Flow visualization to determine the flow structure in a vortex tube

Yunpeng Xue, Maziar Arjomandi and Richard Kelso

School of Mechanical Engineering, the University of Adelaide
Adelaide, South Australia 5005, Australia

Abstract

This paper reports on a study in progress exploring the flow structure in a vortex tube. Flow visualization, using water as a working fluid, was used to reveal the velocity distribution and multi-circulation of the flow within the vortex tube. This research contributes to understanding of the flow behaviour and supports the hypothesis presented by Xue et al. [3], that cold air is the result of the expansion near the cold nozzle and hot air is the result of air friction during multi-circulation.

Introduction

Due to its many advantages, such as design simplicity and cost effectiveness, the vortex tube is used in applications such as heating, cooling, thermal testing, dehumidification, gas liquefaction and ice production. A vortex tube is a simple device, which can generate instant cold and hot flow from a single injection. The main part of a vortex tube is a hollow cylinder, in which compressed air or other fluids are injected tangentially. The hot nozzle is located at the periphery, and the cold nozzle is placed at the centreline of the tube. Passing through the vortex chamber, the injected compressed air forms a strong vortical flow. The vortical airflow, which is moving towards the hot end, later is forced back by a plug that is placed at the hot end of the tube. The plug adjusts the balance of the amount of air that is allowed to escape peripherally, which is hot and the amount that is forced back to escape from the centre of the tube, which is cold. The airflow in a counter-flow vortex tube is shown in Figure 1.

Since the discovery of the temperature separation in the vortex tube, investigations of the unusual thermal separation focus on improving the performance of the vortex tube and explaining the complex physical process. Ranque proposed the compression and expansion effects as the main reasons for the temperature separation in the tube [1]. Further to this, the geometrical parameters and performance optimisation of the tube were investigated by Hilsch [2] by adding the effect of inner friction to the Ranque’s model of compression and expansion. A detailed summary of the outcomes of experimental, theoretical and numerical investigations of the vortex tube was published [3], in which different explanations, including pressure gradient, acoustic streaming, internal friction, secondary flow and static temperature gradient, were discussed. Due to the complexity of the flow structure in the vortex tube, none of those factors is proven to be the reason for energy separation in the RHVT.

To explain the thermal separation in the vortex tube, description of the physical process of the air flow inside the tube and analysis of the velocity distribution are required. In early research, flow visualization was employed to show the flow structure. Roy [4] injected colour liquid into the RHVT system to investigate the flow pattern and in 1959, Lay [5] injected water inside the RHVT system, but this failed to reveal an image. A mixture of powdered carbon and oil by Sibulkin [6] and smoke by Smith [7, 8] were used to visualize the flow. The structure of the vortical double helix was visualized by Arbuzov [9] in 1997 using Hilbert dichromatic filtering and observed the formation of an intense vortex braid near the axis. In 2005, Aydin [10] also applied flow visualization in their investigation, and the clear flow trace was shown in figure 2. However, the different flow trace in the tube indicates that more investigation in the vortex tube is required.

Experimental apparatus

To get a clear visualization of the flow behaviour inside a vortex tube, an acrylic tube (diameter × length = 5.8 × 45 cm) is employed as the main part of the vortex tube in this research. Water is pumped into the vortex tube at the velocity 1 m/s from a tangential inlet, which has 12-millimeter diameter. A 10-millimeter cold nozzle along the centre line and an adjustable peripheral hot exit (0.6 mm and 1.5 mm gap) are positioned at different ends of the tube. The whole vortex tube is immersed under water during the experiments, by which the influence of ambient pressure and gravity of the working fluid can be ignored. A frame, which is designed to hold the hydrogen wire, can be placed at different positions of the tube. Figure 3 shows the structure of the clear vortex tube, needle for injecting air bubbles and hydrogen bubble wire.

Figure 2. Result of the flow visualization for the optimum geometry [10]

This paper focuses on the flow structure in a vortex tube. To achieve a clear understanding of the flow behaviour, incompressible fluid is employed in this research, by which compression and expansion can be avoided. The incompressible fluid was visualized by hydrogen bubbles, air bubbles and small size particles. Fluid velocity was calculated and the presented hypothesis [3] is discussed based on the experimental results.
force and floatage of the air bubbles, small needle is used to
generate small air bubbles. Furthermore, due to the unknown
axial velocity of the injected air bubbles, the axial velocity
conducted from experiments can not be trust and only the swirl
velocity of the air bubbles is reliable.

