Effect of Nozzle Depth to Acoustic Signals Produced by a Ranque-Hilsch Vortex Tube

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ABSTRACT

This paper aims to present the analysis of acoustic sound produced from a Ranque-Hilsch Vortex Tube. Two microphones are used to capture the sound produced at the hot and cold tubes. Different nozzle depths of the swirl generator are tested and different inlet pressure gages are applied. It is observed that, for one swirl generator, the sound produced contains a specific set of frequencies. These frequencies remain present when the inlet pressure is varied, while the magnitude of these frequencies changes. Different swirl generator produces different set of frequencies. These sets of frequencies-magnitudes represent acoustic signatures of the configurations. This acoustic signature is then linked with their thermofluid performance.

Keywords: *Ranque-Hilsch Vortex Tube; Acoustic Analysis; Fast-Fourier Transform.*

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Introduction

Ranque-Hilsch Vortex Tube (RHVT) (see Figure 1) is a device that is capable of separating compressed air into hot and cold streams. Compressed air is supplied at the inlet and flows through the swirl generator that creates swirl motion of the flow along the tube toward the conical valve at the hot outlet. The swirl flow at the outer periphery near the tube wall exits through the valve with a temperature higher than the inlet temperature. The centre part of the flow hits the conical valve and bounces back towards the orifice before exiting at the cold outlet with a temperature lower than the inlet temperature.

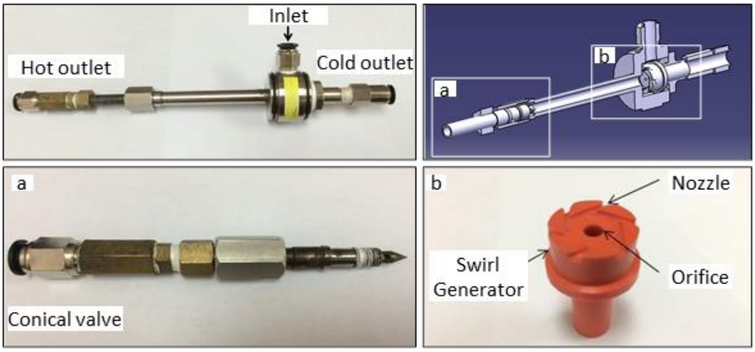

Figure 1: BWB-UAV Prototype

Many empirical studies have been conducted by researchers around the world. They studied mainly on the effect of RHVT parameters to the performance of the device. There are many parameters involved on the performance of the RHVT, such as the shape of swirl generator, the number of intake nozzles, the nozzle area, the shape and the opening of conical valve, the orifice diameter, etc. Devade and Pise achieved lowest cold temperature of 5˚C when investigating the optimum nozzle geometry for the device [1]. Aydin and Baki concluded that higher inlet pressure was needed to obtain greater temperature difference [2]. Kandil and Abdelghany investigated the effect of orifice size and the length-to-tube-diameter ratio on the performance of the RHVT. Computational fluid dynamics simulation was used to conclude that the orifice diameter needed to be lowest to obtain maximum cooling [3]. Mohammadi and Farhadi conducted experimental analysis to optimize the number of nozzles and their diameters. High number of nozzle is observed to produce more turbulent flow that mixed the hot and cold flows resulting a decrease in performance. The maximum isentropic efficiency obtained in their experiment was 6.8% [4]. Wisnoe et al. and Ismail et al.

performed experimental investigation on the effect of conical valve shape, swirl generator, orifice diameter and inlet pressure on the performance of the RHVT. A maximum isentropic efficiency of 33.6% was obtained when the smallest nozzle depth and the medium conical valve were used [5, 6]. In her thesis, Ismail observed that swirl motion in the hot tube had a major role in the performance of the device [7]. The effect of swirl motion was also investigated by Shukri et al. to study the temperature distribution in an annular diffuser [8]. Farzaneh-Gord and Meisam tried to improve vortex tube based on the vortex generator design. Their study covered the effect of orifice angle, orifice diameter and nozzle area. The maximum isentropic efficiency obtained was around 23% [9]. From all the experiments that have been done, the performance of the device in term of isentropic efficiency is considered low which is below than 35% [1].

