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A REVIEW FOR A VORTEX TUBE PERFORMANCE

Zahraa S. Ismaiel [1] **Raad Kadhim Mohammed [2]**
zahraaarb@gmail.com raad.k.mohammed@nahrainuniv.edu.iq
[1,2]Al-Nahrain University, College of Engineering, Mech. Eng. Dept.

ABSTRACT

This research provides a comprehensive review of previous studies on the performance of vortex tubes, offering detailed information derived from both experimental, theoretical, and experimental and theoretical investigations. Vortex tubes are classified into two main types: counterflow and parallel flow, to facilitate the reader's understanding of their operating mechanisms. Performance parameters of vortex tubes are extensively presented, based on the available experimental and theoretical results to date. These include the maximum recorded values for performance coefficient, temperature differences at both hot and cold outlets, as well as the overall cooling efficiency of the device, thus providing a clear and simplified reference for researchers interested in this field. It has been observed that the influence of multiple nozzle manifolds and their inclination angles has not been sufficiently investigated. Therefore, it is recommended that future research be directed towards studying the impact of these factors on improving the performance of vortex tubes more accurately and comprehensively. The objective of this study is to collect and analyze previous research on vortex tubes and to classify the studies into three main categories: experimental, numerical, and combined experimental-numerical. This classification aims to facilitate researchers' review of existing literature and support the development of future research.

Keywords: Vortex tube, Experimental study vortex tube, Numerical vortex tube, Vortex tube COP, Vortex tube supply pressure

NOMENCLATURE

COP	Coefficient of Performance
ΔTc	Temperature Difference Between the Inlet and Cold Side Outlets
ΔTh	Temperature Difference Between the Hot Side Outlets and The Inlet
ΔT	Temperature Difference Between the Outlets (Hot-Cold)
CFD	Computational Fluid Dynamics
RHVT	Ranque-Hilsch Vortex Tube
SPL	Sound Pressure Level
SU2	Stanford University Unstructured
T_c	The air temperature at cold outlet (˚c)
T_h	The air temperature at hot outlet (˚c)
T_i	The temperature was measured (˚c)
P_i	The air pressure inlet (bar)
Pa	The standard atmospheric pressure (bar)
R	The specific gas constant ($J.K^{-1}. Mol^{-1}$)

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COP_c The coefficient of performance of cooling
COP_h The coefficient of performance of heat
Q_c The heat transfer by vortex tube affected by cooling (J/s)
W The work input to the device (J)
C_p Specific heat at constant absolute pressure ($J.kg^{-1}.K^{-1}$)
RH Relative humidity (%)
i, s &c Inlet, Isentropic & cold
η Efficiency
K Heat capacity
E Cold Mass Fraction
γ Specific heat ratio
θ Angle (°)
α Cold flow ratio
Cv specific heat at constant volume (kJ/kg.K).
T_L Temperature of tube length

INTRODUCTION

The vortex tube is a mechanical device that utilizes compressed fluid to generate two separate hot and cold air streams. Monitoring the internal parameters such as pressure, temperature, and velocity distribution is crucial to understanding its behavior (Bruun H,1969). As an environmentally friendly technology, the vortex tube produces rotating streams with thousands of rotations per second, resulting in the formation of two distinct airflows: one hot and one cold (Bruun H,1969). The unique energy separation phenomenon of the vortex tube has been extensively studied. Two primary configurations exist: the counterflow type, where hot and cold streams exit from opposite ends, and the parallel flow type, where both streams exit from the same side through separate outlets (K.S. Kulkarni and R.J, 2009).Experimental investigations have been conducted to evaluate flow parameters such as temperature and velocity distributions inside the tube (Zhuohuan Hu et al., 2020). The internal flow structure consists of various regions: the hot region, mixing and separation zone, cold core, peripheral flow, and vortices formed at the tube angle (K. Dincer et al., 2010). The vortex tube comprises several components: an inlet, vortex chamber, hot-end tube, and a control valve, forming a stationary device widely used in industrial applications such as gas drying and mixture separation (H. Takahama, 1965). Multiple parameters influence vortex tube performance, including internal flow conditions, geometrical factors, mass flow rates, reservoir conditions, and fluid properties. The geometrical parameters include tube length, inner diameter, intake nozzles, and vortex chamber dimensions. Mass flow parameters involve total mass flow rate and cold mass fraction, while fluid properties encompass pressure, temperature, density, viscosity, thermal conductivity, heat capacity, and the isentropic exponent (Sendogan Karagoz et al., 2009).The vortex tube serves various applications such as miner body cooling, electronic component cooling, leakage prevention, waste heat recovery, respiratory air systems, food industry cooling, high-speed manufacturing, precision power generation, and laser cutting of fiberglass-reinforced composites (Upendra Sharan Gupta et al., 2017).In this study, previous works were systematically reviewed and categorized into experimental, numerical, and combined experimental-numerical studies. Additionally, the results and relevant mathematical formulations from the reviewed studies were summarized where available.

