Trans. Phenom. Nano Micro Scales, 7(1): 9-27, Winter and Spring 2019
DOI:10.22111/tpnms.2018.25051.1153

ORIGINAL RESEARCH PAPER

Fluidic Oscillators' Applications, Structures and Mechanisms– A review

Soheil Ghanami & Mousa Farhadi *

Babol Noshirvani University of Technology, Babol, Mazandaran, Iran

Received 10 May 2018; revised 15 November 2018; accepted 17 November 2018; available online 30 January 2019

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, instrumentations, 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.

*Corresponding Author Email: *m.farhadi@nit.ac.ir*
Tel.: +98(11)32334205; Note. This manuscript was submitted on May 10, 2018; approved on November 17, 2018; published online January 30, 2019.

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.

Nomenclature

			Greek Symbols
a	sound velocity of the working fluid (m/s)	∀	volume of fluid (m^3)
d	diameter (m)	ε	roughness (m)
f	sweeping frequency of exit flow (Hz)	θ	diverging angle
H	depth (m)	μ	dynamic viscosity (pa.s)
I	turbulence intensity (%)	ν	kinematic viscosity (m^2/s)
L	characteristic length of feedback tubes (m)	ρ	density (kg/m^3)
$\dot{m}$	mass flow (kg/s)	τ	characteristic time (s)
P	pressure (pa)		**Subscripts**
ΔP	pressure drop (pa)	c	chamber
Q	volumetric flow (m^3/s)	f	feedback
U	mean inlet velocity (m/s)	H	hydraulic
w	width (m)	o	discharge
		s	supply or switching

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).

Todays, 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 of the fluid caused by temperature or pressure changes. 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

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 (θ) and cross section shapes of exit diffusers, characteristic dimensions of feedback channels (w_f, L), volume of amplifier (V_c), volumes of feedback channels (V_f), roughness (ε), 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 ($\dot{m}$), supply pressure (P_s), pressure drop inside the chamber (ΔP_c) and feedback channels of the oscillators (ΔP_f), discharge pressure (P_o) and thermo-physical properties of the working fluid and discharge environment (such as density (ρ) and viscosity (μ)).

[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,

$$f = f\,(w, H, L, w_f, a, \forall_c, \forall_f, Q, Q_f, P_s, P_0, \Delta P, \Delta P_f, \rho, \mu, \varepsilon, \theta, I) \tag{1}$$

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):

$$A = \frac{w}{H}, \quad Re = \frac{\rho V w}{\mu}, \quad F^+ = \frac{f w^2}{\nu} \quad .or. \quad Sh = \frac{f w}{V} \tag{2}$$

According to the Tippet et al. (126) Stokes number, $St = F_f^{\,+} = f w_f^{\,2}/\nu$, has great effect in laminar flows inside the feedback channels and also pressure drop coefficient, $K = 2\Delta P/\rho V^2$, and Mach number, $Ma = V/a$, 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.

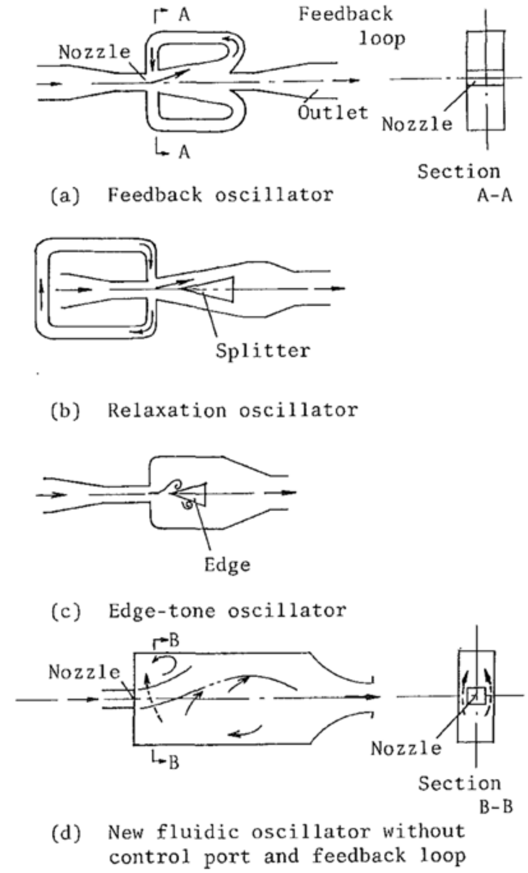


Fig. 1. Shakouchi classification of the fluidic oscillators (Shakouchi, 1989, ASME) (125)

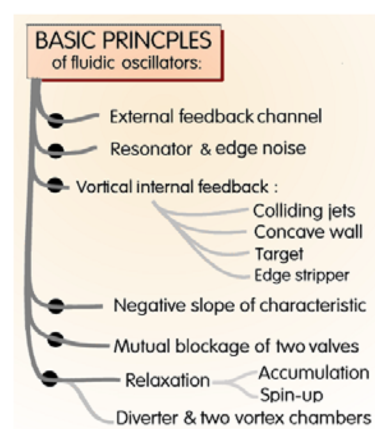


Fig. 2. Tesař's fluidic oscillator taxonomic tree (Tesař, 2017) (127)

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).

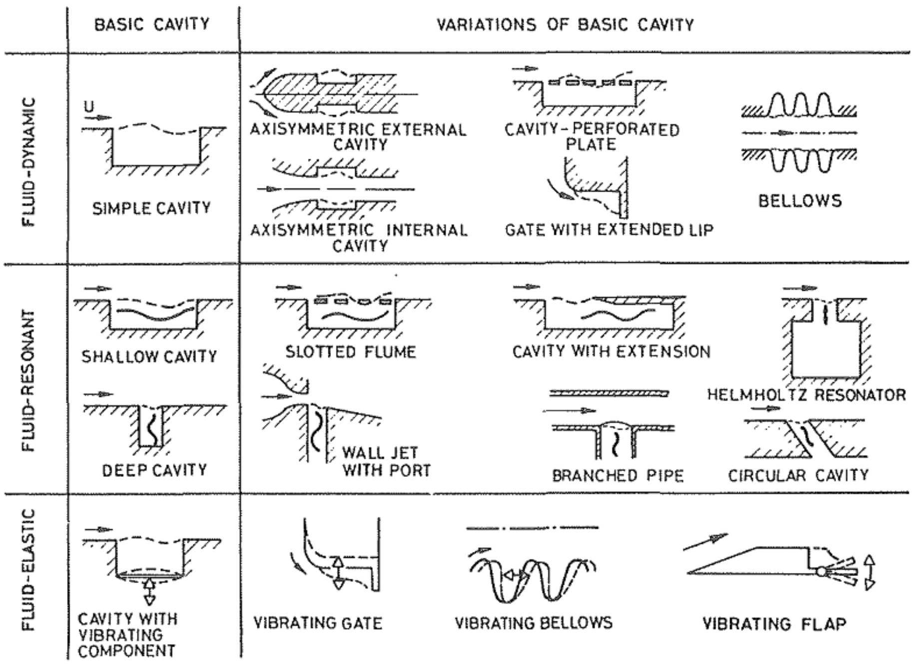


Fig. 3. classification of the cavity oscillations into fluid-dynamic, fluid-resonant and fluid-elastic groups (Rockwell & Naudascher, 1978, ASME) (130)

OPERATING MECHANISMS OF FLUIDIC OSCILLATORS

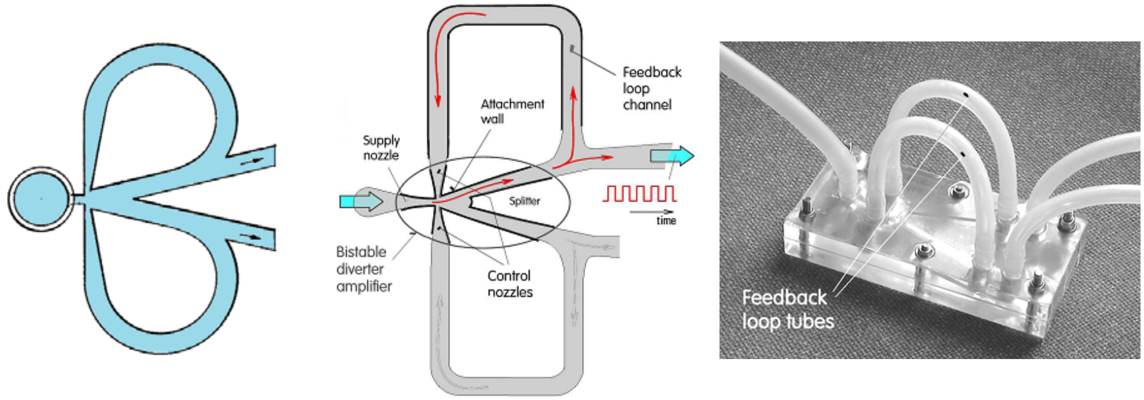
Every changes in a fluid field accompany with formation and travel of pressure waves. If these pressure waves superimpose on each other or fed back from more intense areas to less intense areas, it could deviate the existing flow way and switch the flow in the fluidic oscillator. Also, periodic vectoring 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 Oscilators

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).

