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Dynamic Characteristics of an Unsteady Flow Through a Vortex Tube

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Dynamic flow characteristics of a counter-flow vortex tube is investigated using hot-wire and piezoelectric transducer (PZT) measurements. The experimental study is conducted over a range of cold air outlet ratios (Y=0.3, 0.5, 0.7, and 1.0) and inlet pressure 0.15 MPa. Temperatures are measured at the cold air outlet and along the vortex tube wall. Hot-wire is located at cold outlet and PZT is installed at inner vortex tube by mounting at throttle valve. The cold outlet temperature results show that the swirl flow of vortex tube is not axisymmetric. The hot-wire and PZT results show that there exist two distinct kinds of frequency, low frequency periodic fluctuations and high frequency periodic fluctuations. It is found that the low frequency fluctuation is consistent with the Helmholtz frequency and the high frequency fluctuation is strongly related with precession oscillation.

Key Words : Vortex Tube, Flow Frequency, PZT, Precession Oscillation, Helmholtz Frequency

1. Introduction

The vortex tube is a very interesting invention since it can separate compressed air into hot and cold air without any moving part or any chemical reactions. This energy separation phenomenon by the vortex tube has attracted substantial interest due to its simple design and specialized commercial applications as air-cooled suits for high temperature work environments, and in cooling devices for cutting tools and electronic equipments.

Many studies on the vortex tube have been performed since its invention by Ranque (1932). Hilsh (1947) investigated the influence of the geometrical configuration of the vortex tube on the energy separation process. Kassner and Knoernschild (1948) proposed two different geometries of the vortex tube, a counter-flow type and a uni-flow type. Hartnett and Eckert (1957) measured the distribution of the total temperature in a vortex tube and found that the minimum total temperature occurs in the central region. Lukachev (1981) was the first to use the PZT in the vortex tubes to measure the inner flow characteristics in radial directions. Schlez (1982) reported the difficulties associated with the use of non-invasive measurements, such as Laser Doppler Velocimetry, due to the high centrifugal acceleration associated with vortex tube flows. Arbuzov (1997) visualized the inner flow of a vortex tube under limited conditions and confirmed the formation of an intense large vortex structure near the axis. Ahlborn and Groves (1997) measured the axial and radial velocities using a pitot probe and proposed the existence of a secondary circulation flow in a vortex tube. Sohn, Kim and Gowda (2006) visualized the wall streak lines and numerically simulated the vortex tube to investigate the energy separation mechanism. Many other researchers have also carried out investigations to explain the energy separation mechanism in the vortex tube, but the fundamental energy separation mechanism

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in a vortex tube is still not clear.

Most of the studies on a vortex tube have been conducted with steady state condition only. Therefore, the purpose of this study is to investigate the dynamic flow characteristic of the vortex tube by using hot-wire and piezoelectric transducer (PZT). The temperatures were also measured at the cold air outlet and along the sidewalls at different locations.

2. Experimental Procedures

Figure 1 shows a schematic diagram of the experimental apparatus for the counter-flow type vortex tube. It consists of three components viz., input air supply parts, a test section and a data acquisition unit. Air supply parts consist of air-compressor, 40 μm mesh sized pre-filter, after-cooler, main-filter and air-dryer. Pressure-regulator is provided at the front of the vortex tube generator to supply air at constant pressure. Input air pressure is measured by a pressure module. More details of test parts are shown in Fig. 2 and Table 1 shows the detailed dimensions of vortex tube and experimental conditions. Fig. 2(a) shows the thermocouple locations for vortex tube wall temperature measurement as described in Table 2 and PZT location. PZT is mounted at the throttle valve and it faced inner vortex tube so the flow characteristic in a vortex tube can be measured without disturbance of outer air flow. A piezoelectric transducer (AN5800, Silicon Microstructures Inc.) having high dynamic range (10^{-6}) and remarkable linearity (Richards, 1977) is used. Hot-wire is also used to measure the instantaneous fluctuation of exit cold air flow as shown in Fig. 2(b). The position of the hot-wire probe was controlled with a three-axis traverse. A hot-wire calibrator (Kanomax, CTA-1024) and a temperature calibrator (Omega, CT-23A) were used to calibrate the equipment. A thermocouple probe is used at the same position as the hot-wire and the thermocouple outputs were acquired from Data Acquisition System (Fluke, 2645). An oscilloscope (Lecory, 9635AM) was used to acquire analog signals from the hot wire and piezoelectric transducer for 1 sec (250,000 samples/sec). These data were transferred to a computer through the GPIB (National Instruments, LabVIEW) and were later analyzed with Power Spectral Density