1. Experimental studies

Numerous researchers have conducted experimental studies to enhance vortex tube performance, improve efficiency, and investigate energy separation under different operating and geometrical conditions, as categorized below:

a) Studies on the Effect of Pressure, Temperature, and Environmental Conditions

- (Waraporn and Krairin, 2014) employed a thermoelectric model to study the influence of temperature on the cold fraction and air pressure. Their findings revealed that efficiency, relative humidity, and cooling capacity are influenced by heat extraction from the hot tube.

- (Kumar, Vivekanand, and S. Subudhi, 2017) identified the optimum relative humidity value at an inlet pressure of 4 bar.

- (Mohammad O. Hamdan, Salah B. Al-Omari, and Ali S. Oweimer, 2018) determined the optimal vortex tube parameters, including tube length, tapering angle, inlet pressure, and temperature, achieving maximum performance.

- (Wasan Naksanee and Ratthasak Prommas, 2018) utilized a counterflow vortex tube with different inner diameters and snail nozzles. Their study showed that low-pressure inlet air reduces the hot air discharge temperature, acting as a cooling agent.

- (Alfan Sarifudin et al., 2020) investigated the effects of pressure and cold mass fraction under natural and forced cooling conditions and compared both scenarios for their impact on vortex tube performance.

b) Studies Related to Design and Geometrical Parameters

- (Yunpeng Xue et al., 2019) analyzed flow patterns within a cylindrical vortex tube system, emphasizing the significance of the rotating vortex core's interaction with previous results.

- (Sarifudin et al., 2020) examined natural and forced cooling effects under different temperature changes, heat transfer rates, isentropic efficiency, refrigerant performance, and heat pump performance. Results showed that as pressure increases, isentropic efficiency and refrigeration performance coefficients decrease.

- (P. Samruaisin et al., 2021) demonstrated that energy separation is influenced by multiple inlet snail entrances, six nozzles, and double vortex chambers. The study found that cold gas exit temperature increased with inlet air pressure, nozzle number, and distance ratio, reaching a maximum temperature difference of 31.5°C.

- (Zhuohuan Hu et al., 2023) applied the Taguchi method to investigate cooling efficiency in a vortex tube fitted with a rectifier. Factors such as inlet pressure, hot end to rectifier distance, rectifier position and height, blade number, length, and inclination angle significantly impacted performance, with blade length and rectifier height being most influential.

c) Studies Using Advanced Analytical Methods

- (Hüseyin Gökçe, 2020) applied the Taguchi method and multiple linear regression using carbon dioxide as the working fluid. The study evaluated the effects of inlet pressure, connection type, number of orifices, and nozzle material, concluding these factors primarily influence optimal temperature gradients.

- (Fachun Liang et al., 2021) investigated the acoustic properties and energy separation behavior using air as the working fluid. Parameters such as inlet pressure, nozzle count, and cold mass fraction were analyzed. Results indicated that sound pressure level increased with higher inlet pressure but decreased with larger cold mass fractions. A strong relationship was found between sound intensity and energy separation performance.

d) Application of Vortex Tube with Internal Combustion Engines

- (Adem Celik et al., 2021) examined emissions during cold starts of a 6-cylinder diesel engine using a vortex tube. Compressed air cylinders drove the vortex tube, improving engine start-up, fuel efficiency, and reducing start-up duration. Additionally, carbon monoxide and particulate emissions decreased, though hydrocarbons and nitrogen oxides slightly increased.

e) General Performance Studies of Vortex Tubes

- (Nafiz H.K. Chowdhury and Thomas Povey, 2024) studied the performance of cylindrical counter-flow Ranque-Hilsch vortex tubes under varying inlet pressures and cold gas mass fractions. It aims to review previous research on the performance and highlight of the vortex tube that needs to investigate the effects of nozzle collectors and their inclination angle. Their work evaluated COP, energy separation, temperature separation, and isentropic efficiency, identifying optimal coefficients based on cold mass fractions.

Many Previous studies have the effects of the operating conditions (such as temperature, pressure, and humidity) and the geometrical design (such as the angles, the nozzle number, and rectifiers) on vortex tube performance. The Taguchi approach and linear regression methods were applied for some advanced studies analytically. In addition, practical applications such as assisting internal combustion engine start-up have been investigated. However, the effect of multiple nozzle collectors and their inclination angles still requires further research and evaluation.

2. Numerical studies

Numerical investigations have played a crucial role in understanding and enhancing vortex tube performance by analyzing complex flow behaviors through advanced computational techniques such as CFD modeling and 3D simulations. The studies are categorized as follows:

a) CFD-Based Studies and Parameer Effects

• (Abbas Moraveji and Davood Toghraie, 2017) investigated the effects of inlet number, tube length, and cold outlet diameter on temperature and flow rates using CFD simulations. The study concluded that increasing cold outlet diameter decreases flow rate, while increasing the number of inlets and tube length slightly increases outlet temperatures. Additionally, larger cold outlet radius increases mass flow.

• (Muhammad Abdul Qyyum et al., 2019) employed a steady-state CFD model with the standard k–ε turbulence model to analyze vortex tube geometry for air separation and natural gas processing. Parameters such as inlet pressures, cone valve geometry, and control valve shape were evaluated, identifying the truncated cone control valve as the most effective.

