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EXPERIMENTAL STUDY OF SYNTHETIC JETS WITH RECTANGULAR ORIFICE

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Abstract. *Rapid evolution of technology has produced more compact electronic devices and with higher processing power, which also results in increased heat generation. Therefore, new cooling techniques are needed to replace current technology based on fans and heat sinks. The use of synthetic jets is still under development but these devices are considered an excellent alternative due to their ability to increase turbulence mixing. In this study, a synthetic jet actuator was constructed with a speaker coupled to two acrylic plates to form the cavity and exit plate containing a rectangular orifice. The device was subjected to an experimental study where different parameters were analyzed. Three configurations of the rectangular orifice were tested with different hydraulic diameters (4 - 8 mm) and two aspect ratios (2 and 4). Jet velocities were measured at distances of 2, 4, 6 and 8 orifice widths away from the exit plate. Variations in frequency and Reynolds number were performed in order to determine the optimum combination which would generate a stronger jet. While the depth of the cavity is known to have an influence on the speed of the jet, results showed that the geometry of the orifice plays a more significant effect in the jet format, where a larger hydraulic diameter in conjunction with a smaller aspect ratio provides better results.*

Keywords: *synthetic jets; Reynolds number; electronic cooling devices.*

1. INTRODUCTION

The rapid development of electronics is resulting in ever more compact devices with higher processing power. This results in a direct increase in heat generation and a growing need for more efficient heat dissipation. Consequently, new heat dissipating techniques are needed to ensure that the devices can function within normal operating parameters. The most conventional electronic cooling technique consists of forced convection through heat sinks with air as the working fluid due to its low cost and reliability. However, this technique requires a considerable amount of airflow in order to force air through the narrow network of fins and channels that make up the heat sink (Chaudhari, *et al*., 2010). Moreover, an efficient heat dissipation system has conflicting requirements. While a large or high volumetric airflow fan may be ideal, the compact size of current electronic devices limits the overall size of the final product and, by extension, the size of the heat dissipation system. Consequently, there is a present need to study alternative forms of electronic cooling if this technique is to remain in use in the future.

Among the new cooling techniques being studied, synthetic jets are of particular interest (Chaudhari, *et al*., 2010). Synthetic jets are formed by the periodic suction and ejection of surrounding air through an orifice connected to a cavity equipped with a diaphragm. Thus, although the average result is the displacement of air away from the orifice, there is no need for a separate, external source of fluid (Smith and Glezer, 1998). There is no uniform nomenclature for a device capable of generating a synthetic jet but some names are more commonly used: ZNMF (Zero-Net-Mass-Flux) by Zhang and Tan (2007), SJA (Synthetic Jet Actuator) by Mallinson, *et al*., (2001) or simply "synthetic jet" by Smith and Glezer (1998), which is more prevalent.

Several studies have been performed on the characteristics of a synthetic jet. Smith and Swift (2003) compared the performance of synthetic and steady jets. Results show that, for distances beyond a transition region away from the orifice, synthetic jets behave very similar to steady jets and the average normalized streamwise velocity profiles are identical. Additionally, in the near region of the orifice, the vortex pairs that make up the synthetic jet provide additional fluid entrainment and results in a wider structure with more displaced fluid than a steady jet. Similarly, Smith and Glezer (1998) observed a substantial amount of fluid being drawn into the synthetic jet core in the near region but the average volumetric flowrate of a synthetic jet far away from the orifice was shown to be less than of a steady jet. However, in regions closer to the orifice, spots were identified where the flowrate of the synthethic jet would be as large as 4 times than for a steady jet.

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Chaudhari *et al*., (2009) measured the effect of several parameters, such as cavity depth, orifice hydraulic diameter and pulsing frequency on the jet exit velocity. Results show that there is a combination of pulsing frequency and a minimal cavity depth to produce a jet with substantial exit velocity. In particular, it was observed that for a cavity height of 6.3 mm, no jet was produced for frequencies above 1200 Hz. The ideal pulsing frequencies were found to correspond to the resonant frequency of the device and the Helmholtz frequency of the cavity. Exit jet velocity also benefited from larger hydraulic diameters and rectangular orifices with smaller aspect ratios. Overall, the cavity depth was deemed an important factor at high pulsing frequencies and smaller hydraulic diameters, which are the combination of parameters more frequently found in real synthetic jets.

In engineering, there are other applications for synthetic jets beyond cooling. Chaudhari *et al*., (2009) noted that in addition to improved heat transfer, synthetic jets may be used to enhance air-fuel mixing in combustion chambers, generating or controlling local turbulence and even propulsions systems. Thus, the objective of this study is to build a working experimental synthetic jet and determine its performance parameters for use in future projects.

2. SYNTHETIC JETS

As mentioned previously, unlike a steady jet, a synthetic jet does not require an external source of mass and operates with the surrounding fluid (Smith and Swift, 2003). Internally, the diaphragm, cavity and orifice can be said to behave like a Helmholtz resonator. Under certain operating conditions, the ejected fluid is drawn back into the cavity when the diaphragm reverses actuation and no jet is formed. However, under the proper combination of amplitude and frequency of oscillation of the diaphragm, separation of the ejected fluid occurs on the edges of the orifice. The resulting shear layer creates vorticity which moves away from the orifice so that is not drawn back into the cavity. Continuous operation of the diaphragm creates a sequence of vortex pairs or rings, which make up the body of the synthetic jet (Lasance and Aarts, 2008) and whose presence produces an average velocity along the jet axis away from the orifice (Holman *et al*., 2005). Thus jet formation is related to vorticity generated by the synthetic jet. Figure 1 shows a schematic of a synthetic jet generator and resulting jet. The relevant characteristics of the device are the cavity height (*Hc*), cavity width (*Wc*), orifice hydraulic diameter (*D*), orifice height (H_0) and maximum amplitude of deflection of the diaphragm (*Ad*).