Acoustic has been used in analysis engineering problems. Baccar and Soffker used wavelet-based acoustic analysis for wear detection [10]. Pavic analysed fluid flows in pipes using acoustical signal processing. He identified physical parameters of fluid-filled pipes using acoustic signal in order to analyse the speed of the fluid and to relate its properties with the frequencies produced [11]. Usually measurement of thermofluid parameters of RHVT consists of measuring temperature, pressure and mass flow rate. Measurement devices are tapped directly at the inlet and outlets of RHVT to obtain the readings. This type of measurement allows obtaining output readings without observing the process inside the tube. Gao conducted experiments on the flow inside the RHVT using hot wire to measure the velocity at the cold end [12]. Introducing hotwire inside the tube may disturb the swirl flow behaviour as the presence of the hotwire creates blockage to the flow. This disturbance may be neglected when the blockage ratio is small enough. But as the size of RHVT is usually small, the blockage ratio becomes significant. Kurosaka attempted to analyse the RHVT effect through acoustic streaming. He found that the temperature separation was related to the flows which created acoustic wave known as whistle effect [13]. The whistle effect occurs when the air flows through a blockage which makes the air to vibrate. This phenomenon can also be explained by the acoustic of flute. When a musician blows a rapid jet of air across the embouchure hole the air flow creates resonances and vibrate. The vibration is released in form of sound energy out of the end of the holes. This is explained by Fritz and Wolfe in their paper [14]. Wavelet transform of acoustic signals produced by an RHVT was presented by Istihat and Wisnoe. They presented the transform of the acoustic signals recorded at the outlet of cold and hot tubes [15].

The objective of this research is to link the acoustic characteristic of the sounds captured by microphones located at specific positions at the outer part of the hot and cold tubes of an RHVT to the thermofluid performance of the device. The acoustic characteristic is represented by a set of main frequencies (frequency value and magnitude) that is called signature. In this paper, the effect of swirl generator nozzle area (or nozzle depth) in an RHVT to the acoustic sounds produced is presented for different inlet pressures.

Methodology

Figure 2 shows the schematic diagram of the experimental setup. The setup is designed to measure thermofluid data such as pressure, temperature and mass flow rate at the inlet and the two outlets and to record the acoustic sound produced by the RHVT. The dimension of the RHVT is depicted in Figure 3.

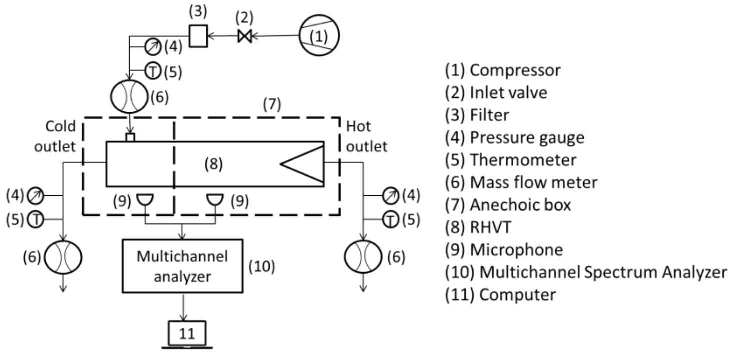

Figure 2: Experimental setup schematic diagram

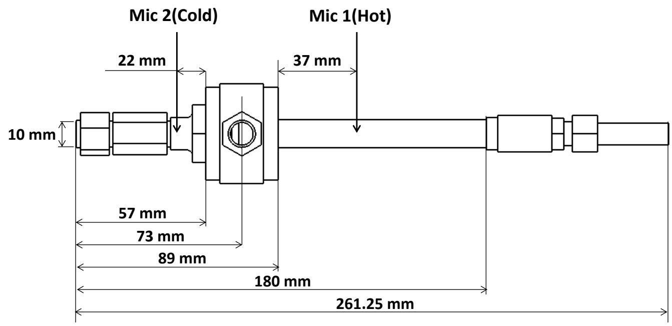

Figure 3: RHVT dimension and microphones location

The inlet pressure (gage) applied during the experiments were 10 psi (68947.6 Pa), 15 psi (103421 Pa) and 20 psi (137895 Pa). These pressures were chosen so that the mass flow rate produced at the outlets (cold and hot) did not exceed the limitation of the mass flow meter. Four swirl generator nozzles represented by their depth were used, i.e.: 1 mm, 2 mm, 3 mm and

4 mm (see Figure 4). For this experiment, the opening of the conical valve was fixed at one rotation from the closed position. The atmospheric pressure in the laboratory during the experiments ranges between 100.6 kPa and 100.9 kPa.

