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Experimental Investigation Of Multistage Nozzle Manifolds In A Vortex Tube For Enhanced Energy Separation

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Abstract: *The vortex tube is a simple mechanical apparatus that utilizes the temperature separation phenomenon to divide compressed air into hot and cold streams, without any moving parts. The aims of this study are to enhance the energy separation efficiency and to increase the temperature differential between the cold and hot ends of the vortex tube, thereby improving its overall performance.*

This study is distinguished by its investigation of a vortex tube equipped with a multi-stage nozzle system installed at various inclination angles. To the best of our knowledge, and based on the reviewed literature, this specific configuration has not been explicitly addressed in previous research.

A locally fabricated test rig was constructed, comprising an air inlet, chamber, nozzle manifold, hot tube, cold outlet, and hot outlet. The effects of varying inlet air pressure and multiple nozzle stages were investigated experimentally.

The results showed that increasing the inlet air pressure leads to an increase in ΔTh, while both ΔTc and the coefficient of performance (COP) decrease. Furthermore, the optimal tube lengths were found to be 600, 620, 750, and 800 mm for nozzle inclination angles of 0°, 5°, 10°, and 15°, respectively. These optimal lengths were influenced solely by the nozzle inclination angle and not by the number of nozzle stages. Among the tested angles, 5° proved to be the most effective.

The triple-nozzle manifold with a 5° inclination achieved optimal outlet temperatures of 2.5 °C and 43.2 °C for the cold and hot streams, respectively. Additionally, the optimum COPh and COPc values were observed for the triple-stage configuration at 5°, with average improvements of 4.92% and 15.01%, respectively.

This study contributes new insights to the field, as the effect of employing multi-stage nozzles with varying inclination angles on the performance of the vortex tube has not been explicitly addressed in previous research. These findings highlight the potential of using multi-stage nozzles with optimized inclination angles to significantly improve the thermal performance of vortex tubes, making them more effective for practical applications in energy separation and industrial spot cooling systems

1. INTRODUCTION

Energy is the fundamental for a nation's economic growth. It is an essential gradient for human performance in all tasks [1],[2]. The vortex tube is an important device that has a direct and interesting relationship with energy, particularly in the conversion of thermal and mechanical energy transformation. A vortex tube is a device without a moving part that uses a single injection of air to create two hot and cold streams through the energy separation phenomenon (the compressed gas enters the tube and splits into a hot and cold stream without external work or moving parts) [3]. This apparatus is also known as the Ranque-Hilsch vortex tube. The vortex tube, due to its simplicity, compactness, lightness, and quietness, is widely utilized in various cooling and heating processes. Other applications include setting solders to cool machine parts, dehumidifying gas samples, cooling electronic control cabinets, chilling environmental chambers, cooling food, and testing temperature sensors. Inlet nozzles, one or more, a vortex chamber, the body of a tube, a cold end orifice, and a hot end control valve consist of a vortex tube. There are two types of vortex tubes according to the direction of existing flows: (1) the cold and hot stream in a similar direction is called the uni-flow vortex tube, and (2) the cold and hot stream in the opposite direction is called the counter-flow vortex tube [4].

Previous studies are classified into several categories based on design configuration and operating conditions.

Firstly, several studies adopted an experimental (practical) approach to investigate the vortex tube's behavior under various configurations and conditions. [5] studied two types of parameters that affected vortex tube operation: geometrical and thermo-physical.[6] used nitrogen as a working fluid in a vortex tube and based their findings on the two thermodynamic laws. [7] found the optimal number of nozzle inlets for the vortex tube by using the Taguchi method. [8] explored the ideal geometry of a cold orifice for a vortex tube at different inlet pressures and