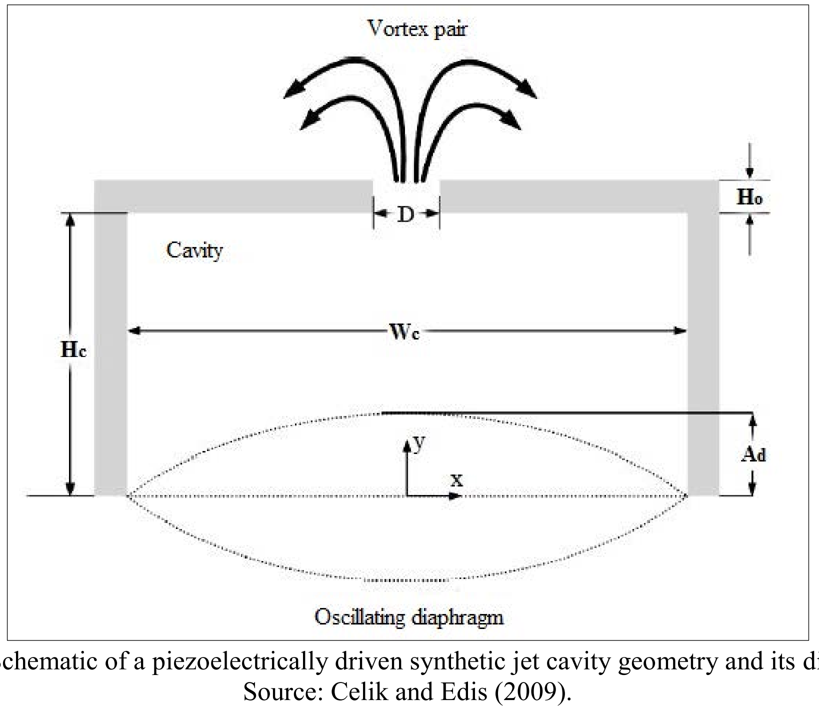

Figure 1. Schematic of a piezoelectrically driven synthetic jet cavity geometry and its dimensions.
Source: Celik and Edis (2009).

2.1 Physical Principles of Synthetic Jets

The main parameter utilized to characterize the performance and flow regime of a synthetic jet is the Reynolds number, *Re*, defined as Eq. (1):

$$Re=\frac{\rho U_0 D}{\mu} \tag{1}$$

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where ρ is the fluid density, U_0 is the average jet exit velocity, D is the orifice hydraulic diameter and μ is the fluid viscosity. The average jet exit velocity is given based on the oscillating frequency of the membrane, f, and the average jet length, L_0, as in Eq. (2):

$$f=\frac{U_0}{L_0} \tag{2}$$

The average jet length L_0 is the average length of a column of fluid pushed through the orifice during the blowing phase, as in Eq. (3):

$$L_0=\int_0^{\tau/2} U_0\,(t)dt \tag{3}$$

Additionally, the Strouhal number, St_0, is an dimensionless parameter used in oscillating flows. It is defined as in Eq. (4):

$$St_0=\frac{fD}{U_0} \tag{4}$$

3. METHODOLOGY

This study describes the construction and testing of an experimental synthetic jet test bed. Parametric studies are also conducted on the cavity depth and dimensions of a rectangular orifice. The finished synthetic jet test bed is shown schematically on Fig. 2. It consists of an Eastech speaker, model FSB51 with a 76 mm diameter, 8 Ohms impedance and 30 W maximum power. Two square acrylic plates are mounted on the speaker with long screws. The top plate measures 200 mm in side (L) and 8 mm in thickness (Hc), while the bottom plate measures 200 mm in side (L) and 3 mm in thickness (H_0). The plates are carved with a high precision laser so that the top plate contains a circular cavity while the bottom plate contains the orifice. The cavity of the top plate has a diameter of 76 mm, identical to the speaker.