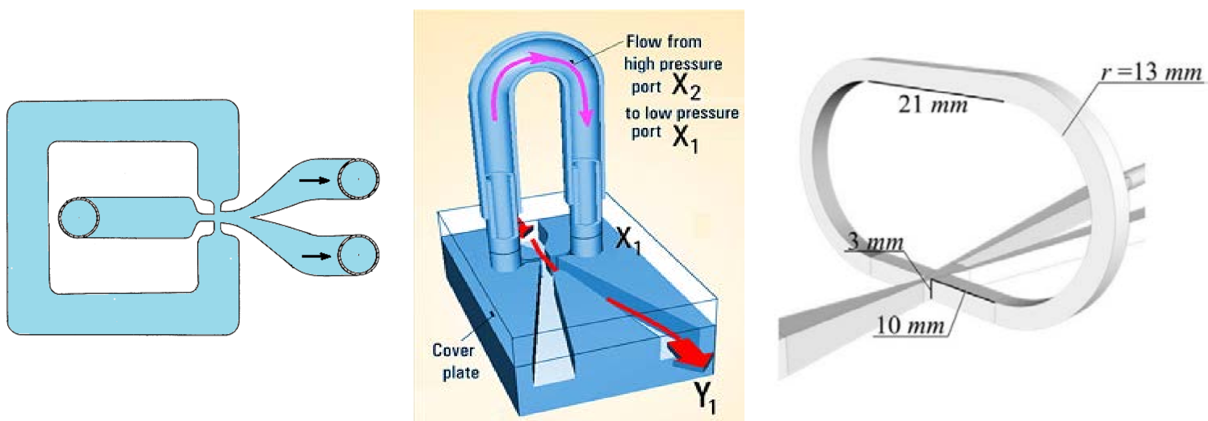


(a) Warren, 1964, US patent No. 3158166 (134) (b) Tesař, 2017 (127) (c) Tesař, 2013 (118)

Fig. 4. Two feedback channel fluidic oscillators; (a) forefather of negative feedback fluidic oscillators, (b) a schematic of switching mechanism, (c) a typical real design

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.



(a) Warren, 1962, US patent No. 3016066 (106) (b) Zimmerman, 2011, ELSEVIER (135) (c) Mcdonough & et al., 2017, ELSEVIER (122)

Fig. 5. Single feedback loop fluidic oscillators; (a) a primary design for air flow oscillator, (b) a schematic of switching mechanism, (c) a schematic of a typical real design

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.

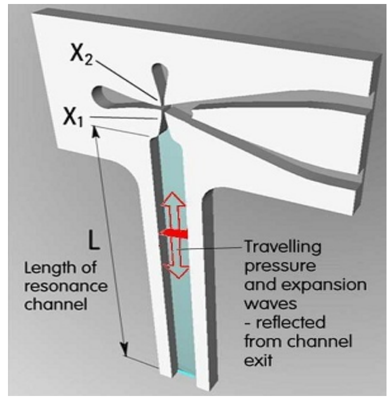
The second control port is open to the atmosphere freely. When the jet is injecting to the amplifier through the power nozzle, it may be deflected to the either sides because of its intrinsic instabilities. Deflected to one side, Coanda Effect intensifies the inclination and attach the jet to the corresponding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

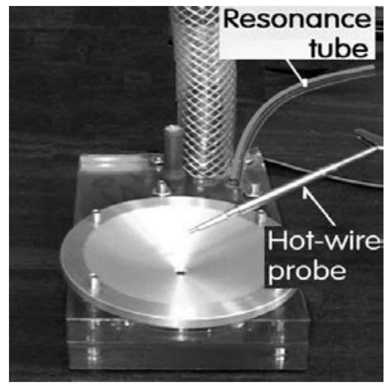
Therefore, the attachment of the power jet to this side of the amplifier with open control port is not stable and the power jet will ejected immediately when it tends to the side.

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.



(a) A schematic of working principle, Tesař, 2017 (127)



(b) A fabricated sample, Tesař, 2014 (30)

Fig. 6. Resonance tube feedback channel fluidic oscillators

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.

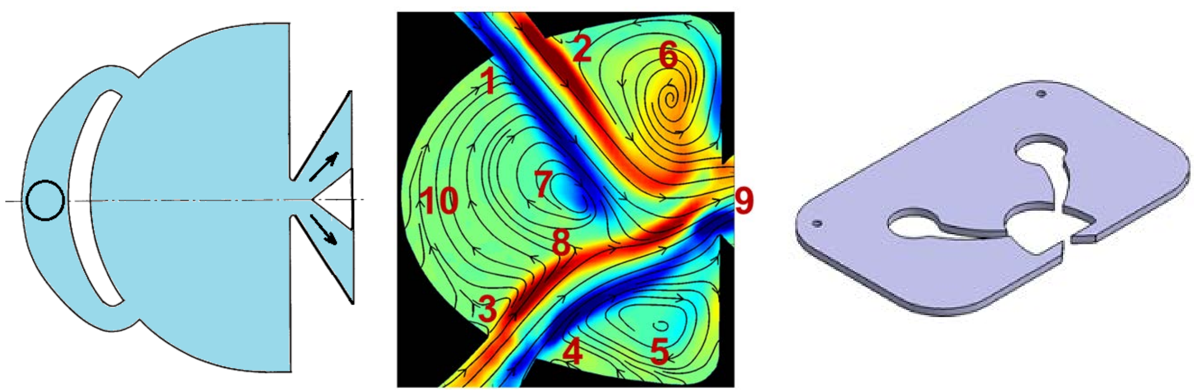
Tomac et al. (108) explained the physics and details of sweeping nature of the flow at the exit of feedback-free fluidic oscillator for low flow rates. Suppose that the upper jet's core is dominated the exit; now, the lower jet is bifurcated and a part of its kinetic energy transfers to the upper jet. 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.



(a) Raghu, 2001, US patent No. 6253782B1 (138)

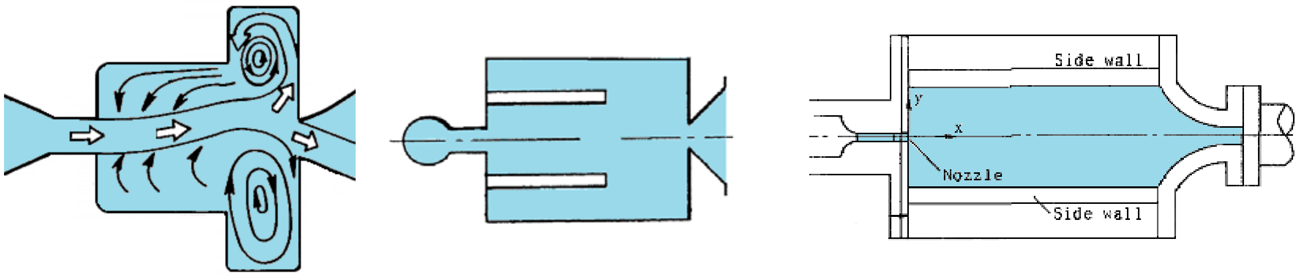
(b) Tomac & Gregory, 2014, Springer (108)

(c) Gregory & Tomac, 2014 (139)

Fig. 7. Feedback-free fluidic oscillator; (a) a design with splitter at exit, (b) streamlines in a working mode & (c) middle part of a fabrication

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.



