Copyright © 2018 Tech Science Press FDMP, vol.14, no.3, pp.201-212, 2018

Effect of Geometrical Parameters on Vortex Fluidic Oscillators Operating with Gases and Liquids

T. Chekifi[1, 2, *], B. Dennai[2] and R. Khelfaoui[2]

Abstract: The fluidic oscillator is an interesting device developed for passive flow measurement. These microsystems can produce a high oscillating jet frequency with high flow velocity. The main advantages of fluidic oscillators are that no moving parts is included in the device. Commercial CFD code FLUENT was used to perform analysis of flows in fluidic oscillator. Numerical simulations were carried out for different flow conditions, where water and air were used as working fluids. The oscillation frequencies were identified by the discrete fast Fourier transform method (FFT). Furthermore a low-pressure vortex of fluid flow in the oscillating chamber was observed. The effect of the operating pressure and the oscillating chamber shape on the fluidic oscillator performance is investigated. Moreover the velocity fluctuations of the feedback flows through both feedback channels and the output were determined quantitatively. In addition, the behaviour of the low-pressure vortex in both models is analysed. Also, numerical result revealed small vortices are developed at the end of nozzle while oscillation, which maintains the deflection of jet flow between attachments wall. Comparison of our numerical simulations with available results showed reasonably and good agreement.

Keywords: Fluidic oscillator, CFD, oscillating chamber, vortex, size effect, Coanda effect.

Nomenclature

f: Frequency (Hz)

R: Rayon (mm)

L: Length (mm)

u: Velocity (m/s)

n: Unit vector normal to the interface.

α: Phase fraction

B: Incline angle of the straight attachment wall

σ: The surface tension coefficient

τ: Time (s)

CFD: Computational fluid dynamics

---

[1] Research Center in Industrial Technologies CRTI, P.O. Box 64, Cheraga Algiers, Algeria.

[2] ENERGARID Laboratory, University Tahri Mohamed Bechar, B. P. 417, route de Kenadsa, 08000 Bechar, Algeria.

[*] Corresponding Author: T. Chekifi. Emai: chekifi.tawfiq@gmail.com.

FDMP. doi:10.3970/fdmp.2018.00322 www.techscience.com/fdmp

F: The surface tension force
W: Width (mm)
H: Depth (mm)
ρ: Density (kg/m^3)
μ: Dynamic viscosity (kg/m^{-1}.s^{-1})
HF: Height function
SFO: Small fluidic oscillator
LFO: Large fluidic oscillator
MPA: Minimal pressure admissible.

1 Introduction

Over the last few decades, microfluidic oscillators have been used for a several applications, including mixing [Gregory, Sullivan and Raghu (2004)], flow separation [Sarpkaya (1986)], flow control [Simões, Furlan, Leminski et al. (2005)], flow selection [Raman and Raghu (2004)] and flow measurement [Simões, Furlan, Leminski et al. (2005)], etc. Recently, with the development of microfabrication techniques [Unger, Chou, Thorsen et al. (2000)], the small-scale feedback fluidic oscillator has been investigated for application to complicated lab-on-a-chip systems [Dittrich and Manz (2006)], such as μTAS [MDS-Ocata (2000)], an oscillator actuator-microsystem for bio-medical application [Gebhard, Hein, Just et al. (1997)], and small scale blowers in clean rooms [Biermaier (1994)]. The Reynolds number (*Re*) in such small-scale feedback fluidic oscillators is usually low [Tesař, Hung and Zimmerman (2006)] and the Strouhal number in such cases is usually not constant [Blevins and Iwan (1974)], because the flow conditions in such devices usually vary between the onset condition and the critical flow condition [Li, Someya, Koso et al. (2013)]. The principle of operation of the oscillator is based on the Coanda effect (discovered by Henri Coanda [Davies (1970)], the fluidic oscillators consists in disturbing the flow of jets issuing from a nozzle, then expanding between two attachments walls, after that, the jet will attach to the less curved one or to the wall which is closer from the jet axis [Gebhard, Hein and Schmidt (1996)], which leads it to oscillate and flow into feedback channel. the frequency is a function of the geometry of the actuator, the size and flow provided. Experimentally, Shakouchi et al. [Shakouchi, Kuzuhara and Yamaguchl (1986)] investigated the oscillatory phenomena of an attached jet in a suddenly enlarged flow passage without feedback channels and observed that the oscillation frequency is negligibly influenced by the attachment wall length [Meng, Xu and Yu (2013)], but highly dependent on the jet nozzle exit width, inlet width, and the diverging angle of the enlarged flow passage [Chekifi, Dennai, Khelfaoui et al. (2016)]. Yang et al. [Yang, Chen, Tsai et al. (2007)] presented a novel feedback fluidic oscillator that incorporates step-shaped attachment walls. This design makes the recirculation vortices oscillate more effectively and stably, and subsequently broadens the effective operating range. Xie et al. [Xie, Fang, Li et al. (2007)] investigated the effects of the attachment walls with a polygonal line on oscillation via computational fluid dynamics. The lower limit of measurement in this design is 1 m/s and the pressure loss performance is improved relative to conventional oscillators with planar attachment walls. To characterize performance of feedback fluidic oscillators, Tippetts [Tippetts, Ng and Royle (1973)] deduced four major parameters such as Strouhal number (Sr), Reynolds number (Re), Euler number (Eu), and a dimensionless control loop inductance, the author found that Sr remains constant for Re in a certain range; the oscillation frequency thus becomes linearly proportional to the flow rate, i.e. the Reynolds number. Bobusch et al.