• (Karthik Vigneshwar Cuddalore Balakumar and Peter J. Disimile, 2021) utilized RANS-based CFD simulations to study turbulent structures and energy separation mechanisms. They discovered that temperature drops exceeded predictions, with 80% of energy transfer attributed to turbulent shear work.

• (Raphaël Oberti et al., 2024) applied SU2 (Stanford University Unstructured) solver for 3D CFD analysis using two-phase transcritical CO_2 . The study revealed gas effects causing temperature separation inversion and demonstrated increased irreversibility around acute vortex tube angles at high cold mass fraction and pressure.

b) Studies Focused on Design Improvements through Modeling

• (Adib Bazgira et al., 2018) developed a 3D steady-state turbulent swirling airflow model for counter-flow vortex tubes. Water cooling enhanced cold air temperature differences and system efficiencies, while optimal nozzle number and ratios maximized performance.

• (Ahmad M. Alsaghir et al., 2021) used 3D modeling to analyze forced and free vortex formations, heat transmission, and cold mass fraction effects on energy separation. The study found that mass fractions of 0.19 and 0.8 resulted in the lowest and highest temperature separations, respectively.

• (Ahmad M. Alsaghir et al., 2022) applied response surface methodology to optimize performance parameters such as inlet pressure, vortex tube length and diameter, nozzle number and diameter, and hot outlet pressure. Increased inlet pressure led to improved energy separation.

c) Studies on Energy Separation Mechanisms

• (Shuyang Liu et al., 2024) examined the energy separation mechanism by analyzing compressible fluid dynamics in asymmetric cavity spaces. A model of trajectory deflection and microelement fluid forces was developed, showing that vortex chamber size affects hot-end temperature rise and inlet fluid pressure.

After reviewing multiple studies, most researchers concluded that the standard k–ε turbulence model offers better agreement with experimental results, providing more accurate performance predictions.

3. Experimental and Numerical studies

This section presents studies that integrate both experimental and numerical approaches to enhance the understanding of vortex tube performance, improve efficiency, and investigate separation energy under various operating conditions. The comparison between experimental measurements and numerical simulations helps identify discrepancies, validate models, and refine design parameters.

a) The Studies focused on the Temperature Separation and Insulation Effects

• (S. E. Rafiee and M. M. Sadeghiazad, 2017) analyzed the thermal behavior of vortex tubes equipped with various hot valve shapes. Results indicated that spherical control valves improve cooling capacity with increasing injection pressure while reducing stagnation point distance enhances performance. Additionally, slotting the valves showed a minimal effect on cooling efficiency.

b) The Studies on the Valve Design and Geometry Impact

• (S.E. Rafiee and M.M. Sadeghiazad,2017) studied the thermal properties of a vortex tube fitted with different shapes of hot valves. The result showed that the cooling capabilities of a spherical control valve improve with increased injection pressure and minimize the distance between stagnation points. It also discovered that the slots don't affect the valve's cooling capability.

• (Shuyang Liu et al., 2024) explored how valve shape and angle affect heat and cold separation. The study demonstrated that a 60° truncated cone valve provides superior cooling, with significant improvements in temperature separation and more stable temperature gradients at the cold outlet. The merging rate of vortices was also influenced by the valve geometry.

c) Studies Combining CFD Modeling and Experimental Validation

• (Radomír Chýlek et al., 2018) used compressed gas as the working medium to investigate separation temperatures, which are strongly influenced by fluid flow behavior inside the tube. Both experimental and numerical approaches were employed to compare results and validate CFD models

• (Lizan Mahmood Khorsheed Zangana, and Ramzi Raphael Ibraheem Barwari, 2020) this study focused on the Ranque-Hilsch vortex tube's design. Using FLUENT to solve the governing equations, focused on convergent and divergent throttle diameters. The result found the optimal performance with different tube diameters, with a 6.5% deviation between experimental results and numerical simulation.

• (Jaber Sadeghiseraji et al., 2020) developed a model for temperature separation under varying inlet pressures using CFD simulations. Navier-Stokes, Reynolds, and turbulence equations were solved. The standard turbulence model demonstrated better accuracy at 7 bar inlet pressure, highlighting the significance of internal flow dynamics on energy separation.

4.Conclusions

This article provides a comprehensive overview of vortex tube performance, covering prior literature and design parameters to present a consolidated reference for its operational characteristics and influencing factors. The review summarizes key findings from experimental and theoretical studies conducted to date, as detailed below:

1. Effect of External Cooling and Performance Improvement

- Utilizing thermoelectric modules for heat extraction from the hot tube enhances cooling capacity and efficiency by 4.3% and 9.6%, respectively.
- Applying forced cooling to the hot tube surface reduces heat performance but improves cooling capacity.
- Water cooling the hot tube increases the cold air temperature difference (ΔTc) and boosts isentropic efficiency by 6.3–10.3% and 5.8–10.6%, respectively.