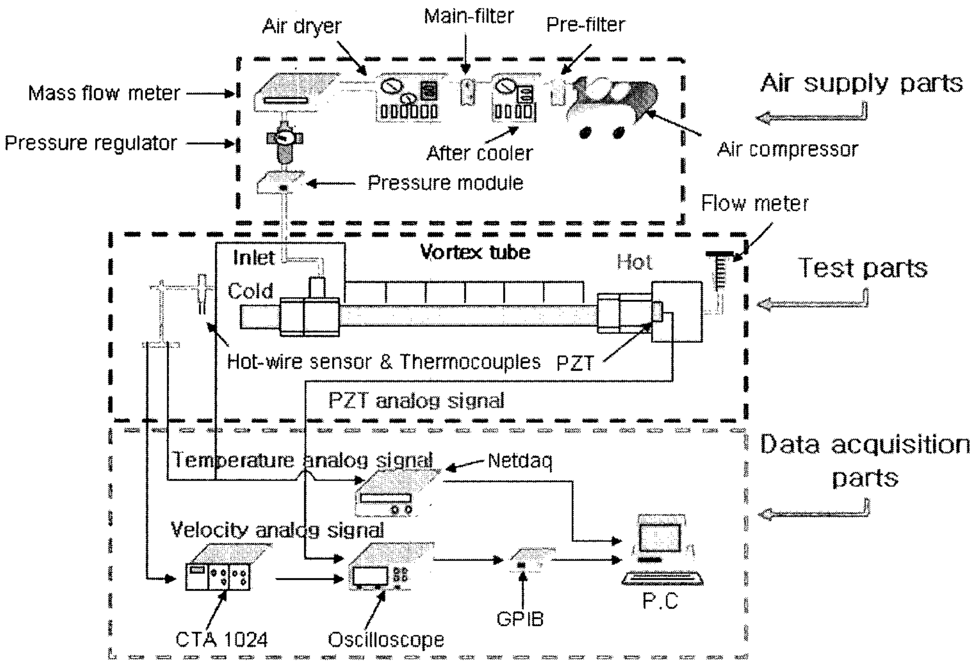
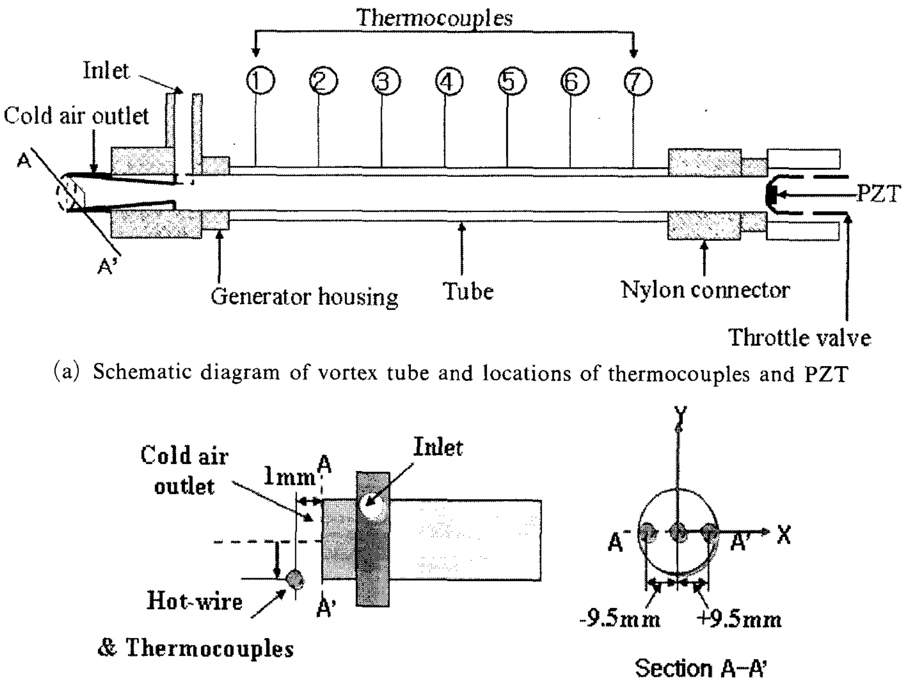