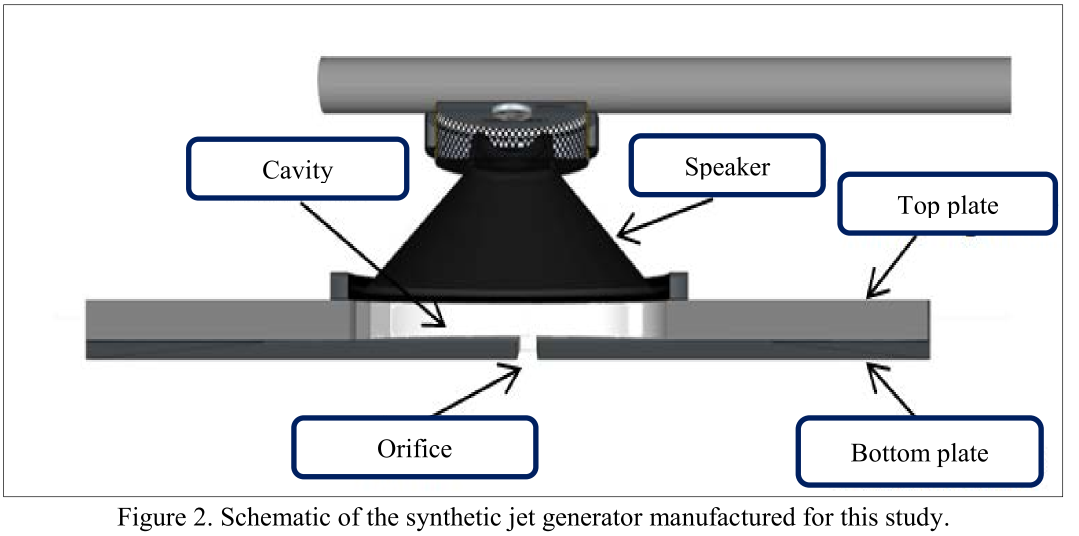

Figure 2. Schematic of the synthetic jet generator manufactured for this study.

The rectangular orifice of the bottom plate has dimensions l x w and three different lower plates were prepared with dimensions shown on Tab. 1. Thus, the device contains a cylindrical cavity but a rectangular orifice. This mismatch in shapes does not influence the resulting jet and is similar to the configuration used in other numerical studies such as Chaudhari et al., (2009). Configuration 1, in particular, matches the one used by Chaudhari et al., (2009) and is initially used to assess the initial performance of this device.

Table 1. Orifice configurations used in the study.

Configuration	*l x w* (mm)	Hydraulic diameter (mm)	Aspect ratio *l/w*
1	20 x 5	8	4
2	10 x 2.5	4	4
3	12 x 6	8	2

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The input signal to the speaker is provided by a Hewlett-Packard Company model 33120a signal generator and consisted of a sinusoidal wave with an amplitude of 3.5 V_{rms}. The signal frequency, which was one of the parameters examined in this study, varied from 0 to 4 kHz when determining the resonant frequency and from 100 to 200 Hz when examining the performance of the synthetic jet. An oscilloscope is connected at the speaker input to measure the signal amplitude, verify the wave shape and to check measurements obtained with a multimeter.

Constant temperature hot-wire anemometry is used to measure the jet velocity. This technique is based on the convective cooling of a heated wire by the airflow. The convective heat transfer rate is proportional to fluctuations of velocity in the flow. As the wire cools, a control system adjusts the electrical current to maintain the wire temperature constant. The hot-wire anemometer system consists of a Dantec model 55P11 hot-wire probe, with a tungsten filament measuring 1 mm in length and 5 μm in diameter mounted on a fork-like needle probe. The probe is connected to a Dantec StreamLine control system model 90N10. The velocity readings were transmitted to a personal computer through a National Instruments A/D converter model 9215-A, with a USB interface, capable of handling up to 4 analog signals, 16 bit resolution and a range of +/- 10 V. The system is controlled through Dantec StreamWare software, version 3.4, which calibrates the probe and displays velocity readings. Figure 3 shows the synthetic jet generator and how-wire anemometer system used in this study.

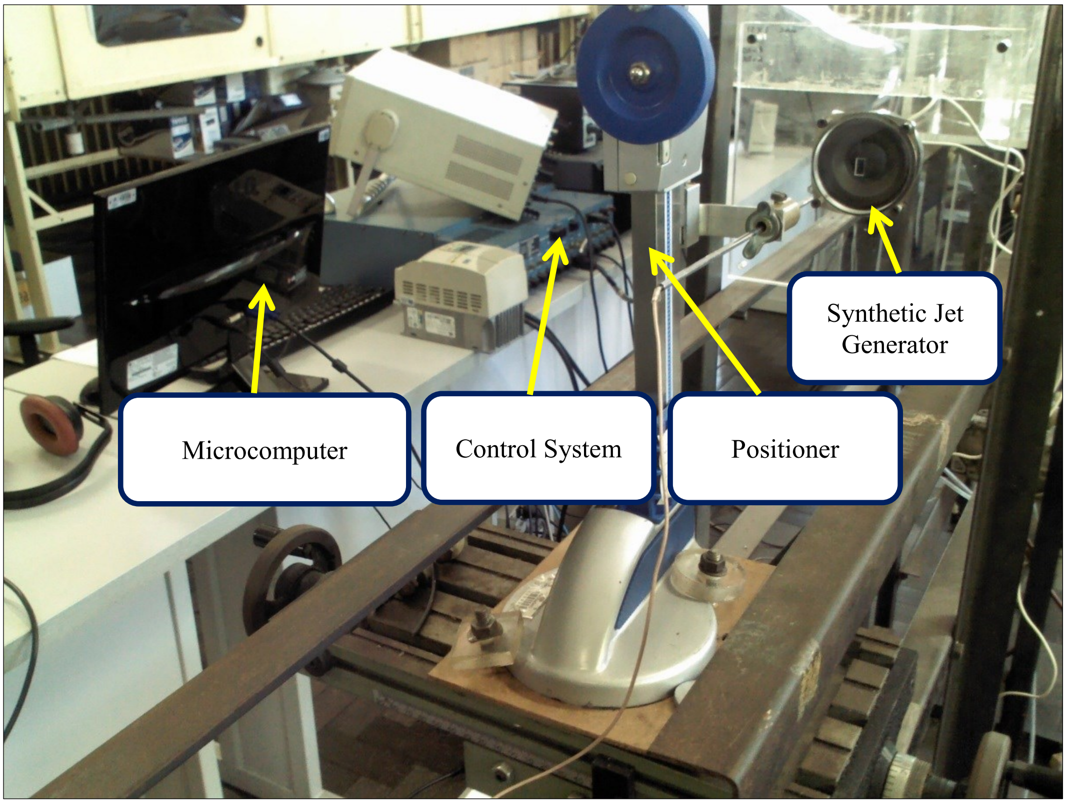

Figure 3. Equipments used for calibration and testing of the synthetic jet generator. Fluid Mechanics Laboratory - UFRGS.