cold mass fractions. [9] found that the enhancement of performance for the vortex tube was affected by cooling.[10] used the temperature difference by the thermoelectric generator as a thermal energy harvester to generate power and improve the cooling capacity and efficiency. In contrast [11] used oxygen and air as the fluid to examine the amount of inlet pressures and effects of the number of orifice nozzles on the functions of cooling and heating for a counterflow vortex tube. On the other hand [12], studied two types of vortex tubes, with and without insulation, by an experimental study developed for both temperature and relative humidity separation in vortex tubes. [13] discussed the effect of energy separation under various geometrical dimensions to analyze the performance of vortex tubes. [14] used a snail nozzle for a vortex tube; this study aimed to use low-pressure inlet air as a cooling agent to decrease the hot air discharge temperature. [15] used different geometrical parameters to investigate the performance of energy separation in a vortex tube through an experimental study. [16] conducted an experimental study under various circumstances on the flow behavior in a confined cylindrical system with several configurations that match the real flow field in a vortex tube. In the same year, [17] aimed to determine the impact of pressure and mass fraction on the vortex tube. In a similar study, [18] analyzed the impact of vortex tube design using variations in pressure and mass fraction to improve its efficiency by cooling the surface of the hot tube both naturally and forcefully. [19] used CO_2 as a compressed fluid and applied the multiple linear regression method to improve the performance of Ranque–Hilsch vortex tubes (RHVTs), using different parameters such as inlet pressures, connection nozzle materials, and the number of orifices. [20] studied the emissions from a six-cylinder vortex tube direct diesel engine during operation in cold start conditions. [21] used a counter-flow vortex tube type to study the impact of double vortex-chambers with multiple inlet snail entries and multiple nozzles on the energy separation. [22] conducted an experimental study investigating the cooling efficiency using Taguchi method analysis on a vortex tube equipped with a rectifier.[23] carried out high-accuracy experimental measurements of the cylindrical counter-flow Ranque-Hilsch vortex tube to improve the performance characteristics of an optimized design.
Secondly, some studies followed a theoretical or numerical approach to understanding the phenomena or predict performance. [24] studied two-component model yields and found the upper limit for the temperature rise on the hot side and a lower limit for the temperature reduction on the cold side.[25] numerically examined energy separation and fluid flow. [26] Studied physical parameters such as the number of air inlets, the length and diameter of the cold outlet on temperature, and the flow rates that pass through the vortex tube. [27] they used the 3D numerical model of a vortex tube between low-pressure and high-pressure system to develop an investigation of difference of flow and heat transfer characteristics
Finally, some studies conducted a combined or analytical evaluation between theory and experiments or explored deeper characteristics. [28] investigated analytically and experimentally the hydraulic characteristics of an intensely swirling flow in the energy separation chambers of Ranque-Hilsch vortex tubes. [29] investigated various nozzle profiles and numbers of a vortex tube using both experimental and numerical approaches. [30] studied the classification and type of vortex tube; they also provided every criterion for design in detail. [31] studied the flow characteristics and discussed the process inside a vortex tube by which hot and cold streams are created. [32] developed curve-fitting equations using data from literature that can predict the required temperature. [33] used thermodynamic analysis to study the impacts of various design parameters on vortex tube performance characteristics. [34] studied the acoustic signal characteristics and discussed the energy separation phenomenon of a Ranque-Hilsch vortex tube. [35] used carbon dioxide to analyze a transcritical heat pump cycle and demonstrated the vortex tube's usefulness in increasing heat pump efficiency.

2. METHODOLOGY

This study adopts an experimental approach to evaluate the performance of a vortex tube under various operating conditions. The methodology includes the following main steps:

1- Design and Fabrication of the Vortex Tube
2- Data Collection Mechanism, which involves:
   – System Preparation
   – Flow Stabilization
   – Data Acquisition

3- Repetition for Accuracy
4- Data Analysis and Performance Evaluation

The research investigates the influence of nozzle inclination angles, the number of nozzle stages, and supply pressure on the performance of the vortex tube. The inclination angles tested were 0°, 5°, 10°, and 15°, with various inlet airflow values. The study specifically evaluated the impact of nozzle inclination angles using a single-stage nozzle manifold under different supply pressures.Experimental testing was conducted over nine specific days (January 8, 9, 10, 11, 12, 15, 16, 17, and 18, 2025), with all tests performed at approximately the same time each day (10:00 AM) to ensure consistency in environmental conditions.

