Flow Visualization in a Ranque-Hilsch Vortex Tube

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ABSTRACT

This paper presents the results of flow visualization in a Ranque-Hilsch vortex tube (RHVT). The RHVT has been newly designed and locally fabricated. Dimensional analysis and similarity was carried out by taking comparison between real model (Blue Model) of RHVT and prototype (Clear Prototype) using acrylic. The research objective is to visualize flow patterns inside the tube and water is chosen as the flowing fluid. Several methods of visualization were adapted in this exercise especially for observing the particles movement throughout the process. Still pictures and videos were recorded and formation of vortex was studied. It is observed that the flow pattern of circulation was presented and visible. The existence of two swirling flows can be seen and documented. The frames of pictures show a flow pattern of forward and backward flows obtained from the vortex tube.

Keywords: *Flow Visualization, Flow Pattern, Ranque-Hilsch Effect, Dimensional Analysis, Frame Frequency.*

Nomenclature

Lpm	Liter per minute	CFD	Computational Fluid Dynamics
d	diameter	h	height of conical valve
ρ	density	r	radius
F_ω	centrifugal force	D_o	outer diameter
g	gravitational acceleration	D_i	inner diameter
μ	fluid viscosity	fps	frame per seconds

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Q	volume flow rate	ABS	Acrylonitrile Butadiene Styrene
v	velocity	t	thickness
ω	vortex angular velocity	V	volume
f	swirling frequency	L	tube length

Introduction

The vortex tube is a thermos-fluidic device which can produce different pressures and temperatures at each exit. The device was invented by Georges J. Ranque in 1933 and its capability was improved by Hilsch in 1947. Most researchers are interested to study the energy/temperature separation inside the tube. Numerical and CFD approach was often used in explaining the phenomena. Till today, the physical behaviour of the flow is not fully covered due to uniqueness of experimental results. Regarding the radial static temperature gradient, Scheller & Brown [1] found that it is inversely proportional to the vortex tube's radius but some researchers found in different manner. Figure 1 illustrates the flow pattern inside the vortex tube.

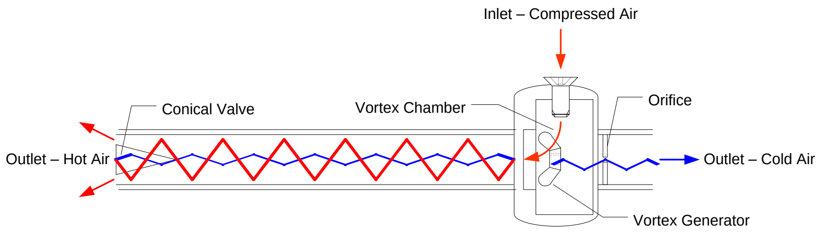


Figure 1: Flow pattern in vortex tube

In the study of Ranque-Hilsch effect, flow pattern knowledge is part of paramount importance especially when dealing with unique phenomena. Flow pattern in Computational Fluid Dynamics (CFD) will give exact colour scheme visualisations which interprets Ranque-Hilsh effect in acceptable manner. Complicated flow pattern due to high swirl effect makes the interpretation more challenging and to simplify the issue, flow visualisation should be introduced. In this approach, it is significance that the flow will be projected as laminar flow in order to get basic trend of swirling in RHVT. Y. Xeu et al. [2] have contributed a research on flow visualisation to understand the flow behaviour. They revealed a multi-circulation region which is dominant in generating heat by viscous friction. Aydin and Baki [3] studied the optimum geometry for energy separation and came out with flow visualization. Meanwhile, Arbuzov et al. [4] used the method of Hilbert chromatic filtering and obtain the formation of vortex flow in double helix profile.

The main objective of this paper is to present flow visualization of RHVT using water. The ultimate goal is to obtain flow pattern observation during short time interval and study the formation of vortex generation in Ranque-Hilsch vortex tube.

The principal work of RHVT was initiated by compressed air that flows through the inlet and passes out through the hot and cold exits. Swirling generator located at the inlet chamber stimulate a swirling flow inside the tube. This swirling flow distributes temperatures along the tube [5]. The compressed air is injected tangentially to the inlet and causes a rotational speed of air near the interior wall. The moving air at this region is released to the hot exit and produce hot air. Conical valve transmits the moving air in the central part to opposite direction and pass through the orifice; expansion occurred and the moving air is discharged as cold air to the cold exit.

The performance of RHVT is influenced by many factors such as supply pressure, conical valve shape, swirl generator, etc. Variation on these parameters will change the mass cold fraction that affects the isentropic efficiency of RHVT [6]. M. Kurosaka [7] used uniflow arrangement of RHVT in acoustic streaming study. He demonstrated through analysis and experiment that the acoustic streaming affects the temperature separation. Y. Xue et al. [8] studied the flow structure in a counter flow vortex tube by measuring velocity distribution and presented velocity fluctuation in time domain. Chang-Soo and Chang-Hyun [9] observed that the vortex tube has two distinct kinds of frequency: low and high frequency periodic fluctuations. Y. Istihat and W. Wisnoe [10] confirmed the presence of two bands of frequencies in the vortex tube. The analysis was done using Wavelet transform. Hazwan and Katanoda [11] studied the flow visualization of flow pattern discharged at the cold exist of RHVT. They found that a negative (suction) and positive pressure region exist at a certain pressure and cold fraction area, and observed a reverse flow in the negative pressure region.

