Fluidic Oscillators’ Applications, Structures and Mechanisms– A review

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ABSTRACT: Enhancement of heat and mass transfer and decrease of energy dissipation are great necessities of the evolution of fluid flow devices. Utilizing oscillatory or pulsatile fluid flow for periodic disturbing of velocity and thermal boundary layers is one of the methods with exciting results. Passive methods of generating oscillatory flow are preferred to active methods because of simplicity, no need for an external source of power and low cost of implementation and maintenance. Fluidic oscillators are a kind of no-moving part devices which convert steady pressurized inlet flow to oscillatory flow or pulsatile flows at exit without any need for external power. In this article, various conventional fluidic oscillators are introduced and categorized and their physical mechanisms are discussed. Also, numerical and experimental studies with the subject of fluidic oscillators are reviewed and existing correlations are presented.

KEYWORDS: Feedback mechanism; Fluidic oscillator; Oscillation Frequency; Passive method; Sweeping flow

INTRODUCTION

Feeding a fluidic oscillator with pressurized fluid cause to a continuous but spatially oscillating jet at the exit which is completely self-induced and self-sustaining. Oscillating or pulsatile fluid flow in many applications issue to improve integral quantities such as mass diffusion, skin friction, heat transfer and overall sound pressure level due to interruption of velocity and thermal boundary layer and facilitation of the transition to the turbulent regime. Efficiency of apparatuses utilizing this type of fluid flow has been verified in many industries including controllers, chemicals and processes, medicals, instrumentation, HVAC and recently heat transfer.

Fluidic or flueric devices emerged about 60 years before; when engineers at the Harry Diamond Laboratory tried to find simple and reliable ways to implement controlling actions. They believed that this action should be done by some no moving part fluid devices. In 1959, Horton suggested deflecting a fluid jet with another to get amplification. To improve the small gain of Horton’s method, Warren and Bowles used slit-like nozzles and surrounded the jet with top and bottom plates and walls.

The result was rediscovering of wall attachment effect, emergence of bi-stable fluid devices and formation of fluidic logic to sensing, amplification, analog and digital operations in the fields of electricity and telecommunications by fluid dynamics (1-2). Bi-stable devices and fluidic oscillators had a large progress in their first 10 years of emergence in the fields of controllers and measurements.

Development of semi-conductor technology and tiny dimensions transistors to do large computations in a glance almost ceased progressive growth of researches on fluid logic and kicked it to background. But ceding the competition to semi-conductor technology caused the bi-stable devices and fluidic oscillators to find new applications.

Numerous patents and reports are the evidences of the evolution (3-27). Some of the patents include the use of fluidic oscillators in more accurate fluidic timers (3, 7), binary counters (4), differential comparator (5), specified oscillating patterns of jet flow (19), cycling valve in respirator (6), sprays (12-13), SPA nozzles and shower heads (8,18,20), windshield defroster (9, 14), boundary layer separation control (21 -22,26), thrust augmentation system (10), shock absorber (11), fluid flow measuring (23,25,27), fuel injector system (24), electronic modules’ cooling (15, 17) and cooling of stator and rotor inside a gas turbine (16).

Todays, capability of fluidic oscillators are not limited to the typical aforementioned patents and they have strengthen their presence; so that utilizing the fluidic oscillators in applications like fluidic amplifiers (28-30), combustion (31-34), flow separation control and drag reduction (35-46), controlling actions (47-52), flow meters (53-58), mixing or separation of chemical components (59-65), micro-bubble and micro-drops generating (66-71), noise control (72-73), injector nozzles (74-79), combustion instabilities suppressing (34), synthetic jets’ generating (80-82), thrust vectoring (83-85), different types of sensors (86-91), valves (92-97), well drillings (98-103), and impinging jet heat/mass transfer enhancement (104-105) is ever increasing.
The purpose of this article is to introduce different existing and more utilized fluidic oscillators. With describing structures, materials and manufacturing methods, affecting parameters and performance mechanisms of different customary fluidic oscillators, we try to make a clear picture of these devices for the readers.

Explanation of the physics of the sweeping fluid flows issued from these devices, makes innovative ideas for researchers and engineers in different fields of performance improvement of technical apparatuses to test the capabilities of fluidic oscillators in their favorite areas.

MATERIALS AND MANUFACTURING

If the material of a fluidic oscillator and the working fluid is chosen correctly and appropriate to its application, it could suffer any harsh anomalies. The fluidic oscillators may be made from ceramic, glass, high-strength plastic (such as PMMA\(^1\)), Photoceram (Corning), stainless steel, beryllium copper, or any other rigid substance. These elements are producible with casting, stamping, molding, etching, CNC machining and laser cutting (106-108).