Fig. 1 Vortex tube test apparatus



(a) Schematic diagram of vortex tube and locations of thermocouples and PZT

(b) Hot-wire locations at cold air outlet

Fig. 2 Schematic diagrams of vortex tube and measurement's locations

Table 1 Dimension of the vortex tube and experimental conditions

(Unit : mm)

Classification		Size
Dimension	Tube diameter (D)	20
	Tube length (L)	500
	Hydraulic diameter of vortex generator (Dn)	5.7
	Cold end orifice diameter (Dc)	8.9
	Cold end diameter (De)	20
	Cold air outlet length (Le)	10
Experimental conditions	Working fluid	Air
	Ambient temperature	20℃
	Inlet air temperature	22℃
	Inlet air Pressure (gauge pressure)	0.15 MPa
	Cold air flow ratio (Y)	0.3, 0.5, 0.7, 1.0

Table 2 Thermocouple locations for vortex tube wall temperature measurement

Location No	1	2	3	4	5	6	7
L/D	3	6	9	12	15	18	21

distributions.

3. Results and Discussion

Experimental test were conducted with inlet pressure of 0.15 MPa. The cold air flow ratio (Y=cold flow rate/inlet flow rate) was varied from 0.3 to 1.0 by adjusting the throttle valve. The cold air flow ratio Y=1.0 is the case of no hot air flow rate and the vortex tube works as a return flow-type cyclone.

3.1 Energy separation performance and cold outlet flow structure of vortex tube

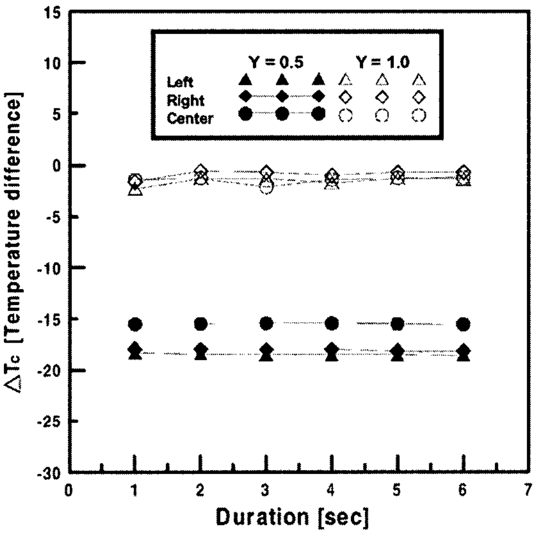
Figure 3 shows the cold temperature difference ($\Delta T_c = T_{cold} - T_{inlet}$) with different cold air flow ratio Y and the different probe positions (Left, Right and Center) as shown in Fig. 2(b). The experimental result for Y=1.0 in Fig. 3(a) show that the cold temperature differences, ΔT_c are slightly lower than zero and indicating the energy separation performance is very weak than at other Y values. The maximum energy separation performance in this experiment is obtained for Y=

0.5 case since the cold temperature differences, ΔT_c are much lower than zero. However, the values of ΔT_c at center position for Y=0.5 show some deviation with left and right thermocouple values. The measured cold temperature Tcold is static temperature and it has the following relation, $T_{static}=T_{total}-T_{dynamic}$. If the speed is low, then T_{cold} increases and the cold temperature difference ($\Delta T_c=T_{cold}-T_{inlet}$) reduces. Therefore, the results for Y=0.5 show that the speed in center region of cold outlet is lower than the speed of outer region.

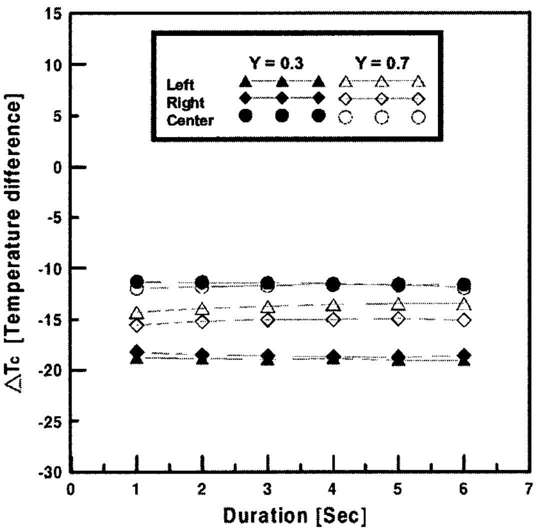
Figure 3(b) shows the measured cold temperature difference ΔT_c for Y=0.3 and Y=0.7 cases. In the case of Y=0.3, the difference of the center and outer (right or left) value of ΔT_c is higher than at other Y values. In the case of Y=0.7, the energy performance is not better than Y=0.5 case and there is maximum deviation among the values of ΔT_c. The difference in values of ΔT_c between left and right positions indicate that the cold outlet swirl speed is not axisymmetric.