3. Theoretical background:

3.1 Heating Capacity:

The cooling and heating capacity can be expected by [36]:

$$Q_c = \dot{m}\, cp_c\, (T_i - T_c) \quad (1)$$

$$Q_h = \dot{m}\, cp_h\, (T_h - T_i) \quad (2)$$

Where: Qc is heating transfer by vortex tube affected by cooling, $\dot{m}$ is mass flow rate, cp_c is The air capacity at ambient cooling, T_i is temperature was measured, T_c is air temperature at cold outlet,(1-6) Q_h is heat transfer by vortex tube affected by heating, cp_h The air capacity at ambient of heating(1-5) and T_h is air temperature at hot outlet.

The mass flow rate multiple by specific heat is called heat capacity rate:

$$C_c = \dot{m}_c cp_c \quad \text{And} \quad C_h = \dot{m}_h cp_h \quad (3)$$

Where: C_c is heating capacity for cooling side and C_h is heat capacity rate for heating side.

The equations (1) and (2) also expressed as:

$$q_c = C_c(T_i - T_c) \text{ And } q_h = C_h(T_h - T_i) \quad (4)$$

The heat capacity for this study is calculated by equations (4) for the heating and cooling side

T_i is temperature measured, T_c is air temperature at cold outlet, (1-6) , T_h is air temperature at hot outlet.

3.2 The difference between hot and cold temperature:

The temperature difference for the heating and cooling side measured by using by below [37]:

$$\Delta T_c = T_i - T_c \quad (5)$$

$$\Delta T_h = T_h - T_i \quad (6)$$

Where: ΔT_c is change in cold temperature and ΔT_h is change in hot temperature, Ti is temperature measured, Tc is air temperature at cold outlet, (1-6), T_h is air temperature at hot outlet.

3.3 Coefficient of performance (COP):

The coefficient of performance (COP) is given by [34] as follows:

$$cop_c = \frac{Q_c}{W} = \frac{\dot{m}_c\, c_p\, (T_i - T_c)}{\dot{m}\, R\, T_i\, \ln\left(\frac{P_i}{P_a}\right)} \quad (7)$$

Where: cop_c is coefficient of performance of cooling, W is work input to the device, R is specific gas constant, P_i is air pressure inlet and P_a is standard atmospheric pressure.

$$cop_h = \frac{Q_h}{W} = \frac{\dot{m}_h\, c_p\, (T_h - T_i)}{\dot{m}\, R\, T_i\, \ln\left(\frac{P_i}{P_a}\right)} \quad (8)$$

Where: cop_h is coefficient of performance of heat.

3.4 Mass Flow Rate

The mass flow rate according to the equilibrium equation is obtained by [38] as follows:

$$\dot{m}_i = \dot{m}_{c\ out} + \dot{m}_{h\ out} \quad (9)$$

Where: $\dot{m}_i$ is inner mass flow rate, $\dot{m}_c$ is mass flow rate at the cold outlet and $\dot{m}_h$ is air mass flow rate at the hot outlet.

3.5 Cold Mass Fraction

Cold mass fraction [39] is the ratio of the mass flow rate of cold air to the mass flow rate of all outgoing air given by:

$$\varepsilon_c = \frac{\dot{m}_c}{\dot{m}_i} \quad (1\text{-}9) \quad (10)$$

Where: ε_c is Cold Mass Fraction.

3.6 *Uncertainty of Measuring Instruments*

$$\omega_{xi} = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \bar{x})^2}{N-1}}$$

ω_{xi}: standard deviation of individual parameter
N: number of observations recorded
X: is the average value of parameter X recorded N number of times
i: is the index of parameter X.
The result R is function of the independent variables x_1, x_2, x_3... x_n. Thus,
$R=f(x_1, x_2, x_3,.....x_n)$
The uncertainty in the result can be calculated by:

$$w_R = \left[\sum_{i=1}^{n}\left(\frac{\partial R}{\partial x_i}\omega_{xi}\right)^2\right]^{\frac{1}{2}}$$

W_R = the uncertainty in the result and w_1, w_2. . . w_n be the uncertainties in the independent variables.

