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Experimental Analysis of Pressure Drop Behavior in Jet-Driven Vortex Chambers Across a Wide Range of Aspect Ratios

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Abstract

This study presents a comprehensive experimental investigation into the static pressure drop behavior across vortex chambers with various aspect ratios, ranging from 1.36 to 22.36. Vortex chambers are essential components in several fluidic systems, including separators, atomizers, and vortex tubes, where efficient pressure drop management is vital for optimal performance. Despite numerous previous studies focusing primarily on medium aspect ratios (~2–3), limited work has been done on understanding the pressure drop characteristics across a broader range of aspect ratios. Using a jet-driven vortex chamber with interchangeable vortex generators and swirlers, experiments were conducted under controlled inlet conditions with varying flow rates and swirl angles (30° and 40°), employing air as the working fluid. The Reynolds numbers covered were from 1811 to 2898, and contraction ratios varied over a wide spectrum by adjusting the exit port size. Dimensional analysis was employed to reduce the data into a general form, revealing that the dimensionless pressure drop is a function of the Reynolds number, aspect ratio, and inlet angle. Results show that the experimental data collapse into a single curve for a given contraction ratio, confirming the robustness of the derived non-dimensional formulation. Furthermore, the analysis demonstrates that increasing aspect ratio significantly affects the flow behavior and pressure drop characteristics. The study concludes with a generalized chart that correlates key geometric and flow parameters, offering a valuable design tool for engineers and researchers working on vortex flow systems. This work extends the foundational understanding of vortex-induced pressure drops and provides crucial insights into optimizing vortex chamber geometries for improved energy efficiency and fluid control.

Keywords: Pressure Drop; Aspect Ratio; Vortex Chamber; Inlet Flow Angle.

Nomenclature

A_o	cross sectional area of the chamber (πR_o^2)
A_{in}	total inlet area ($n\pi R_{in}^2$)
C_p	dimensionless pressure drop ($2\ \Delta P / \rho V_{in}^2$)
D_o	chamber diameter ($2 R_o$)
d_{in}	diameter of the inlet port ($2\ R_{in}$)
D_e	diameter of the exit port ($2\ R_e$)
n	numbers of the inlet holes
P_{in}	static pressure at the inlet
p_{out}	static pressure at the outlet
Q_{in}	volumetric flow rate
V_{in}	total average velocity vector through the inlets
R_{eo}	Reynolds number ($\frac{Q_{in}}{\pi D_o \nu}$)
R_e	exit port radius
R_{in}	inlet hole radius
R_o	chamber radius

Greek Symbols

ΔP	static pressure difference ($P_{in} - P_{out}$)
ν	kinematic viscosity
μ	dynamic viscosity
ρ	density of the fluid
φ	inlet angle

1. Introduction

Vortices, being an essential feature of fluid flow, are often encountered in a number of scientific and technological problems. Consequently, these play a central role in the proper operation of engineering devices such as vortex separators, dust collectors, Ranque-Hilsh vortex tubes, spray dryers, the liquid atomizers, vortex valves, combustors, and many others.

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One of the most important operational characteristics of vortex chambers is the pressure drop and the aim of the designer is to produce swirl with a minimum pressure drop. Due to its importance the pressure drop across vortex chambers has been the subject of many investigations; see for example Shakespeare and Levy [1], Escudier [2], Vatistas and Sakaris [3]. The vast majority of studies dealt however, with chambers having aspect ratios in the medium range (~ 2-3). The study by [4] experimentally examined flow and pressure drop behavior to formulate a methodology for optimizing diode geometry and attaining the desired diodicity.

Jawarneh and Vatistas [5] studied how inlet conditions affect pressure drop in a jet-driven vortex chamber, finding that increasing the diameter ratio and Reynolds number enhances the pressure coefficient and vortex strength. Double generators yielded higher pressure coefficients but lower actual pressure drops compared to single generators.

An experimental and numerical study by [6] investigated the impact of cold orifice diameter and inlet pressure on vortex tube performance, identifying 5 mm at 5 bar as the optimal configuration. Results showed a 66.18% improvement in cold temperature separation. Vortex identification criteria and entropy production theory reveal strong correlations between vortex intensity and energy loss, especially in the impeller and reflux hole regions during cavitation [7].