Figure 4 shows the speeds with different cold air flow ratio Y at cold air outlet by hot-wire measurement. It can see that the speed in center region of cold outlet is lower than the speed of outer region and the speeds increase with increasing Y value. Fig. 4 also shows that the speeds distribution along radius is not symmetric and it supports the non-axisymmetric flow structure of vortex flow of vortex tube.

A schematic flow diagram at the cold air outlet can be sketched as shown in Fig. 5. In the Y=0.7 case, the swirl flow center may be most offset from the geometric center. For Y=0.3 case the difference of speed between that at the center position and those at the outer positions is maximum in these experiments. Fig. 5 is not the inner schematic flow diagram ; however, the inner vor-



(a) Y=0.5 and 1.0



(b) Y=0.3 and 0.7

Fig. 3 Cold air outlet temperature difference with Y=0.3, 0.5, 0.7 and 1.0

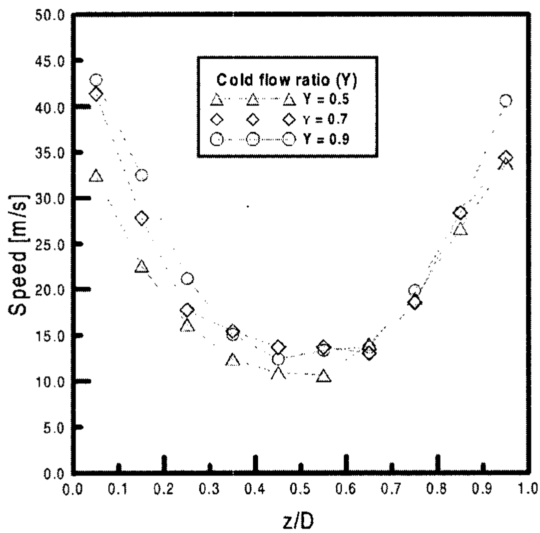


Fig. 4 Cold outlet speeds at difference with Y

tex flow also may not be axisymmetric flow and a precession motion may exist in a vortex tube. To find the period of the dynamic motion of vortex flow, time accurate measurement method is needed.

Figure 6 shows the measured wall temperature difference ($\Delta T_w = T_{wall} - T_{inlet}$) distribution with various cold air flow ratios. The wall temperature difference, ΔT_w increases along with increasing cold air flow ratio (Y), and the gradients of ΔT_w near vortex generator are higher than hot outlet region. Sohn, Kim and Gowda (2006) reported the existence of strong correlation between the wall temperature increase and stagnation position. They also showed that the stagnation position moves towards the vortex generator as cold flow ratio increases but it attains a fixed position at higher Y values. In the Y=1.0 case, the position of maximum wall temperature is at a relatively short distance from air inlet and these results are consistent with the previous experiments. Unlike at other cold air flow ratio, the wall temperature for Y=1.0 decrease after the maximum point as indicated by the dashed lines in Fig. 4 since there is no hot outlet flow through the throttle valve.