3.1 Natural Diaphragm Frequency

The natural diaphragm frequency is the resonant frequency of the diaphragm and attached voice coil. As an electrical signal is sent to the speaker, the diaphragm/voice coil assembly displace from their position at rest. When the input signal is interrupted abruptly, the diaphragm/voice coil assembly oscillates with a fixed frequency and decreasing amplitude. This frequency corresponds to the resonant or natural diaphragm/voice coil frequency (Vassallo, 2005). The natural diaphragm/voice coil frequency depends on the particular characteristics of a speaker. It is measured experimentally by applying a 1 V signal to a suspended speaker with at least 1 m clearance around it free of any objects or surfaces. A 1000 Ohms resistance is placed to reduce the current fed to the speaker. The signal amplitude and wave shape are checked by an oscilloscope before and after the resistance while a multimeter measures the tension after the resistance. This test assembly is shown on Fig. 4. The frequency of the input signal is varied and the frequency at which the multimeter register the maximum tension is the natural diaphragm/voice coil value.

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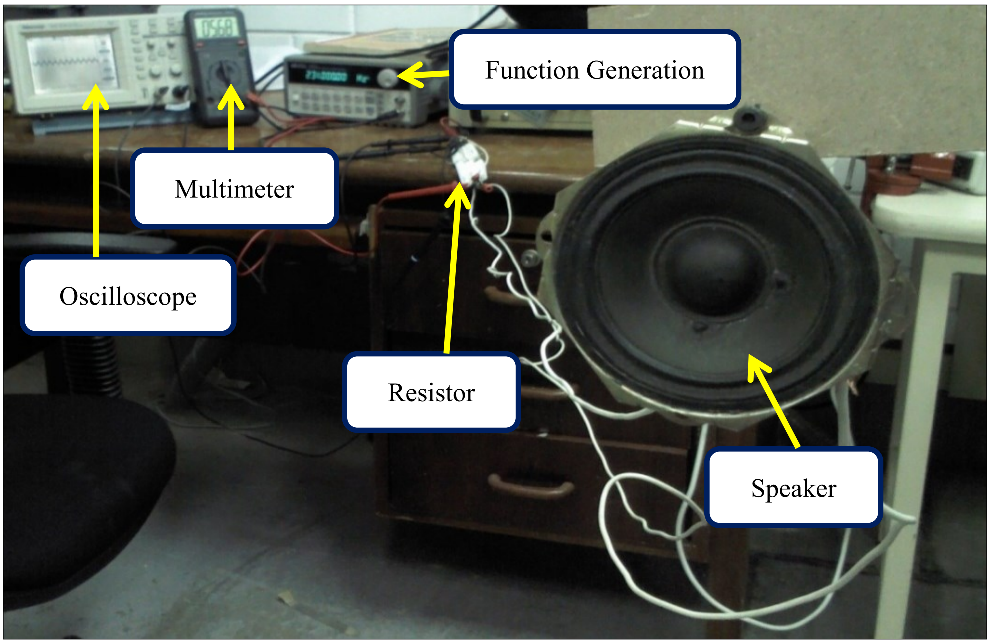

Figure 4. Speaker mounting for measuring the resonance frequency outdoors.

In woofer-type speakers, the natural diaphragm frequency is usually found around 100 Hz. For mid-range speakers, the corresponding frequency is obviously higher. In order to ensure that all possible values were tested, a range of 0 to 4 kHz was used. Figure 5 shows that for this range of frequencies, a single peak with maximum tension of approximately 2.6 mV was found at 233 Hz, which is taken to be the natural diaphragm frequency of this particular speaker model.

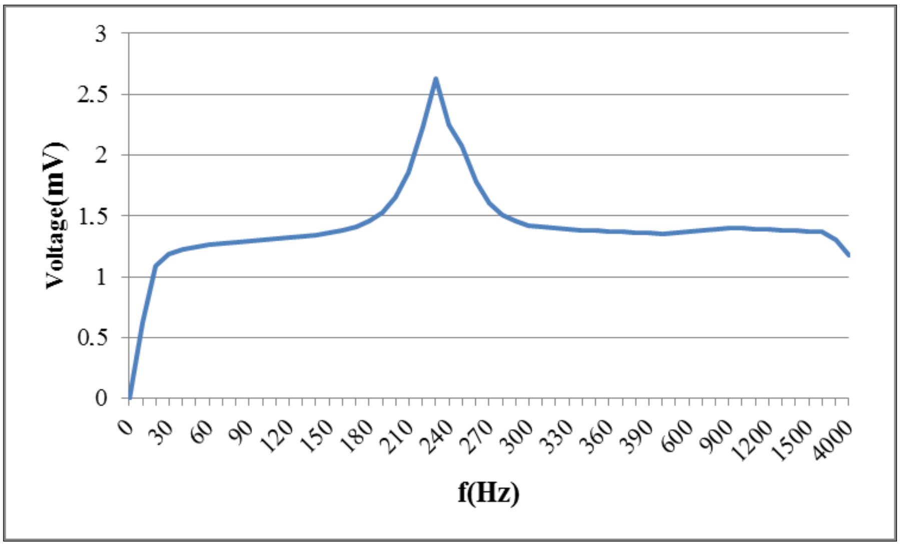

Figure 5. Natural diaphragm frequency measurements.