Experimental Apparatus and Setup

To explain the Ranque-Hilsch effect in a vortex tube, a good understanding of the flow behaviour inside the tube is required. Flow visualization techniques have been used to investigate the flow field within the vortex tube, such as dyes and smoke injection. With the injection of dyes or smoke, all subsequent investigations concentrated on tracking the flow trail on the wall near the ends of the tube, and used a clear tube as the main part of the device for tracking the visual elements.

Figure 2 below shows the drawing of RHVT. Main parts of body were made from acrylic and conical valve was made from aluminium. Standard size of acrylics were used meanwhile a conical shape was manufactured using lathe machine.

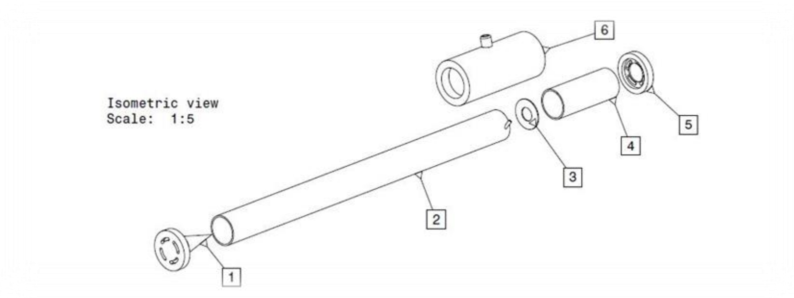


Figure 2: Exploded view of Clear Prototype RHVT

Table 1: Detailed dimension for Clear Prototype

No.	Parts	Quantity	Dimensions (mm)
1	Conical Valve	1	h = 110.12, r =18.79
2	Long Tube	1	D_o = 60, D_i = 54, L = 750
3	Orifice	1	D_o = 60, D_i = 27, t = 17
4	Cold End Tube	1	D_o = 60, D_i = 54, L = 150
5	Web Cap (Outlet)	2	D_o = 54, 4 holes
6	Vortex Chamber	1	D_o = 90, D_i = 84

Table 1 above illustrates the detail dimension of Clear Prototype in this study. The drawing was scaled from a real model (Blue Model) of RHVT which is tested for the Ranque-Hilsch effect.

Dimensional Analysis and Similarity

There are three necessary conditions for completing similarity between a model (Blue Model) and prototype (Clear Prototype). First condition is geometric similarity, the model must be the same shape as the prototype, but may be scaled by some constant scale factor. Second condition is kinematic similarity, which means that the velocity at any point in the model flow must be proportional by a constant scale factor to the velocity at the corresponding point in the prototype flow. The velocity at corresponding point has to be scale in magnitude and must point in the same direction. The third and most restrictive similarity condition is that of dynamic similarity. It is achieved when all the forces in the model flow, scale by a constant factor to corresponding forces in the prototype flow.

List of parameters influencing the angular velocity (ω) of vortex in the vortex tube.

a. Inlet diameter (d)
b. Fluid density ($\rho = m/V$)
c. Centrifugal force (F_ω)
d. Gravitational acceleration (g)
e. Fluid viscosity (μ)
f. Volume flow rate ($Q = Av$)
g. Velocity (v)
h. Vortex angular velocity (ω)
i. Swirling frequency (f)

Using Buckingham Π theorem:-

$$\emptyset(\Pi_1, \Pi_2, \Pi_{3\ldots}, \Pi_{n-m}) = 0$$

n = 9 (number of variables)

m = 3 (3 fundamental dimensions: M, L, T only. The effect of temperature θ is not in this study)

n-m = 6 (limit the parameter that are both controllable and measureable in the lab)

Statement of vortex angular velocity can be seen through equation (1) to (12)

$$\emptyset(\Pi_1, \Pi_2, \Pi_3, \Pi_4, \Pi_5, \Pi_6) = 0 \quad (1)$$

Take ρ, v and d as a primary variable. The Π terms are;

$$\Pi_1 = \rho^{a_1} v^{b_1} d^{c_1}, F_\omega \quad (2)$$
$$\Pi_2 = \rho^{a_2} v^{b_2} d^{c_2}, g \quad (3)$$
$$\Pi_3 = \rho^{a_3} v^{b_3} d^{c_3}, \mu \quad (4)$$
$$\Pi_4 = \rho^{a_4} v^{b_4} d^{c_4}, Q \quad (5)$$
$$\Pi_5 = \rho^{a_5} v^{b_5} d^{c_5}, \omega \quad (6)$$
$$\Pi_6 = \rho^{a_6} v^{b_6} d^{c_6}, f \quad (7)$$