(a) Kondo & et al., 1988, US patent No. 4721251(140) (b) Stouffer & Srinath, 1993, US patent No. 5181660 (141) (c) Shakouchi, 1989, ASME (125)

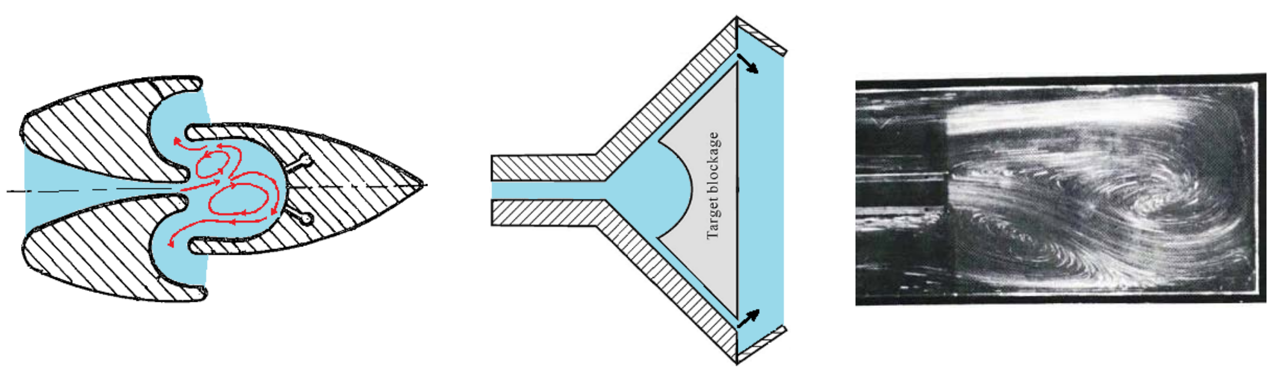
Fig. 8. Various designs of confined jet fluidic oscillators for applications of fluid dispersal devices (a & b) and flowmeters (c)

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.

The flow pattern is so unstable due to mutual effect of the branches on each 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.



(a) Bauer, 1981, US patent No. 4244230 (142) (b) Huang & Chang, 2007, ASME (145) (c) Shakouchi, 1981 (146)

Fig. 9. Various designs of cavity-jet fluidic oscillators for applications of flowmeter (a), and oscillatory flow creation (b & c)

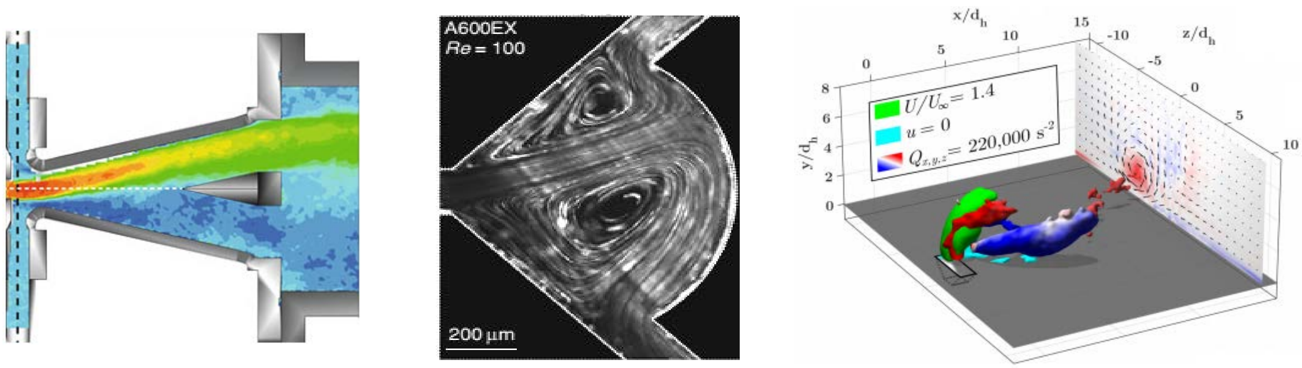
Finally, the dominant vortex locates on the center line and the defeated vortex blocks its corresponding exit. Now, almost all of the fluid flow discharges from the corresponding exit of the dominant vortex. Since the defeated vortex approached to the power jet so close and its corresponding exit has 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 minatory 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.



(a) Wassermann & et al., 2013, Springer (137)

(b) Sun & Sun, 2011, Springer (148)

(c) Ostermann & et al., 2016 (153)

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-ω SST) and solved using ANSYS-FLUENT/CFX commercial software.

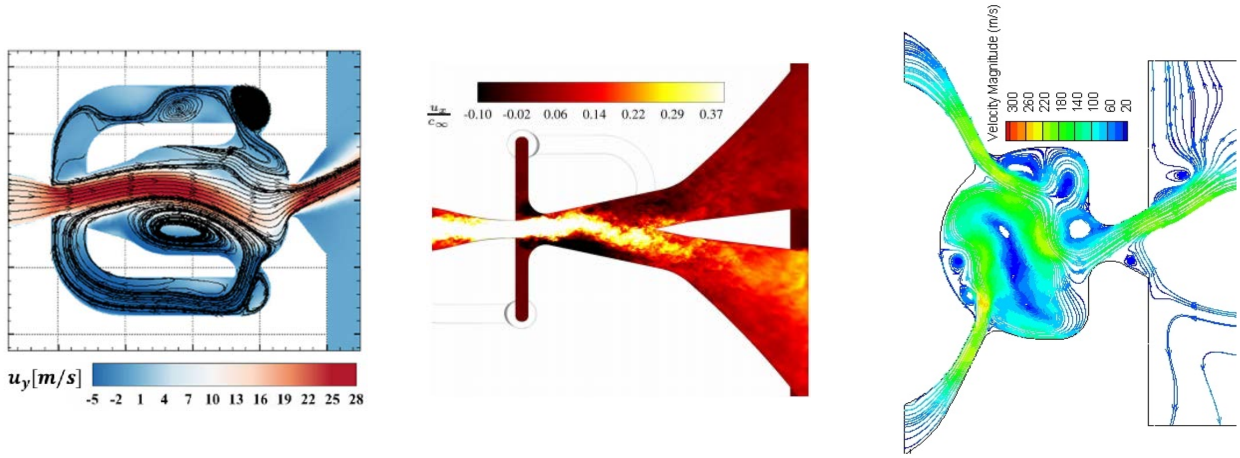
Kim and Moin (136) did large eddy simulation for internal flow field of a single feedback fluidic oscillator; Tomac et al. (115) and Meier et al. (156) simulated internal and external flow fields and changes of some affecting parameters of jet oscillation in feedback-free fluidic oscillators. Also, researches 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 1
A brief review of numerical simulations of fluidic oscillators.

Author	F.O.[1] Type	Numerical Method	Code/Software	Method	Re
Shakouchi (1981) (146)	Cavity-Jet	FDM-2D	Code	Laminar Solution	1000 < Re < 16000
Gebhard (1996) (110)	2F[2]	FEM	ANSYS/FLOTRAN	-	-
Nakayama (2005) (168)	2F	FVM - 2D	-	Laminar Solution	4400-12000
Sotero-Esteva (2007) (161)	2F	FEM – 2D	COMSOL 3.3	-	-
Gokoglu 2009) (163)	2F	FVM – 2D	Fluent 6	k-ω (SST)	-
Ries (2009) (169)	M & S[3] 2F	FVM-2D	ANSYS CFX-11	k-ω (SST)	420-19160
Kruger (2013) (164)	2F	FVM-2D,3D	ANSYS CFX 14.5	k-ω (SST)	16034
Li (2013) (165)	2F	FVM-3D	STORM/CFD2000	-	238-714
Kim (2014) (136)	1F[4]	FVM-3D	CharLES	LES	64000
Childs (2016) (155)	2F	FVM-3D	Overflow 2.2f	Unsteady SST-RANS & SST-D/DES	-
Hossain (2017) (170)	2F	FVM	FLUENT	k-ω SST	-
He (2015) (166)	2F	FVM	FLUENT	RNG k-ε	361678 < Re_{inlet} < 651405
Meier (2014) (156)	0F[5]	FVM-2D	ANSYS Fluent 14.5	k-ω SST	-
Iachachene (2015) (158)	Cavity-Jet	FVM-2D	Code	k-ω SST	2600 < Re < 8000
Hossain (2017) (167)	2F	FVM-D	FLUENT	k-ω SST	-
Lundgreen (2017) (171)	2F	FVM	-	k-ε v^2f	-
Xie (2017) (65)	2F	FVM-2D	ANSYS Fluent 14.5	-	16.7 < Re < 100