3.2 Helmholtz Frequency

The Helmholtz frequency is related to the cavity size, shape and jet orifice. It is a result of the air contained within the cavity resonating with the air being forced through the orifice. The experimental procedure to measure the Helmholtz frequency is identical as in the natural diaphragm frequency. However, instead of the speaker, the entire synthetic jet generator assembly is suspended and no clearance is needed since the critical factor is the air enclosed within the cavity. The chosen orifice corresponds to Configuration 1 and the same range of frequencies (0 to 4 kHz) is applied. Results shown on Fig. 6 allows the identification of a 1.4 mV peak at a frequency of 180 Hz. This measured value of Helmhotz frequency is a reference value for the remainder of this study. Later results show that the optimum performance of each synthetic jets occurs at frequencies closer to this value than the natural diaphragm frequency.

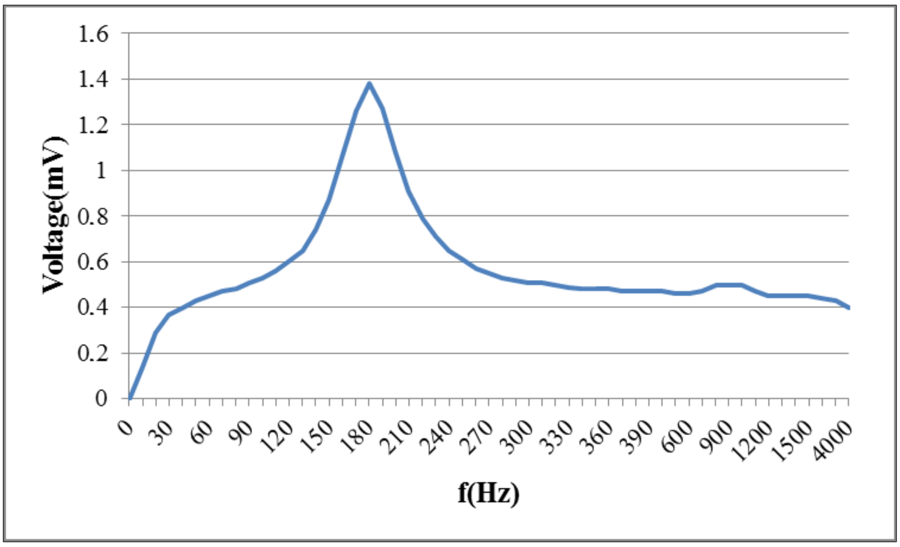

Figure 6. Helmholtz resonance frequency measurements.

4. RESULTS

Synthetic jet performance depends on many factors but mainly the cavity size and orifice geometry. In order to better analyze the effect of these parameters, it is necessary that the device operates at peak frequency. Table 2 shows the variation of St_0 and *Re* with frequency drawn from the Helmholtz frequency sweep of Fig. 6. Based on Fig. 6, a narrower range starting around 90-100 Hz and ending between 240-250 Hz was identified and a higher resolution sweep is conducted. Results shown on Tab. 2 allow the identification of the optimum pulsing frequency for Configuration 1 by searching for a peak in *Re*. It should be noted that the corresponding St_0 reaches a minimum at the same frequency.

Table 2. Excitation frequency, Strouhal and Reynolds numbers, for Configuration 1.

Frequency (Hz)	U_{avg} (m/s)	St_0	*Re*
100	1.5	0.533	769
150	3.3	0.364	1692
160	3.4	0.376	1743
161	3.5	0.368	1794
162	3.4	0.381	1743
170	3.4	0.400	1743
180	3.4	0.423	1743
190	3.1	0.490	1589
200	2.7	0.593	1384
250	1.5	1.333	769

Table 2 shows that the optimum frequency is found to be 161 Hz, where *Re* peaks at 1794 and St_0 reaches a minimum of 0.368. This value of *Re* corresponds to a laminar jet and the resulting frequency is approximately 90% of the measured Helmholtz frequency. A low St_0 is desirable, since the optimum pulsing frequency favors the formation of vortex pairs as noted by Surhone, *et al*., (2010). The values of *Re* and St_0 are similar to the devices tested by Chaudhari *et al*., (2009). This optimum frequency should also be applicable to the other configurations of this study since the speaker and cavity shape are the same as in Configuration 1.

4.1 Effect of Orifice Dimension

The effect of orifice dimension is examined by maintaining the cavity depth at 8 mm and testing each configuration at frequencies of 100 Hz, the optimum frequency of 161 Hz and 200 Hz. The average centerline jet velocity is measured at distances (*H*) away from the orifice in intervals of 2 hydraulic diameters up to final distance of *H/D*=8 to examine its decay as a result of pulsing frequency.