Example of analysis for

$$\Pi_1 = \rho^{a_1} v^{b_1} d^{c_1}, F_\omega$$

a. MLT system

$$[MLT]^0 = [ML^{-3}]^{a_1}[LT^{-1}]^{b_1}[L]^{c_1}[MLT^{-2}]$$

b. Homogeneity left and right

$$\begin{aligned} &M \rightarrow 0 = a_1 + 1 && \rightarrow a_1 = -1 \\ &L \rightarrow 0 = -3a_1 + b_1 + c_1 + 1 && \rightarrow c_1 = -4 - b_1 \\ &T \rightarrow 0 = -b_1 - 2 && \rightarrow b_1 = -2, so\ c_1 = -2 \end{aligned}$$

c. Final form of Π_1

$$(\Pi_1 = \rho^{-1} v^{-2} d^{-2} F_P)$$

$$\left(\Pi_1 = \frac{F_\omega}{\rho v^2 d^2}\right)$$

With the same approach, all equations can be written as

$$\begin{aligned} \Pi_1 &= \frac{F_\omega}{\rho v^2 d^2} \\ \Pi_2 &= \frac{gd}{v^2} \rightarrow Richardson\ Number, Ri \\ \Pi_3 &= \frac{\mu}{\rho v d} \rightarrow 1/Reynolds\ Number, Re \\ \Pi_4 &= \frac{Q}{v d^2} \\ \Pi_5 &= \frac{\omega d}{v} \\ \Pi_6 &= \frac{fd}{v} \rightarrow Strouhal\ Number, St \end{aligned}$$

Finally,

$$\emptyset(\Pi_1, \Pi_2, \Pi_3, \Pi_4, \Pi_5, \Pi_6) = 0$$

$$\emptyset\left(\frac{F_\omega}{\rho v^2 d^2}, \frac{gd}{v^2}, \frac{\mu}{\rho v d}, \frac{Q}{v d^2}, \frac{\omega d}{v}, \frac{fd}{v}\right) = 0 \qquad (8)$$

$$\Pi_5 = \emptyset_5\left(\frac{F_\omega}{\rho v^2 d^2}, \frac{gd}{v^2}, \frac{\mu}{\rho v d}, \frac{Q}{v d^2}, \frac{fd}{v}\right) \quad (9)$$

$$\frac{\omega d}{v} = \emptyset_5\left(\frac{F_\omega}{\rho v^2 d^2}, \frac{gd}{v^2}, \frac{\mu}{\rho v d}, \frac{Q}{v d^2}, \frac{fd}{v}\right) \quad (10)$$

$$\omega = \frac{v}{d}\emptyset_5\left(\frac{F_\omega}{\rho v^2 d^2}, \frac{gd}{v^2}, \frac{\mu}{\rho v d}, \frac{Q}{v d^2}, \frac{fd}{v}\right) \quad (11)$$

The final expression for vortex angular velocity was given by

$$\omega = \frac{v}{d}\emptyset_5\left(\frac{F_\omega}{\rho v^2 d^2}, Ri, \frac{1}{Re}, \frac{Q}{v d^2}, St\right) \quad (12)$$

The vortex angular velocity (ω) is equal to some coefficient times *v/d*, where the coefficient is a function of other five dimensionless numbers consist of Richardson, Reynolds, Strouhal and other dimensional numbers.

Parameter Setting for Experiment

For parameter setting, a model of vortex tube (Blue Model) has been used to figure up similarity with the prototype (Clear Prototype). This similarity analysis will provide required velocity from Reynolds number study. All the comparison data was extracted from Blue Model experiments [12]. Figure 3 below shows the RHVT model for air which is fabricated using thermoplastic resin ABS (Acrylonitrile Butadiene Styrene) pipe. Figure 4 below shows experimental setup for Blue Model conducted at UiTM Shah Alam and Clear Prototype at UNISEL Bestari Jaya.