[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



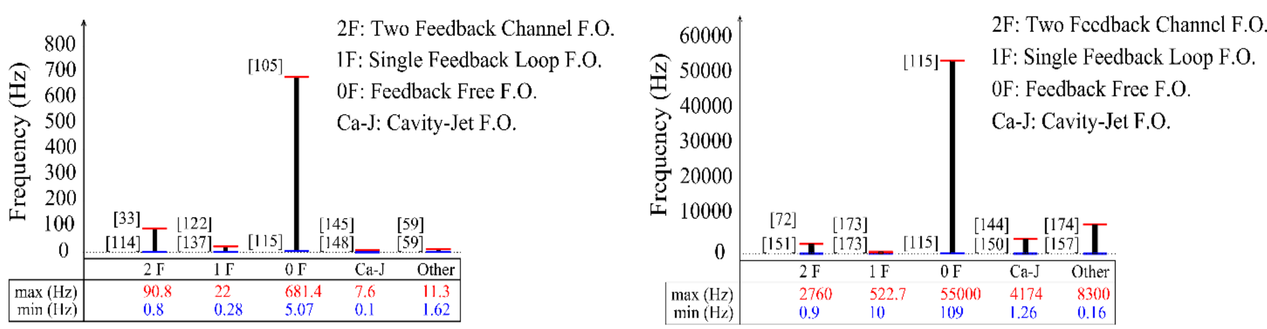
(a) Hossain & et al., 2017 (167)　　(b) Kim & Moin, 2014 (136)　　(c) Meier & Heister, 2015 (172)

Fig. 11. Numerical simulations for 2F, 1F and 0F fluidic oscillators; a) Time resolved velocity field and streamlines, b) Instantaneous contours of streamwise velocity, and c) Velocity magnitude streamlines

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 previewed fluidic oscillators resulted to Figures 12a and 12b for liquid and gas working fluids, respectively.



(a)　　(b)

Fig. 12. (a) Frequency limits obtained in various fluidic oscillators with liquid working fluids (b) Frequency limits obtained in various fluidic oscillators with gas working fluids

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 2
Correlations for oscillation's frequency in various feedback channel fluidic oscillators.

Authors	Correlation			Special Parameters
	F.O. Type	**Characteristic Length (mm)**	**Working fluid**	
Wilson (1970) (175)	$f = A + BQ$			A, B: geometry depended empirical constants
	2F		Water, Water-Ethylene Glycol Mixture, Bayol 35	
Tippetts (1973) (126)	$f = f_1 \cdot \frac{2\pi}{b}\sqrt{\frac{V_c L_c}{A_c}}\ St \cdot Ma;\ f_1 = \frac{a}{2\pi}\sqrt{\frac{A_c}{V_c L_c}}$			f_1: control loop critical low frequency, A_c: cross-sectional area of the control port, V_c: volume of the control loop, L_c: length of the control ports
	1F		Air, Water	
Simoes (2002) (111)	$f = \frac{1}{2(\tau_t + \tau_S)} = A + BQ$		N_2, Ar, CO_2	τ_t: transmission time, τ_S: switching time, A, B: empirical constants
	$f = \frac{1}{2\tau_S} = A + BQ$		Water, Alcohol, Acetone	
	2F		Gas & Liquid	
Seifert (2006) (22)	$f \approx \frac{r_v a}{2L(1 + r_v)}$			r_v: the ratio between the typical velocities in exit direction (port), L: length of resonance tube (Feedback tube)
	2F		Air, Water	
Cerretelli (2007) (112)	$f = \frac{1}{2\tau_S} = \frac{1}{2\frac{R_1 R_2 C}{R_1 + R_2}\ln\left(\frac{\Delta P}{(R_1 + R_2)\rho} + \Delta\dot{m}_S \Big/ \frac{\Delta P}{(R_1 + R_2)\rho} - \Delta\dot{m}_S\right)}$			R_1, R_1: fluid resistors in feedback channels, C: capacitor of fluidic oscillator, ΔP: pressure drop, $\Delta \dot{m}_S$: mass flow difference between switch-enacting and receiving branches
	2F		Air, Helium, Neon	
Arwatz (2008) (173)	$f = \frac{1}{2(\tau_{ac} + 0.36\tau_{LR})} = \frac{1}{2\left(\frac{l_f + 2l_c}{a} + \frac{0.52}{C}\sqrt{\frac{l_c \cdot d_c}{l_f \cdot d_f}}\frac{Q\rho(l_f + l_c)}{AP_c}\right)}$			τ_{ac}: the acoustic time delay, τ_{LR}: time constant of inductor-resistor circuit, l_c: channel length of valve's control port, C: a dimensionless empirical constant, d_c: valve control port channel width (diameter), A: cross-sectional area, P_c: control differential pressure
	1F		Air	
Ries (2009) (169)	$f = \frac{1000}{\ln(Re)},\quad 1.0 < Re < \infty$			
	master & Slave		Air	
Dennai (2012) (60)	$f = \frac{\sqrt{\gamma \cdot R}}{2 \cdot (l_b + 2 \cdot L_o)}\sqrt{T}$			γ: the ratio of specific capacities (1.4 for air), R: gas constant, L_0: outlet length
	2F		Gas	
Xu (2013) (119)	$f = 6.05\left(\frac{2\rho}{\mu}\frac{Q}{H+b}\right)^{\frac{-f}{3.30}} + 14.5\left(\frac{2\rho}{\mu}\frac{Q}{H+b}\right)^{\frac{-f}{0.859}} + 0.669$			
	2F	2, 4, 6, 8	Water	

Most of the presented correlations are derived from curve fittings of the experimental or theoretical results that researchers derived for their investigated fluidic oscillators and the correlations are not comprehensive for all types of fluidic oscillators or even for oscillators of that special kind unless it has a structured theoretical background for the involved time and length scales, turbulence levels, working fluid's thermo-physical properties, geometry, physical boundary conditions (at entrance, exit and walls) and involved main and lateral physical phenomena. However, the

Table 3
Correlations for oscillation's frequency in various fluidic oscillators without any feedback channel.

Authors	Correlation			Special Parameters
	F.O. Type	**Characteristic Length (mm)**	**Working fluid**	
Kelley (1967) (47)	$f = k \cdot T^{0.491};\ k = 13.34$			T: Temperature
	Positive feedback fluidic amplifier		Air	
Shakouchi (1989) (125)	$f = \frac{U}{b}St = \frac{U}{b}\cdot\left(c_1 + \frac{c_2}{Re}\right);\ c_1 = AR \cdot b^3 k_1,\ c_2 = \frac{b^2}{\nu}k_2$			k_1, k_2: empirical constants, AR: aspect ratio of the nozzle (h/W),
	Rectangular-shaped container		Water, Air	
Lalanne (2001) (176)	$f = \frac{U}{b}St = \frac{U}{b}\cdot\left(\frac{f_0 b^2}{\nu}\frac{1}{Re} + \frac{\alpha b^2}{\nu}\right) = \frac{U}{b}\cdot\left(\frac{\beta}{Re} + St_\infty\right)$			α: empirical constant, β: $f_0 d^2/\nu$ f_0: 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 ***
	Horse shoe chamber containing a horse shoe target		Air, Water	
Mataoui (2003) (157)	$f = \frac{u_a}{2\pi \times A\sqrt{8}},\quad u_a = \frac{1.2 \times U}{\sqrt{0.41 + 0.22(A/b)}}$			A: an empirical value (mean location of the impingement of the jet to the side wall)
	Confined jet in a rectangular cavity		Air	
Tesař (2009) (59)	$f = \frac{\beta U}{2b(\mu + \sigma)}$			β, σ, μ: geometrical non-dimensional constants,
	Colliding-jet valve	1.0, 3.4	Two immiscible liquids	

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.

REFERENCES

[1] Brown FT. A Combined Analytical and Experimental Approach to the Development of Fluid-Jet Amplifiers. Journal of Basic Engineering. 1964 Jun 1;86(2):175-82.

[2] Kirshner JM. Design theory of fluidic components. Academic Press; 2012 Dec 2.

[3] Reader TD, inventor; Sperry Corp, assignee. Pneumatic clock. United States patent US 3,159,168. 1964 Dec 1.

[4] Peter B, inventor; Sperry Corp, assignee.Binary counter stages having two fluid vortex amplifiers. United States patent US 3,193,197. 1965 Jul 6.

[5] Bowles RE, inventor. Differentiator comparator. United States patent US 3,238,959. 1966 Mar 8.