4. Experimental setup

The experimental tests for the vortex tube were conducted on the Al-Nahrain University laboratory Iraq, Baghdad as part of the system illustrated in Figure 1. The rig consists of the following components:
1. Air compressor.
2. Air tank.
3. Manual pressure regulator valve.
4. Flexible hose and connectors.
5. Vortex tube.
6. Measurement devices (3Thermocouples, 2 Pressure gauges and 2 Flowmeters)

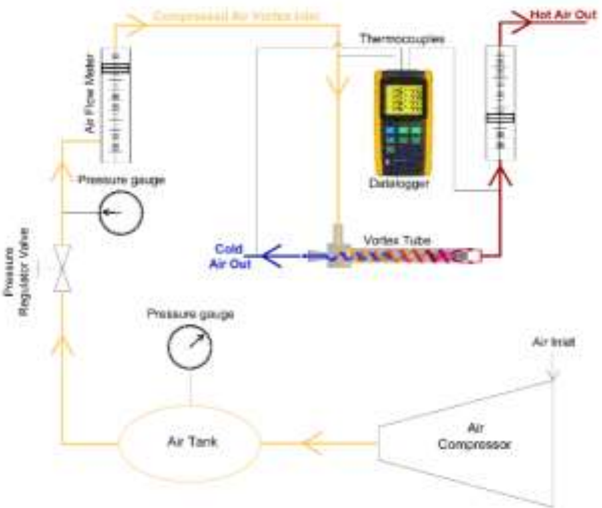


Figure 1. Schematic Experimental Rig

The vortex tube was manufactured locally using various engineering tools and software for the purpose of design and implementation. AutoCAD software was used to draw a preliminary schematic (shown in Fig. 2) of the dimensions and cross-section, while the vortex tube was modeled in SolidWorks as separate parts.

Air inlet Vortex Chamber Vortex Tube Hot Air Outlet

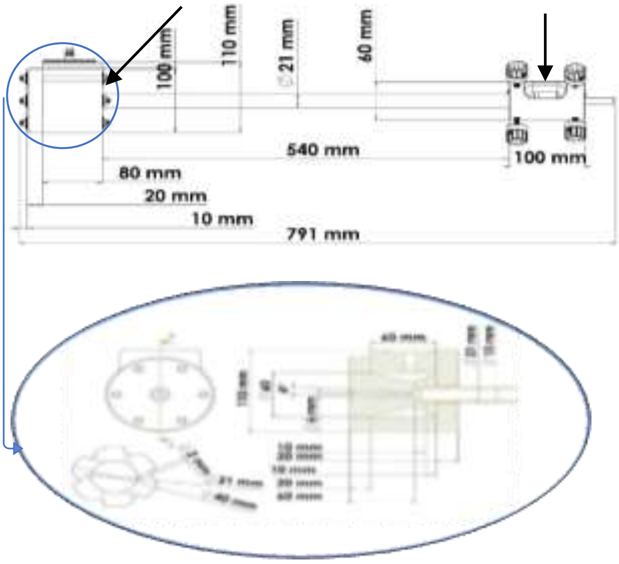


Figure 2. sketch of vortex tube and its chamber cross section

The main components of the vortex tube are: air intake and vortex chamber: was manufactured from PLA material by using a 3D printer (Creality Ender 3 PRO printer), nozzle manifolds: consist of six nozzle were made from acrylic material cutting by Co2 CNC Machine, hot tube: is simple PVC pipe which using the thermal camera to help determine the optimal tube length for each case as shown in fig.3, cold air outlet and hot air outlet: which assembly consists of control valve (control cone), hot air chamber and the hot air outlet pipe. All these parts are shown in fig. 4A and 4B