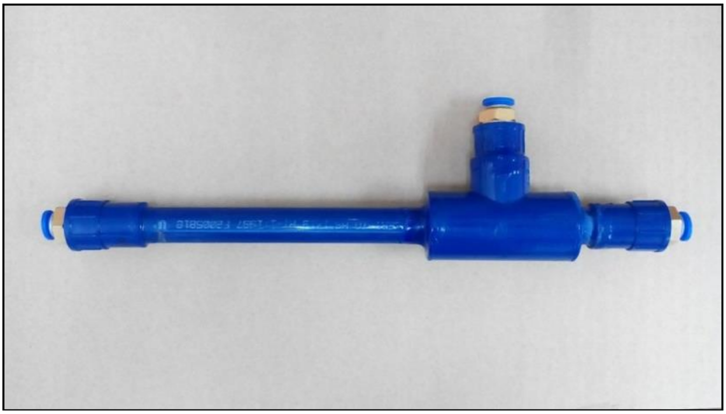


Figure 3: Fabricated Blue Model of RHVT using air as working fluid

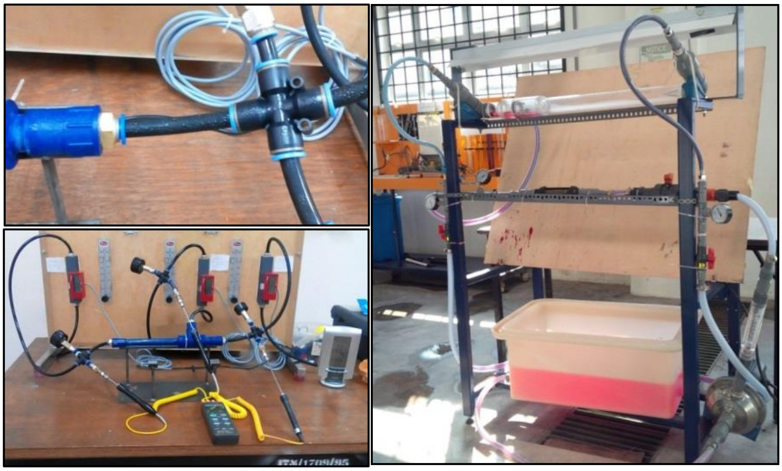


Figure 4: Experimental setup for Blue Model and Clear Prototype

From experimental data [13], velocity for Blue Model is 1157 m/s so the value was divided by two inlets, hence 578.5 m/s will be taken as the velocity value in the experiment. From this value, the dynamic similarity analysis was carried out:

$$(Re\ )_{model} = \ (Re\ )_{prototype} \tag{13}$$

$$\left(Re = \frac{\rho v D}{\mu}\right)_{model} = \left(Re = \frac{\rho v D}{\mu}\right)_{prototype}$$

$$\frac{(1.18667)(578.5)(1.78 \times 10^{-3})}{1.84516 \times 10^{-5}} = \frac{(1000)(v)(6 \times 10^{-3})}{0.891 \times 10^{-3}}$$

$$66{,}224.59 = \frac{(1000)(v)(6 \times 10^{-3})}{0.891 \times 10^{-3}}$$

$$v = 9.83\ m/s$$

Table 2: Input parameters for experiment

No	Blue Model	Clear Prototype	
	v **(m/s)**	***v*** **(m/s)**	***Q*** **(Lpm)**
1	578.5	9.83	33.32
2	809.88	13.77	46.67
3	1080.84	18.38	62.28
4	1329.20	22.60	76.62
5	1521.09	25.86	87.66

Table 2 above shows the flow rate values for both Blue Model and Clear Prototype. Nevertheless, the parameters are too extreme for such experiment using water. The volume flow rate is scaled down to accommodate the pump power and other devices.

Although a centrifugal pump has a capability of delivering 80 Lpm flow rate but the maximum flow rate that the existing system can carry is up to 28 Lpm only. New parameters setting for the volume flow rate were set to 10, 15, 20, 25 and maximum 28 Lpm. All the visualization results were captured from these inputs.

Setup

Though numerical studies using computer simulations can stimulate research activity among researchers but the practice of experiment using actual test rig still cannot be replaced. Results obtained from the experiments are more viable compared to the simulations [14]. The visualization experiments were conducted to realize the existence of vortex phenomena in the tube. Flow visualization experiment using dye injection technique [15] also referred. The research findings mention about vortical motions. The motions can be classified into transverse and longitudinal vortices. The axis of a transverse vortex lies perpendicular to the flow direction while longitudinal vortices have their axes parallel to the main flow direction. The longitudinal vortex flow may swirl around the primary flow and exhibits three dimensional characteristics. In general, longitudinal vortices are more effective than transverse vortices from the heat transfer perspective.

The current experiment was conducted based on interpretation how to visualize the flow pattern inside the tube. A number of techniques were adapted in the experiments specifically to extract the forward and backward flow. Some phenomena were recorded in still picture and a series of movement flows' video was documented as segregated frame. The usage of bubble and dye gave significant result therefore forward and backward flow was investigated.

In order to create a controlled and nearly axisymmetric vortex flow, an enclosed tube was used. The vortex was created in the vortex chamber. Two inlets with 30° incidence angle each were created on the tube wall which direct fluid flow towards cone sides. Upon reaching a stationary cone, the fluid was swirled towards the center and picks up azimuthal velocity due to the conservation of angular momentum. Finally the fluid was drawn towards the cone at the end and formed a vortex line on the central axis of the tube.

Figure 5 below shows the schematic diagram meanwhile Figure 6 represents the experimental setup of flow visualization experiment. The experiment was conducted at ambient room temperature, 29.4 °C with relative humidity of 72%. Temperature of water was recorded as 29°C. The centrifugal pump provided 80 Lpm of water to the system and the flow went through valve, flow meter and pressure gauge. Dye and bubbles were injected at injection port hence the visualizing aids simultaneously fill the Ranque-Hilsch vortex tube at one inlet. The flow was recorded by camera with the assistance of pendaflour lamp. Two discharge outlets (forward and backward flows) released the flow from the Ranque-Hilsch vortex tube and selected parameters were read by two instruments which was pressure gauge and flow meter. Finally, the discharge flow passed a valve and was collected to the water tank.