2. Effect of Cold Mass Fraction and Inlet Pressure:

- An increase in inlet pressure leads to a higher temperature difference.
- The cold outlet temperature difference (ΔTc) rises with both air inlet pressure and the number of inlet nozzles.
- Temperature separation (ΔT) is influenced by inlet pressure, connection type, orifice number, and nozzle material.
- For both insulated and uninsulated configurations, temperature separation improves as inlet pressure increases.

3. Thermal Efficiency and Performance

- Maximum cooling efficiency achieved is 41.6%.

- The coefficient of performance (COP) improved by 11%.
- The best recorded COP is 0.137, while the highest isentropic efficiency reached 0.16.
- Optimal vortex tube design includes a tube length of 194 mm, diameter of 14.6 mm, 4 inlet nozzles with 1.8 mm diameter, and a hot outlet pressure of 60.303 Pa.

4. Airflow Characteristics and Acoustics

- Vortex tube acoustic energy primarily falls within the 4000–5000 Hz range, with notable peaks at ~1500 Hz and ~4200 Hz.
- Sound pressure level (SPL) increases with inlet pressure, while cold mass fraction shows an inverse relation with SPL.
- Reducing the throat diameter from 8 mm to 2.5 mm enhances cooling capacity.

5. Geometric Design and Structural Effects

- Optimal thermal performance is achieved using a truncated cone control valve.
- Decreasing the distance between the stagnation point and the control valve enhances cooling performance.
- A divergence angle of 2° provides superior refrigeration efficiency.
- Reducing vortex initiation chamber volume strengthens vortex intensity, improving energy separation.

6. Simulation and Experimental Validation

- CFD predictions show deviations of less than 4.12% (2D models) and 2.3% (3D models) compared to experimental data.
- Maximum and minimum temperature differences between simulation and experiment are 4.41% and 3.52%, respectively.

7. Energy Transfer Analysis

- The energy difference between core and annular flows is predicted to be approximately 10% accuracy.
- About 80% of energy transfer is attributed to turbulent shear work, while the remaining 20% results from heat transfer.

8. Additional Flow and Structural Effects

- Increasing the number of inlets reduces outlet temperatures.
- Enlarging the cold outlet radius increases both mass flow rates and outlet temperatures.

9. Dynamic Formation Effects

- A convergent-divergent virtual duct forms within the vortex chamber, leading to supersonic expansion (Mach > 1) and temperature drop.

- Free vortices, forced vortices, and secondary circulation flows strongly contribute to energy separation phenomena.

10. Effect of Vortex Tube Use on Engine Performance

- Vortex tube application increases air intake temperature, reduces engine start-up time, decreases fuel consumption, and lowers carbon monoxide and particulate emissions. However, it raises hydrocarbon and nitrogen oxide emissions.

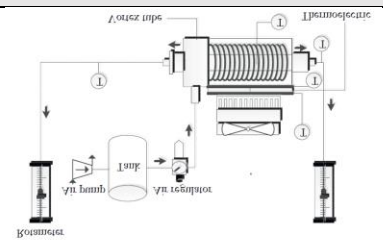
11. Flow Distribution Inside the Tube

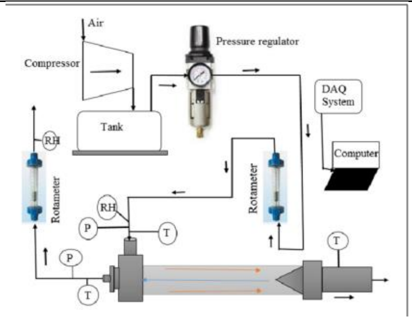
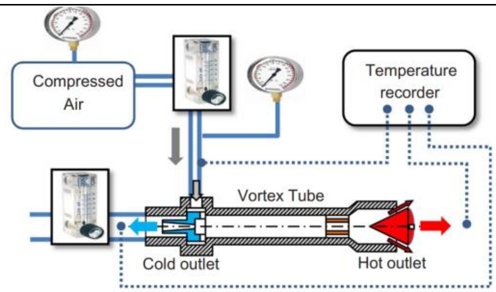
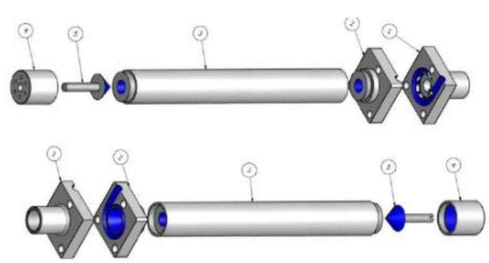
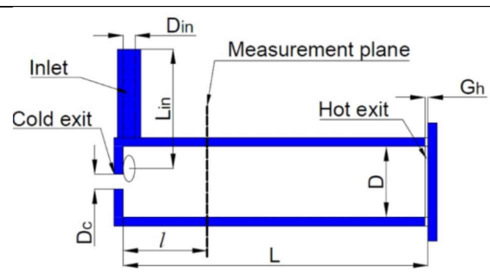
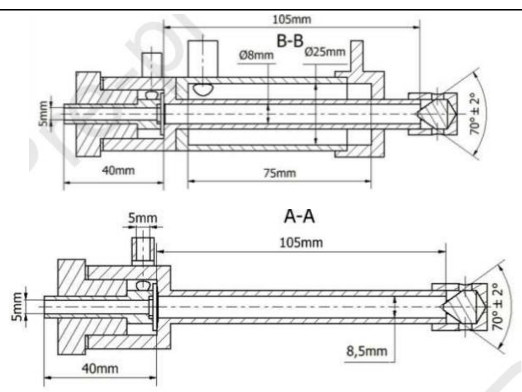
- Internal flow consists of a free vortex (r/R = 0 – 0.9) and a forced vortex (r/R = 0.9–1).
- At cold mass fractions of 0.19 and 0.8, the lowest cold temperatures and highest hot temperatures are observed, respectively.