[Bobusch, Woszidlo, Bergada et al. (2013)], employed Particle Image Velocimetry (PIV) to visualize and identify the internal flow patterns of fluidic oscillator, the author observed that a growing recirculation bubble between the main jet and the attachment wall, moreover, the inlet and outlet of the mixing chamber effect immediately on flow characteristics such as oscillation frequency and the jet deviation. More recently, Václav Tesa [Tesař (2017)] has presented the most fluidic oscillator deign, following the analogous approach used in biological sciences, the author classified the fluidic oscillator according to three main approaches; Feedback principle criterion, the working mode and Number of amplifiers.

Recent advances in computational fluid dynamics (CFD) methods, have made it possible to simulate the effect of active flow control devices on major aircraft components [Xie, Fang, Li et al. (2007); Roohi, Zahiri, Passandideh-Fard et al. (2013)]. It is an established fact that fluidic oscillator performance is significantly influenced by the oscillator configurations, Shakouchi et al. [Shakouchi, Kuzuhara and Yamaguchl (1986)] have examined the flow field in the fluidic oscillator. A full set of fluid dynamic equations can be solved numerically. The author investigated the condition causing the oscillation and the effect jet velocity on the oscillatory frequency. He also focused qualitatively on the mechanism identifying the oscillatory flow pattern. Guilmineau et al. [Guilmineau and Queutey (2002)], proposed a numerical simulation of vortex shedding from an oscillating circular cylinder, thus, the author focused on two phenomenon; the first one is the harmonic in-line oscillation of cylinder in water at rest, the second one is; an investigation of a transversely oscillating cylinder in a uniform flow at fixed Reynolds, he deduced that the process is function of streamline patterns. Chen et al. [Chen, Wang, Yang et al. (2006)] have also numerically suggested and analyzed a periodic flow structure in oscillatory gas flow meters, the author has classified the flow patterns into two stages of induction and sustainable periodic oscillation. In addition, the numerical simulation revealed that a low pressure vortex in the oscillating chamber and the small vortices play important rule in jet flow oscillation. Xie et al. [Xie, Fang, Li et al. (2007)], have also numerically designed a new fluidic flowmeter to investigate the adaptability and stability of his model, using The CFD software FLUENT, Xie found that that the oscillation of the fluidic flowmeter is stable and reliable. Also the formulation of the flowrate and the frequency of jet flow were identified. Vatsa et al. [Vatsa, Koklu and Wygnanski (2012)] also investigated the characteristics of fluidic actuator for active flow control applications, the authors deduced that the fluidic actuators produce a sweeping jets. The frequency of sweeping jets depends on the geometric parameters and the mass flow entering the device.

Although several works were focused on fluidic oscillator and actuators, nevertheless there are still points that require investigation in this field. In this paper, we use the commercial code FLUENT 6.3.26 to solve the Navier Stoks equation via control volume approach. These equations are solved by converting the complex partial differential equations into simple algebraic equations. Motivated by the our previous work [Chekifi, Dennai, Khelfaoui et al. (2016)], we will examine the effect of working fluids, the operating pressure, and the oscillating chamber shape on the flow oscillation performance, that is insensitive to the geometrical factors. Therefore, we suggest two models of fluidic oscillator, small fluidic oscillator (SFO) with small oscillation chamber and small diameter of output channel and large fluidic oscillator (LFO) with large oscillation chamber and large diameter of the output. In addition, the effect of the oscillating chamber shape and flow conditions on the low-pressure vortex will be focused, referring to analysis and comparison with available results.

2 Geometrical characteristics of both models

Fig. 1 presents the geometrical characteristics of suggested fluidic oscillator; it shows the main parts both devices, that basically include: two inlets for fluids supply, the oscillation chamber; where the jet flow balance, the attachments wall; which determine the oscillation chamber limits (in this zone both main vortex and small vortices are assumed to be developed), the output and two feedback channels; where the main jet stream is deviated after the attachments toward.