The digital measurement devices took measurements at certain sampling frequencies and showing the average value. The reading was taken when the value shown is stabilized. The accuracy of readings for pressure, temperature and mass flow rate are given in Table 1.

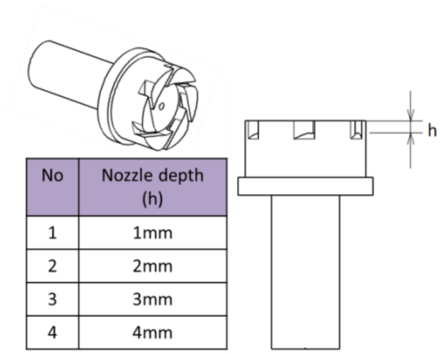

Figure 4: Swirl generator used in the experiment

Table 1: Experimental reading accuracy

Readings	**Accuracy**
Pressure	± 1 psi (or ± 0.1 kgf/cm^2 or ± 9806.65 Pa)
Temperature	± 0.2% × reading value + 1°C
Mass flow rate	± 4.8 g/min

Two microphones were used to capture the sound produced close to the hot and cold tubes. The microphones were located at 22 mm and 37 mm from the swirl generator casing respectively (see Figure 3). To reduce the noise coming from the surrounding, the device was put inside an anechoic box.

Mass fraction is used instead of mass flow rate to represent the non-dimensional rate of air flow in the tube. In this case the rate of air flow in the cold tube is referred. Cold mass fraction is the ratio of the mass flow rate at the cold exit to the inlet (or total) mass flow rate. The equation is given by:

$$\mu_c = \frac{\dot{m}_c}{\dot{m}_i} \tag{1}$$

where μ_c : cold mass fraction,

$\dot{m}_c$: mass flow rate at cold outlet (kg/s),

$\dot{m}_i$: mass flow rate at inlet (kg/s).

The cold temperature difference is defined as the difference in temperature between the inlet and the cold outlet [16], i.e.:

$$\Delta T_c = T_i - T_c \tag{2}$$

where ΔT_c : difference of temperatures between inlet and cold outlet (°C or K),

T_i : temperature of air at inlet (K),

T_c : temperature of air at cold outlet (K).

Isentropic efficiency of the RHVT is obtained using the principle of adiabatic expansion of ideal gas [17]. It is needed to determine the performance of the device compared to the ideal process. It is expressed by:

$$\eta_{isen} = \frac{T_i - T_c}{T_i\left(1 - \left(\frac{P_a}{P_i}\right)^{\frac{\gamma-1}{\gamma}}\right)} \tag{3}$$

where η_{isen} : isentropic efficiency,

T_i : temperature of air at inlet (K),

T_c : temperature of air at cold outlet (K),

P_a : atmospheric pressure (Pa),

P_i : pressure at inlet (Pa),

γ : ratio of specific heats (for air, $\gamma \approx 1.4$).

For the acoustic part, the recorded sounds are processed using Fast-Fourier Transform (FFT). The FFT transforms the time representation of the recorded sounds to its frequency representation. This helps in determining the frequency content of the signals. For this purpose, the FFT module available in the MATLAB software was used. The magnitudes of the FFT results are presented in this paper. From the frequency representation, main frequencies were extracted and replaced by bars to represent the frequency location (value) and magnitude.

Results and Analysis

Thermofluid Characteristics

The measurement of thermofluid data is intended to obtain the thermofluid characteristics of the device for the applied inlet pressures. The thermofluid characteristics, in this case, cover the cold mass fraction, the cold temperature difference, and the isentropic efficiency. These data will be linked later to the acoustic signature for each configuration.