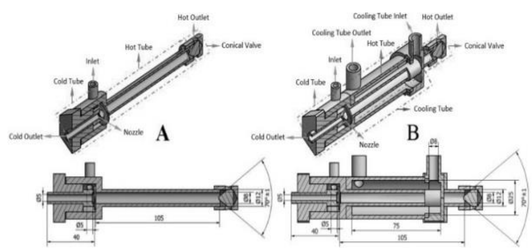
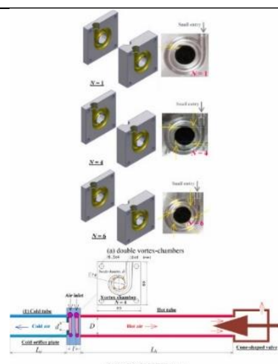
The summary of these study reviews the performance of vortex tubes, highlighting the effect of external cooling, the inlet pressure, the cold mass fraction, and the geometric design on the efficiency and the heat separation. Experimental and simulation results depend on the optimal design parameters (such as nozzle number, the shape of control valve, and the chamber geometry) significantly enhance the isentropic efficiency and cooling capacity. Energy separation is driven by the turbulent shear work, with additional effects observed in the engine applications and the internal flow dynamics.

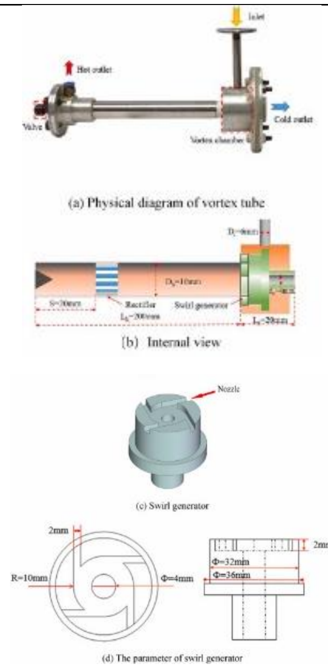
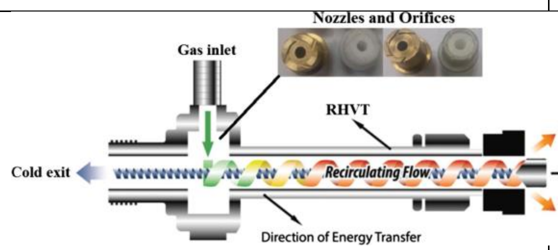
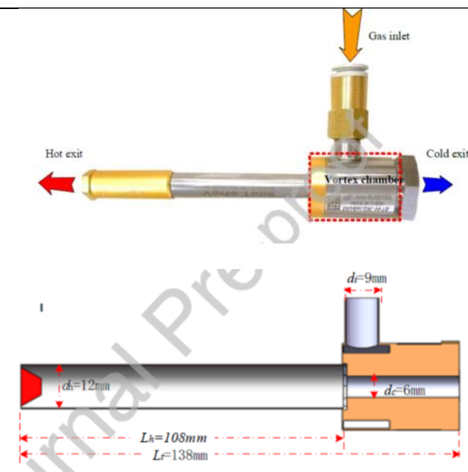
Tables

Table 1 summaries research table of experimental studies

Reference	The study model	Equations	Improvement parameter
Waraporn and Krairin (2014)		$\eta s = \Delta Tc/\Delta Ts$ $\Delta T_s = T_i[1 - (\frac{P_a}{P_i})^{\frac{C_p}{C_v}-1/(\frac{C_p}{C_v})}]$ $Q_c = m^{\cdot}_c C_p (T_i - T_c)$	Efficiency (72%) and cooling capacity 65W
Kumar et al. (2017)		$\frac{RH_i - RH_c}{RH_i} = \frac{\Delta RH_c}{RH_i}$ $\eta = \frac{\Delta T_c}{T_i - T_s}$	

		relative humidity (68%) and isentropic efficiency (18%)
Mohammad et al. (2018)		$COP_R = \varepsilon \frac{k}{k-1} \frac{1-\frac{T_L}{T_i}}{lnP_i/P_\circ}$ $COP = 0.12$
Wasan and Ratthasak (2018)		$\eta = \frac{\Delta T_c}{T_i - T_s} x\mathbf{100}$ $T_s = [(\frac{P_i}{P_a})^{\frac{(\gamma-1)}{\gamma}} -1]$ The cooling efficiency = *41.6 %*
Yunpeng et al. (2019)		Total energy (11.8%)
Alfan et al. (2020)		$\eta_{isc} = \frac{T_i - T_c}{T_i[1-(\frac{P_a}{P_i})^{\frac{(\gamma-1)}{\gamma}}]}$ $\eta_{ish} = \frac{T_h - T_i}{T_i[1-(\frac{P_a}{P_i})^{\frac{(\gamma-1)}{\gamma}}]}$ $COP_{ref} = \dot{Q}_c/\dot{W}$ $COP_h = \dot{Q}_h/\dot{W}$