Figure 7 shows results for Configuration 1, which corresponds to *D*=8 mm and an aspect ratio of 4. The average centerline velocity of each pulsing frequency is normalized according to its respective peak values (U_{avg}/U_{max}) and the distance away from the orifice normalized according to the hydraulic diameter (*H/D*). Peak average centerline velocities were measured as 0.5 m/s at 100 Hz, 2.3 m/s at 161 Hz and 0.5 m/s at 200 Hz. However, the normalized results of

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Fig. 7 show that the optimum frequency of 161 Hz had a steeper decay initial decay at H/D = 4 than all the other frequencies while the 100 Hz frequency presented the least amount of decay among the 3 tested frequencies.

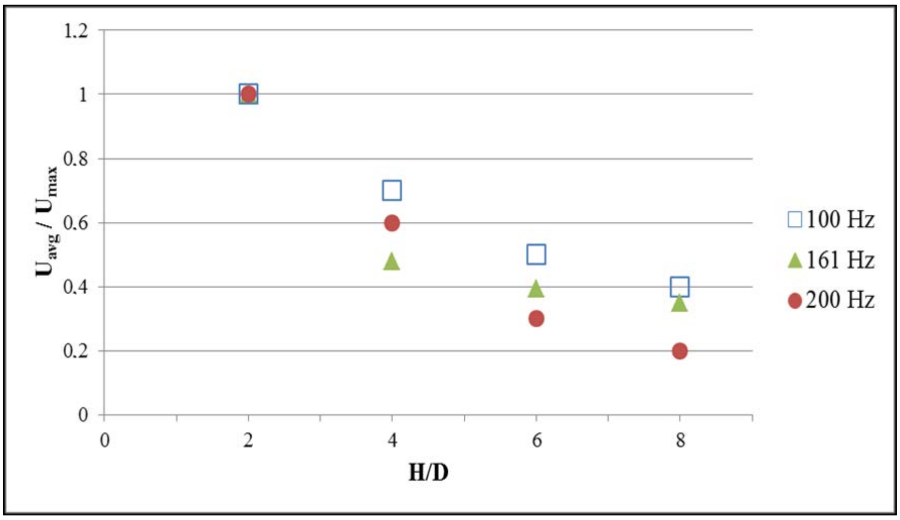

Figure 7. Normalized average speed (U_{avg}/U_{max}) at distances H/D=0 to 8 with a 20 x 5 mm rectangular orifice (Configuration 1) for three frequencies.

Results for Configuration 2 are shown on Fig. 8. In this configuration, the dimensions of the orifice were reduced in half, in order to increase the jet velocity. As a result, the hydraulic diameter was also reduced in half to D=4 mm while the aspect ratio remained at 4. Figure 8 shows that there is overall a shallower decay for this configuration. All 3 pulsing frequencies had similar decay curves with less of a velocity variation than seen on Fig. 7. It is theorized that the narrow size of the orifice favors the movement of air at the higher frequencies corresponding to the 3 values tested and resulted in the shallow decay curves shown. However, since a higher Re is desired for cooling applications, this configuration is not recommended. Despite the increase in jet velocity, the decrease in hydraulic diameter cancels out any gains in Re. As a matter of fact, the peak value of Re for this configuration is 1230 at 161 Hz, much lower than the values shown on Tab. 2.

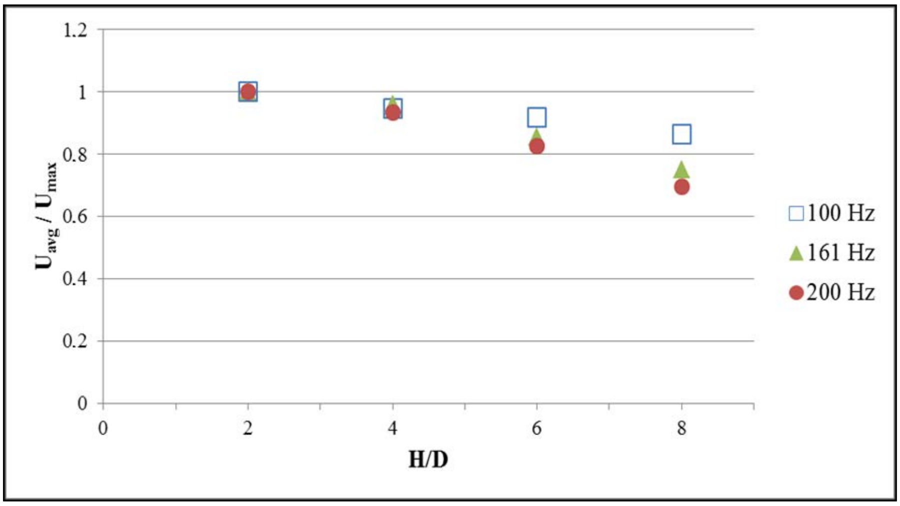

Figure 8. Normalized average speed (U_{avg}/U_{max}) at distances H/D=0 to 8 with a 10 x 2.5 mm rectangular orifice (Configuration 2) for three frequencies.

For Configuration 3, the hydraulic diameter was kept the same at D=8 mm but the dimensions of the orifice were changed to 12 x 6 mm so that the aspect ratio was reduced to 2. Results are shown on Fig. 9. Unlike the previous configurations, the optimum frequency of 161 Hz presented the least decay of all 3 frequencies. Moreover, peak Re was the highest of all configurations, reaching a value of 2660 at an H/D=2 and 161 Hz. The corresponding St_0 was calculated as 0.248, which is within a range where Surhone, *et al*., (2010) indicate vortex formation is instantaneous. Thus, this configuration would be the most recommended among the 3 of this study to be used in cooling. This result is not surprising since other experimental work, such as Chaudhari *et al*., (2009), also concluded that impacting jets provide the most cooling when the orifice geometry contains larger hydraulic diameters and smaller aspect ratios.