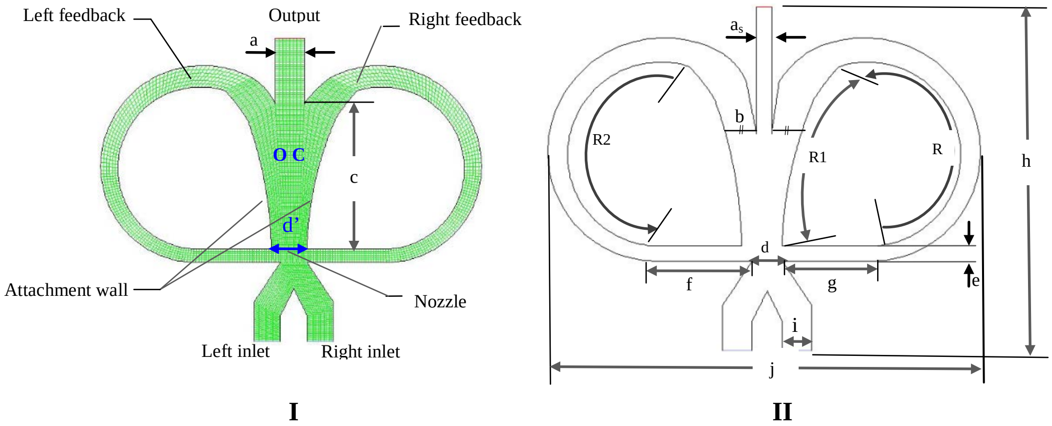


Figure 1: Schematic of fluidic oscillators for: I (large fluidic oscillator LFO) and II (small fluidic oscillator SFO), the dimensions are in millimetre: a=0.84, a_s=0.38, b_L=1.21, b_S=0.6, c_L=3.20, c_s=2.34, d=0.77, d’=1.07, e=0.42, f=g=2.23, h=9.1, i=0.84, j=11.5, R_1=5.65, and R_2=7.11, R=7.56. OC: Oscillating chamber

The feedback fluidic oscillator has an inlet nozzle, an oscillator body having two attachment walls that define the oscillation chamber, and two feedback channels connect the upstream and downstream of the oscillation chamber, respectively. Two splitters guiding the fluid flow enter the feedback channels and feedback the fluid to the inlet of the oscillation chamber. The fluidic oscillator is shown schematically in Fig. 1. Our Oscillator is similar to many previous deign, we cite as examples, Xu et al. [Xu and Meng (2013)] and Li et al. [Li, Someya, Koso et al. (2013)] models. However, we intentionally proposed a small shift in the supply nozzle to exploit the Coanda effect which will slightly approach the right Attachment wall to the centre of the nozzle relative to the left Attachment wall. This modification leads the stream flow to attach the right feedback channel.

3 Numerical method

FLUENT is a finite volume code, so one needs to solve the integral form of Eq. (1) which in conservative form reads as:

$$\int_v \frac{\partial \rho F}{\partial t} + \int_v \nabla . (\rho u F) = 0 \tag{1}$$

For the unsteady term, FLUENT employs first order Euler discretization [Vierendeels, Dumont, Dick et al. (2005)]. For the convective term, the Green-Gauss theorem is applied and the volume integral is transformed into a surface integral [Uygun and Kırkköprü (2005)]. Fluent uses a mid-point rule integration of the surface integral which is second-order accurate [Gente (2017)]. It also provides five schemes to interpolate the face values (Ff) , namely: First order upwind, second order upwind, power law, QUICK, and MUSCL [Shukla, Shukla and Ghosh (2011)]. If the pressure field is known, one can solve for the velocity field. However, the pressure field is not known a priori and must be obtained as part of the solution [Mathur and Murthy (1997)]. FLUENT offers several pressure-velocity coupling algorithms like SIMPLE (Semi-Implicit Pressure Linked Equations), SIMPLEC (SIMPLE Consistent), and PISO (Pressure Implicit with Split of Operators) [Barton (1998); Gaspar, Barroca and Pitarma (2003)].