Figure 3. Experimental setup for flow visualization

Small particles, which have similar density of water, are also
used in this research in order to show the flow structure
accurately. Pictures and videos of the hydrogen bubbles, air
bubbles and particles are taken. Motion traces of air bubbles and
small particles appear as light lines, shown in figure 4. Knowing
the shutter duration and length of the light lines, the velocity
of the air bubbles and small particles, which are considered to
present the velocity of the working fluid in this research, can be
calculated. Similarly, analysing the videos frame by frame, the
velocity distributions of the air bubbles, hydrogen bubbles and
small particles can be conducted.

Figure 4. Appearance of the air bubbles in the vortex tube

Axial velocity distribution is obtained from the hydrogen bubbles
displacements between two continuous frames. A clear picture of
the hydrogen bubbles is shown in figure 5, from which the axial
velocity can be calculated.

Figure 5. Wire for generating hydrogen bubbles

Result and analysis

Analysing the picture of air bubbles and small particles, swirl
velocities of the air bubbles and particles, which are consider
presenting the flow velocity, are calculated. The needle for
injecting air bubbles is positioned near the wall to ensure that the
movement of the air bubble is along the inner wall of the tube.
The length of the motion trace of the air bubbles or particles are
measured and the shutter duration is set at 1/100 second. Thus
dividing the displacements of the air bubbles or particles by the
shutter duration, swirl velocity can be calculated. Since the real
trace of the particle is an arc instead of the light line in the
picture, analysis of the accuracy is required. For a 58 millimetres
circle, which is the inner diameter of the vortex tube, difference
between a 10 millimetre line and its corresponding arc is less
than 0.5%. Thus the length of the light line is used instead of the
real length of the arc in the calculation. Swirl velocity
distributions near the wall along the tube are summarised in
Figure 6 for the vortex tube with 10 mm cold exit and 1.5 mm
gap at the hot exit with the needle and recording the particles
positioned at different height. It can be concluded from the figure
that for the 1 m/s injection, the peripheral swirl velocity
decreases from about 0.3 m/s at height 12 cm above the hot exit
to around 0.23 m/s near the hot exit.

Figure 6. Swirl velocity distribution near the wall at different height

When particles are injected, they move with the fluid in the tube.
This allows the location of a single particle in a video. By doing
this, the swirl velocity and axial velocity of the particle can be
calculated. Verifications of the diameters of the particle traces
show the position of the particles in radial direction. Time is
counted after the particle completes an entire circle, and the
angular velocity is calculated by this time. Figure 7 shows the
swirl velocity inside the vortex tube at the height 6 cm above the
hot exit, including both angular velocity and linear velocity. The
angular velocity decreases from the centre to the periphery from
45 rad/s at 5 mm to 8 rad/s at periphery. The linear velocity
increases from 0.25 m/s at 5 mm to 0.29 m/s at 11 mm and
decreases to 0.17 m/s at 27 mm. This measurement of the swirl
velocity shows similar distribution as others’ research [4] that the
swirl velocity increases to a peak value and decreases after the
peak. However, difference can be located in some numerical
studies [3], in which force vortex is stated as the motion in the
tube.

Figure 7. Swirl velocity inside the tube at H=6 cm

Pictures and videos of the flow visualization using hydrogen
bubbles were used to analyse the axial velocity. As shown in
figure 8, upward flow is shown by the hydrogen bubbles
generated by the wire, and the displacement △X in two
continuous frames can be measured. Knowing the time between
two frames, the axial velocity is determined by the displacement
and the time difference. Similarly, figure 9 shows the measurement of both upward flow and downward flow, where $\Delta X$ and $-\Delta X$ present upward and downward displacements respectively.

![Figure 8. Hydrogen bubbles showing the centre flow](image)

![Figure 9. Hydrogen bubbles showing both upward and downward flow](image)

Figure 8. Hydrogen bubbles showing the centre flow

Figure 9. Hydrogen bubbles showing both upward and downward flow

Figure 10 shows the axial velocity in the vortex tube with a 1.5 mm gap at the hot exit and at height 2 cm above the hot exit. The axial velocity decreases from 0.135 m/s at the centre to 0 m/s at 12.3 mm, which means the fluid flows upwards within the 12.3 mm-radius-circle. Downward flow starts from 0 m/s at 12.3 mm and increases to 0.08 m/s at periphery.