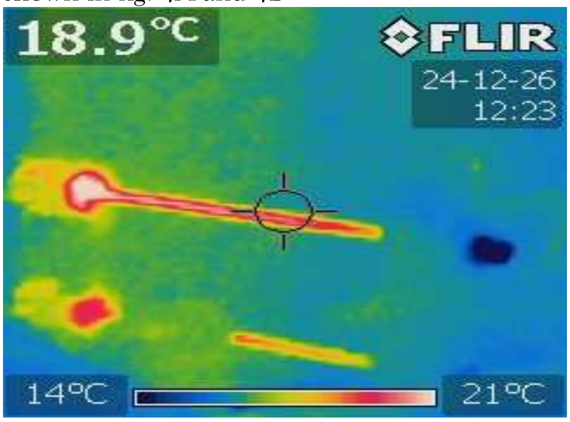
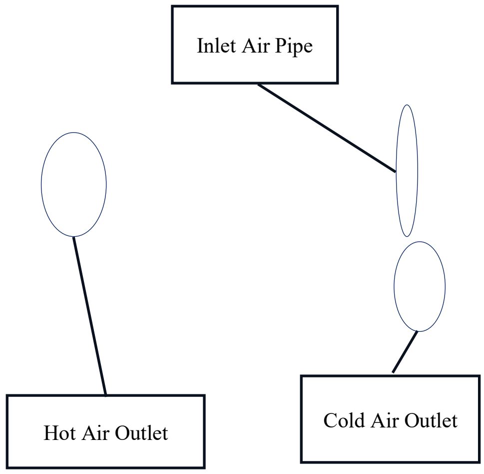
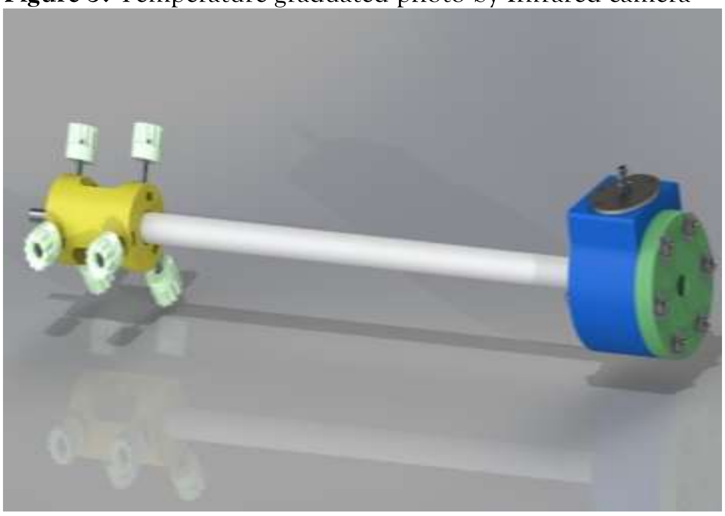


Figure 3. Temperature graduated photo by Infrared camera





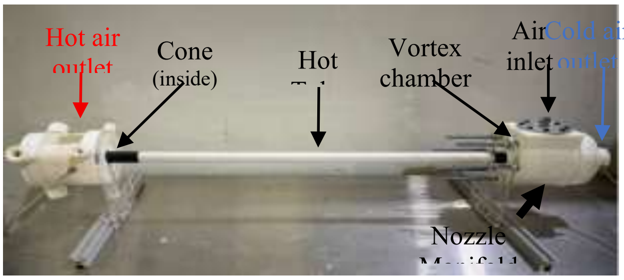


Figure 4A. 3D Vortex Tube PartsFigure 4B**.** Vortex Tube Parts

3.1 Measurement devices

Two pressure gauges were installed on the air tank and the suppling air (after the manual valve) to measure the air pressure inside the tank and the suppling respectively. The Uncertainty for the pressure gauge was ±0.006 Bar as shown in the table below.

Table 1 measures the uncertainty of an instrument's characterization.

Instrument	Range	Resolution	Uncertainty (95% Confidence)
Rotameter 1	0 - 600 LPM	10 LPM	±5.8 LPM
Rotameter 2	0 - 150 LPM	10 LPM	±5.8 LPM
Pressure gauge 1	0-16 BAR	0.01 Bar	±0.006 Bar
Pressure gauge 2	0-20 BAR	0.01 Bar	±0.006 Bar
K – type Thermocouples 1, 2, 3	-20 C° to 199.90 C°	0.1 C°	±0.06C

The pressure gauges were calibrated by using a hand pump device shown on Fig. (5)

Figure 5. Hand pump

Three K- type thermocouples were used in this experimental system. They were installed on the experimental rig to measure the air temperature on air inlet (Ti), hot air outlet (Th), cold air outlet (Tc). All the three thermocouples were connected to data logger type (BTM-4208SD) to display and record the air temperature. The Uncertainty for K- type thermocouples were equal ±0.06 °C.

The infrared camera is used in this study to specify the peak length for the hot tube in each case, also for validating the temperature difference that's measured by the thermocouples. A FLIR i5 infrared camera shown in Fig. 6 was used for this purpose.