Numerical study by [8] investigated the effects of nozzle number and inlet pressure on energy separation in vortex tubes, revealing that three nozzles at 0.6 MPa yield the maximum temperature difference of 66 K.

Experiments in a large-scale Ward-type tornado simulator examined flow and surface pressure characteristics of tornado-like vortices. The study focused on how aspect ratio and swirl ratio influence the transition from single- to two-celled vortices and the resulting surface pressure deficits [9].

CFD study by [10] to assess how non-uniform inflow conditions affect scroll vortex drop-shaft performance, focusing on head-discharge behavior and air core size. Results showed that velocity distribution shape, more than peak intensity, significantly influences flow regimes, especially with shorter approach channels.

Jawarneh et al. [11] investigated the impact of jet-induced vortex flow on heat transfer enhancement in a double pipe heat exchanger using a custom-designed vortex generator with varying inlet angles. Results showed that increasing the vortex strength (via inlet angle and Reynolds number) significantly improves the Nusselt number and overall heat transfer, with up to 82% enhancement at a 60° inlet angle.

Jawarneh [12] investigated decaying swirling flows and forced convection in a narrow concentric annulus under laminar and turbulent conditions, highlighting the significant impact of inlet swirl number on heat transfer enhancement. Results showed that increased swirl intensifies near-wall velocity and turbulence, boosting heat transfer, with good agreement between simulations and experimental data.

The study conducted by [13] analytically examines flow in a jet-driven vortex chamber across a broad range of dimensionless parameters, linking geometry and flow characteristics through dimensional analysis and integral equations. It reveals that the pressure drop decreases with length due to decaying centrifugal forces and confirms that prior models are mainly applicable at high Reynolds numbers.

The present study examines the static pressure drop across vortex chambers with aspect ratios (defined here as the chambers length/diameter ratio) varying from 1.36 to 22.36. Dimensional analysis suggests that the dimensionless pressure drop to be a function of the Reynolds number, the aspect ratio, and the inlet flow angle. Measurements confirm the finding.

2. Experimental Apparatus

The present experiment has been conducted using a jet-driven vortex chamber similar to the one utilized by Vatistas et al. [14]. The latest version shown schematically in figure 1, offers a wider flexibility in the selection of inlet conditions. The main chamber has a cylindrical shape with constant cross-sectional area ($A_o = 153.8\,cm^2$). The exit area is adjusted by replacing end-plates with a different size of the exit hole. A modular vortex generator assembly makes the variation of the area ratio (A_{in}/A_0) and inlet flow angle φ easier, see figure 2. The required set of inlet conditions is obtained by the insertion of the appropriate swirler (with a specified angle φ.) into the vortex generator assembly. When air is forced through the swirler, in addition to the radial velocity, it develops a tangential component that depends on the value of the inlet angle. Swirlers with two inlet angles; φ = 30^o and 40^o were used for the present experiments. The swirler with an inlet angle of 30^o had 16 holes with diameter (d_{in}) 1.267 cm each, while the 40^o swirler had 8 holes with a diameter 1.905 cm.