Figure 5 shows the variation of cold mass fraction of the RHVT as function of nozzle depths for three inlet pressures. It indicates the portion of air that exits through the cold outlet. It is observed that cold mass fraction is almost constant for each inlet pressure. The cold mass fraction is about 0.38 at inlet pressure of 10 psi and about 0.45 at inlet pressures of 15 and 20 psi. This means, with the existing opening of the conical valve, at inlet pressure of 10 psi, the air tends to flow more to the hot outlet if compared with 15 and 20 psi.

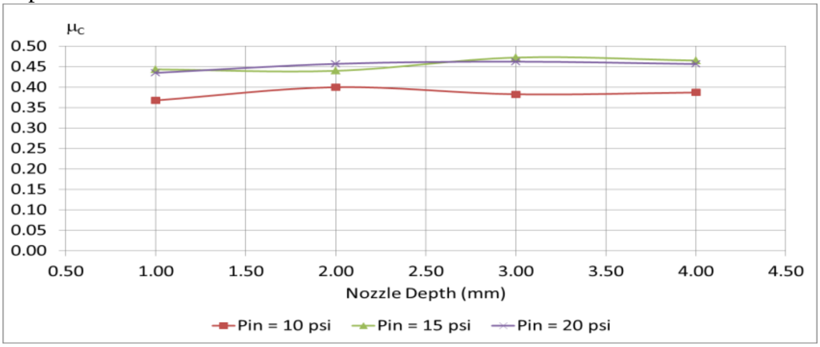

Figure 5: Variation of cold mass fraction with nozzle depths for three inlet pressures

Figure 6 shows the variation of cold temperature difference of the RHVT when the nozzle depth is varied. Three inlet pressures were applied. For each inlet pressure, an exponential trend line is plotted. It is observed that the cold temperature difference is getting lower when the depth of the nozzle is increased for every inlet pressure. On the other hand, the temperature difference is bigger when the inlet pressure is higher. A maximum difference of temperature of 14.8°C is obtained when using a nozzle depth of 1 mm with 20 psi pressure applied at inlet. If a bigger nozzle is used, the expansion process that occurs when the compressed air passes through the nozzle is not as strong as through a smaller nozzle. A stronger expansion produces lower temperature, thus higher temperature difference. The maximum difference of temperature obtained in this experiment is considered low compared to the real capability of the device. In other occasions, the difference of temperature could reach up to 80° with higher inlet pressure.

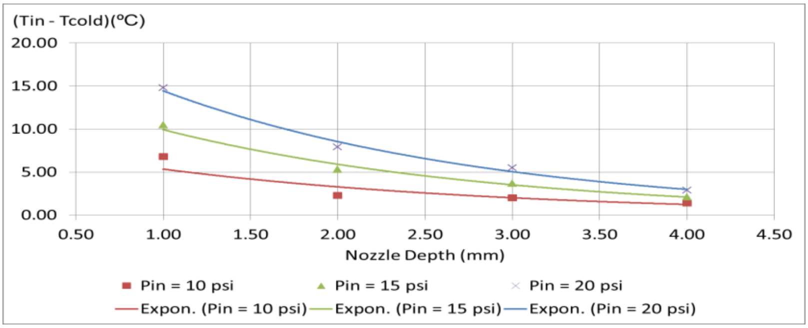

Figure 6: Variation of temperature difference between the inlet and the cold outlet with nozzle depths for three inlet pressures

The variation of isentropic efficiency with nozzle depth for three inlet pressures is shown in Figure 7. Exponential trend lines are added. The efficiency drops when the nozzle depth is increased. This is due to the reduction of the difference of temperature between the inlet and the cold outlet when the nozzle depth is increased. Higher pressure at inlet produces better efficiency. By increasing the pressure at the inlet, it reduces the pressure ratio between the cold outlet (atmospheric pressure) and the inlet, that for consequence increasing the efficiency. The maximum isentropic efficiency recorded here is 23% when using a nozzle depth of 1 mm with 20 psi pressure applied at inlet. The low efficiency obtained is due to the low pressures used. At higher inlet pressure, the efficiency can go higher.