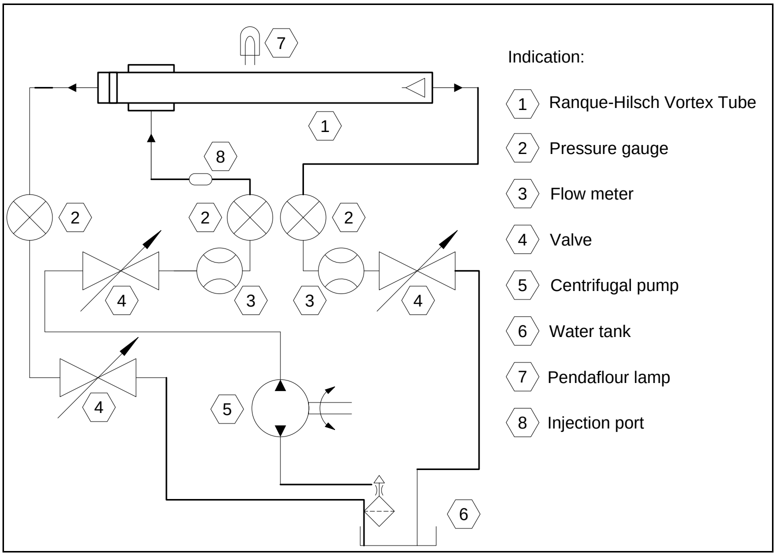


Figure 5: Schematic diagram

Figure 6: Experimental setup of flow visualization experiment

Visualization Results

Visualization of air bubbles

Still photos and video images are recorded and analysed from the flow visualization experiment. The 61 seconds video illustrates the phenomena of RHVT. The video has 1296 frames of pictures which correspond to frame frequency of 21.2 fps. Figure 7 below shows four images representing frames no. 1, 20, 40 and 60.

Three zones are labelled in the figure; Zone 1 (vortex chamber and cold exit), Zone 2 (tube) and Zone 3 (conical valve and hot exit). At first stage, water is pumped to the system continuously until the vortex tube is fully occupied with water. The process is done repeatedly and remaining water is halved when the pump is turning off. This situation creates bubbles in the system as soon as water is injected through the inlet. Referring to Zone 1, it is observed that a vortex is generated at the two inlets at 30^o incidence angle. From observation, bubbles fill entire vortex chamber and creates forced vortex through the tube. Zone 2 shows flow movement of vortex in the whole tube. The projected vortex clearly occupied the tube from the beginning process at (a). Rotation of two vortex layers inside the tube was clearly seen (b). Turbulence fills three-quarter of the tube’s space and the effect of conical valve is taking place (c). Tube is fully occupied by water and a suction of back flow can be seen at (d). Video observation for this zone clearly shows rotation of vortex inside the tube. The swirling is nearby internal wall to hot exit and going back to opposite direction (cold exit) in core side. Zone 3 is positioned as conical valve and central of reversal flow. Videos give clear picture of conical valve which serve to redirect the reverse flow [16], [17].

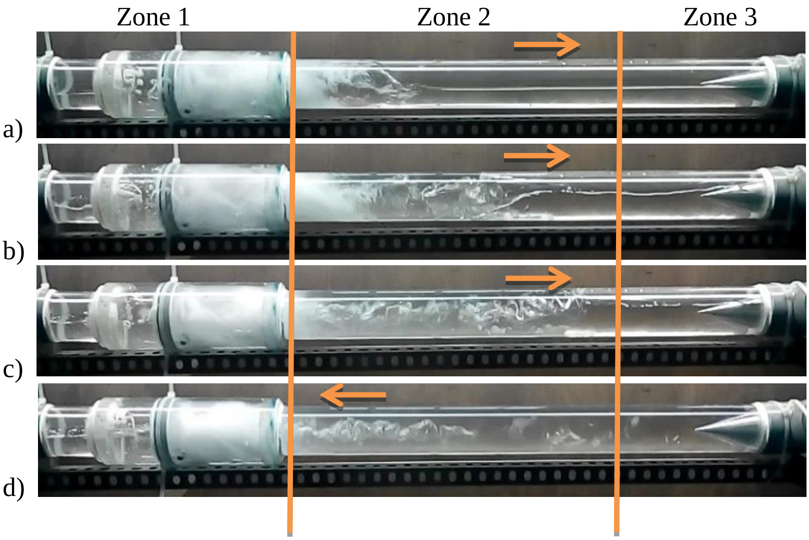


Figure 7: Flow visualization experiment using water at four different instants

Figure 8, 9 and 10 show the flow visualization at Zone 1, 2 and 3 respectively. From the figures, a particle of air bubbles movement can be seen obviously. The captured figures were adapted from 31 seconds video consists of 641 frames which correspond to 21.37 fps [18]. Figure 8 below consists of four pictures showing fluctuation of bubbles in the vortex generator. With high revolution of injected water through the inlet, viscous flow in the peripheral side will move the helical flow to the right side where the conical valve is located. The existing bubbles occur only at the core side of the chamber whereby the revolution at the core side is lesser compared to the peripheral. A line of bubbles is discharged to the left side and it is visible just after the flow passed the orifice. The slow movement of bubbles in this region have a close relation with reverse flow at cold exit [11].