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Today’s, development of 3D additive manufacturing process or 3D Print with methods like FDM\(^2\), SLA\(^3\), DLP\(^4\) and SLS\(^5\) made the construction of special and complex elements simple and it has become the first choice of many designers to meet their ideas including fluidic oscillators. Available time, complexity of the design, material and required final finishing specifies the suitable technique for manufacturing with 3D Printers.

AFFECTING PARAMETERS

It should be noticed that variation of temperature and pressure of the working fluid may change its’ thermo-physical properties, hence great changes in fluid dynamics and oscillating characteristics of the outlet flow may occur due to the change of resistance, capacitance and inductance since the structures of different fluidic oscillators and their flow dynamics differ, their affecting parameters are also different. In literature, many of these affecting parameters are studied and their effects on oscillating characteristics of fluidic oscillators have been investigated (36, 109-122). These parameters could be classified under three general titles of geometric, kinematic and dynamic parameters.

General geometric affecting parameters of fluidic oscillators are including characteristic dimensions (such as width (w), height (H) or hydraulic diameter (d\(H\)) of power nozzles’ throat or exit diffuser’s throat), diverging angle (\(\theta\)) and cross section shapes of exit diffusers, characteristic dimensions of feedback channels (w\(f\), L), volume of amplifier (V\(_f\)), volumes of feedback channels (V\(_f\)), roughness (ɛ), symmetry situation of the amplifier and feedback channels, position and geometric dimensions of target or splitter. Sound velocity of the working fluid (a), characteristic velocity of jet flow at the entrance or exit nozzle (V) or corresponding supply fluid’s volumetric flow (Q), characteristic velocity (V\(_f\)) or relevant volumetric flow (Q\(_f\)) inside feedback passages and turbulence intensity (I) at the power nozzle’s throat are such a kinematic affecting parameters in fluidic oscillators.

In addition, flow dynamics inside the fluidic oscillators have great effects on the formation and strengthening of oscillating flow at the exit. Some of the affecting dynamic parameters are mass flow (\(m\)), supply pressure (P\(_s\)), pressure drop inside the chamber (\(\Delta P\_c\)) and feedback channels of the oscillators (\(\Delta P\_f\)), discharge pressure (P\(_d\)) and thermo-physical properties of the working fluid and discharge environment (such as density (\(\rho\)) and viscosity (\(\mu\))).

The dependence of oscillating characteristics of the fluidic oscillators to the thermo-physical properties of the working fluid may be utilized for measurement or control of the properties (47, 86, 88, 123, 124). Therefore, sweeping flow

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1. Poly Methyl Meth-Acrylate
2. Fused Deposition Modeling
3. Stereo-Lithography Apparatus
4. Digital Light Projector
5. Selective Laser Sintering
frequency at the exit of a typical fluidic oscillator is a function of different factors that could be summarized as below,

\[ f = f (w, H, L, \omega_f, a, \nu_f, Q_f, P_f, P_0, \Delta P_f, \rho, \mu, \varepsilon, \theta, \beta) \]

(1)

Shakouchi did a dimensional analysis and derived the following non-dimensional affecting parameters (Aspect ratio, Reynolds number, Stokes number, Strouhal number) in a confined jet fluidic oscillator (125):

\[ A = \frac{w}{H}, \quad Re = \frac{DV_w}{\mu}, \quad F^* = \frac{fw^2}{v} \quad \text{or} \quad Sh = \frac{fw}{V} \]

(2)

According to the Tippet et al. (126) Stokes number, \( St = F_{f^*} = \frac{fwv^2}{\nu} \), has great effect in laminar flows inside the feedback channels and also pressure drop coefficient, \( K = \frac{2\Delta P}{\rho V^2} \), and Mach number, \( Ma = \frac{V}{a} \), should be considered for involving pressure drop and compressibility effects inside the oscillator.

**CLASSIFICATION OF FLUIDIC OSCILLATORS**

Fluidic oscillators include every no-moving part devices capable of converting pressurized inlet flow to completely self-induced and self-sustaining flow oscillations at their exit section.

Thus, this type of oscillators have extensive domain of inclusion and various devices have also patented under the name of fluidic oscillator.

Shakouchi (125) categorized the fluidic oscillators to four main groups of feedback oscillators, relaxation oscillators, edge-tone oscillators and control port-free feedback-free oscillators (Fig. 1).

Yang (114) categorized the fluidic oscillators to three groups of feedback oscillators, Karman vortex oscillators and concave-type oscillators (Vee gutter or U-concavity) according to the channel’s structure and operating principle.

Tesař (127) presented various classifications of fluidic oscillators by considering three approaches: basic feedback principle, operating mode, and number of amplifiers. Figure 2 shows one of the taxonomic trees presented by Tesař on the basis of basic principles of fluidic oscillators.