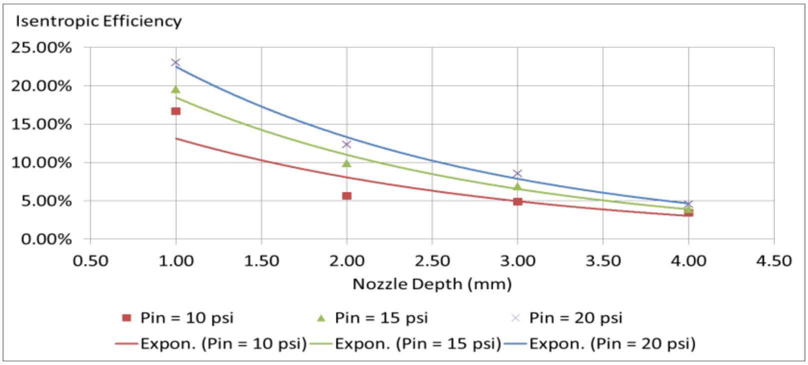

Figure 7: Variation of isentropic efficiency with nozzle depths for three inlet pressures

Acoustic Analysis

Figures 8 and 9 show the sound recorded for 80-ms duration for 3 inlet pressures using 3 different nozzle depths at hot tube and cold tube respectively. The sound signal obtained from 4 mm nozzle depth is not included in the analysis because the magnitudes of the frequencies produced are relatively weak. In these figures, the signals are presented in time domain (horizontal axis) with amplitude shown in Pascal (vertical axis).

Observing the time domain representation, the signals consist of fast oscillating waves carried by low frequency waves. The low frequency may be originated from the surrounding noise, such as from the air-conditioning vent (around 1200 Hz), compressor (around 2500 Hz), etc. The use of "anechoic" box eliminates the noise coming from the air-conditioning system. However, as the compressor is always connected to the device through the inlet pipe, the noise coming from the compressor (when it is running) is more difficult to eliminate. During experiments, the compressor ran intermittently. The Low frequency signals produced by the compressor can be seen in Figures 8 (a) and (e) and in Figures 9 (a) and (e).

Overall, it is observed that when the inlet pressure is increased, the fluctuation amplitude of the acoustic signals becomes more significant; our ears will hear the sound louder. When bigger nozzle is used, the sound produced is weakened (lower in amplitude). It is also noticed that the high-amplitude signals are more on the hot side of the tube (Figure 8) compared to the cold tube (Figure 9). This is due to the fact that more sounds can be heard from the hot tube side rather than from the cold tube side. By observing the design of the RHVT, one can see that most structures inside the device are directed towards the hot tube (see Figure 1).

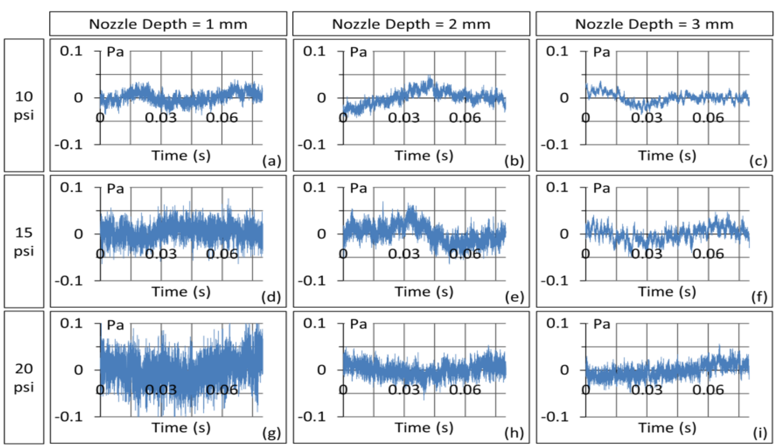

Figure 8: Time representation of sounds recorded for different inlet pressure using different nozzle depth at hot tube