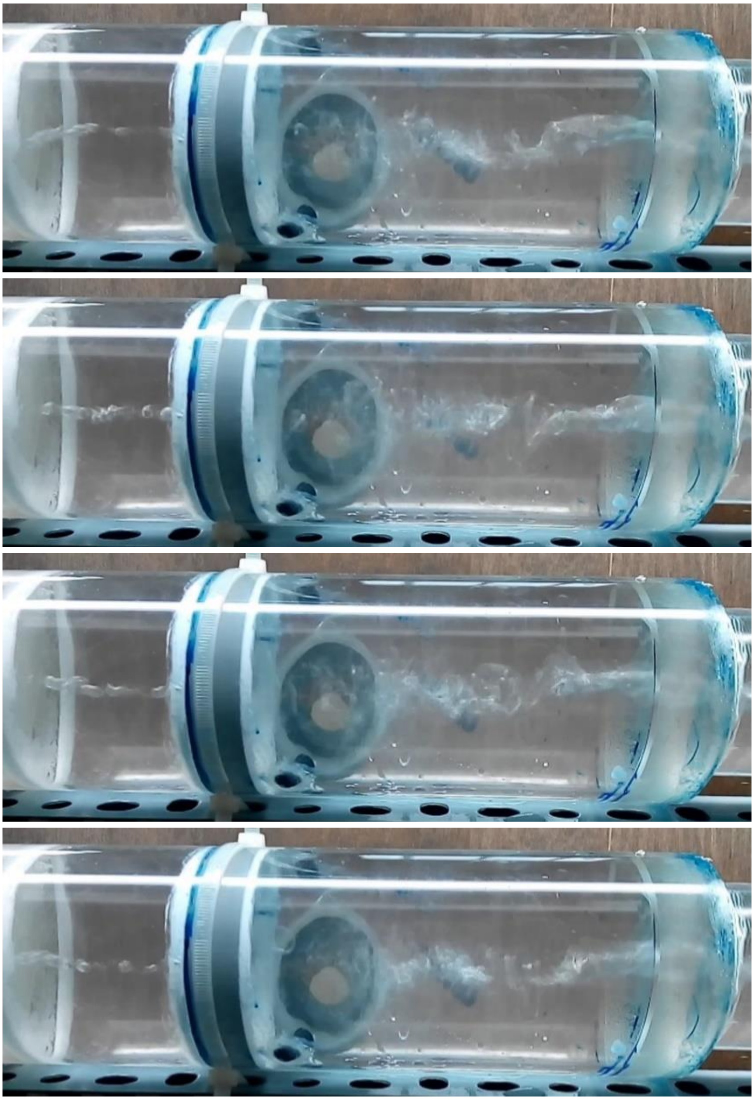


Figure 8: Flow visualization at Zone 1

Figure 9 below shows eight pictures of rotating bubbles inside the tube. The elongation of bubbles can be seen clearly. This phenomenon is a result of discharge flow in the core side of vortex tube. A helical shape of bubble represents the flow pattern of back flow in the system.