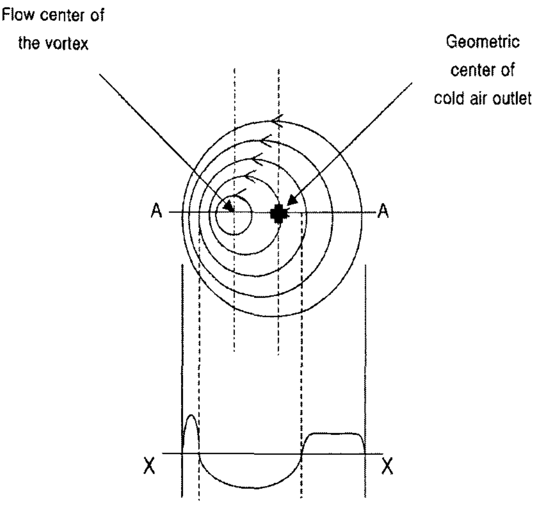


Fig. 5 Schematic flow diagram of the precession motion at the cold air outlet

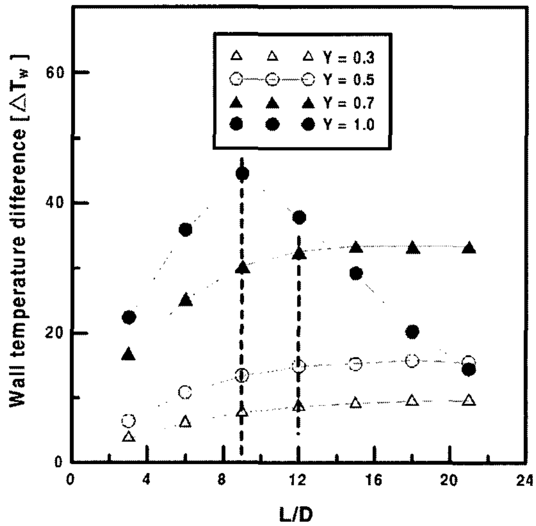


Fig. 6 Distributions of wall temperatures difference profile with various cold flow ratios

3.2 Frequency characteristics of swirling flow in a vortex tube

Hot-wire and piezoelectric transducer (PZT) measurements are employed to get frequencies of dynamic flow in vortex tube. It is very difficult to install hot-wire at the inner vortex tube without disturbance to the vortex flow field ; hence, the position of measurement of hot-wire is at the cold outlet as shown in Fig. 2(b). Since the location of hot-wire is on the outer side of vortex tube, the instantaneous fluctuations contain also the effect of outer side air flow mixing with the cold outlet flow from inner vortex tube.

Figures 7 and 8 show the power spectral density (PSD) obtained by hot-wire for various cold flow ratios at different measurement locations of the cold air outlet. The PSD distribution of left and right positions are very similar as shown in Figs. 7 and 8 and it means that the noise of flow motion is nearly same. The peak frequencies of vortex tube by hot-wire measurement are about 417 Hz for Y=0.3, 515 Hz for Y=0.5 and 655 Hz for Y=0.7. However for the Y=1.0 case, the most apparent peak frequency is about 2100 Hz and this frequency is relatively at a higher frequency band than the measured peak frequency around 500 Hz at various other cold air flow ratios. The physics of these frequencies of swirling flow in a vortex tube will be discussed along with the PZT results.