Despite different mechanisms of various fluidic oscillators, one main characteristic of all the fluidic oscillators is the necessity of existence of a kind of feedback mechanism to derive the oscillations (128-129).

Fluidic oscillators with one or more separate apparent channels for feedback operation are usually named feedback fluidic oscillators. Three of the most conventional feedback fluidic oscillators are two-feedback channel oscillator, single-feedback loop oscillator and quarter-wave resonance tube oscillator.

The oscillators usually produce oscillations with fixed Strouhal number or flow rate independent frequency; although, there are exceptions (128). Also, fluidic oscillators could be classified on the basis of their internal mechanisms into two main branches of wall attachment fluidic oscillators (sonic or relaxation types) and fluidic oscillators with jet (or jets) interactions in a confined geometry without any feedback channels (129).
As seen, some words like relaxation have different implications in different references. Here we accept the terminology of Tesař taxonomy. Another classification may be done according to the exit flow’s appearance. The output of a fluidic oscillator may be as a planar sweeping jet or two alternatively pulsating jets at two exit ports which the latter is called a fluidic diverter too (117).

The most important fluidic oscillators (planar sweeping or alternatively pulsating) utilized in different engineering processes are classified below according to their main working mechanism;
A) Two feedback channel fluidic oscillators;
B) Single feedback loop fluidic oscillators;
C) Resonance tube feedback channel fluidic oscillators;
D) Feedback-free fluidic oscillators;
E) Confined jet fluidic oscillators;
F) Cavity-jet fluidic oscillators.

Beside these types of passive oscillators, there are other methods and mechanisms for production of oscillating flows without any moving part interposition. For example, fluid flow inside or next to cavity-type geometries could create unstable flow and cause self-sustaining or self-controlling oscillatory flow. Rockwell (130) classified the physics of these unstable flows into three main groups of fluid-dynamic, fluid-resonant and fluid-elastic (Fig. 3).

OPERATING MECHANISMS OF FLUIDIC OSCILLATORS

Every changes in a fluid field accompany with formation and travel of pressure waves. If these pressure waves superimpose on each other or feedback from more intense areas to less intense areas, it could deviate the existing flow way and switch the flow in the fluidic oscillator. Also, periodic vectoring of the flow’s momentum in fluidic oscillators through feedback channels or generated vortex from jet’s (jets’) interaction with the chamber (and each other) could switch the flow and deviate the power jet. McDonough et al. (122) counted the governing phenomena of flow switching inside the fluidic oscillators as wall attachment, jet turbulence, separation bubble growth, secondary vortex in case of concave walls and feedback flow regime. Also, Hartman quarter-wave resonator characteristics could be added to the collection. In this section, the operating mechanisms of the previewed fluidic oscillators are explained briefly.

Two Feedback Channel Fluidic Oscillators

In two feedback channel fluidic oscillators (Fig. 4), the flow oscillation is creating due to Coanda or wall attachment effect. Coanda Effect is the result of fluid entrainment between a jet and a wall (or two jets) and formation of a low pressure area among them which intensifies the inclination of the jet toward the curved wall (or one of the jets). The jet is remained attached to the wall while no external force or no other effect is exerted on the jet (131-133).

Entering a jet through a power nozzle into a two feedback channel fluidic oscillator (Fig. 4b), the jet may be tended to a side due to its intrinsic dynamic instabilities and then the Coanda Effect dominates it. Thus, the jet attaches to the wall and a part of its downstream flow injects to the
corresponding control port through the feedback channel of that side. This part of the returned flow supplies to the separation bubble immediately downstream of the control port and grows it. With the growth of the circulating area and its’ propagation to the downstream, the attached jet gets separated and moves to the opposite side wall.

Therefore, it is clear that the switching process relies not only on the exerted momentum through the feedback channels, but mainly due to the growing circulating bubble fueled from the feedback flow. Altogether, the responsible factor of the flow switching in this kind of oscillator is feedback flow through the feedback channels (116).

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**Single Feedback Loop Fluidic Oscillators**

In this kind of fluidic oscillators, there is just a single feedback loop (Fig. 5). Similar to the previous case, wall attached jet inside the amplifier is steady with respect to the time and has no oscillation in absence of external forces or other effects, if there isn’t any feedback channel.

When the jet tends to one of the walls due to its intrinsic instabilities, the Coanda Effect causes the jet to attach to a wall. The Coanda Effect increases the fluid entrainment and its acceleration in the side where the jet deviated towards. Hence, the pressure decreases there and it forms a pressure gradient across the jet so that the pressure in the jet inclined side becomes less than that of the opposite side. Locating a feedback loop on the sides of the pressure gradient, compression waves from the high pressure side and rarefaction waves from the low pressure side travel to the opposite side with the speed of sound in the fluid medium of feedback loop. Receiving the existing pressure gradient message at the sides of the feedback loop, the fluid flows in the loop from high pressure side to the low pressure side.