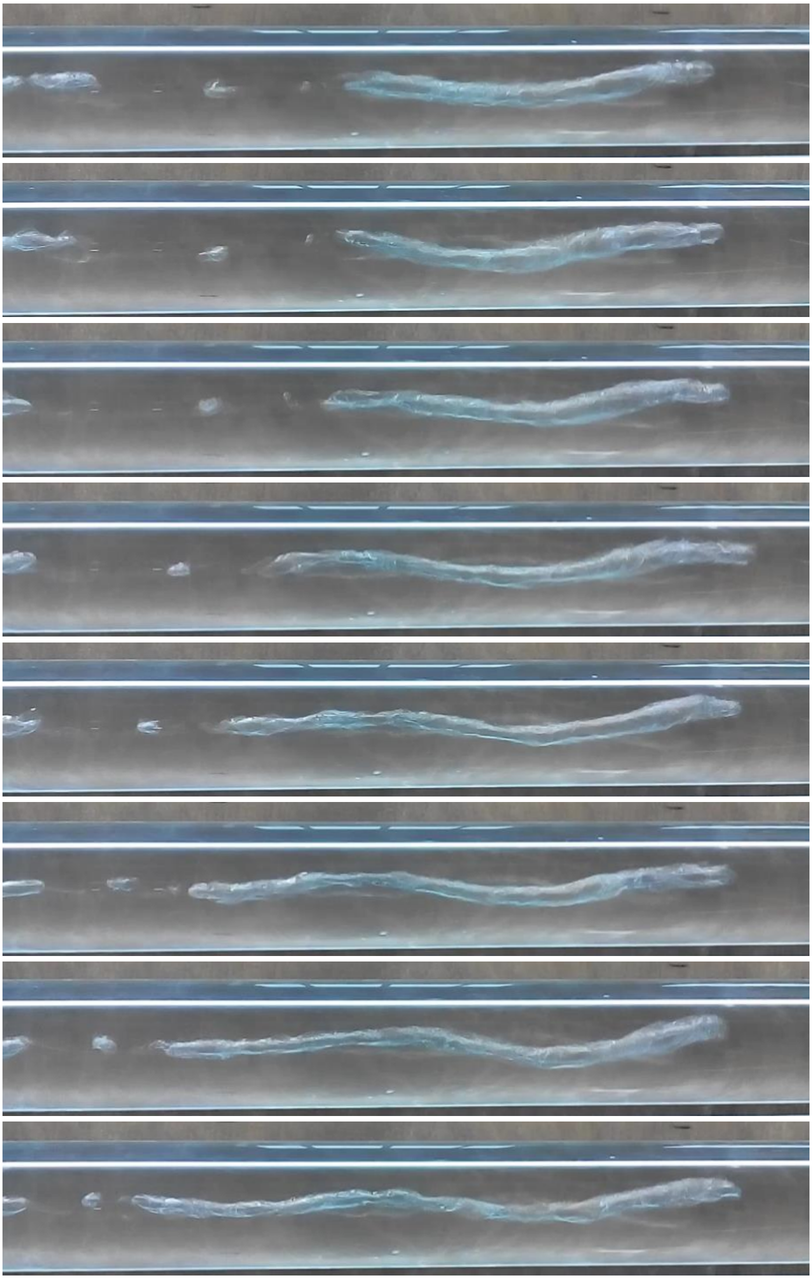


Figure 9: Flow visualization at Zone 2

Figure 10 below consists of seven pictures showing rotational bubbles at the tip of conical valve. A formation of tornado-like bubbles exhibits a high speed rotation flow. Vortex is generated from the con’s tip, moves through core side, elongates and splits into small bubbles. The flow continuously moves to the vortex chamber, passes through orifice and discharges at cold exit.

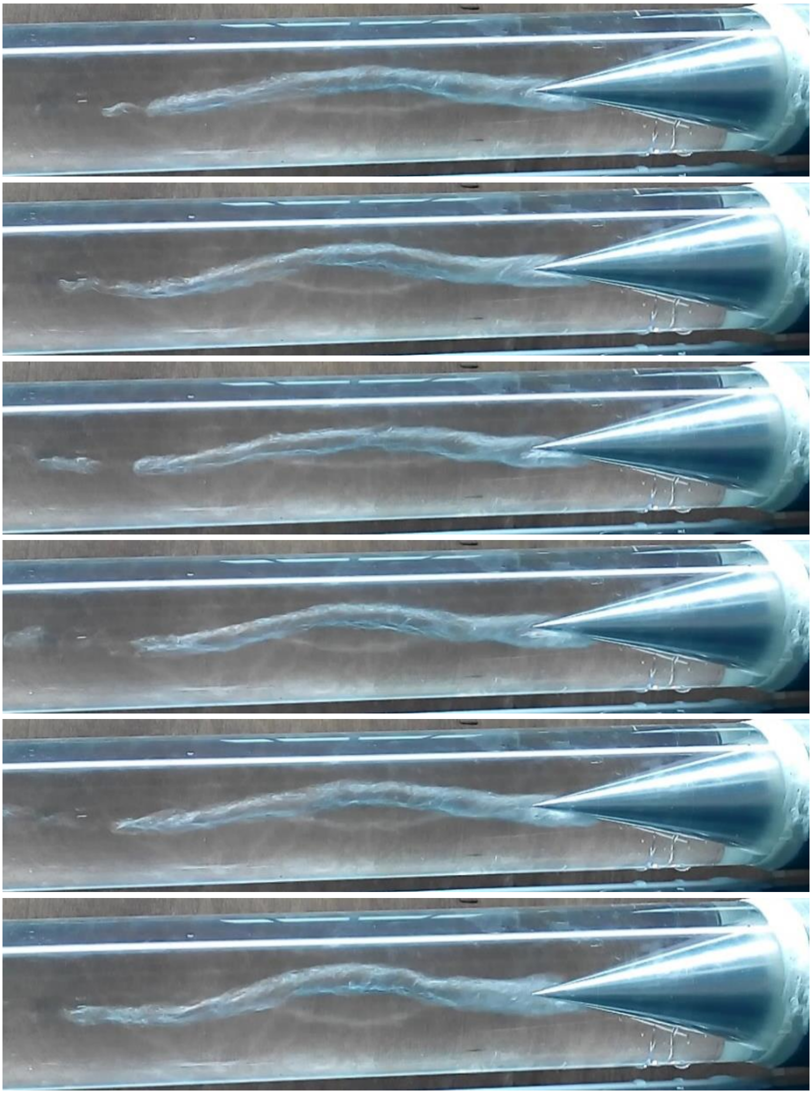
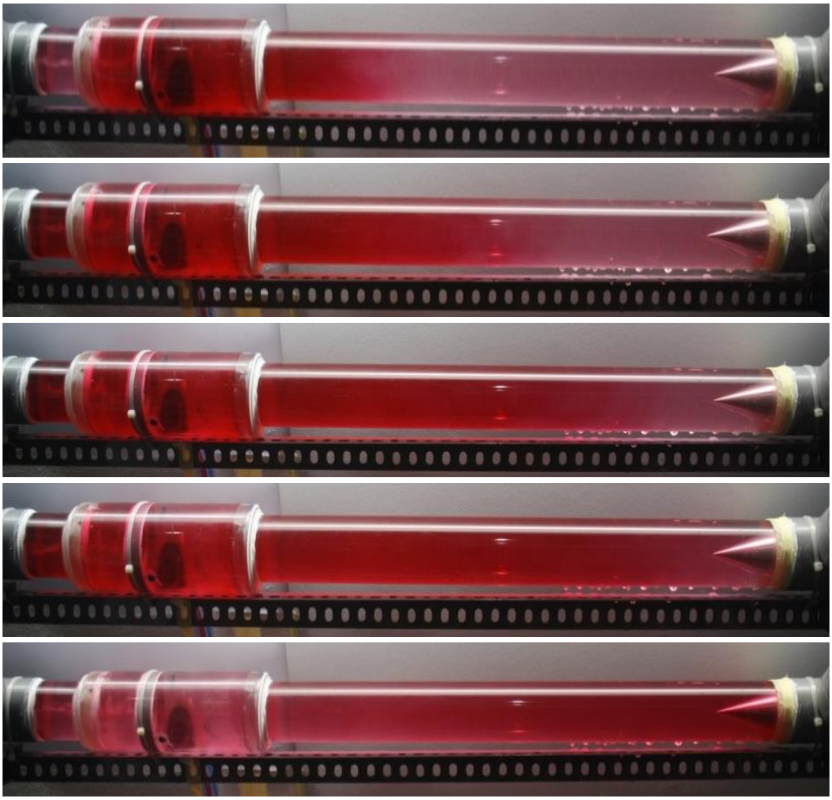