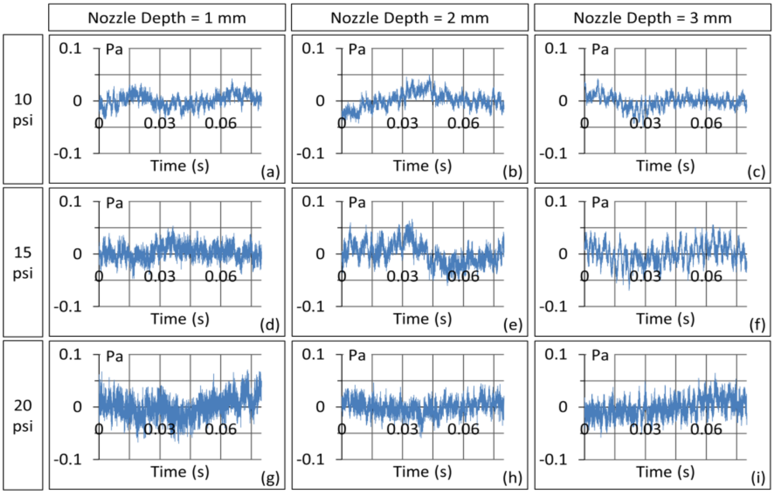

Figure 9: Time representation of sounds recorded for different inlet pressure using different nozzle depth at cold tube

When Fast-Fourier Transform is applied to the signals from Figure 8 and Figure 9, the notion of time disappears, and one can see the frequencies carried by the signals. The results are shown in Figure 10 and Figure 11 as variations of magnitudes (in Pa) with frequencies (in kHz).

From each of Figure 10 and Figure 11, it is observed that when the inlet pressure increases (from top to bottom) the magnitude of the signals increases. There is similarity between the frequencies captured by the microphones at the hot tube (Figure 10) and at the cold tube (Figure 11). The same frequencies are present in both figures but different in strength of their magnitude. This implies when a frequency is captured by a microphone, the strength of its magnitude indicates the proximity of the sound source to the microphone. For example, if Figures 10(g) and 11(g) are put close to each other (see Figure 12), it can be noticed that both curves contain the same frequencies. The same frequencies are produced at around 4000 Hz, 7000 Hz, 11000 Hz and 17500 Hz. It is also observed that the frequencies of 7000 Hz, 11000 Hz and 17500 Hz are higher in magnitude in hot tube compared with cold tube. This means that the frequencies are generated on the hot tube. For 4000 Hz frequency, the magnitude is higher at the cold side compare to the hot side. This frequency is generated by the opening at the cold tube which is the orifice. The frequency at around 11000 Hz is heard louder by the microphone at the hot side but very weak from the cold side. This means that this frequency is produced by a source located close to the “hot” microphone but far from the “cold” microphone. It may come from the conical valve

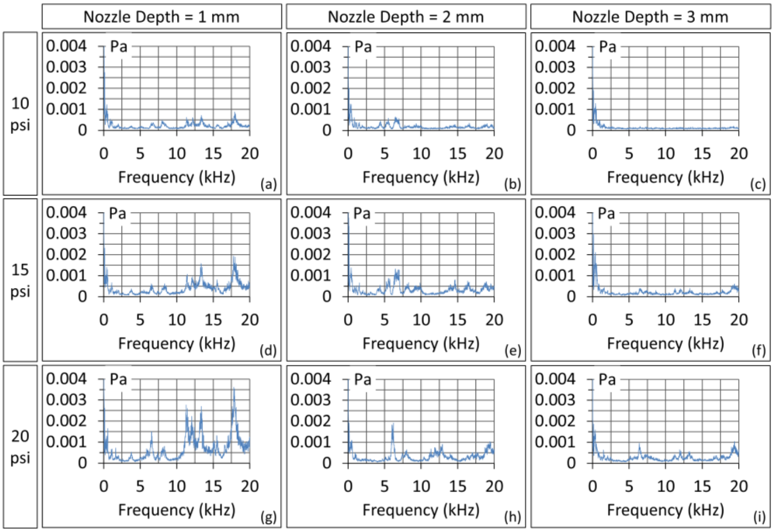

Figure 10. FFT results for different inlet pressure using different nozzle depth (hot tube)