[6] Burns HL, inventor; RETEC Inc, assignee. Cycling valve. United States patent US 3,280,832. 1966 Oct 25.

[7] Freeman JD, inventor; General Time Corp, assignee. Fluid operated timer circuit. United States patent US 3,276,689. 1966 Oct 4.

[8] Bauer P, inventor; BOWLES ENG CORP, assignee. Oscillator and shower head for use therewith. United States patent US 3,563,462. 1971 Feb 16.

[9] Kakei J, Yamaguchi H, inventors;Nissan Motor Co Ltd, assignee. Defroster. United States patent US 3,832,939. 1974 Sep 3.

[10] Viets H, inventor; US Air Force, assignee. Thrust augmentation system with oscillating jet nozzles. United States patent US 3,926,373. 1975 Dec 16.

[11] Bowles RE, inventor; Bowles Romald E, assignee. Acceleration controlled fluidic shock absorber. United States patent US 4,082,169. 1978 Apr 4.

[12] Bauer P, inventor; Bowles Fluidics Corp, assignee. Fluidic spray device of simple construction. United States patent US 4,185,777. 1980 Jan 29.

[13] Bray Jr HC, inventor; Bowles Fluidics Corp, assignee. Cold weather fluidic fan spray devices and method. United States patent US 4,463,904. 1984 Aug 7.

[14] Stouffer RD, inventor; Bowles Fluidics Corp, assignee. Novel inertance loop construction for air sweep fluidic oscillator. United States patent US 4,694,992. 1987 Sep 22.

[15] Mon G, inventor; US Secretary of Army, assignee. Pulsatile impinging cooling system for electronic IC modules and systems using fluidic oscillators. United States patent US 5,190,099. 1993 Mar 2.

[16] DeMarche TE, Abreu ME, inventors; General Electric Co, assignee. Pulse-cooled gas turbine engine assembly. United States patent US 5,397,217. 1995 Mar 14.

[17] Sutton TG, inventor; Honeywell International Inc, assignee. Fluidic feedback-controlled liquid cooling module. United States patent US 5,815,370. 1998 Sep 29.

[18] Srinath DN, Stouffer RD, inventors; Bowles Fluidics Corp, assignee. Fluidic SPA Nozzles with dual operating modes and methods. United States patent US 6,729,564. 2004 May 4.

[19] Stouffer RD, inventor; Bowles Fluidics Corp, assignee. Means for generating oscillating fluid jets having specified flow patterns. United States patent US 6,805,164. 2004 Oct 19.

[20] Hester R, Crockett S, Thurber Jr JW, Schloer K, inventors; Bowles Fluidics Corp, assignee. Fluidic spa nozzle. United States patent US 6,904,626. 2005 Jun 14.

[21] Cerretelli C, Kirtley KR, inventors; General Electric Co, assignee. Method and system for flow control with fluidic oscillators. United States patent US 7,128,082. 2006 Oct 31.

[22] Seifert A, Pastuer S, inventors; Ramot at Tel Aviv University Ltd, assignee. Method and mechanism for producing suction and periodic excitation flow. United States patent US 7,055,541. 2006 Jun 6.

[23] Fallet T, inventor; Sinvent AS, assignee. Means for measuring fluid flow in a pipe. United States patent US 7,464,609. 2008 Dec 16.

[24] Oskam GW, inventor; Solar Turbines Inc, assignee. Fuel injector system with fluidic oscillator. United States patent application US 13/362,189. 2013 Aug 1.

[25] Vaidya AS, inventor. Fluidic oscillator flow meter. United States patent US 8,091,434. 2012 Jan 10.

[26] Raghu S, inventor. Method and apparatus for aero-dynamic flow control using compact high-frequency fluidic actuator arrays. United States patent US 8,382,043. 2013 Feb 26.

[27] Schultz RL, Pipkin RL, Cavender TW, Skinner NG, inventors; Halliburton Energy Services Inc, assignee. Fluidic oscillator flowmeter for use with a subterranean well. United States patent US 8,573,066. 2013 Nov 5.

[28] Tesař V. "Master and Slave" fluidic amplifier cascade. InEPJ Web of Conferences 2012 (Vol. 25, p. 01093). EDP Sciences.

[29] Liu H, Yin K, Peng JM, Yin QL. Fracture failure analysis of baseplates in a fluidic amplifier made of WC-11Co cemented carbide. Frattura ed Integrità Strutturale: Annals 2014: Fracture and Structural Integrity: Annals 2014. 2014 Jan 1;8.

[30] Tesař V, Smyk E, Peszynski K. Fluidic oscillator with bi-stable turn-down amplifier. In Colloquium Fluid Dynamics 2014 (Vol. 2014, pp. 1-14).

[31] Schadow KC, Gutmark E.Combustion instability related to vortex shedding in dump combustors and their passive control. Progress in Energy and Combustion Science. 1992 Jan 1;18(2):117-32.

[32] Guyot D, Bobusch B, Paschereit CO, Raghu S. Active combustion control using a fluidic oscillator for asymmetric fuel flow modulation. In44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit 2008 Jul (p. 4956).

[33] Bobusch BC, Berndt P, Paschereit CO, Klein R. Investigation of fluidic devices for mixing enhancement for the shockless explosion combustion process. InActive Flow and Combustion Control 2014 2015 (pp. 281-297). Springer, Cham.

[34] Meier E, Casiano MJ, Anderson WE, Heister SD. Investigation of combustion control in a dump combustor using the feedback free fluidic oscillator.

In51st AIAA/SAE/ASEE Joint Propulsion Conference 2015 (p. 4209).

[35] Gokoglu S, Kuczmarski M, Culley D, Raghu S. Numerical studies of an array of fluidic diverter actuators for flow control. In41st AIAA Fluid Dynamics Conference and Exhibit 2011 Nov 1 (p. 3100).

[36] Mack M, Niehuis R, Fiala A. Parametric Study of Fluidic Oscillators for Use in Active Boundary Layer Control. InASME 2011 Turbo Expo: Turbine Technical Conference and Exposition 2011 Jan 1 (pp. 469-479). American Society of Mechanical Engineers.

[37] Woszidlo R, Wygnanski I. Parameters governing separation control with sweeping jet actuators. In29th AIAA Applied Aerodynamics Conference 2011 Jun (p. 3172).

[38] Choephel T, Coder J, Maughmer M. Airfoil Boundary-Layer Flow Control Using Fluidic Oscillators. In30th AIAA Applied Aerodynamics Conference 2012 (p. 2655).

[39] Seele R, Graff E, Gharib M, Taubert L, Lin J,Wygnanski I. Improving rudder effectiveness with sweeping jet actuators. In6th AIAA Flow Control Conference 2012 Jun (p. 3244).

[40] Mack M, Niehuis R, Fiala A, Guendogdu Y. Boundary layer control on a low pressure turbine blade by means of pulsed blowing. Journal of Turbomachinery. 2013 Sep 1;135(5):051023.

[41] Tesař V, Zhong S, Rasheed F. New fluidic-oscillator concept for flow-separation control. AIAA journal. 2013 Feb 19;51(2):397-405.

[42] Wilson J, Schatzman D, Arad E, Seifert A, Shtendel T. Suction and pulsed-blowing flow control applied to an axisymmetric body. AIAA journal. 2013 Aug 6;51(10):2432-46.

[43] Shtendel T, Seifert A. Three-dimensional aspects of cylinder drag reduction by suction and oscillatory blowing. International journal of heat and fluid flow. 2014 Feb 1;45:109-27.

[44] Woszidlo R, Stumper T, Nayeri C, Paschereit CO. Experimental study on bluff body drag reduction with fluidic oscillators. In52nd Aerospace Sciences Meeting 2014 (p. 0403).

[45] Andino MY, Lin JC, Washburn AE, Whalen EA, Graff EC, Wygnanski IJ. Flow separation control on a full-scale vertical tail model using sweeping jet actuators. In53rd AIAA Aerospace Sciences Meeting 2015 (p. 0785).

[46] Schmidt HJ, Woszidlo R, Nayeri C, Paschereit CO. Fluidic oscillators for bluff body drag reduction in water. In54th AIAA Aerospace Sciences Meeting 2016 (p. 0591).

[47] Kelley LR. A fluidic temperature control using frequency modulation and phase discrimination. Journal of Basic Engineering. 1967 Jun 1;89(2):341-8.