This flow grows the vortex or separation bubble in the low pressure area and finally win the stabilizing Coanda Effect and the jet detaches from the wall.
After the jet detachment and its passing from the central axis, collaboration of feedback flow’s momentum and Coanda Effect moves the jet to the other wall and it attaches soon.

An oscillation cycle completes with a repetition of the process (106, 122, 136). Observations imply that fluid entrainment into the feedback loop from a control port and its discharge from the other control port causes the detachment and jet’s switching (137). Although the compression and rarefaction wave’s travel inside the feedback channel start the formation of a sufficiently strong pressure gradient to cope with the Coanda Effect, but the main factor of flow switching is the fluid entrainment from the high pressure side and its momentum release on the other side of Coanda dominated region. In fact, the momentum transfer changes the cross pressure gradient strength and direction.

However, it seems that the main difference between two feedback channel fluidic oscillator and single feedback loop fluidic oscillator relies on the beginning nature of the feedback processes; partial splitting of the flow’s momentum in the former versus compression and rarefaction wave’s transfer in the later.

**Resonance Tube Feedback Channel Fluidic Oscillators**

Resonance tube feedback channel fluidic oscillator is a different type of feedback fluidic oscillators (Fig. 6) which introduced by Tesař (41). Here, changes of flow field caused by wall attachment effect don’t feed back to the control ports to switch the power jet; instead, the flow is switched by acoustic wave’s traveling inside a resonance tube connected to one of the control ports.

The other side of the resonance tube is open to the atmosphere.

The second control port is open to the atmosphere freely. When the jet is injecting to the amplifier through the power nozzle, it may be deflected to the either sides because of its intrinsic instabilities. Deflected to one side, Coanda Effect intensifies the inclination and attach the jet to the corresponding wall.

If the jet is deflected to the side which its control port is open to the atmosphere, the jet is ejected to the opposite side because of the domination of atmospheric pressure on the fluid’s local pressure.

Therefore, the attachment of the power jet to this side of the amplifier with open control port is not stable and the power jet will ejected immediately when it tends to the side.

In the other hand, the resonance tube has more hydrodynamic resistance relative to the opposite side; so, the jet’s pumping effect on the wall of the resonance tube side produces less pressure values than the other side.

Therefore, the jet prefers to deflect to the side where the resonance tube is there.

The deflection decreases the local pressure due to the fluid entrainment and pumping effect and a rarefaction wave forms which propagates toward the open end of the resonance tube. Upon reaching to the open end of the channel and leaving it, a compression sonic wave forms due to the reflection effect of waves and it moves toward the upstream of the channel.

The compression wave reaches to the interaction cavity and crosses the convergent surface of the control nozzle; so the local pressure in this region of the amplifier increases which switches the power jet to the opposite wall. However, the jet won't stay attached to the wall; because the corresponding control port is open to the atmosphere and it couldn’t sustain the local pressure gradient across its sides.

When the compression wave finishes its action, the power jet switches back and the cycle repeats. As mentioned before, the jet’s deflections occurs in the reason of weak shock waves traveling inside the resonance tube. The switching time of the power jet depends on the propagation time of the acoustic wave in the resonance tube.

Hence, the sweeping frequency of the flow is determined by characteristics of the resonance tube (especially its length, L) and it does not depend to the flow rate of the amplifier.

One of the important issues of these fluidic oscillators is the freedom from the law of constant Strouhal number. These oscillators could achieve high frequencies without the need of high jet velocities (41).
These type of oscillators could be classified as feedback channel fluidic oscillators; because the response of the environment to the changes of the flow field is fed back to the control port through a specific channel.

**Feedback-Free Fluidic Oscillators**

Fluidic oscillators may be designed to be free of feedback channel and perform according to the interactions of two jets with each other and with the surrounding geometry.

In this type of fluidic oscillators, the generated vortexes between the jets and the boundaries of the surrounding geometry play the role of feedback loop with no physical boundary (129).

In feedback-free fluidic oscillators (Fig. 7), flow configuration is symmetric when the upper and lower jets enter to the oscillator with the same velocities. After jets collision, most of the fluid flows toward the exit and a little distribute in the enclosed spaces in between the jets and the chamber. The enclosed spaces fill gradually and their pressure rise locally; with the first instability and deviation of a tinny mass of the fluid, jets’ balance disturbs and the momentum of one jet dominates and it catches the exit space. Tomac et al. (108) explained the physics and details of sweeping nature of the flow at the exit of feedback-free fluidic oscillator for low flow rates. Suppose that the upper jet’s core is dominated the exit; now, the lower jet is bifurcated and a part of its kinetic energy transfers to the upper jet. Lower jet left shear layer in dome region creates a vortex and grows its size constantly. The growth of the vortex finally bifurcate the upper jet and forms a saddle point. By bifurcation and degrading of the upper jet, a part of the lower jet finds a way at the exit. The process of the upper jet’s bifurcation alters the flow direction in dome region in contrast to the previous phase angle. By and by, with the collision of the lower dome vortex with the saddle point, both of them disappear and the upper jet’s connection with the output is interrupted. Now, the lower jet’s core is connected to the output; the upper jet is bifurcated and a part of its kinetic energy is transferred to the lower jet. Half a cycle has completed so far. Repetition of the procedure by the upper jet completes the cycle and the process continues periodically.

