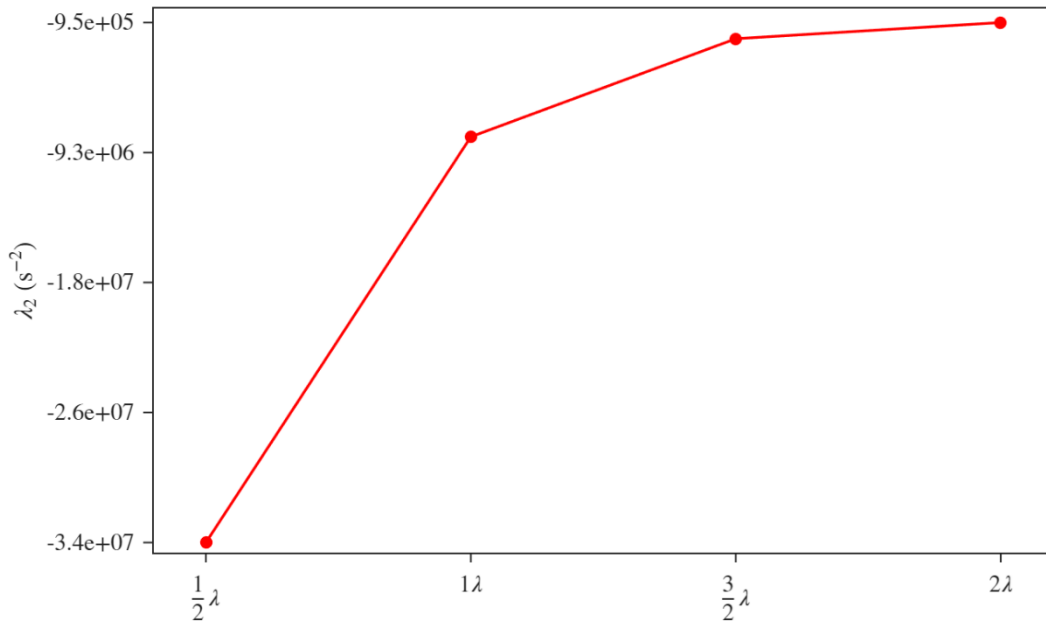


Figure 20. Minimum values of λ_2 in the vortical structure during the different stages.

5.0 Conclusions

A detailed numerical study has been carried out to quantify the dynamics of coherent vortical structures in an oscillating jet nozzle and analyse their effect on the jet's shape-shifting behaviour and impact force fluctuations. Computational Fluid Dynamics (CFD) based multiphase flow solver has been employed to evaluate the complex flow physics associated with oscillating jets and numerically predict the jet impact force on the cleaning surface. The results obtained from the verified numerical solver have been validated against controlled experimental results to ascertain their accuracy and the cleaning superiority of the oscillating jets over straight jets. The main conclusions of this study are:

- The jet characteristics in the cleaning region are dictated by the jet dynamics in the mixing chamber of the nozzle. The jet in the mixing chamber depicts a reversed S shape (2) at the start of the oscillation when the jet in the cleaning region is at its far-right position. As the jet in the cleaning region approaches its central position, the jet in the mixing chamber shifts its shape to reversed C (3). At the completion of half-oscillation, the jet shape changes to normal S, while at $3/2$ of the oscillation, the jet shape again changes to normal C.

- The straightening of the jet in the cleaning region when it is at its extreme positions, corresponding to the start, completion of half and full oscillations, results in higher impact force on the cleaning surface.
- In comparison with an equi-sized straight jet, the oscillating jet results in 37.3% higher impact force and 4.28 times larger cleaning area, leading to considerable water and power savings and reducing the carbon footprint of cleaning operations.
- The oscillatory nature of the jet inside the mixing chamber is controlled by dynamics of coherent vortical structures that starts to form at the top of the chamber as the jet in the cleaning region starts its oscillation. Distinct stages of their evolution have been identified as formation, growth, diffusion and dissipation during one complete oscillation of the jet, where each stage covers 1/4th of the oscillation.
- From formation to dissipation, the minimum pressure of the coherent vortical structure increases from 90 kPa to 205 kPa, while the pressure fluctuations decrease from 100 kPa to almost zero, indicating weakening centrifugal forces and velocity gradients, local acceleration and pressure recovery. Meanwhile, the vortical structure stretches (during growth), gets detached from the mixing chamber wall and propagates downstream (during diffusion), shrinks in size and eventually dissipates into the main flow (during dissipation).
- The core of the coherent vortical structure is constantly displaced during the evolutionary stages. During the diffusion stage, the core displacement is 83% higher than during the growth stage, indicating local acceleration due to advection and weakening velocity gradients (42% lower). During the dissipation stage, core displacement reduces to 26% compared to the diffusion stage, indicating loss of momentum and strength, and viscous dissipation into the bulk flow.
- The strength and the coherence of the vortical structure have been computed. Its strength increases during the growth stage, while it decreases during the diffusion and dissipation stages. The vortical structure is most coherent during the formation stage and keeps losing it during its evolution. During the growth, diffusion and dissipation stages, the vortical structure loses its coherence by 76%, 76% and 52% respectively. By the time the vortical structure reaches its dissipation stage, it has already lost most of its strength and coherence.

Funding: This work was supported by the Innovate UK Accelerated Knowledge Transfer scheme [project number 1850, 2024].

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