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Figure 6. Infrared camera

Two flow meters were used to measure the air flow rate in this study, one installed on the compressor outlet to measure the hot outlet flow rate, the second one was measuring the cold outlet flow rate. A rotameter-type of flow meter was selected due to its simplicity and the Uncertainty was equal ±5.8 LPM. (1-11)

The devices connected online to the airflow, the inlet flowmeter rate range is 0-600 LPM, while for the hot outlet it is 0-150 LPM.

There is no flowmeter on the cold outlet, but the cold outlet flow rate was measured theoretically by using Eq. 9. All the measurement devices explained in Fig. 7.

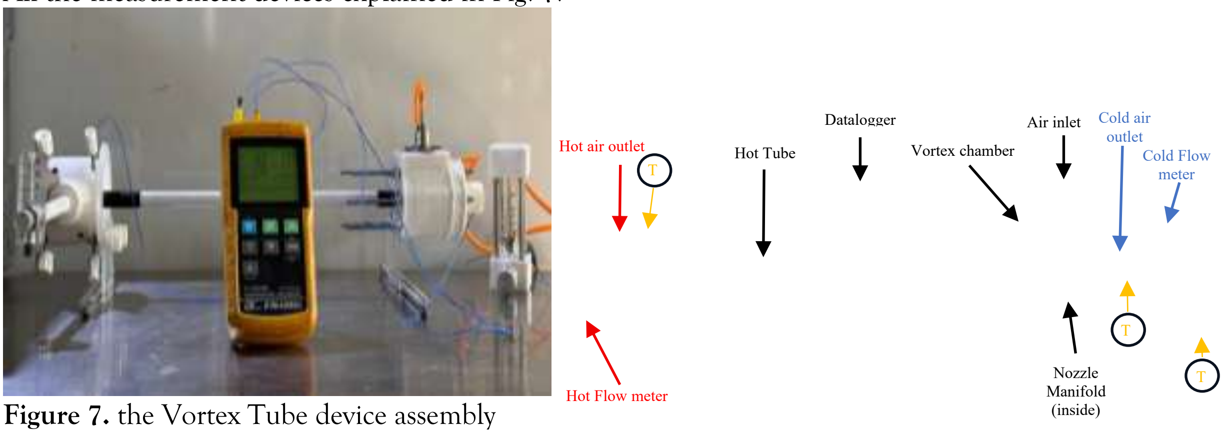

Figure 7. the Vortex Tube device assembly

5. RESULTS AND DISCUSSION

5.1 Studied Variables

This study explores how nozzle angle, number of stages, and supply pressure affect vortex tube performance, focusing on angles from 0° to 15° and varying airflow rates.

The optimal nozzle inclination angle for single-stage nozzle manifolds was applied to double-stage, triple-stage, and quadruple-stage nozzle manifolds to examine the impact of increasing manifold number on performance. Additionally, a preliminary study was conducted on the hot tube length using an infrared thermal camera.

The flow rate distribution was modified by adjusting the position of the conical valve (control valve) at the hot air outlet. After determining the optimal configuration, achieving the maximum difference temperature between the hot and cold air outlets the valve position was fixed, and its adjustment screws were securely tightened. The study used specific airflow rates and laboratory capabilities, conducting experiments on the nozzle inclination angles and manifold number at compressed air inlet flow rates of 70, 75, 100, 120, and 135 liters per minute. As explained in fig. 8.