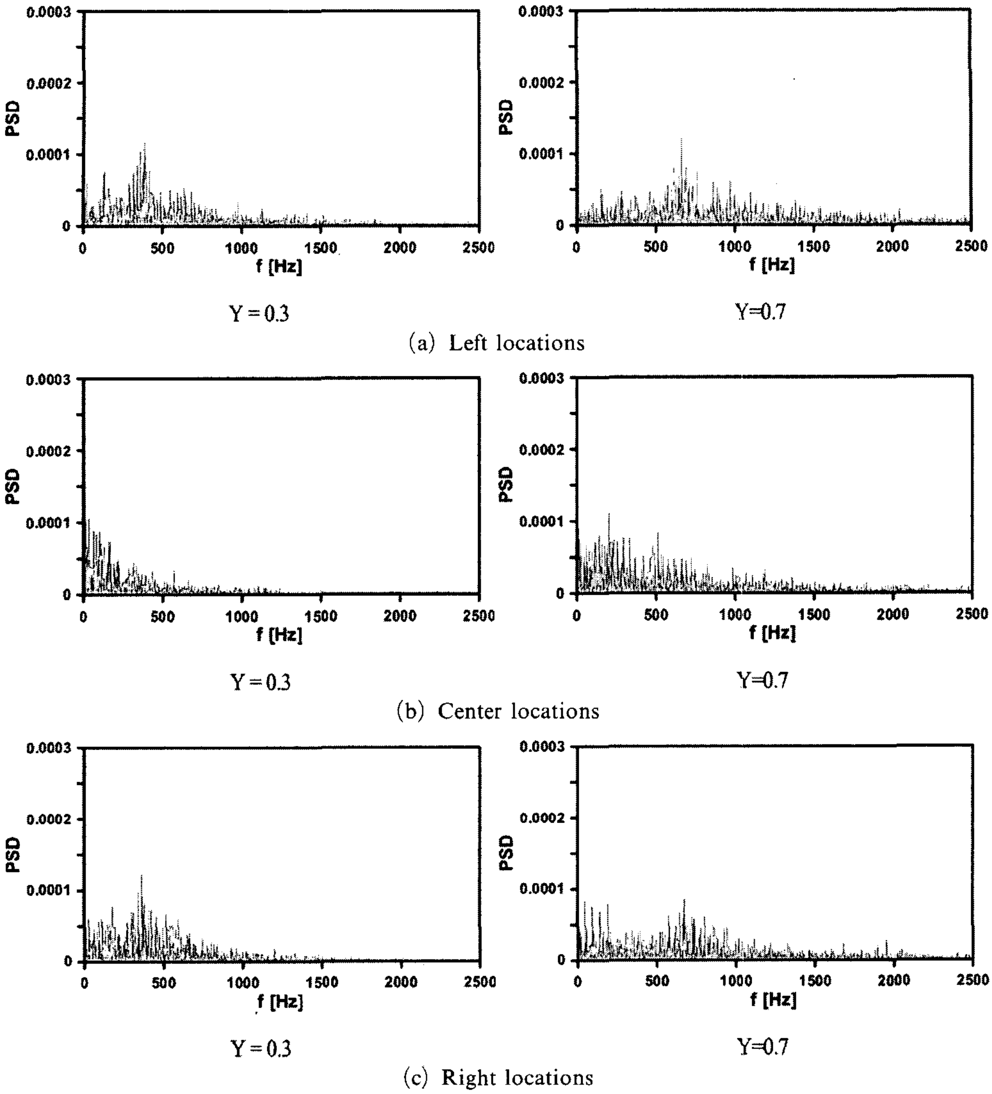


Fig. 7 PSD results using hot-wire at the cold air outlet for Y=0.3 and 0.7

Figure 9 shows the PSD results by PZT measurement and the peak frequencies are clean and apparent. Since the PZT is installed at the inside of vortex tube by mounting it at the throttle valve as shown in Fig. 2(a), the frequency signal does not include the air mixing noise with surrounding air. The measured lower peak frequency in a vortex tube by PZT is about 520 Hz and this value is consistent with the measured low peak frequency by hot-wire. However the lower frequency values by PZT are almost constant for various Y compared with the results of hot-wire. The relatively high peak frequency by PZT measurement is about 2100 Hz and this value is the same as the measured frequency by hot-wire.

The periodic oscillations of swirling flow in a vortex tube may exist as two oscillation types, longitudinal oscillation and precession oscillation (or rotational oscillation). If there is rotational oscillation, the radial oscillation is also induced by it to satisfy mass conservation.

The longitudinal oscillation occurs by axial compression and expansion of air in the inner vortex tube and this frequency can be expressed by Helmholtz frequency (Kinsler, 2000). Helmholtz frequency is calculated by equation (1)