![Figure 10. Axial velocity distribution at height 2 cm](image)

Figure 10. Axial velocity distribution at height 2 cm

The wire was positioned at different heights above the hot exit and the axial velocity distribution inside the tube is summarized in figure 11. It can be concluded from the figure that the axial velocity of the vortex flow changes with different locations. The still point at 12.3 mm in radial direction separates the upward flow and downward flow. Thus connection of these still points at different height gives a clear understanding of the upward and downward flows and forms a stagnation line. However, the axial velocity at height 6 cm shows different distribution that peak value does not appear in the centre. This might be due to the start of the multi-circulation, which will be discussed later, but more investigation is required. Axial velocity distribution of a vortex with a 0.6 mm hot exit is shown in figure 12. Similar velocity distribution can be found in figure 12. With a smaller gap at the hot exit, axial velocity of the upward flow is larger and axial velocity of downward flow is smaller, which means more fluid flows out from the cold end.

![Figure 11. Axial velocity distribution in the vortex tube with 1.5 mm gap](image)

![Figure 12. Axial velocity distribution in the vortex tube with 0.6 mm gap](image)

Figure 11. Axial velocity distribution in the vortex tube with 1.5 mm gap

Figure 12. Axial velocity distribution in the vortex tube with 0.6 mm gap

Figure 13 shows a clear process of the flow near the hot exit in a vortex tube. When air bubbles are injected into the vortex tube near the hot exit, they almost move with the fluid. Some of the
bubbles leave from the hot exit, the others are forced back by the conical plug and move to the cold exit (a). When moving the needle away from the hot exit, fewer air bubbles are exhausted from the hot end and more bubbles leave from the cold end (b). When the air bubbles are injected at 21 cm from the hot end, all the bubbles leave from the cold exit (c).

Figure 13. Flow visualization with air bubbles injected
When the needle is positioned in the centre, all the air bubbles are exhausted from the cold exit along the centre line, which shows the upward flow in the centre region. However, it can be seen in figure 14 that some of the air bubbles are moving from the centre to the periphery and forced back by the conical plug. Motion trace of these bubbles proves the formation of the multi-circulation in that some fluid in the centre is flowing back to the hot end from the periphery and being forced back by the plug. Then part of these forced back bubbles flow back to the hot end again and form the multi-circulation. This multi-circulation is supposed to be the reason for the temperature rise in a vortex tube in the review [4]. Also the start of the multi-circulation at 6-7 cm above the hot exit can be used to explain the axial velocity distribution at height 6 cm.

Figure 14. Flow visualization with air bubbles injected in the centre
Moreover, observations of the motion traces of injected particles demonstrate this multi-circulation too. The peripheral flowing particles move downwards helically to the hot end and are forced back at the conical plug. In this process, the radius of the particle’s rotation is getting smaller, which means the centre upward flow is formed. Then the particles move upward in the centre region, and at height 6-8 cm some of the particles flow outside and join the downward peripheral flow. This process presents the formation of the multi-circulation near the hot end in a vortex tube.

Conclusions
The temperature separation in a vortex tube is still unclear, and this research focus on the flow structure in a vortex tube using flow visualization. The vortex angle of the flow in a clear tube with tangential injection is summarized and decreases along the tube. The wave in the vortex angle distribution shows the existence of the main stream and the rotation of the swirling axis.

Influence of compression and expansion in the vortex tube can be avoided when incompressible material is used as the working fluid. Thus, water has been selected in this research. Using hydrogen bubbles, air bubbles and small particles, the flow structure in the vortex tube is shown and swirl velocity and axial velocity are summarized. Existence of the multi-circulation near the hot exit is proved with both the picture of air bubbles and videos of particles.

Due to the limitation of flow visualization in this research, more accurate measurement of the flow parameter using water as working fluid is recommended. As discussed in [3], expansion near the cold exit can be considered as the main reason for temperature drop and temperature rise is hypothesized as the result of flow structure. Thus, investigation focusing on the flow structure near the hot exit can provide useful clues for the exploration of temperature rise, such as the multi-circulation. Since in a real vortex tube the inlet velocity is much higher than the inlet velocity in this research, when high velocity is applied investigation of the flow behaviour is recommended.

Acknowledgments
The authors express their appreciation to Mr Silvio De leso for his dextrous instrumentation and Ms Karen Adam for her English language expertise.

References