4 Boundary and calculation conditions

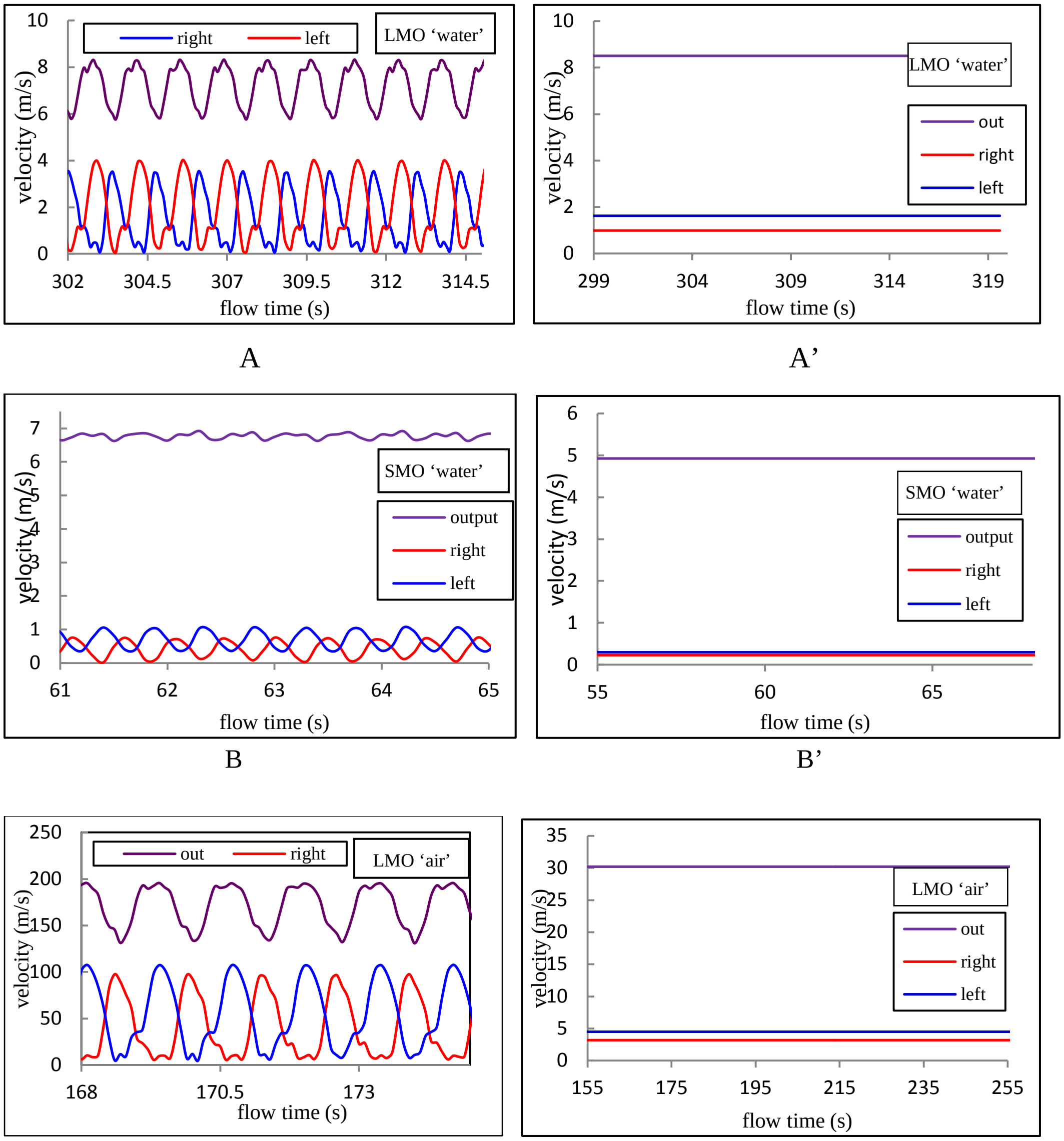
Computational fluid dynamics software (CFD) was used to investigate the flow field in the fluidic oscillator, it solves the two-dimensional Reynolds-averaged Navier-Stokes equations in a general curvilinear coordinate system, which provides conservation equations for mass, momentum, and energy. As a first step, the system's boundaries, its subdivisions, the types of interface and the contour faces were performed using commercial software (Gambit 2.2.3). Fluent 6.3 was used to set up the virtual unit and perform calculation. We have started by defining the plan of two-dimensions (2D) to study the flow evolution reported in this study, however, for the SFO, the mesh consists of 5088 quadrilateral cells and 5654 nodes, while for LFO, the mesh consists of 5408 quadrilateral cells and 5942 nodes. The test of oscillation performance for fluidic oscillator modeling is assumed with water and air. The density and viscosity of both fluids are 998.2 kg/m^3, 0.001 kg/m.s^{-1} for water and 1.225 kg/m^3, 1.78x10^{-5} kg/m.s^{-1} for air, it is assumed that no-slip boundary conditions at all walls. As the flow is axisymmetric the complete geometry is taken into consideration. For the outlet of both models the pressure Atmospheric is taken in consideration. Additionally, the flow is computed using the laminar solution, with a time step 0.1.

5 Results and discussion

Numerical simulations are conducted to study the flow characteristics in two models of fluidic oscillator for (Fig. 1). In this models, air and water are used as working fluids, the minimal pressure admissible (MPA) for the fluid flow oscillation, the vortex results of the depression in the oscillation chamber, the frequency of the fluid flow are investigated as function of geometrical parameters, fluid viscosity and the operating pressure.

5.1 Water and air Oscillation test

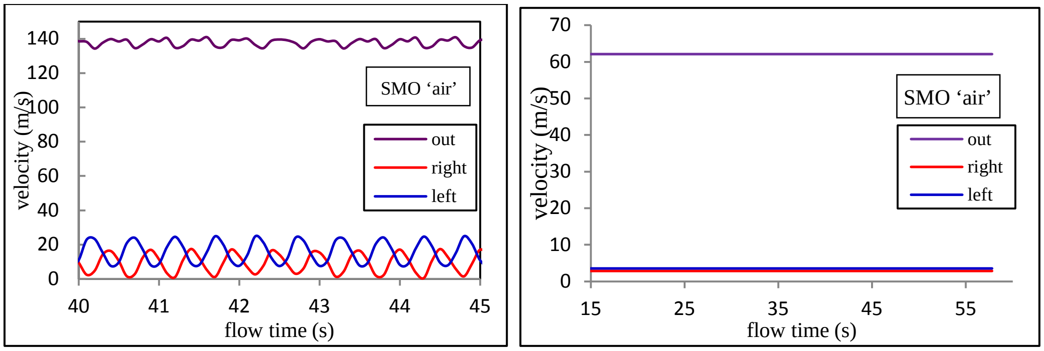
In the first step, we investigated the minimal pressure admissible to have (MPA) which allows to get stable oscillation of flow velocity, for that we have tested several values of operating pressure for both models with air and water, we present in the following figures the velocity evolution at the output, right feedback channel and left feedback channel as function of flow time, working fluids for both models (LFO and SFO):