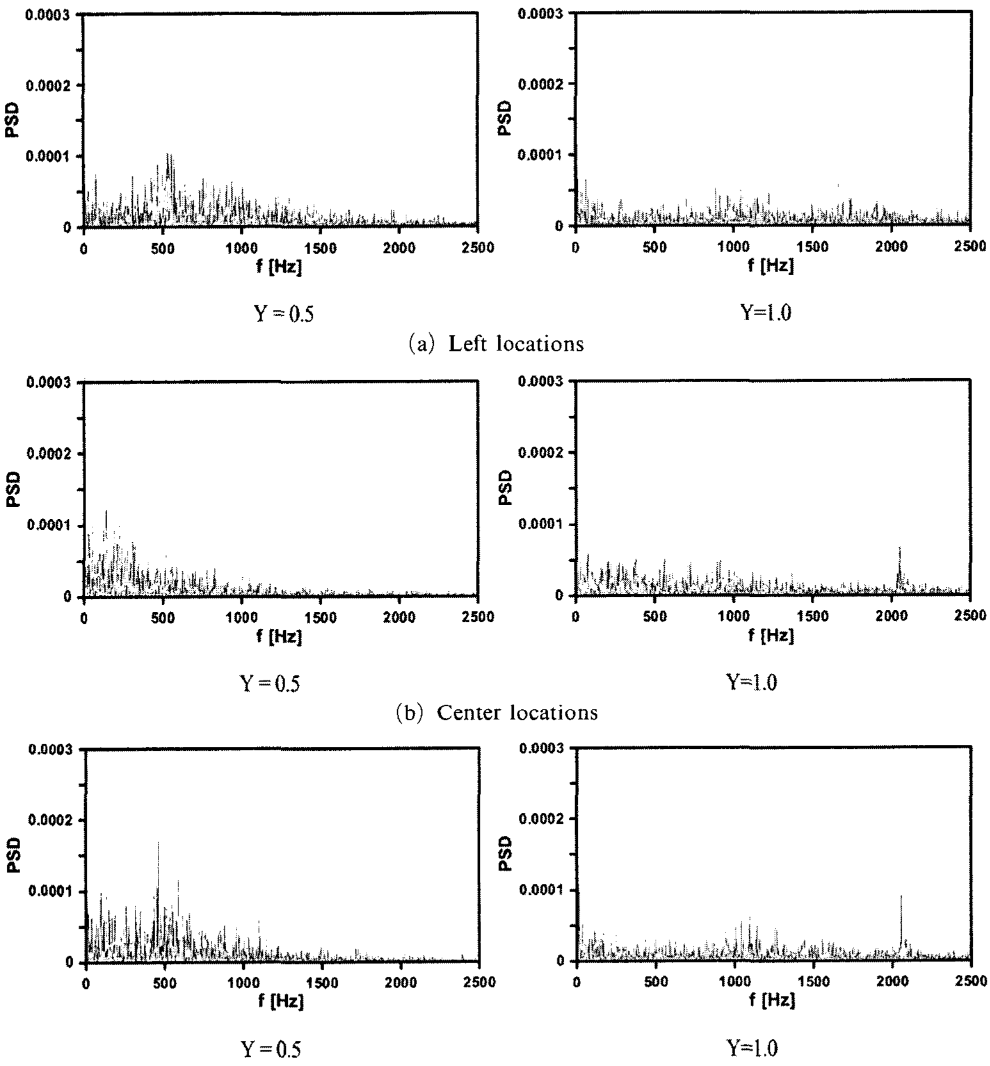


Fig. 8 PSD results using hot-wire at the cold air outlet for Y=0.5 and 1.0

$$f=\frac{c}{2\pi}\sqrt{\frac{A}{Vl}} \tag{1}$$

In Eq. (1), c is the sound speed, $A=\pi D_c^2/4$ is throat area, $V=\pi D^2 L/4$ is the volume of vortex tube and l is effective length of the throat. The sound speed c is about 343 m/sec at air temperature of 20℃ and D_c, D, L are given in Table 1. Since the cold air outlet shape is not that of a pipe but has a nozzle shape, it is difficult to determine the effective length of the throat l. If l is given for the cold air outlet length as (Le) the calculated Helmholtz frequency is about 344 Hz. If l is given for the cold air outlet length as $(Le/4)$ the calculated Helmholtz frequency is about 687 Hz. Since the measured low peak frequency is very close with the estimated Helmholtz frequency, the low peak frequency may be a Helmholtz frequency created by the longitudinal compression and expansion of air in vortex tube.

The reasons of precession or rotating oscillation in swirling flow may be supposed to be due to the existence of offset swirl center with the geometric center as shown in Fig. 5. If the vortex flow is axisymmetric then the measured instantaneous fluctuation frequency only includes the