		Isentropic efficiency *(24%)* and *COP= 0.125*
Alfan et al. (2020)		$\eta_{ish} = \frac{T_h - T_i}{T_i[1 - (\frac{P_a}{P_i})^{\frac{(\gamma-1)}{\gamma}}]}$ $COP_{ref} = \dot{Q}_c / \dot{W}$ The hot isentropic efficiency *24.21%, COP 0.097* (refrigerant)
Samruaisin et al. (2021)		$\Delta T_c = T_i - T_c$ ΔT_c=31.5 ℃
Zhuohuan et al. (2023)		$COP = \frac{Q_c}{W} = \frac{C_p}{R}\frac{\alpha(T_i - T_c)}{ln(\frac{P_i}{P_c})}$ $=\frac{k}{k-1}\frac{\alpha(T_i - T_c)}{ln(\frac{P_i}{P_c})}$

		*COP= 0.11*
Hüseyin Gökçe (2020)		$\Delta T=55℃$
Fachun et al. (2021)		$COP=\frac{\gamma}{\gamma-1}\frac{\mu_c \Delta T_c}{T_i\, ln\frac{P_i}{P_c}}$ *COP= 1.5*

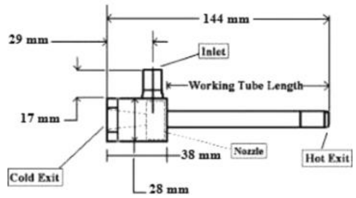
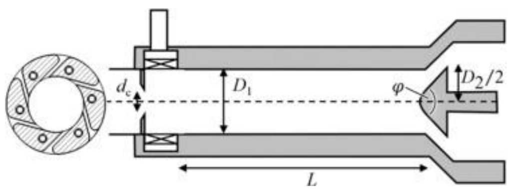
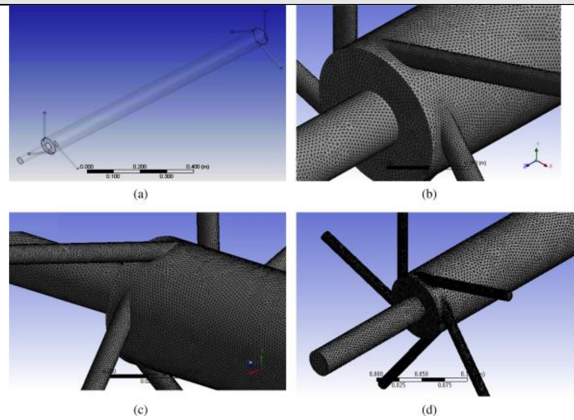
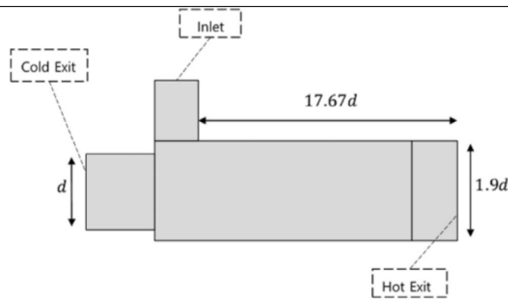
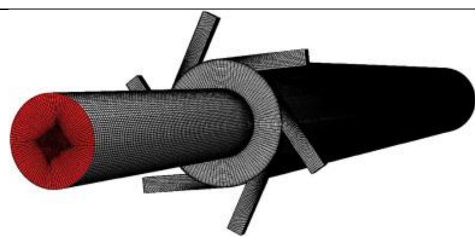
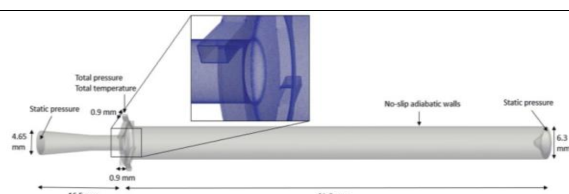
Adem Celik et al. (2021)	  	Exhaust gas temperature *=150 ℃*
Nafiz and Thomas (2024)	 	$\eta_1\left(\mathcal{E},\frac{P_{01}}{P_c}\right) = \frac{m^{\cdot}{}_c c_p (T_{01}-T_{0c})}{m^{\cdot}{}_c c_p T_{01}[1-(\frac{P_c}{P_{01}})^{\frac{\gamma-1}{\gamma}}]}$ $= \frac{1-\theta_c}{1-(\frac{P_c}{P_{01}})^{\gamma-1/\gamma}}$ $COP_c\left(\mathcal{E},\frac{P_{01}}{P_c}\right) = \frac{m^{\cdot}{}_c c_p (T_{01}-T_{0c})}{m^{\cdot}{}_1 c_p \frac{\gamma-1}{\gamma} T_{01} ln(\frac{P_{01}}{P_c})}$ $= \mathcal{E}\frac{\gamma}{\gamma-1}\frac{(1-\theta_c)}{ln(\frac{P_{01}}{P_c})}$ Isentropic efficiency *=16%* , *COP= 0.137*