A A'

B B'

C C'



D D'

Figure 2: Evolution of the fluid flow velocity at the output and both inlet of feedbacks as function of flow time. The operating pressure is A: 1.8 bar while A' 1.6 bar, B: 1.4 bar, B':1.04 bar, C: 1.6 bar, C': is 1.01 bar, D: 1.4 bar, D' 1.04 bar

In the figures above, we introduced the velocity evolution in the entrance of both feedback channel and the output of both models small and large fluidic oscillator. The numerical analysis shows that the shape of oscillation chamber, the working fluid and the operating pressure have a strong impact on the oscillation mechanism, which is based on the Coanda effect. Due to the difference between water and air viscosity, a stable oscillation was produced for low operating pressure with air fluid for both oscillators where the amplitude is much bigger. On the other hand, water required high pressure to ensure the jet flow oscillation; As a result, the Coanda effect efficiency is mainly depending on viscosity of operating fluid. In addition, the oscillation chamber size also affected the jet flow oscillation, short fluidic oscillator required high operating pressure.

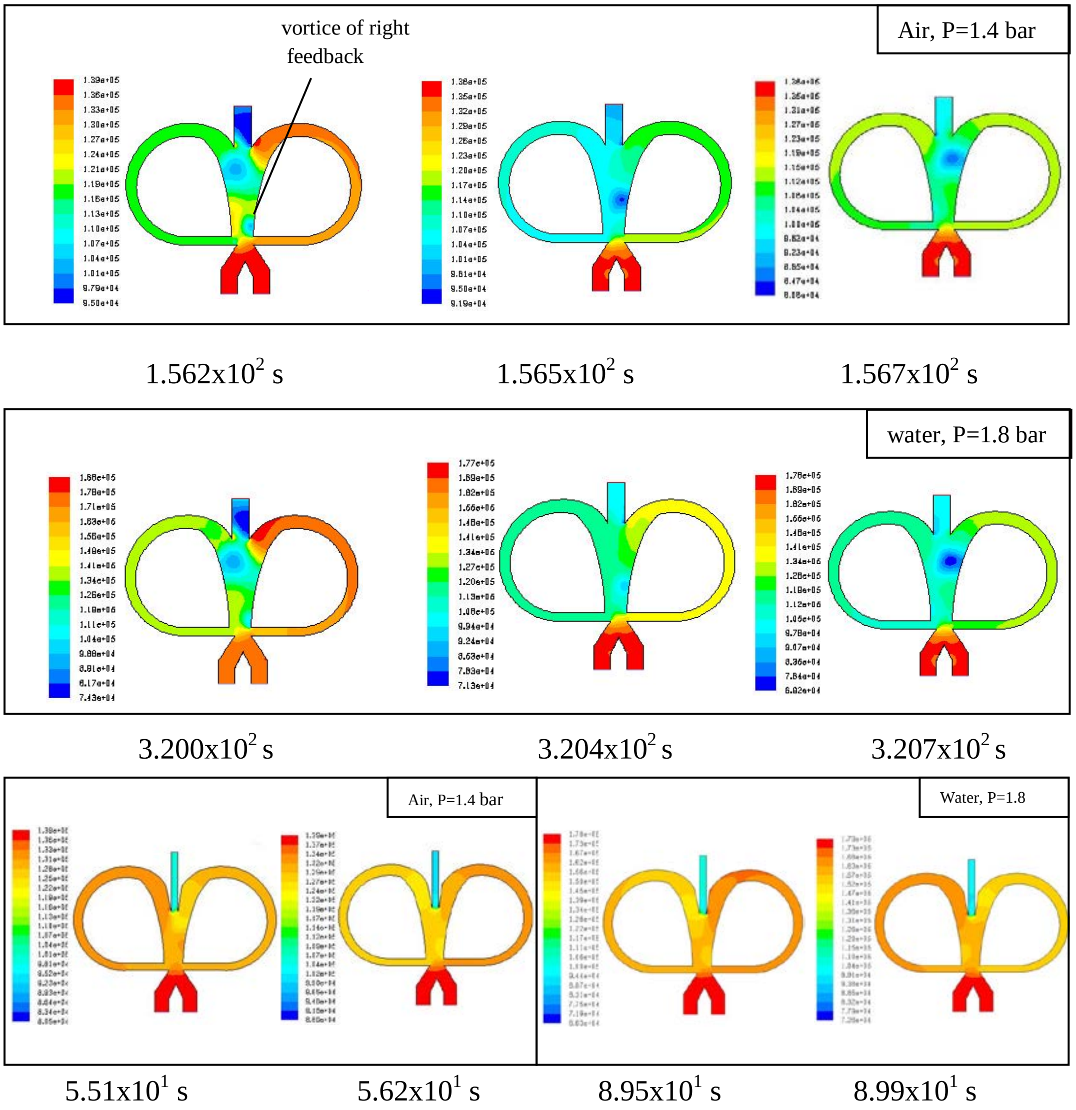
5.2 The minimal pressure admissible (MPA)