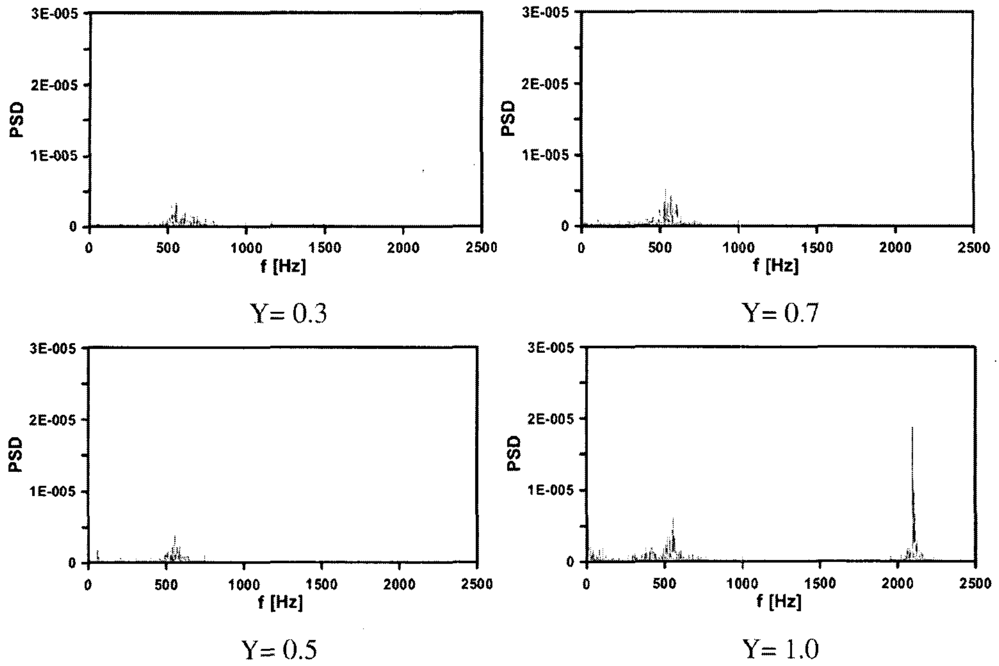


Fig. 9 PSD results using PZT on the inner wall of throttle valve

random turbulence fluctuation and the turbulent fluctuations are usually of higher frequency than the frequency 2000 Hz.

Ahlborn and Groves (1997) measured the swirl velocity for various cold air flow ratio and reported the peak swirl velocity is about 130 m/sec. Ahlborn and Groves (1997) used a vortex tube with $D=25.4$ mm, $L=600$ mm $D_c=8.2$ mm and test inlet air pressure was 0.146 Mpa. Compared with the present test conditions as shown in Table 1, the dimensions of vortex tube and test conditions of both experiments are very similar.

From the simple oscillation theory for rigid body, the rotation speed is calculated as $v_\theta=\omega r=2\pi rf$. Hartnett and Eckert (1957), Ahlborn and Groves (1997) showed that the swirl velocity in a vortex tube increases linearly with radius just like forced vortex flow and the swirl velocity decreases with radius at a certain radius as free vortex flow. Therefore, the forced vortex regions in a vortex tube have same angular velocity and the generation of the frequency by precession oscillation is the same as the frequency of swirl motion in a vortex tube.

From the above idea, it is possible to calculate the swirl velocity by the measured high peak frequency as $v_\theta=2\pi rf$ and is about 132 m/sec with the present vortex tube radius $r=0.01$ m. This roughly estimated swirl velocity is almost same as the measured maximum swirl velocity (about 130 m/sec) by Ahlborn and Groves (1997).

The question arises, if the peak frequency is induced by swirling velocity in a vortex tube, why the experiment can not measure the high peak frequency at different Y values? In the Y=1.0 case there is no hot flow rate through throttle valve and it can be guessed that the throttle valve reduces non-axisymmetric tendency since the holes of throttle valve can work as a damper of oscillation.

It can be noticed that the offset swirl or precession motion generates the fluctuation of pressure at the geometric center point since the rotating center is offset of the geometric center point. Therefore, PZT can measure the precession motion if the precession motion is strong. Authors believe that the precession motion exists at every Y value but the present installed PZT can measure only for strong precession motion such as Y=1.0 case. If the PZT is installed in the radial direction along the wall, more apparent radial fluctuation for low cold flow ratio can be measured and it will be examined in the next study.

4. Conclusions

In this study the dynamic flow characteristics in a vortex tube is investigated by hot-wire and piezoelectric transducer (PZT) measurements. The experimental study was conducted over a range of cold air outlet ratio, Y=0.3, 0.5, 0.7, and 1.0, and inlet pressure 0.15 MPa. The cold outlet temperatures of left and right locations are different and show that the swirl flow of vortex tube is not axisymmetric. The temperature measurement results show that the speed in center region of cold outlet of vortex tube is lower than the speed of outer region of vortex tube. It is found that a vortex tube has two distinct kinds of frequency, low frequency periodic fluctuations and high frequency periodic fluctuations. The low frequency fluctuation is consistent with the calculated Helmholtz frequency and the high frequency fluctuation is strongly related with precession oscillation by the offset of swirl center with geometric center.

Acknowledgments

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