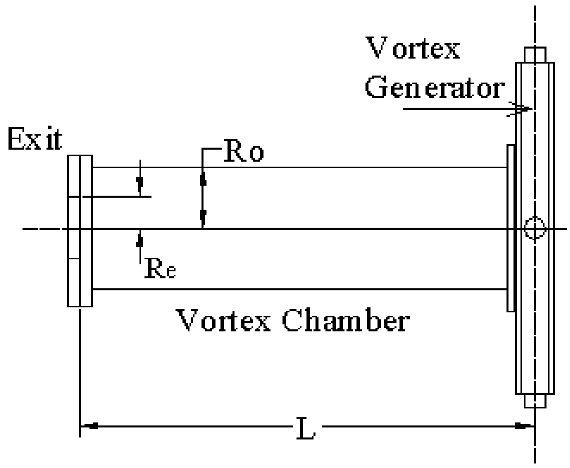

Figure 1. Schematic of the vortex chamber

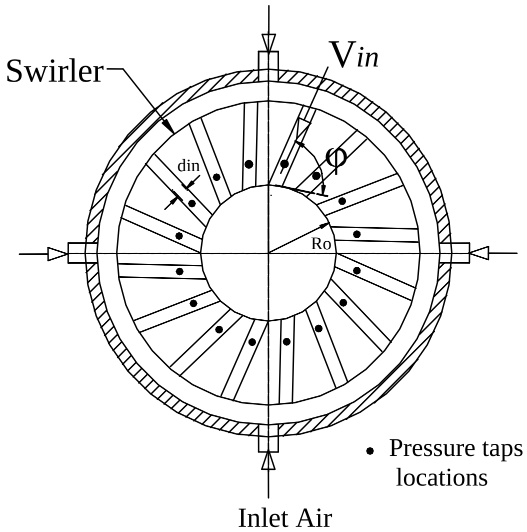

Figure 2. Vortex generator

Measurements were made at different inlet air flow rates: 0.0117, 0.014, 0.0163, and 0.0187 m^3/s which correspond to the four Reynolds numbers ($R_{eo} = \frac{Q_{in}}{\pi D_o \nu}$) of 1811, 2174, 2535, and 2898 respectively, where Q_{in} is inlet flow rate, D_o is Chamber Diameter, and ν the kinematics viscosity.

The contraction ratio (R_e / R_o), defined as the ratio of the radius of the exit hole (R_e) to the radius of the vortex chamber (R_o) was varied from 0.1016, 0.1125, 0.1343, 0.1412, 0.1546, 0.1723, to 0.1892. Tests were performed for the seven aspect ratios (L/D_o); 1.35, 2.78, 5.7,8.9, 11.5, 15.85, and 22.36. The static pressure from each of the tangential inlet ports was averaged by connecting all the pick-up tubes into a common tube. The value of the mean static pressure ($P_{in} - P_a$) was then obtained using a "well type" manometer containing Meriam oil with specific gravity equal to 1. The estimated uncertainty for the pressure drop measurements is between 2-4%. The inlet volumetric flow rate was recorded using a calibrated variable area rotameter. This was calibrated at standard conditions (1 atmosphere and 0° C). For the flowrates used, the uncertainty was estimated to be from 1.4 % to 2.0 %. Air at standard temperature was the working fluid

3. Analysis

In order to reduce the experimental effort along with presenting the results in a generalized form, dimensional analysis was performed.

The expected functional relationships for the pressure drop inside the vortex chamber are:

$$\Delta P = f_n(\rho, \mu, V_{in}, D_e, D_o, L, A_{in}, \varphi) \quad (1)$$

where

$\Delta P = P_{in} - P_a$, is the static pressure difference between the inlet and atmospheric pressure. The rest of the parameters; $\rho, \mu, V_{in}, D_e, D_o, L, A_{in}, \varphi$ are the density, dynamic viscosity, total average velocity vector through the inlets, diameter of the exit, diameter of the chamber, length of the chamber, total inlet area, and inlet angle respectively.

Buckingham's π -theorem provides the functional relations among the main dimensionless parameters:

$$C_p = f_1\left(R_E, \frac{L}{D_o}, \frac{D_e}{D_o}, \frac{A_{in}}{A_o}, \varphi \right) \quad (2)$$

where,

$$C_p = \frac{2\,\Delta P}{\rho V_{in}^2} \ , \ R_E = \frac{\rho V_{in} D_o}{\mu}$$

If the Reynolds number (R_{eo}) is defined as:

$$R_{eo} = R_E \frac{A_{in}}{A_o} = \frac{Q_{in}}{\pi D_o \nu}$$

and

$$\frac{D_e}{D_o} = \frac{D_e}{L} \frac{L}{D_o}$$

then, at specified aspect ratio $\frac{L}{D_o}$, the dimensionless pressure drop C_p is a function of three dimensionless groups:

$$C_p = g\left(R_{eo}, \frac{L}{D_e}, \varphi \right) \quad (3)$$

All the experimental observations were treated using the above functional relationship that was suggested by dimensional analysis considerations. The results are shown in figure 3. It is indeed evident that given the contraction ratio, the corresponding test data collapse into a single curve. As it is expected, the dimensionless pressure drop depends strongly on the chamber's aspect ratio. The latter confirms the original hypothesis. In addition, it makes available through a chart the generalized relationship among the most important geometrical and fluid properties.