The minimal pressure admissible (MPA) is an important characteristic for fluidic oscillator, it determines the lower threshold allowing oscillation of jet flow, in our study it is represented by the minimum pressure, this parameter is depends on geometrical parameters (nozzle, attachments wall placements, fluid proprieties and flow conditions) Regarding the MPA of LFO with water was 1.8 bar otherwise for the SFO was decreased to 1.4 bar. The same impact is observed for air as working fluid, but the MPA was found lower 1.02 bar for LFO and 1.04 bar for SFO

Table 1: Results of the minimal pressure admissible with both fluids and models

	Long fluidic oscillator		**Short fluidic oscillator**	
Working fluids	water	air	water	air
MPA (bar)	1.8	1.02	1.4	1.02

The oscillation or balance of jet flow results in the first attachment of the fluid on the wall, the coming out the feedback channel to the oscillation chamber. Subsequently, the jet changes the direction to enter in the opposite feedback channel, consequently, an oscillation of the flow occurred. For both models, the minimal pressure admissible (MPA) of the flow oscillation of air fluid is lower than MPA of water, due the low viscosity of air. However the Coanda is applicable for large interval of pressure for fluids with low viscosity, where the attachment of the jet flow to the wall required a small pressure, inversely when the viscosity is high. In this case the jet flow requires more pressure to attach the wall.



1.562x10^2 s 1.565x10^2 s 1.567x10^2 s

3.200x10^2 s 3.204x10^2 s 3.207x10^2 s

5.51x10^1 s 5.62x10^1 s 8.95x10^1 s 8.99x10^1 s

Figure 3: Contour of static pressure inside both fluidic oscillators for different instants and operating pressure

The numerical static pressure distributions indicate that the Coanda effect tends to deflect the jet flow toward the upper attachment wall in the oscillation chamber. The jet stream attached to the wall due to the development of the sub-vortex Fig. 3. Subsequently, a negative-pressure region appears between the jet stream and the attachment wall. Moreover, the negative pressure region (the vortex) moved from the down region to the up region in the oscillation chamber (Figs. (E) and (F)). After that, the vortex entered the feedback channel where the pressure drop flow back to the down region in the oscillation chamber. Then, the transmitted pressure drop coming from the feedback channel disturbs the pressure balance in the oscillation chamber and causes the jet stream to balance toward the opposite attachment wall (Fig. 3). The repetition of this process forms an oscillation cycle in a short time. This phenomenon is characterized by an oscillation frequency of the jet flow balance, it can be estimated in the oscillation chamber or at the output of microsystem. The most important application of the jet flow oscillation in this device is the passive mixing, so no moving part is included in this kind of devices, results in reduction of required energy and making a flexible device and a simple handling of the microsystem.

6 Approximation of the jet flow oscillation frequency

For liquids, generally, the oscillation frequency f, presented in expression (1), is strongly dependent on the switching time, because the speed of wave propagation is higher than the jet velocity in the nozzle-to-splitter path. Typically, the transmission time for operation with liquids is approximately two or four orders lower than the switching time. For gases, expression (2), the oscillation frequency depends on both the transmission time and the switching time which can be identified by the discrete fast Fourier transform method (FFT)

$$\mathrm{fr} = \frac{1}{2\tau_s} \tag{2}$$

$$\mathrm{fr} = \frac{1}{2(\tau_t+\tau_s)} \tag{3}$$

The oscillation frequency of the fluidic oscillator was evaluated across operating pressure. Fig. 4 shows the variation of oscillation frequency with flow rate for both models of fluidic oscillator using water and air as working fluid. The oscillation frequencies were identified by the discrete fast Fourier transform method (FFT) of Fluent. Oscillations begin at 0.013 Hz with an operating pressure of 1.8 bar using water for SFO and increase in frequency up to 3.14 kHz with operating pressure of 3 bar.