Figure 10: Flow visualization at Zone 3

Visualization using Syrup

Figure 11 below shows several still pictures using syrup. No circulation can be seen except at cold exit. The higher intensity of dye shows water movement from vortex chamber to conical valve. Once tube is fully occupied with dye, all parts are filled with an even tone colour of syrup. Some dyes are discharged at hot exit behind conical valve. Internal core side of flow is seen drawing to hot exit near vortex chamber's inlet.



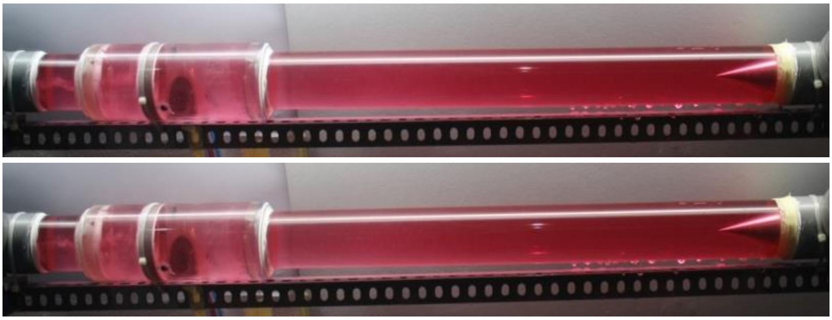


Figure 11: Flow visualization using syrup

Visualization using Bubbles and Syrup

Figure 12 below shows still pictures using bubbles and syrup. This figure gives clear evident in observing flow pattern inside the tube. Circulations of bubbles are apparent and move faster from vortex chamber to conical valve. Back flow return is observed when the circulation touched conical valve. At this point, flow is significantly moved through internal side of the vortex tube. This clearly shows the existence of two flows which is parallel to each other but moved in different direction. Y. Xeu et al [2] showed a multi-circulation region at the same zone and heat was generated by viscous friction.

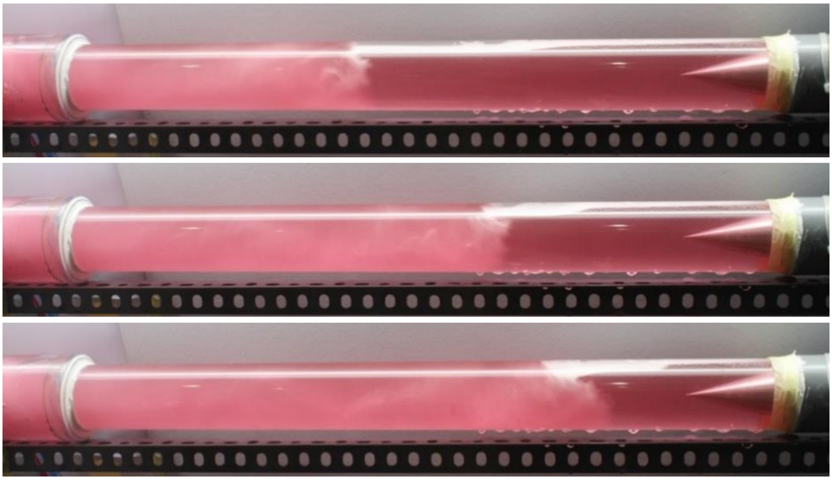


Figure 12: Flow visualization using syrup and bubble

Conclusion

This paper shows the result of flow pattern from flow visualization study. Visualization was conducted using water as the medium. Visualization using bubbles gives interesting result where particles of bubbles can be seen clearly, however the bubbles are a result of unconfined space of filled water. The bubbles are not injected from injection port as in figure 13. Visualization using dye gives fair result but the evident of swirling flow at cold exit is recorded. Experiment using bubbles and syrup contributes to a variety of flow patterns inside vortex tube.

Figure 13: Injection port

The two factors that determine the flow patterns in confined vortex are superimposed axial flow near the peripheral wall and the net flow of fluid which is radially inward or outward with respect to the centreline of the vortex.

Recommendation

It was observed that the bubbles exist in the experiment was not genuinely came from the injection port. It was a result of water pumping at source inlet during the exercise. One alternative method to create bubbles is by using insertion hot wire to the tube. Arrangement of the system should be justified properly and prevention of leakage should be taking into consideration.

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