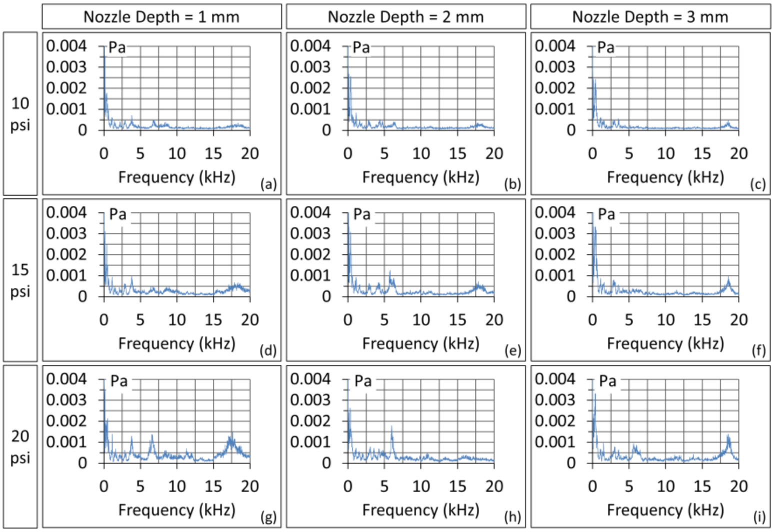

Figure 11. FFT results for different inlet pressure using different nozzle depth (cold tube)

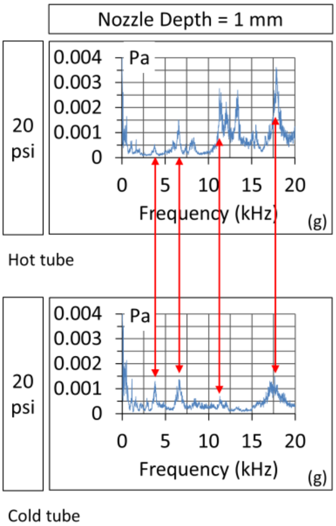

Figure 12. FFT results comparison between hot and cold tubes

To simplify the representation, the significant peaks in the FFT results of figures 10 and 11 are replaced by bars located at the peak location with the same magnitude, producing a set of frequencies called acoustic signatures. This is shown in Figure 13 and Figure 14. It is clearly observed that increasing the pressure at inlet (within the range of this study) does not displace the frequencies significantly when the same swirl generator is used.

On the other hand, different swirl generators produce different sets of frequencies. When the nozzle depth increases, the strength of frequencies produced is decreased. Note that, at 10 psi, most of frequencies are still very weak and they appear at higher pressure for the hot tube. It is also noted that only a few frequencies appear when using bigger nozzles depth for the range of pressure studied. The bar representations in figures 13 and 14 form acoustic signatures of the RHVT for certain configurations of the RHVT.

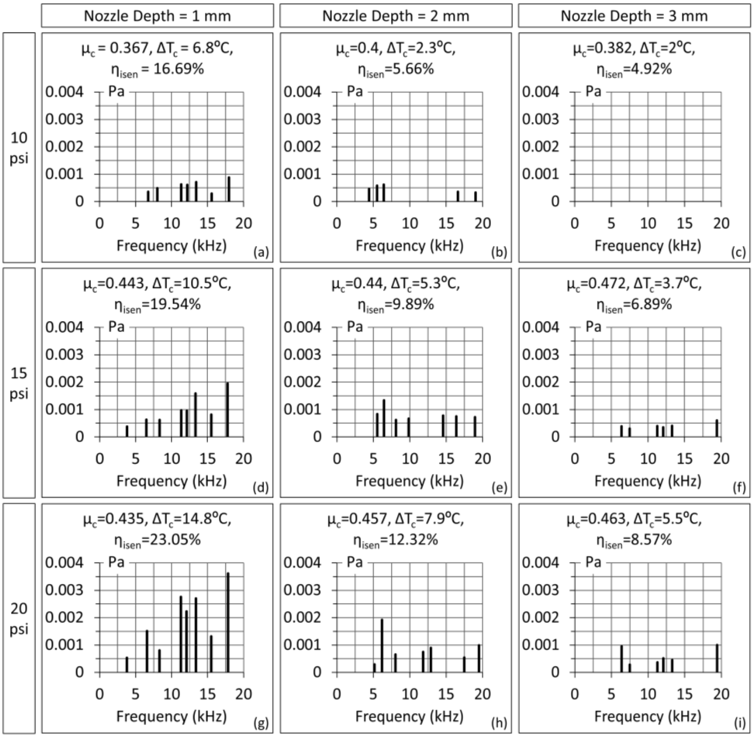

Figure 13. Frequencies signatures for different inlet pressure using different nozzle depth (hot tube)