The variation of frequency with operating pressure is approximately linear. In addition, the jet oscillation frequencies are much higher for air as working fluid in both large and short fluidic oscillator. Due the low viscosity of air, the velocity of jet stream takes a high values inside the oscillation chamber, the flow jet into a small diameter of the feedback channel causes increasing of the flow velocity of the jet stream, consequently, the latter flow out the feedback channel into the oscillation chamber with high pressure drop, which makes the main jet stream to move forward the other attachment wall, the process is occurred in very short time with air which allows to get a high frequency. Inversely, the water flow frequencies are low, due the high viscosity, in this case, the jet flow stream in the oscillation chamber and the feedback channels is slowly, Consequently, the balance of the jet stream between feedback channels takes more time leading to have low flow frequencies. On the other hand, increasing of operating pressure for both models, leads to slightly increasing of the jet stream frequencies.

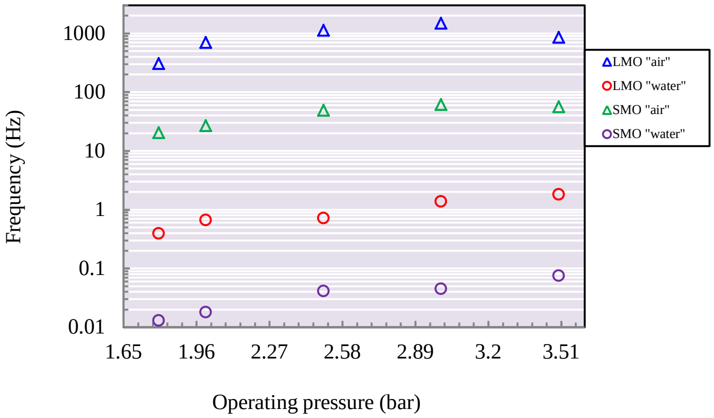


Figure 4: The frequency of the jet flow as function of operating pressure, for both models (SMO and LMO)

7 Conclusion

The fluidic oscillator is an excellent device for the flow control actuator, mixing and many other applications. A distinguishing characteristic of the fluidic oscillator as a flow control actuator is that it spatially modulates the flow in a time-varying manner, as opposed to a typical pulsed jet. One of the most significant advantages of the fluidic oscillator is its simplicity. Fluidic oscillations are generated purely by fluid dynamic phenomena; thus, the lack of moving parts makes the micro oscillator attractive as a practical excitation device. Fluidic oscillators may be implemented for flow control applications in which high frequencies and low flow rates are required. In this study, we suggested two geometrical models to investigate the characteristics of each one, our fluidic instruments produce an unsteady jet that oscillates with the lowest frequencies from 22 Hz for air and 56 Hz for water. The minimal pressure admissible was lowest for the short model with air (1.02 bar). The influence of geometrical characteristic on the flow oscillation was clearly observed. The reduction of oscillation chamber leads to the elimination of flow vortex which is useful for such application as flow control. In the other model (the large fluidic oscillator), the jet flow pulsation involved a low pressure vortex, which is usually used in mixing application, the minimal pressure admissible (MPA) of the flow oscillation of air fluid was lower than MPA of water.

References

Barton, I. (1998): Comparison of SIMPLE-and PISO-type algorithms for transient flows. *International Journal for Numerical Methods in Fluids*, vol. 26, no. 4, pp. 459-483.

Biermaier, H. (1994): Cleaning and disinfecting machine for medical equipment and instruments, anesthetic tubes, catheters, and endoscopes. *Google Patents*.

Blevins, R.; Iwan, W. (1974): A model for vortex induced oscillation of structures. *Journal of Applied Mechanics*, vol. 581.

Bobusch, B. C.; Woszidlo, R.; Bergada, J. M.; Nayeri, C. N.; Paschereit, C. O. (2013): Experimental study of the internal flow structures inside a fluidic oscillator. *Experiments in Fluids*, vol. 54, no. 6.

Chekifi, T.; Dennai, B.; Khelfaoui, R.; Maazouzi, A. (2016): Numerical and experimental investigation of fluidic microdrops manipulation by fluidic mono-stable oscillator. *International Journal of Fluid Mechanics Research*, vol. 43, no. 1.

Chen, C.; Wang, L.; Yang, J.; Chen, L. (2006): Experimental and computational analysis of periodic flow structure in oscillatory gas flow meters. *Journal of Mechanics*, vol. 22, no. 2, pp. 137-144.

Davies, R. C. (1970): Functional characteristics of fluid elements. *Fluidics Quarterly*, vol. 2, no. 2, pp. 1-43.

Dittrich, P. S.; Manz, A. (2006): Lab-on-a-chip: Microfluidics in drug discovery. *Nature Reviews Drug Discovery*,vol. 5, no. 3, pp. 210-218.

Gaspar, P. D.; Barroca, R. F.; Pitarma, R. (2003): Performance evaluation of CFD codes in building energy and environmental analysis. *Building Simulation.*

Gebhard, U.; Hein, H.; Just, E.; Ruther, P. (1997): Combination of a fluidic micro-oscillator and micro-actuator in LIGA-technique for medical application. *International Conference on Solid State Sensors and Actuators.*

Gebhard, U.; Hein, H.; Schmidt, U. (1996): Numerical investigation of fluidic micro-oscillators. *Journal of Micromechanics and Microengineering*, vol. 6, no. 1, pp. 115.