Here, there is no feedback of the changes of the flow field through feedback channels in contrast to the previous cases; but, periodic conquest of the momentum of two similar jets on each other in an enclosed chamber causes the sweeping jet at the exit.

**Confined Jet Fluidic Oscillators**

In fluidic oscillators of the Figure 8, similar to the feedback-free fluidic oscillator, created vortexes between the jet and the boundaries of the confined geometry play the key role in producing sweeping flow.

The vortexes with periodic growth and shrinking share the kinetic energy of the power jet in between, while the pressure distribution changes across the sides and it makes the flow sweeping. Although the fluid dynamics in configurations of the Figure 8 are a little different, but their working mechanism rely on the periodic changes of two main vortexes at the sides of the power jet.

When the power jet enters a suddenly enlarged passage, it entrains the fluid at the adjacent corners and creates two vortexes. If the flow inclines to one of the walls due to its intrinsic instability, the fluid entrainment at that side increases and the Coanda Effect dominates and cause the jet to attach to the wall. Hence, a low pressure region rules there and its corresponding vortex reaches to the lower pressure too.
In Figure 8a, the inclination of the jet to the upper wall cause the most of the jet’s kinetic energy to conduct to the upper cavity and to form a high pressure region which conquers the Coanda Effect, detaches the jet and moves it to the opposite side wall. Repeating the procedure in the lower cavity, the switching process completes and repeats periodically. The story is somehow different for cases of Figures 8b and 8c.

After the inclination of the power jet to a side and attachment of the jet to the corresponding wall, the local pressure decreases there. Due to special design of the power nozzle and dimensions of the chamber, there are ways between the chamber sides from above and below the power jet; so the low pressure vortex with higher rotation speed entrains the fluid from adjacent spaces that increases the vortex volume and develops it toward the downstream. Therefore, the attached side vortex’s pressure rises and the opposite side vortex’s pressure decreases gradually (125). Hence, the jet is detached and ejected to the opposite side in the reason of the growth of the separation bubble and the change of the pressure balance. Repetition of the procedure at the opposite side completes the flow switching cycle and the process repeats periodically.

Cavity-Jet Fluidic Oscillators

This type of fluidic oscillators introduced by Bauer (142) for flow measurements. It had successful results in flow detection in the Reynolds number range of 0.2 to 5.4 (143), and it examined for periodic injection of the working fluid into the wake region of a V shape nozzle as a flame holder inside a combustion chamber too (144). The mechanism of the creation of oscillations is almost similar in various types of cavity-jet fluidic oscillators (Fig. 9). First of all, when fluid jets to the oscillator through the power nozzle, it strikes to the target cavity and gets bifurcated such that each branch conducts to its relevant exit. The direction change of the velocity vector of the branches forms a vortex for each branch with counter rotation relative to the other. As soon as a dynamic instability occurs in the inlet jet, one of the vortexes overcomes and gets most of the inlet fluid and its kinetic energy and develops toward the center of the cavity. Hence, the defeated vortex becomes smaller and gets moved toward its corresponding exit.

Finally, the dominant vortex locates on the center line and the defeated vortex blocks its corresponding exit. Now, almost all of the fluid flow discharges from the corresponding exit of the dominant vortex. Since the defeated vortex approached to the power jet so close and its corresponding exit has been blocked too, it receives the inlet...
fluid with a higher velocity relative to the dominant vortex at the center of the cavity; so its rotational speed raises gradually. The vortex moves along the power jet to the center of the cavity and seize more kinetic energy from the power jet continuously and dominate the vortex at the center finally. Now, a half-cycle oscillation is complete and the process is reversed (142, 147). In some designs where the concave target plate is located in front of a V-shape passage, the fluid entrainment and the Coanda Effect at the exit ports are involved in the oscillation mechanism too (148).