Finally, it should be noted that the decay rate of the non-optimum frequencies is similar to the one seen on Fig. 7 which suggests a result of the same hydraulic diameter.

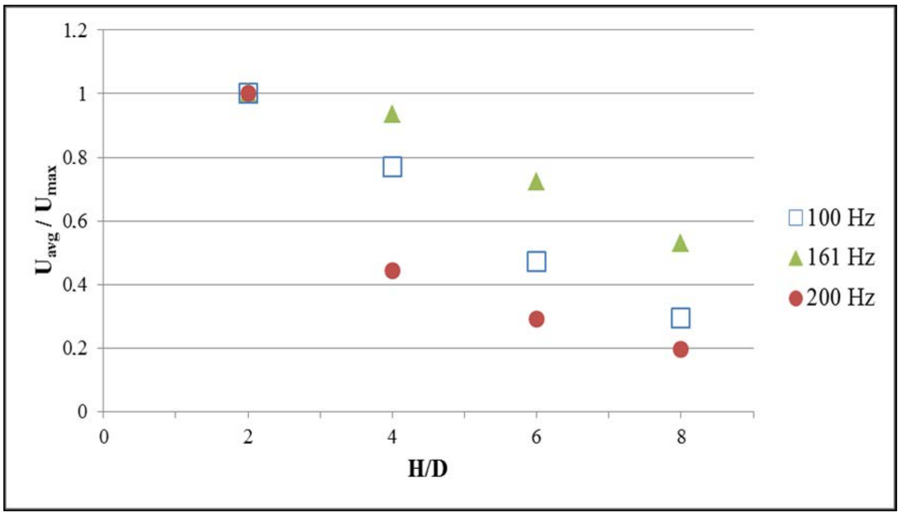

Figure 9. Normalized average speed (U_{avg}/U_{max}) at distances *H/D*=0 to 8 with a 12 x 6 mm rectangular orifice (Configuration 3) for three frequencies.

The relative performance of all 3 configurations is shown on Fig. 10, where the actual average centerline velocity (U_{avg}) is shown as a function of normalized orifice distance (*H/D*). The margin of error in U_{avg} is calculated to be ±5%. Results clearly shown that Configuration 3 resulted in higher jet velocities than Configurations 1 and 2. Configuration 2 presented similar peak values of velocity as Configuration 1 but as mentioned previously, this results is deceptive since the reduction in hydraulic diameter which increased the velocity also decreased *Re*. It should also be noted that, for each configuration, these values of velocity were the highest amongst the tested values of frequency. Consequently, despite the less favorable decay characteristics for Configurations 1 and 2, it is concluded that the optimum frequency of 161 Hz should still be used for other parametric studies.

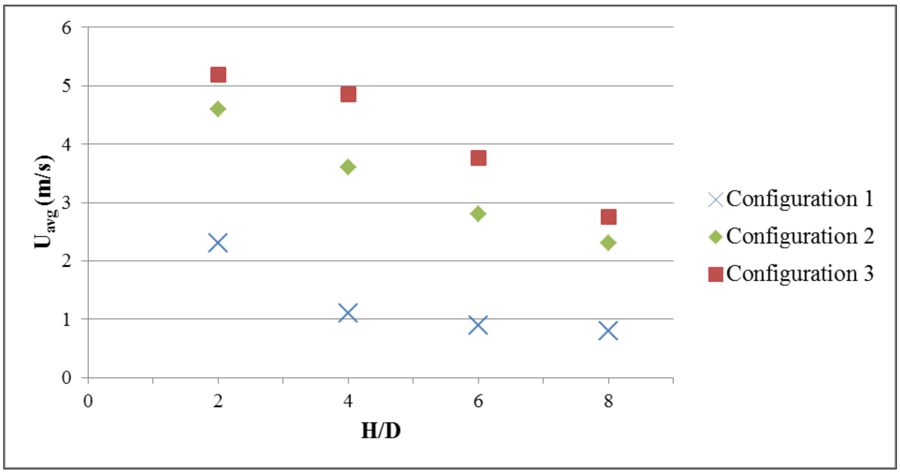

Figure 10. Average speed at distances *H/D*=0 to 8, for all three configurations with the optimal frequency of 161Hz.

4.2 Study of the Radial Region to the Jet Axis

The radial region of the jet was studied by mapping the jet width at several distances *H/D* away from the orifice. It was chosen to work with Configuration 3 at the optimum pulsing frequency of 161 Hz. As seen on Fig. 11, the hot-wire probes are sweeped laterally, transversally to the orifice. Average streamwise jet velocities (in the direction away from the place) are measured and the jet width is determined at the position where this value becomes negligible.