[48] OTSAP B, YANKURA G. A fluidic fuel control system for an advanced ramjet engine. In3rd Propulsion Joint Specialist Conference 1967 Jul (p. 497).

[49] Davies GE. Fluidics in aircraft engine controls. Journal of Dynamic Systems, Measurement, and Control. 1981 Dec 1;103(4):324-30.

[50] Raman G, Rice EJ, Cornelius DM. Evaluation of flip-flop jet nozzles for use as practical excitation devices. Journal of fluids engineering. 1994 Sep 1;116(3):508-15.

[51] Haines RW, Hittle DC. Control systems for heating, ventilating, and air conditioning. Springer Science & Business Media; 2006 Jan 19.

[52] Tesař V, Šonský J. Plasma-discharge control in fluidics. InProc. of Conf.'Topical Problems of Fluid Mechanics 2015' 2015 (pp. 221-236).

[53] Cascetta F, Vigo P. The future domestic gas meter: Review of current developments. Measurement. 1994 Apr 1;13(2):129-45.

[54] Sanderson ML. Domestic water metering technology. Flow Measurement and Instrumentation. 1994 Apr 1;5(2):107-13.

[55] Wang H, Beck SB, Priestman GH, Boucher RF. Fluidic pressure pulse transmitting flowmeter. Chemical Engineering Research and Design. 1997 May 1;75(4):381-91.

[56] Yamamoto K, Hiroki F, Hyodo K. Self-sustained oscillation phenomena of fluidic flowmeters. Journal of visualization. 1999 Dec 1;1(4):387-96.

[57] Martinelli M, Viktorov V. A mini fluidic oscillating flowmeter. Flow Measurement and Instrumentation. 2011 Dec 1;22(6):537-43.

[58] Meng X, Xu C, Yu H. Feedback fluidic flowmeters with curved attachment walls. Flow Measurement and Instrumentation. 2013 Apr 1;30:154-9.

[59] Tesař V. Oscillator micromixer. Chemical Engineering Journal. 2009 Dec 15;155(3):789-99.

[60] Brahim D, Rachid K, Boumédiène B, Asma A. Flow control mono and bi-stable fluidic device for micromixer-injection system. Energy Procedia. 2012 Jan 1;18:571-80.

[61] Hanotu J, Bandulasena HH, Chiu TY, Zimmerman WB. Oil emulsion separation with fluidic oscillator generated microbubbles. International Journal of Multiphase Flow. 2013 Oct 1;56:119-25.

[62] Dennai B, Bentaleb A, Chekifi T, Khelfaoui R, Abdenbi A. Micro Fluidic Oscillator: A Technical Solution for Micro Mixture. InAdvanced Materials Research 2015 (Vol. 1064, pp. 213-218). Trans Tech Publications.

[63] Xu C, Chu Y. An oscillating feedback microextractor with asymmetric feedback channels. Chemical Engineering Journal. 2014 Oct 1;253:438-47.

[64] Abdulrazzaq N, Al-Sabbagh B, Rees JM, Zimmerman WB. Separation of azeotropic mixtures using air microbubbles generated by fluidic oscillation. AIChE Journal. 2016 Apr;62(4):1192-9.

[65] Xie T, Xu C. Numerical and experimental investigations of chaotic mixing behavior in an oscillating feedback

micromixer. Chemical Engineering Science. 2017 Nov 2;171:303-17.

[66] Zimmerman WB, Hewakandamby BN, Tesař V, Bandulasena HH, Omotowa OA. On the design and simulation of an airlift loop bioreactor with microbubble generation by fluidic oscillation. Food and Bioproducts Processing. 2009 Sep 1;87(3):215-27.

[67] Zimmerman WB, Tesař V, Bandulasena HH. Towards energy efficient nanobubble generation with fluidic oscillation. Current Opinion in Colloid & Interface Science. 2011 Aug 1;16(4):350-6.

[68] Zimmerman WB, Zandi M, Bandulasena HH, Tesař V, Gilmour DJ, Ying K. Design of an airlift loop bioreactor and pilot scales studies with fluidic oscillator induced microbubbles for growth of a microalgae Dunaliella salina. Applied Energy. 2011 Oct 1;88(10):3357-69.

[69] Tesař V. Microbubble generator excited by fluidic oscillator's third harmonic frequency. Chemical Engineering Research and Design. 2014 Sep 1;92(9):1603-15.

[70] Tesař V. Mechanisms of fluidic microbubble generation Part II: Suppressing the conjunctions. Chemical Engineering Science. 2014 Sep 6;116:849-56.

[71] Rehman F, Medley GJ, Bandulasena H, Zimmerman WB. Fluidic oscillator-mediated microbubble generation to provide cost effective mass transfer and mixing efficiency to the wastewater treatment plants. Environmental research. 2015 Feb 1;137:32-9.

[72] Raman G, Raghu S. Cavity resonance suppression using miniature fluidic oscillators. AIAA journal. 2004 Dec;42(12):2608-12.

[73] Raman G, Cain AB. Innovative actuators for active flow and noise control. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering. 2002 Jun 1;216(6):303-24.

[74] Viets H. Flip-flop jet nozzle. AIAA journal. 1975 Oct;13(10):1375-9.

[75] VIETS H, BALSTER D, TOMS, JR H. Time dependent fuel injectors. In11th Propulsion Conference 1975 Oct (p. 1305).

[76] Morris GJ, Jurewicz JT, Palmer GM. Gas-solid flow in a fluidically oscillating jet. Journal of fluids engineering. 1992 Sep 1;114(3):362-6.

[77] Raman G, Hailye M, Rice EJ. Flip-flop jet nozzle extended to supersonic flows. AIAA journal. 1993 Jun;31(6):1028-35.

[78] Trávníček Z, Peszyński K, Hošek J, Wawrzyniak S. Aerodynamic and mass transfer characteristics of an annular bistable impinging jet with a fluidic flip–flop control. International journal of heat and mass transfer. 2003 Mar 1;46(7):1265-78.

[79] Tesař V. New concept: Low-pressure, wide - angle atomiser. Chemical Engineering and Processing: Process Intensification. 2014 Aug 1;82:19-29.

[80] Tesař V, Hung CH, Zimmerman WB. No-moving-part hybrid-synthetic jet actuator. Sensors and Actuators A: Physical. 2006 Jan 10;125(2):159-69.

[81] Tesař V. Configurations of fluidic actuators for generating hybrid-synthetic jets. Sensors and Actuators A: Physical. 2007 Aug 26;138(2):394-403.

[82] Tesař V, Trávníček Z, Kordik J, Randa Z. Experimental investigation of a fluidic actuator generating hybrid-synthetic jets. Sensors and Actuators A: Physical. 2007 Jul 20;138(1):213-20.

[83] Kowal HJ. Advances in thrust vectoring and the application of flow-control technology. Canadian aeronautics and space journal. 2002 Jun 1;48(2):145-51.

[84] Raman G, Packiarajan S, Papadopoulos G, Weissman C, Raghu S. Jet thrust vectoring using a miniature fluidic oscillator. The Aeronautical Journal. 2005 Mar;109(1093):129-38.

[85] Gregory J, Ruotolo J, Byerley A, McLaughlin T. Switching behavior of a plasma-fluidic actuator. In45th AIAA Aerospace Sciences Meeting and Exhibit 2007 Jan (p. 785).

[86] Halbach CR, Otsap BA, Thomas RA. FLUIDIC (PURE FLUID) TEMPERATURE SENSOR. Phase I Final Technical Report. Report 25, 212. Astro, Van Nuys, Calif.; 1967 Jan 1.

[87] Bogue RK, Webb LD. Advanced air data sensing techniques.

[88] Black JI, inventor; Avco Corp, assignee. Signal error compensated fluidic oscillator temperature sensors. United States patent US 3,585,858. 1971 Jun 22.

[89] Riddlebaugh SM. Use of fluidic oscillator to measure fuel-air ratios of combustion gases.

[90] Gregory J, Sakaue H, Sullivan J. Fluidic oscillator as a dynamic calibration tool. In22nd AIAA Aerodynamic Measurement Technology and Ground Testing Conference 2002 (p. 2701).

[91] Ramírez JI, Tonner F, Bindel A. Fluidic oscillations as energy source for flow sensors. Proceedings of Power MEMS. 2008:9-12.

[92] Tesar V. Fluidic valve for reactor regeneration flow switching. Chemical Engineering Research and Design. 2004;82(A3):398-408.