Gente, C. S. C. A. (2017): Erro 404. *Instituto de Ciências Matemáticas e de Computação*.

Gregory, J. W.; Sullivan, J. P.; Raghu, S. (2004): Visualization of internal jet mixing in a fluidic oscillator. *11th International Symposium of Flow Visualization.*

Guilmineau, E.; Queutey, P. (2002): A numerical simulation of vortex shedding from an oscillating circular cylinder. *Journal of Fluids and Structures*, vol. 16, no. 6, pp. 773-794.

Li, Y.; Someya, S.; Koso, T.; Aramaki, S.; Okamoto, K. (2013): Characterization of periodic flow structure in a small-scale feedback fluidic oscillator under low-Reynolds-number water flow. *Flow Measurement and Instrumentation*, vol. 33, pp. 179-187.

Mathur, S.; Murthy, J. (1997): A pressure-based method for unstructured meshes. *Numerical Heat Transfer*, vol. 31, no. 2, pp. 195-215.

MDS-Ocata, D. F. Ÿ. (2000): A revolution in biological and medical sciences. *Analytical Chemistry*, pp. 330-335.

Meng, X.; Xu, C.; Yu, H. (2013): Feedback fluidic flowmeters with curved attachment walls. *Flow Measurement and Instrumentation*, vol. 30, pp. 154-159.

Raman, G.; Raghu, S. (2004): Cavity resonance suppression using miniature fluidic oscillators. *AIAA Journal*, vol. 42, no. 12, pp. 2608-2612.

Roohi, E.; Zahiri, A. P.; Passandideh-Fard, M. (2013): Numerical simulation of cavitation around a two-dimensional hydrofoil using VOF method and LES turbulence model. *Applied Mathematical Modelling*, vol. 37, no. 9, pp. 6469-6488.

Sarpkaya, T. (1986): Force on a circular cylinder in viscous oscillatory flow at low Keulegan-Carpenter numbers. *Journal of Fluid Mechanics*, vol. 165, pp. 61-71.

Shakouchi, T.; Kuzuhara, S.; Yamaguchl, J. (1986): Oscillatory phenomena of an attached jet. *Bulletin of JSME*, vol. 29, no. 250, pp. 1117-1123.

Shukla, S. K.; Shukla, P.; Ghosh, P. (2011): Evaluation of numerical schemes using different simulation methods for the continuous phase modeling of cyclone separators. Advanced Powder Technology, vol. 22, no. 2, pp. 209-219.

Simões, E. W.; Furlan, R.; Leminski, R. E. B.; Gongora-Rubio, M. R.; Pereira, M. T. et al. (2005): Microfluidic oscillator for gas flow control and measurement. *Flow Measurement and Instrumentation*, vol. 16, no. 1, pp. 7-12.

Tesař, V. (2017): Taxonomic trees of fluidic oscillators. *EDP Sciences*.

Tesař, V.; Hung, C. H.; Zimmerman, W. B. (2006): No-moving-part hybrid-synthetic jet actuator. *Sensors and Actuators A: Physical*, vol. 125, no. 2, pp. 159-169.

Tippetts, J.; Ng, H.; Royle, J. (1973): An oscillating bistable fluid amplifier for use as a flowmeter. *Fluidics Quarterly*, vol. 5, no. 1, pp. 28-42.

Unger, M. A.; Chou, H. P.; Thorsen, T.; Scherer, A.; Quake, S. R. (2000): Monolithic microfabricated valves and pumps by multilayer soft lithography. *Science*, vol. 288, no. 5463, pp. 113-116.

Uygun, M.; Kırkköprü, K. (2005): Numerical solution of the euler equations by finite volume methods: Central versus Upwind Schemes. *Journal of Aeronautics and Space Technologies*, vol. 2, no. 1, pp. 47-55.

Vierendeels, J.; Dumont, K.; Dick, E.; Verdonck, P. (2005): Analysis and stabilization of fluid-structure interaction algorithm for rigid-body motion. *AIAA Journal*, vol. 43, no. 12, pp. 2549-2557.

Vatsa, V.; Koklu, M.; Wygnanski, I. (2012): Numerical simulation of fluidic actuators for flow control applications. *6th AIAA Flow Control Conference*, pp. 1-17.

Xie, D.; Fang, T.; Li, G.; Liang, G. (2007): Numerical simulations of fluidic flowmeter with large measurement range. *Instrumentation and Measurement Technology Conference Proceedings*, pp. 1-4.

Xu, C.; Meng, X. (2013): Performance characteristic curve insensitive to feedback fluidic oscillator configurations. *Sensors and Actuators A: Physical* , vol. 189, pp. 55-60.

Yang, J. T.; Chen, C. K.; Tsai, K. J.; Lin, W. Z.; Sheen, H. J. (2007): A novel fluidic oscillator incorporating step-shaped attachment walls. *Sensors and Actuators A: Physical*, vol. 135, no. 2, pp. 476-483.