FLOW FIELD VISUALIZATION OF FLUIDIC OSCILLATORS

Good experimental researches have been done around the visualization of oscillation process of different types of fluidic oscillators. Some of the researches were did to verify the capability of fluidic oscillators to be utilized in special applications (63, 84, 148, 149). However, most of them were did to identify the internal mechanisms of the oscillation, flow pattern, external flow dynamics and characteristics of the oscillation of the fluidic oscillators and to quantify the changes of the important parameters. Figure 10 shows the results of some of the methods. Sampling rate, noise level and output data of various methods of visualizations could be different. Hence, choosing an appropriate visualization method for designed working range of a fluidic oscillator is an important and affecting subject and utilizing the experiences of the others could be so helpful in this way. Most of researchers used the Particle Image Velocimetry (PIV) to visualize the oscillation process inside the fluidic oscillators and to investigate the internal mechanisms of the oscillations (108, 114, 116, 150-152) and external dynamics (84, 116, 151, 153). The merit of some other visualization methods have been verified in case of fluidic oscillators too, including: The tracer method (including PIV) with aluminum powders in water and glycerin solution in the study of a cavity-jet fluidic oscillator (146), particle tracking technique with polyamide plastic particles in water to understanding the dynamic behavior and turbulence properties of the internal and external flow fields of a fluidic oscillator including a crescent target inside a V-shaped cavity (145) and also, in the study of the effects of flow characteristics on mixing mechanism inside a micro-fluidic oscillator including a concave target within a V-shaped cavity (148), porous Pressure Sensitive Paint (PSP) method in the study of unsteady flow field of a mimatory feedback-free fluidic oscillator (154), Phase-locked three-Dimensional three-Component Magnetic Resonance Velocimetry (3D3C-MRV) method also known as 4D-MRV method in the study of phase-resolved internal flow of a single feedback loop fluidic oscillator (137), Visualization with stereoscopic microscope and image recording with digital single-lens reflex camera (63), and surface oil-flow visualization using a mixture of aviation oil, Kerosene and nano-sized fumed silica particles (149) in the study of internal and external flow fields of two feedback channel fluidic oscillator.

NUMERICAL SIMULATIONN OF FLUIDIC OSCILLATORS

Various numerical simulation have been done around the fluid oscillation inside fluidic oscillators and most of them indicate good qualitative and quantitative accordance with experimental results and high capability of the numerical methods to predict the flow quantities, design and analysis of fluidic oscillators have been verified.

![Flow field visualization of (a) single feedback loop, (b) cavity-jet and (c) two feedback channel fluidic oscillators with the methods of 4D-MRV, particle tracking technique and PIV, respectively](image)

Fig. 10. Flow field visualization of (a) single feedback loop, (b) cavity-jet and (c) two feedback channel fluidic oscillators with the methods of 4D-MRV, particle tracking technique and PIV, respectively

In the numerical simulations of fluidic oscillators, often Reynolds averaged Navier-Stokes equations of the turbulent flow field are closed with a eddy-viscosity turbulence model, boundary conditions of no-slip at walls, specified pressure at exits and specified pressure, velocity or mass flow at inlet. Shakouchi (146) solved a finite difference equation which is derived by introduction of the stream function and vorticity definitions into the two-dimensional Navier-Stokes equations (laminar solution) in the flow field of a confined jet inside a rectangular cavity. Most of
researchers used the commercial software including ANSYS-FLUENT, ANSYS-FLOTRAN, COMSOL and STORM-CFD2000 to solve the equations. In some cases, researchers used their own codes such as CharLES (136) and Overflow 2.2f (155).

Table 1 summarizes most relevant numerical simulations of various fluidic oscillators. It can be seen that most of the simulations (more than 70%) were around two feedback channel fluidic oscillators and finite volume discretized governing equations were closed with two-equation eddy-viscosity turbulence model of Menter ($k-\omega$ SST) and solved using ANSYS-FLUENT/CFX commercial software.

Kim and Moin (136) did large eddy simulation for internal flow field of a single feedback fluidic oscillator; Tomac et al. (115) and Meier et al. (156) simulated internal and external flow fields and changes of some affecting parameters of jet oscillation in feedback-free fluidic oscillators. Also, researchers have been done for investigating the capability of numerical methods for prediction of flow field and heat transfer of confined jet inside a rectangular cavity (157, 158), studying the cooling capability of “oscillator fin” (159), and understanding the physical phenomena inside target flowmeters (160). More than 50% of numerical simulations concerning two feedback channel fluidic oscillators were about internal flow field, understanding the physical phenomena, flow structures and fulfilling of the needed data for analyzing the experimental results (65, 112-113, 161-167). Also, some of researchers used the numerical analysis for investigating the effect of changes of important parameters (110, 166). Figure 11 shows velocity contours and streamlines for some of the simulations.