[93] Tesar V. Fluidic valves for variable-configuration gas treatment. Chemical Engineering Research and Design. 2005;83(A9):1111-21.

[94] Tesař V. Valve - less rectification pumps.In Encyclopedia of Microfluidics and Nanofluidics 2015 (pp. 3399-3415). Springer, New York, NY.

[95] Tesař V. Safe pumping of hazardous liquids—A survey of no-moving-part pump principles. Chemical Engineering Journal. 2011 Mar 15;168(1):23-34.

[96] Tesař V, Bandalusena HC. Bistable diverter valve in microfluidics. Experiments in Fluids. 2011 May 1;50(5):1225-33.

[97] Martin ND, Bottomley M, Packwood A. Switching of a Bistable Diverter Valve with Synthetic Jet Actuators. AIAA journal. 2014 May 12;52(7):1563-8.

[98] Galle EM, Woods HB, inventors; Hughes Tool Co, assignee. Drilling methods and apparatus employing out-of-phase pressure variations in a drilling fluid. United States patent US 3,441,094. 1969 Apr 29.

[99] Funke MF, inventor; US Secretary of Army, assignee. Fluidic mud pulse data transmission apparatus. United States patent US 4,134,100. 1979 Jan 9.

[100] Holmes AB, inventor; US Secretary of Army, assignee. Fluidic pulser. United States patent US 4,276,943. 1981 Jul 7.

[101] Holmes AB. The Fluidic Approach to Mud Pulser Valve Design for Measurement-While-Drilling Applications. HARRY DIAMOND LABS ADELPHI MD; 1985 Nov.

[102] Webb ED, Schultz RL, Howard RG, Tucker JC. Next generation fluidic oscillator. InSPE/ICoTA Coiled Tubing Conference & Exhibition 2006 Jan 1. Society of Petroleum Engineers.

[103] Zhang X, Peng J, Ge D, Bo K, Yin K, Wu D. Performance study of a fluidic hammer controlled by an output-fed bistable fluidic oscillator. Applied Sciences. 2016 Oct 20;6(10):305.

[104] Tesař V. Enhancing impinging jet heat or mass transfer by fluidically generated flow pulsation. Chemical Engineering Research and Design. 2009 Feb 1;87(2):181-92.

[105] Narumanchi S, Kelly K, Mihalic M, Gopalan S, Hester R, Vlahinos A. Single-phase self-oscillating jets for enhanced heat transfer. InSemiconductor Thermal Measurement and Management Symposium, 2008. Semi-Therm 2008. Twenty-fourth Annual IEEE 2008 Mar 16 (pp. 154-162). IEEE.

[106] Warren RW, inventor. Fluid oscillator. United States patent US 3,016,066. 1962 Jan 9.

[107] Yeaple F. Fluid power design handbook. CRC Press; 1995 Oct 24.

[108] Tomac MN, Gregory JW. Internal jet interactions in a fluidic oscillator at low flow rate. Experiments in Fluids. 2014 May 1;55(5):1730.

[109] Denshchikov VA, Kondrat'ev VN, Romashov AN. Interaction between two opposed jets. Fluid Dynamics. 1978 Nov 1;13(6):924-6.

[110] Gebhard U, Hein H, Schmidt U.Numerical investigation of fluidic micro-oscillators. Journal of Micromechanics and Microengineering. 1996 Mar;6(1):115.

[111] Simões EW, Furlan R, Pereira MT. Numerical analysis of a microfluidic oscillator flowmeter operating with gases or liquids. InTechnical Proceedings of the 2002 International Conference on Modeling and Simulation of Microsystems 2002 Apr (Vol. 1, pp. 36-39).

[112] Cerretelli C, Gharaibah E. An experimental and numerical investigation on fluidic oscillators for flow control. In37th AIAA Fluid Dynamics Conference and Exhibit 2007 Jun (p. 3854).

[113] Yang JT, Chen CK, Hu IC, Lyu PC. Design of a self-flapping microfluidic oscillator and diagnosis with fluorescence methods. Journal of microelectromechanical systems. 2007 Aug;16(4):826-35.

[114] Yang JT, Chen CK, Tsai KJ, Lin WZ, Sheen HJ. A novel fluidic oscillator incorporating step-shaped attachment walls. Sensors and Actuators A: Physical. 2007 Apr 15;135(2):476-83.

[115] Tomac MN, Gregory J. Frequency studies and scaling effects of jet interaction in a feedback-free fluidic oscillator. In50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition 2012 Jan (p. 1248).

[116] Bobusch BC, Woszidlo R, Bergada JM, Nayeri CN, Paschereit CO. Experimental study of the internal flow structures inside a fluidic oscillator. Experiments in fluids. 2013 Jun 1;54(6):1559.

[117] Raghu S. Fluidic oscillators for flow control. Experiments in Fluids. 2013 Feb 1;54(2):1455.

[118] Tesař V, Peszynski K. Strangely behaving fluidic oscillator. InEPJ Web of Conferences 2013 (Vol. 45, p. 01074). EDP Sciences.

[119] Xu C, Meng X. Performance characteristic curve insensitive to feedback fluidic oscillator configurations. Sensors and Actuators A: Physical. 2013 Jan 15;189:55-60.

[120] Ostermann F, Woszidlo R, Nayeri C, Paschereit CO. Experimental comparison between the flow field of two common fluidic oscillator designs. In53rd AIAA aerospace sciences meeting 2015 (p. 0781).

[121] Woszidlo R, Ostermann F, Nayeri CN, Paschereit CO. The time-resolved natural flow field of a fluidic oscillator. Experiments in fluids. 2015 Jun 1;56(6):125.

[122] McDonough JR, Law R, Kraemer J, Harvey AP. Effect of geometrical parameters on flow-switching frequencies in 3D printed fluidic oscillators containing different liquids. Chemical Engineering Research and Design. 2017 Jan 1;117:228-39.

[123] Vondell C, inventor; US Secretary of Army, assignee. Flueric temperature sensor. United States patent US 3,667,297. 1972 Jun 6.

[124] Dumas A, Subhash M, Trancossi M, Marques JP. The influence of surface temperature on Coanda effect. Energy Procedia. 2014 Jan 1;45:626-34.

[125] Shakouchi T. A new fluidic oscillator, flowmeter, without control port and feedback loop. Journal of Dynamic Systems, Measurement, and Control. 1989 Sep 1;111(3):535-9.

[126] Tippetts JR, Ng HK, Royle JK. A fluidic flowmeter. Automatica. 1973 Jan 1;9(1):35-45.

[127] Tesař V. Taxonomic trees of fluidic oscillators. InEPJ Web of Conferences 2017 (Vol. 143, p. 02128). EDP Sciences.

[128] Tesař V. Microbubble generation by fluidics. Part I: development of the oscillator. InColloquium Fluid Dynamics 2012.

[129] Gregory J, Tomac MN. A review of fluidic oscillator development. In43rd AIAA Fluid Dynamics Conference 2013 (p. 2474).

[130] Rockwell D, Naudascher E. Self-sustaining oscillations of flow past cavities. Journal of Fluids Engineering. 1978 Jun 1;100(2):152-65.

[131] Henri C, inventor. Device for deflecting a stream of elastic fluid projected into an elastic fluid. United States patent US 2,052,869. 1936 Sep 1.

[132] Henri C, inventor. Atomizers. United States patent US 2,713,510. 1955 Jul 19.

[133] Turpin JL.Use of Streaming Potential Measurements for an Investigation of the Coanda Effect. The Physics of Fluids. 1972 Jun;15(6):968-71.

[134] Warren RW, inventor. Negative feedback oscillator. United States patent US 3,158,166. 1964 Nov 24.

[135] Zimmerman WB. Electrochemical microfluidics. Chemical Engineering Science. 2011 Apr 1;66(7):1412-25.

[136] Kim J, Moin P. Detailed simulation of turbulent flow within a suction and oscillatory blowing fluidic actuator. Center for Turbulence Research Annual Research Briefs. 2014.

[137] Wassermann F, Hecker D, Jung B, Markl M, Seifert A, Grundmann S. Phase-locked 3D3C-MRV measurements in a bi-stable fluidic oscillator. Experiments in fluids. 2013 Mar 1;54(3):1487.

[138] Raghu S, inventor; Bowles Fluidics Corp, assignee. Feedback-free fluidic oscillator and method. United States patent US 6,253,782. 2001 Jul 3.