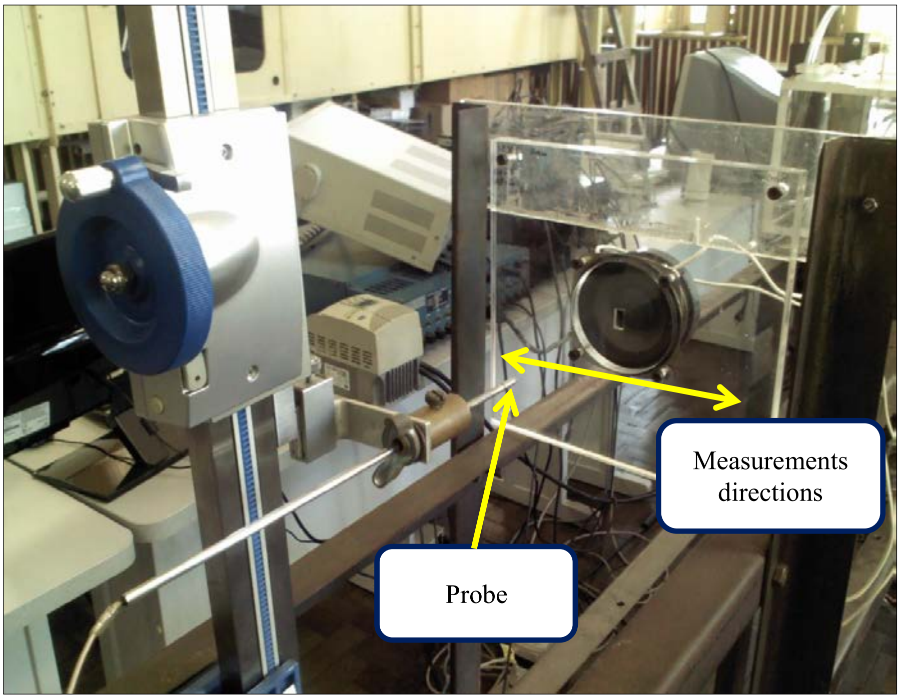

Figure 11. Test section with hot-wire anemometer for mapping the jet width.

Measurements show the jet half-width (b) to be 14 mm at a H/D=2, corresponding to a b/D=0.7. Further away from the orifice, at a H/D=8, the jet half-width was measured to be 20 mm for a corresponding b/D=1. Figure 12 shows the full range of measurements taken, which includes the jet half-width at H/D=4 and 6. Included in Fig. 12 is the correlation derived by Smith and Glezer (1998) for their experimental jet in the near region, corresponding to $b \sim (H/D)^{0.25}$. The experimental data of this study follows closely the same trendline as Smith and Glezer (1998), which indicate both devices have similar mechanisms of entrainment of side fluid that result in the similar jet half-width growth. It should be noted that the actual values of b/D between this study and Smith and Glezer (1998) differ, since the devices had different dimensions and aspect ratios.

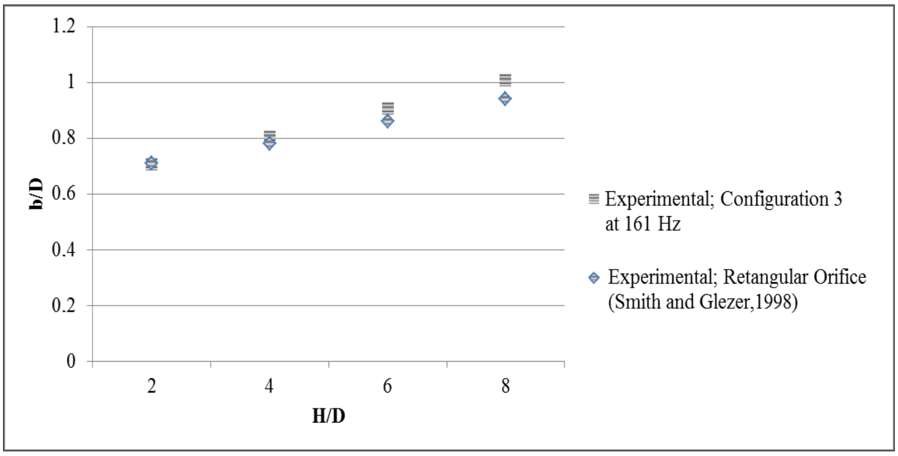

Figure 12. Average width of the jet (b/D) vs. axial distance (H/D) for rectangular orifice with dimensions of 12 x 6 mm (Configuration 3) at optimal frequency compared to the study of Smith and Glezer (1998).

5. CONCLUSION

Synthetic jets are considered to be a viable alternative for electronic cooling. This technique has demonstrated to produce heat transfer rates superior to conventional techniques and has additional benefits such as: less noise pollution, lower power consumption and longer durability. In this study, an experimental synthetic jet generator was constructed in order to conduct future studies of this technique and its performance characteristics were determined. An optimum pulsing frequency of 161 Hz was measured and found to be within 90% of the Helmholtz frequency. At this pulsing frequency, maximum values of Re and minimum values of St_0 were measured for 3 different orifice configurations. Of the 3 configurations tested, Configuration 3, with a rectangular orifice of dimensions 12 x 6 mm with corresponding

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hydraulic diameter of 8 mm and an aspect ratio of 2, resulted in a maximum Re=2660 and minimum St_0=0.248. For all 3 configurations, peak average velocities were observed at the closest measured distance from the orifice, at H/D=2. Jet half-widths were measured to vary from 14 mm to 20 mm between H/D=2 to 8 and the growth rate was found to be similar to other experiments. Results have identified the performance characteristic of the device for future studies in electronic cooling.

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8. RESPONSIBILITY NOTICE

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