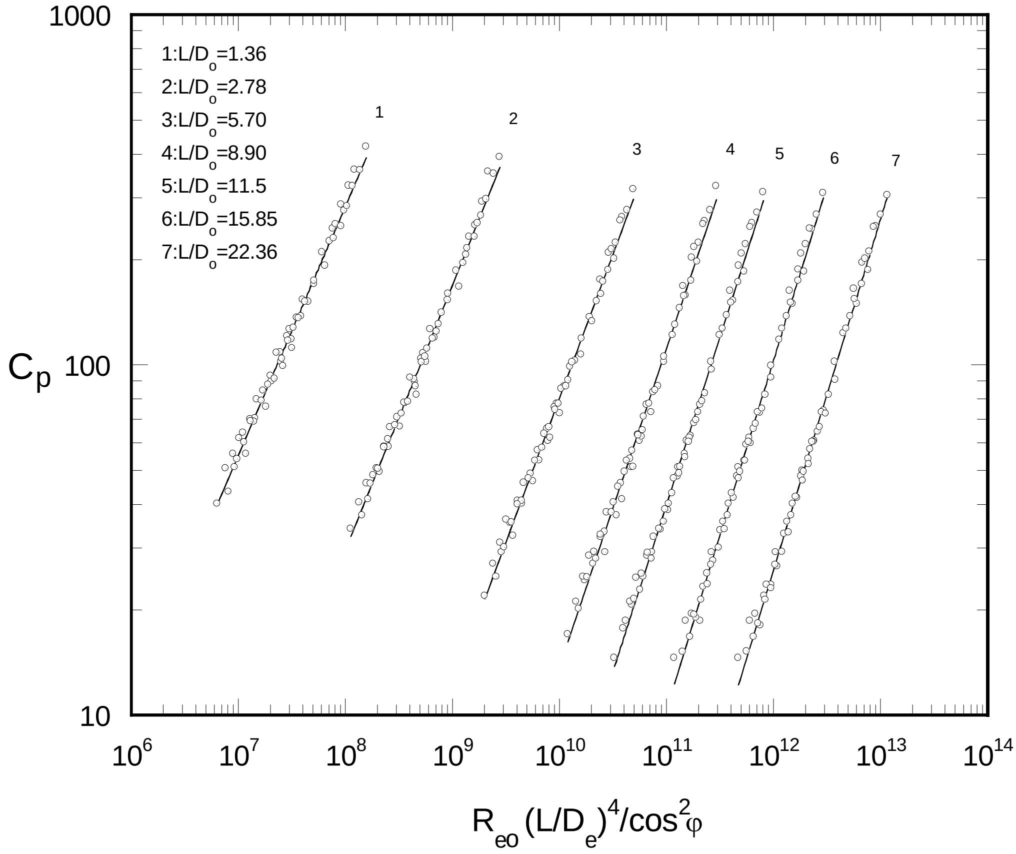

Figure 3. Non-dimensional pressure drop vs the dimensional groups

4. Conclusions

This experimental study has systematically investigated the static pressure drop behavior in jet-driven vortex chambers across a wide range of aspect ratios (1.36 to 22.36). The results confirm that the dimensionless pressure drop is significantly influenced by the aspect ratio, inlet angle, and Reynolds number. By employing dimensional analysis, the data were successfully collapsed into generalized curves, validating the non-dimensional formulation proposed. It was observed that increasing the aspect ratio notably alters the flow characteristics and enhances the sensitivity of pressure drop to geometric and flow variations. The developed chart offers a practical design tool for engineers working on vortex-based systems, contributing to improved efficiency and performance in applications such as vortex tubes, separators, and fluid control devices. This work fills a critical gap in the literature by extending the understanding of vortex chamber behavior beyond the traditionally studied medium aspect ratios.

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