[139] Tomac MN, Gregory JW. Internal flow physics of a fluidic oscillator in the transition regime. Active Flow & Combustion Control AFCC. 2014 Oct.

[140] Kondo Y, Miura K, Maeda O, Kuroyanagi M, Oshiro T, inventors; Denso Corp, Nippon Soken Inc, assignee. Fluid dispersal device. United States patent US 4,721,251. 1988 Jan 26.

[141] Stouffer RD, Srinath D, inventors; Bowles Fluidics Co-rp, assignee. Low cost, low pressure, feedback passage-free fluidic oscillator with stabilizer. United States patent US 5,181,660. 1993 Jan 26.

[142] Bauer P, inventor. Fluidic oscillator flowmeter. United States patent US 4,244,230. 1981 Jan 13.

[143] Lee GB, Kuo TY, Wu WY. A novel micromachined fl-ow sensor using periodic flapping motion of a planar jet impinging on a V-shaped plate. Experimental Thermal and Fluid Science. 2002 Jul 1;26(5):435-44.

[144] Huang RF, Chang KT. Fluidic oscillation influences on v-shaped bluffbody flow. AIAA journal. 2005 Nov;43(11):2319-28.

[145] Huang RF, Chang KT. Evolution and turbulence properties of self-sustained transversely oscillating flow induced by fluidic oscillator. Journal of Fluids Engineering. 2007 Aug 1;129(8):1038-47.

[146] Shakouchi T.An experimental study on the cavity type fluidic oscillator. Research Reports of the Faculty of Engineering, Mie University, Japan. 1981 Dec 21;6:1-3.

[147] Stouffer RD, Santamarina A, inventors; Bowles Flu-idics Corp, assignee. Fluidic oscillator and method. United States patent US 7,134,609. 2006 Nov 14.

[148] Sun CL, Sun CY. Effective mixing in a microfluidic oscillator using an impinging jet on a concave surface. Microsystem technologies. 2011 Jun 1;17(5-7):911-22.

[149] Koklu M, Owens LR. Flow Separation Control Over a Ramp Using Sweeping Jet Actuators. In7th AIAA Flow Control Conference 2014 (p. 2367).

[150] Uzol O, Camci C. Experimental and computational visualization and frequency measurements of the jet oscillation inside a fluidic oscillator. Journal of Visualization. 2002 Sep 1;5(3):263-72.

[151] Gaertlein S, Woszidlo R, Ostermann F, Nayeri C, Paschereit CO. The time-resolved internal and external flow field properties of a fluidic oscillator. In52nd Aerospace Sciences Meeting 2014 (p. 1143).

[152] Hassaballa M, Ziada S.Self-excited oscillations of two opposing planar air jets. Physics of Fluids. 2015 Jan;27(1):014109.

[153] Ostermann F, Woszidlo R, Nayeri C, Paschereit CO. The time-resolved flow field of a jet emitted by a fluidic oscillator into a crossflow. In54th AIAA Aerospace Sciences Meeting 2016 (p. 0345).

[154] Gregory JW, Sakaue H, Sullivan JP, Raghu S. Characterization of miniature fluidic oscillator flowfields using porous pressure sensitive paint. InProceedings ASME Fluids Engineering Division Summer Meeting, New Orleans, LA, USA 2001 (Vol. 29).

[155] Childs RE, Stremel PM, Kushner LK, Heineck JT, Storms BL. Simulation of sweep-jet flow control, single jet and full vertical tail. In54th AIAA Aerospace Sciences Meeting 2016 (p. 0569).

[156] Meier E, Heister SD. Computational Characterization of the Feedback Free Fluidic Oscillator. In50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference 2014 (p. 3583).

[157] Mataoui A, Schiestel R, Salem A. Study of the oscillatory regime of a turbulent plane jet impinging in a rectangular cavity. Applied Mathematical Modelling. 2003 Feb 1;27(2):89-114.

[158] Iachachene F, Mataoui A, Halouane Y. Numerical investigations on heat transfer of self-sustained oscillation of a turbulent jet flow inside a cavity. Journal of Heat Transfer. 2015 Oct 1;137(10):101702.

[159] Uzol O, Camci C. Oscillator fin as a novel heat transfer augmentation device for gas turbine cooling applications. InASME 1998 International Gas Turbine and Aeroengine Congress and Exhibition 1998 Jun 2 (pp. V004T09A032-V004T09A032). American Society of Mechanical Engineers.

[160] Uzol O, Camci C. Oscillator fin as a novel heat transfer augmentation device for gas turbine cooling applications. InASME 1998 International Gas Turbine and Aeroengine Congress and Exhibition 1998 Jun 2 (pp. V004T09A032-V004T09A032). American Society of Mechanical Engineers.

[161] Sotero-Esteva JO, Furlan R, Santiago-Avilés JJ. On the relation between geometric and flow properties of a miniaturized fluid oscillator. Computational Methods and Experimental Measurements XIII. 2007;46:297.

[162] Wang CY, Zou J, Fu X, Yang HY. Study on hydrodynamic vibration in fluidic flowmeter. Journal of Zhejiang University-SCIENCE A. 2007 Aug 1;8(9):1422-8.

[163] Gokoglu S, Kuczmarski M, Culley D, Raghu S. Numerical studies of a fluidic diverter for flow control. In39th AIAA Fluid Dynamics Conference 2009 Jun (p. 4012).

[164] Krüger O, Bobusch BC, Woszidlo R, Paschereit CO. Numerical Modeling and Validation of the Flow in a Fluidic Oscillator. In21st AIAA Computational Fluid Dynamics Conference 2013 (p. 3087).

[165] Yanrong L, Someya S, Koso T, Aramaki S,Okamoto K. Characterization of periodic flow structure in a small-scale feedback fluidic oscillator under low-Reynolds-number water flow. Flow Measurement and Instrumentation. 2013 Oct 1;33:179-87.

[166] He JF, Yin K, Peng JM, Zhang XX, Liu H, Gan X . Design and feasibility analysis of a fluidic jet oscillator with application to horizontal directional well drilling. Journal of Natural Gas Science and Engineering. 2015 Nov 1;27:1723-31.

[167] Hossain MA, Prenter R, Agricola L, Lundgreen RK, Ameri A, Gregory JW, Bons JP. Effects of Roughness on the Performance of Fluidic Oscillators. In55th AIAA Aerospace Sciences Meeting 2017 (p. 0770).

[168] Nakayama A, Kuwahara F, Kamiya Y. A two-dimensional numerical procedure for a three dimensional internal flow through a complex passage with a small depth (its application to numerical analysis of fluidic oscillators). International Journal of Numerical Methods for Heat & Fluid Flow. 2005 Dec 1;15(8):863-71.

[169] Ries T, Mohr F, Baumann J, Rose M, Rist U, Raab I, Staudacher S. LP turbine laminar separation with actuated transition: DNS, experiment and fluidic oscillator CFD. InASME Turbo Expo 2009: Power for Land, Sea, and Air 2009 Jan 1 (pp. 917-927). American Society of Mechanical Engineers.

[170] Hossain MA, Prenter R, Lundgreen RK, Agricola L, Ameri A, Gregory JW, Bons JP. Investigation of Crossflow Interaction of an Oscillating Jet. In55th AIAA Aerospace Sciences Meeting 2017 (p. 1690).

[171] Lundgreen RK, Hossain MA, Prenter R, Bons JP, Gregory JW, Ameri A. Impingement heat transfer characteric of a sweeping jet. In55th AIAA Aerospace Sciences Meeting 2017 (p. 1535).

[172] Meier EJ, Heister SD. Influence of Chamber Geometry and Operating Conditions on the Performance of Feedback-Free Fluidic Oscillators. International Journal of Flow Control. 2015 Jun 1;7.

[173] Arwatz G, Fono I, Seifert A. Suction and oscillatory blowing actuator modeling and validation. AIAA journal. 2008 May;46(5):1107-17.

[174] Tesař V. High-frequency fluidic oscillator.Sensors and Actuators A: Physical. 2015 Oct 1;234:158-67.

[175] Wilson MP, Coogan CH, Southall K. Experimental investigation of a fluidic volume flowmeter. Journal of Basic Engineering. 1970 Mar 1;92(1):139-42.

[176] Lalanne L, Le Guer Y, Creff R.Dynamics of a bifurcating flow within an open heated cavity. International Journal of Thermal Sciences. 2001 Jan 1;40(1):1-0.