Table 2 summaries research table of numerical studies

Reference	The study model	Equations / Improvement parameter
Abbas and Davood (2017)		The cold outlet temperature and the flow rates that inlet through the vortex tube
Muhammad et al. (2019)		$\Delta T_c = T_i - T_c$ $\Delta T_h = T_h - T_i$ ΔT=48℃
Karthik and Peter (2021)		Total energy =*1200,000 J/m^3*
Raphaël et al. (2024)		Heating power =*650W*
Bazgira et al. (2018)		$\eta_{is} = \frac{T_i - T_c}{T_i[1 - (\frac{P_a}{P_i})^{\frac{(\gamma-1)}{\gamma}}]}$ $\Delta T_c = T_i - T_c$

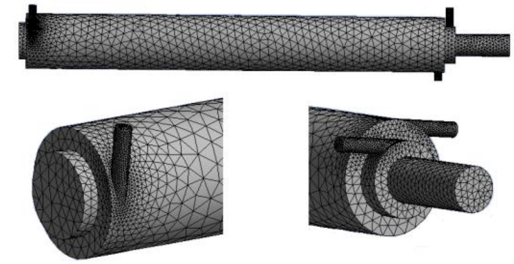
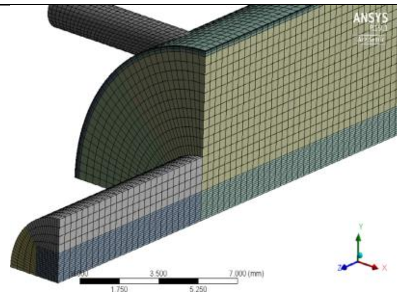
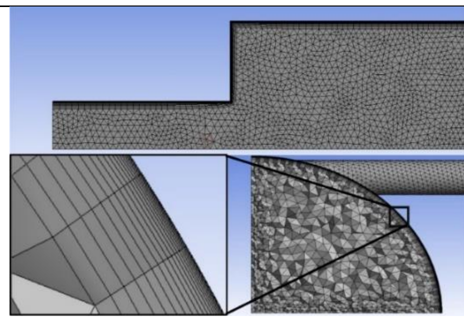
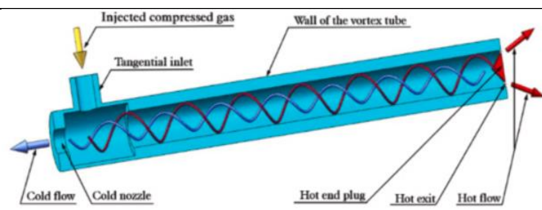
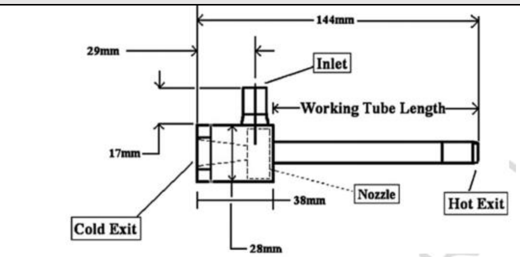
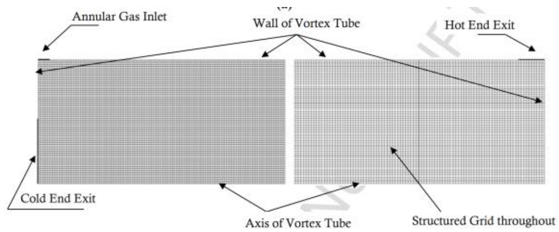
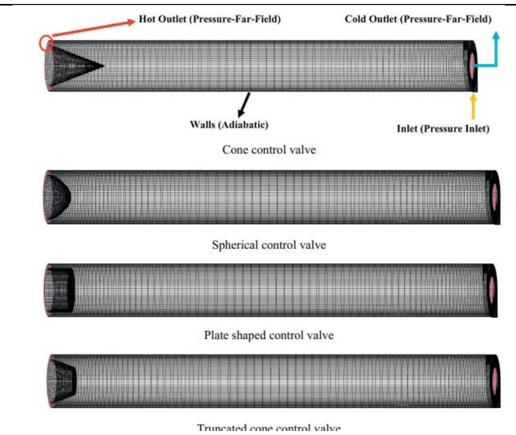
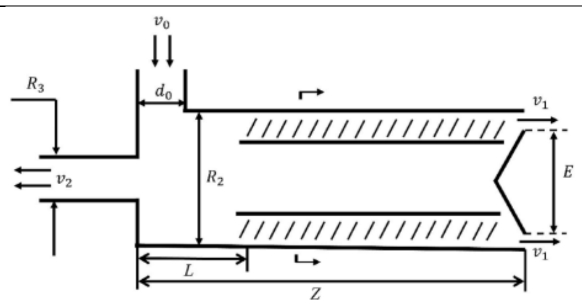
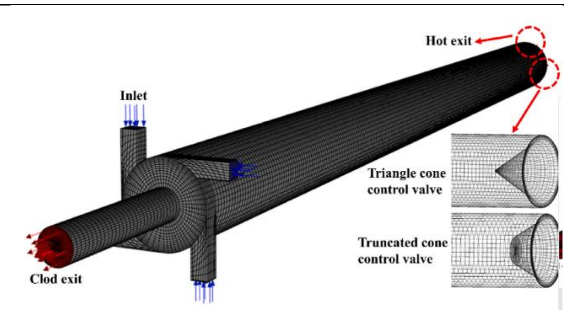
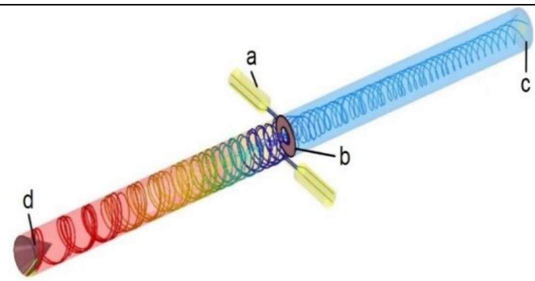
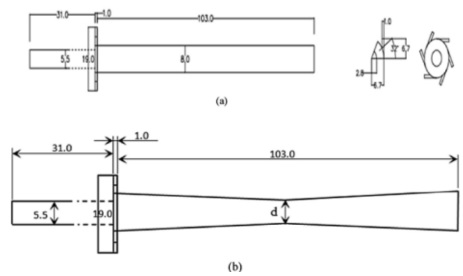
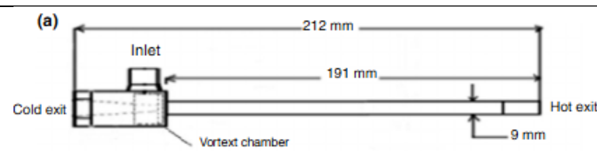
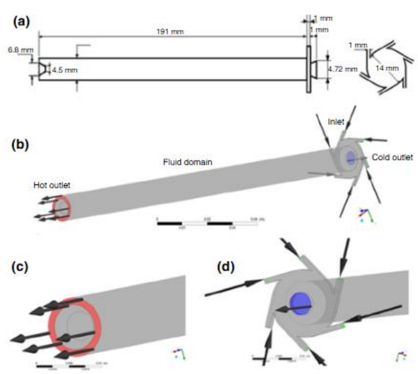
		The isentropic efficiency *=27%, ∆T=25℃*
Ahmed et al. (2021)		The flow inside RHVT: for free and force vortex
Alsaghir et al. (2022)		*COP= 0.8*
Shuyang et al. (2024)		Expansion displacement *=0.09m*