Numerical methods have developed so much, so that, researchers use the numerical experiments for applied studies and investigation of intended effects reliably. Some of the main studies regarding the fluidic oscillators are as follows: Simões et al. (111) in the simulation of performance of micro-fluidic oscillators, Nakayama et al. (168) for presenting a two dimensional model of a three dimensional problem with considerable viscous effects and low depth fluidic oscillator, Ries et al. (169) in the simulation and capability verification of fluidic oscillators in an application for suppressing laminar separation bubbles with actuated transition in LP turbines, Gokoglu et al. (35) in the investigation of effects of various boundary conditions on the behavior of an array of uniformly-spaced fluidic diverters in order to passive control of their output phase, Liu et al. (29) in the analysis of static and dynamic loads’ effects on the strength of the baseplates of fluidic amplifier, Childs et al. (155) in the study of active flow control devices using sweep-jets over a full-scale vertical tail of Boeing 757, Hossain et al. (170) in the estimation of the interaction of an oscillating jet with a cross flow inside a channel, Lundgreen et al. (171) for analyzing the efficiency of impinging sweeping jet issued from fluidic oscillator on heat transfer. Some of the researchers gave attentions to the numerical simulation of the outside flow field of fluidic oscillators in addition to the interior (115, 156, 159, 171).

<table>
<thead>
<tr>
<th>Author</th>
<th>F.O.</th>
<th>Type</th>
<th>Numerical Method</th>
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<td>CharLES</td>
<td>LES</td>
<td>64000</td>
<td></td>
</tr>
<tr>
<td>Childs (2016) (155)</td>
<td>2F</td>
<td>FVM-3D</td>
<td>Overflow 2.2f</td>
<td>Unsteady SST-RANS &amp; SST D/DES</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Hossain (2017) (170)</td>
<td>2F</td>
<td>FVM</td>
<td>FLUENT</td>
<td>k-ω SST</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>He (2015) (166)</td>
<td>2F</td>
<td>FVM</td>
<td>FLUENT</td>
<td>RNG k-ε</td>
<td>361678 &lt; Re_{inlet} &lt; 651405</td>
<td></td>
</tr>
<tr>
<td>Meier (2014) (156)</td>
<td>0F</td>
<td>FVM-2D</td>
<td>ANSYS Fluent 14.5</td>
<td>k-ω SST</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Hossain (2017) (167)</td>
<td>2F</td>
<td>FVM-D</td>
<td>FLUENT</td>
<td>k-ω SST</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Lundgreen (2017) (171)</td>
<td>2F</td>
<td>FVM</td>
<td>-</td>
<td>k-ε v-f</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Xie (2017) (65)</td>
<td>2F</td>
<td>FVM-2D</td>
<td>ANSYS Fluent 14.5</td>
<td>-</td>
<td>16.7 &lt; Re &lt; 100</td>
<td></td>
</tr>
</tbody>
</table>

1 F.O.: Fluidic Oscillator
2 2F: Two feedback channel
3 M & S: Master and Slave
4 1F: Single feedback loop
5 0F: Feedback free oscillator
FREQUENCY CORRELATIONS FOR FLW OSCILLATIONS OF FLUIDIC OSCILLATORS

Since the fluid dynamic is different in various fluidic oscillators, determination of their oscillation’s frequency is dependent on the time and length scales of the involved dynamics.

The time scales are functions of the velocity of the formation and transmission of the changes of fluid velocity, pressure and density in the flow field and also they are functions of the distances which the fluid or pressure waves travel from the formation location to the locations of action. For example, switching time (of the accelerating phase) and dwelling time (of the overshoot and deceleration phases) are the determining time scales of the oscillation’s frequency in wall attachment fluidic oscillators (116, 121). A few theoretical studies were done to understand the affecting parameters, dominant time scales and their effects on the oscillations’ frequency of fluidic oscillators (126, 173). An investigation about flow frequencies in different reviewed fluidic oscillators resulted to Figures 12a and 12b for liquid and gas working fluids, respectively.

It can be observed that Feedback-free fluidic oscillators have had the most extensive range of frequency generations; from 5 Hz to 681 Hz for liquids and from 109 Hz to 55 kHz for gases, approximately.

The smallest and highest frequencies was generated by cavity-jet fluidic oscillator (0.1 Hz) and feedback-free fluidic oscillator (681 Hz) for liquids and rectangular open-end cavity (0.16 Hz) and feedback-free fluidic oscillator (55 kHz) for gases. Tables 2 and 3 show some selected correlations of estimating the oscillation’s frequency of feedback channel and non-feedback channel fluidic oscillators, respectively.