Each set of frequencies can be correlated with the thermofluid performance of the device as written on the title of each graph. Overall, it is observed that, for all nozzle depths, the amplitude of the frequencies becoming more significant with the increase of efficiency and the increase of difference of temperature. This is due to the fact that stronger sound amplitude is produced when the inlet temperature is higher and also when the nozzle depth is smaller. On the other hand, as explained in the previous sections, these conditions produce higher isentropic efficiency. Thus, better efficiency is obtained when the sound heard is louder both at the cold and the hot tube.

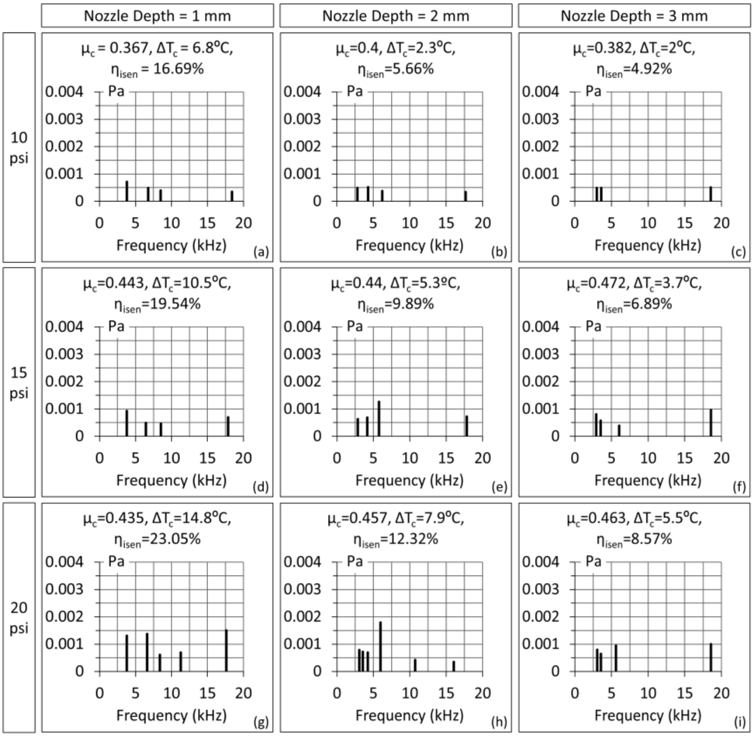

Figure 14. Frequencies signatures for different inlet pressure using different nozzle depth (cold tube)

Conclusion

In this experiment, thermofluid and acoustic analysis has been performed using different swirl generators with different nozzle depth. The RHVT isentropic efficiency increases when the inlet pressure increases. By increasing the inlet pressure, the expansion process is stronger which mean cooler air temperature at the cold outlet. It is also concluded that by reducing the nozzle depth, it increases the isentropic efficiency and the cold temperature difference. The isentropic efficiency of the device is still considered low (less than 23%).

The frequencies produced by the RHVT are not displaced by varying the inlet pressure when the same swirl generator is used. This is the case for the range of inlet pressures applied in this study. The magnitude of the frequencies, however, changes when using different swirl generator. The set of frequencies-magnitudes represent signature of the RHVT for that specific configuration taken at the specific location of the microphone. This signature can be correlated with the thermofluid performance of the device. It is concluded that higher isentropic efficiency is obtained when the amplitude of the sound produced inside the tube is stronger.

It is recommended to widen this thermofluid-acoustic study by varying other parameters of RHVT, such as the orifice diameter, the opening of conical valve (or the cold mass fraction), etc. Reducing the number of nozzles may reduce the number of frequencies produced. It is also suggested to increase the inlet pressure, so that more significant frequencies can be captured. However, higher inlet pressure increases the risk of leakage. Further and deeper study on how each opening/discontinuity (nozzles, orifice, conical valve, etc.) inside the device produces acoustic signals is also interesting to be conducted as this may result more accurate acoustic signatures. The use of several microphones at different location of the tube may help to locate the source of sound.

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