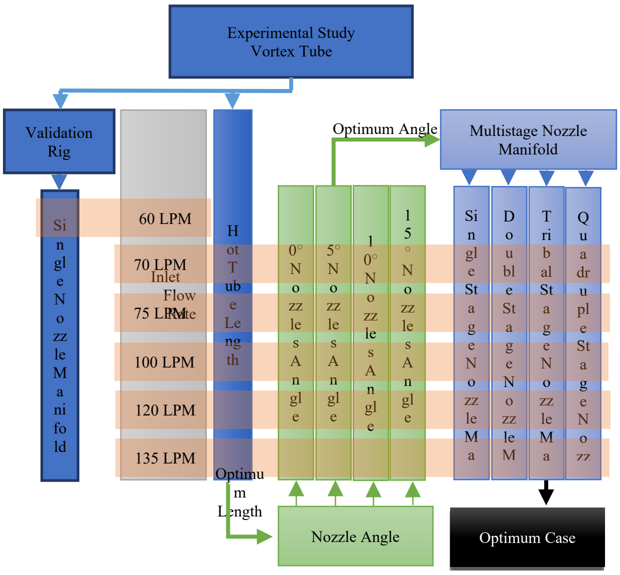

Figure 8. Experimental Study Flow Chart

5.2 Hot Tube Length

An infrared thermal camera was used to calculate the hot tube's length, as mentioned earlier. The maximum temperature difference between the hot and cold outlets was identified along the tube using thermal images, as shown in Fig. 9.

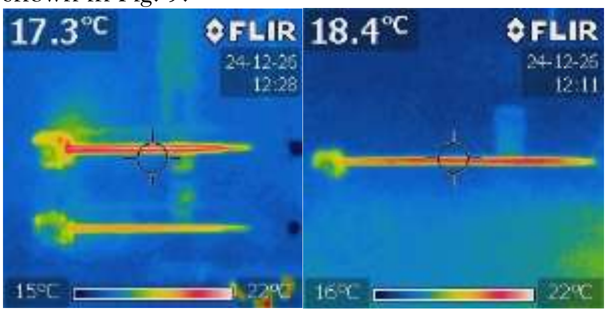

Figure 9. Single stage tube length optimizing

For varying inlet airflow rates the optimal tube length was determined to be influenced by the angle of the nozzle inclination, not the number of the nozzle manifolds. The optimal length for 0° inclination was 600mm, while higher angles resulted in greater lengths.

Figure 10 illustrates the impact of the hot tube length on the temperature difference between the hot and cold outlets at a nozzle inclination angle of 0°.

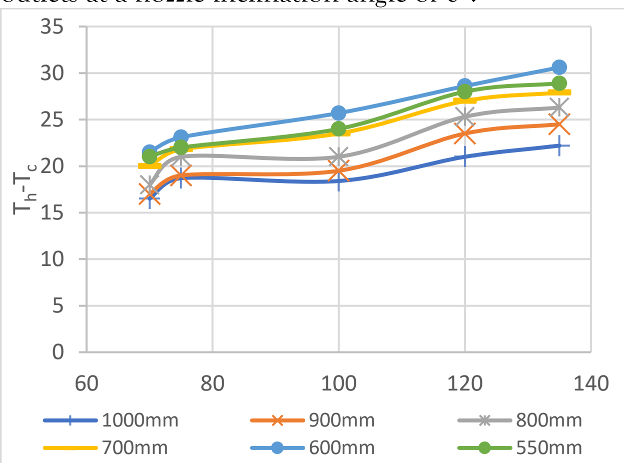

Figure 10. Relation between (Th-Tc) And Air Inlet Flow for a Different Hot Tube Length

This variation is attributed to the path length of the incoming air within the hot tube. As the nozzle inclination angle increases, the vortex flow requires a longer path to reach the optimal temperature.

The optimal length was confirmed after completing all experimental tests (to avoid adding connections to the tube, which could obstruct airflow inside the tube) by cutting an additional 100 cm from the tube length. This verified the accuracy of the selected length, as the temperature difference began to decrease.

5.3 The Nozzle Inclination Angle

The experimental study was done on 4 different sets of the nozzle manifolds, all the 4 manifolds with a single stage for optimizing the nozzle inclination angle. The tested angles were (0°,5°,10° and 15°) toward the hot outlet side. The comparison was done for varying values of compressed airflow supplied by the compressor (70, 75, 100, 120, and 135 LPM) on varying nozzle inclination angle. Fig.11 and Fig.12 explain The Connection between the air intake flow rate with the cold and hot air outlet (Tc and Th) for different nozzle inclination angels.