Table 3 summaries research table of experimental and numerical studies

Reference	The study model	Equations	Improvement parameter
Thakare and Parekh (2017)	 	$Q^{\cdot}_{c} = m^{\cdot}_{c} C_p (T_i - T_c)$	Experimental cold energy separation =*18%*
Rafiee and Sadeghiazad (2017)		$\Delta T_c = T_i - T_c$	ΔTc= *27℃*
Shuyang et al. (2024)			ΔT_c=*32.5℃*

<table>
<tr><td></td><td>
</td><td></td></tr>
<tr><td>Radomír Chýlek (2018)</td><td>

a- tangential inlet nozzle, b-cold exit orifice, c-cold outlet, d-hot control valve and hot outlet.</td><td>ΔT_h= 85.75 ℃</td></tr>
<tr><td rowspan="2">Lizan and Ramzi (2020)</td><td rowspan="2">
</td><td>$\Delta T_c = T_i - T_c$</td></tr>
<tr><td>ΔT_c= 49.71 ℃</td></tr>
<tr><td rowspan="2">Jaber et al. (2020),</td><td rowspan="2">


</td><td>$\Delta T=T_h-T_c$</td></tr>
<tr><td>ΔT=65.43 ℃</td></tr>
</table>

Recommendations

It was observed that most of the studies focused on investigating the effects of operating conditions (such as flow rates, pressures, and outer surface temperature), in addition to studying the influence of certain geometric dimensions. However, it is rare to find previous research addressing the effect of nozzle angles and the number of nozzles on the energy separation process and the performance of the vortex tube. Furthermore, no experimental or numerical studies were found that examine the effect of arranging the nozzles in multiple stages (multi-stage nozzles). Therefore, it is recommended to conduct a numerical study to investigate the effects of the following parameters on the nozzles: the number of nozzles, their inclination angles, and their arrangement in multiple stages (multi-stage nozzles).

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