The Tables present information about type of the oscillators, characteristic length, working fluids, correlations and parameters definitions.
<table>
<thead>
<tr>
<th>Authors</th>
<th>F.O. Type</th>
<th>Characteristic Length (mm)</th>
<th>Working fluid</th>
<th>Special Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tippetts (1973)</td>
<td>1F</td>
<td></td>
<td></td>
<td>f₁: control loop critical low frequency, Aₑ: cross-sectional area of the control port, Vₑ: volume of the control loop, Lₑ: length of the control ports</td>
</tr>
<tr>
<td>Simoes (2002)</td>
<td>2F</td>
<td></td>
<td>Air, Water</td>
<td>t₁: transmission time</td>
</tr>
<tr>
<td>Cerretelli (2007)</td>
<td>2F</td>
<td></td>
<td>Air, Helium, Neon</td>
<td>R₁, R₂: fluid resistors in feedback channels, C: capacitor of fluidic oscillator, ∆P: pressure drop, ∆mسكان: mass flow difference between switch-engaging and receiving branches</td>
</tr>
<tr>
<td>Arwatz (2008)</td>
<td>1F</td>
<td></td>
<td></td>
<td>τₛ: the ratio between the typical velocities in exit direction (port), L: length of resonance tube (Feedback tube)</td>
</tr>
<tr>
<td>Ries (2009)</td>
<td>master &amp; Slave</td>
<td></td>
<td></td>
<td>1.0 &lt; Re &lt; ∞</td>
</tr>
<tr>
<td>Dennai (2012)</td>
<td>2F</td>
<td></td>
<td>Gas</td>
<td>γ: the ratio of specific capacities (1.4 for air), R: gas constant, Lₒ: outlet length</td>
</tr>
<tr>
<td>Xu (2013)</td>
<td>2F</td>
<td></td>
<td>Water</td>
<td></td>
</tr>
</tbody>
</table>
Table 3
Correlations for oscillation’s frequency in various fluidic oscillators without any feedback channel.

<table>
<thead>
<tr>
<th>Authors</th>
<th>F.O. Type</th>
<th>Characteristic Length (mm)</th>
<th>Working fluid</th>
<th>Special Parameters</th>
</tr>
</thead>
</table>
| Kelley (1967)      | Positive feedback fluidic amplifier          |                            | Air                    | T: Temperature
|                    |                                               |                            |                        | k₁, k₂: empirical constants, AR: aspect ratio of the nozzle (h/W),                   |
|                    |                                               |                            |                        |                                                                                     |
| Shakouchi (1989)   | Rectangular-shaped container                 |                            | Water, Air             | α: empirical constant, β: f₀d²/v                                                   |
|                    |                                               |                            |                        | f₀: frequency at Re = 0 (no physical meaning; not constant but it tends to an asymptotical value), |
|                    |                                               |                            |                        | St∞: Strouhal number in the limit of the system at high inlet velocities,            |
|                    |                                               |                            |                        | *** Numerical study ***                                                              |
| Lalanne (2001)     | Horse shoe chamber containing a horse shoe   |                            | Air                    |                                                                                     |
|                    | target                                       |                            |                        |                                                                                     |
| Mataoui (2003)     | Confined jet in a rectangular cavity         |                            | Air                    |                                                                                     |
|                    |                                               |                            |                        |                                                                                     |
| Tesář (2009)       | Colliding-jet valve                          | 1.0, 3.4                   | Two immiscible liquids  |                                                                                     |

A linear relationship between the oscillation’s frequency and the volumetric flow rate is verified in extensive range of affecting parameters of fluidic oscillators, experimentally. It seems that a comprehensive structured study to obtain a physical model and a frequency correlation for each type of fluidic oscillator could be so beneficial.

CONCLUSION

Fluidic oscillators are no-moving part devices capable of generating self-induced self-sustaining flow oscillations. The devices have experienced various applications from their genesis so far and yielded exciting results. In this article, the structure and physics of conventional fluidic oscillators is explained and a comprehensive review over various aspects of their application is done.

Fluidic oscillators have created oscillations in the ranges of 0.1 Hz to 681 Hz and 0.16 Hz to 55 kHz with working fluids of liquids and gases, respectively. Experiments indicated that there is a linear relation between the frequency and volumetric flow rate or a constant Strouhal number in terms of non-dimensional parameters in the most operating conditions of fluidic oscillators, although there are important exceptions.

Various conventional fluidic oscillators could be categorized in six distinct groups of two feedback channel, single feedback loop, resonance tube feedback, feedback-free, confined jet and cavity-jet fluidic oscillators. The responsible factors for the creation of the oscillations are feedbacks of flow’s momentum or local pressure distribution of specific locations to the inlet control ports through feedback passages or generated vortexes.

According to the previous researches and the content provided here, it is clear that fluidic oscillators have great potentials in the fields of mixing enhancement of similar and disparate fluids, separation of mixtures, intensification of turbulence levels, wide spreading of fluid jets instead of impinging spots, stimulation of special vibration modes, creation of various sweeping flow patterns, periodic disturbing of boundary layers, heat transfer enhancement and in general, all processes that oscillatory or pulsatile flow could be effective in their enhancement. Development trend of fluidic devices predicts that fluidic oscillators are the most important passive alternatives to generate required pulsating or sweeping fluid flow patterns in the future.

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