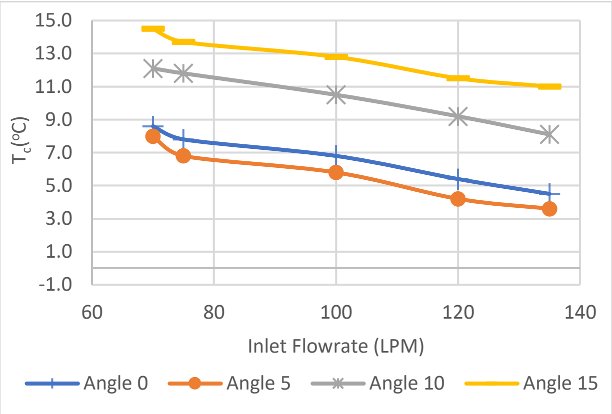

Figure 11. The Connection between the Air Inlet Flow Rate and Cold Air Outlet temperature (Tc) For a Different Inclination Nozzle Angle

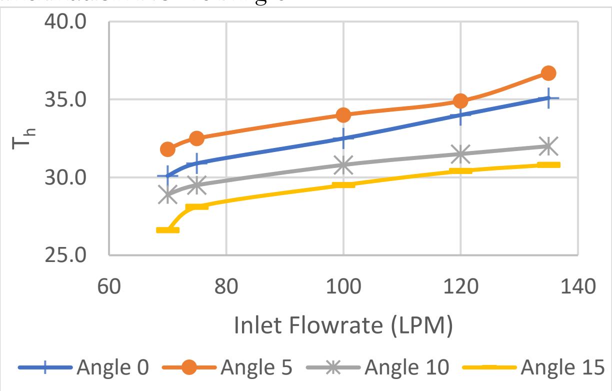

Figure 12. The Connection between the Air Inlet Flow Rate and Hot Air Outlet temperature (Th) For a Different Inclination Nozzle Angle

The experimental study showed that inclination angle of the nozzle improves the temperatures of both outlets (a drop in the temperature of cold air and an increase in hot air temperature) up to a certain limit. As shown in the figures above, the average improvement ratio for the cold and hot air temperature on a variable flow rate values are (14.20%) and (4.49%) when the nozzle inclination angle is increased by 5° compared to the basic inclination angle (0°). This is because the air inlet's inclination, up to a certain limit, positively affects energy separation efficiency by enhancing vortex formation in the hot tube.

Oppositely the inclination nozzle angles of 10° and 15° negatively affected the outlet air temperatures due to the high inclination angle of the incoming air, which may cause the following:

1. The need for an increased hot tube length as shown on Fig. 13.
2. Reduction in the number of rotations and the angular velocity of the airflow inside the hot tube, this reduces the centrifugal force (direct proportion between the center fugal force and the angular velocity).

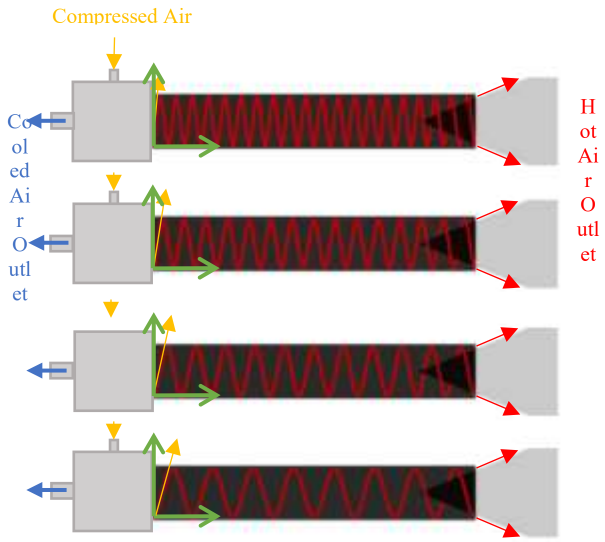

Figure 13. Nozzle inclination angle effect on the air path length

The nozzle inclination angle impact on the temperature differences (ΔTc and ΔTh) were illustrated in Fig. 14 and 15 on variable air flow rates.

The enhancement on the 5° the angle of the nozzle inclination against the 0° of the nozzle angle at the highest flow rate is (4.47%) for the cold side and (7.03%) for the hot side. However, where the nozzle inclined angle was increased in the case of 10° and 15°, the excessive inclination reduced the effective swirl and shortened the air path, causing a reduction in efficient energy separation.

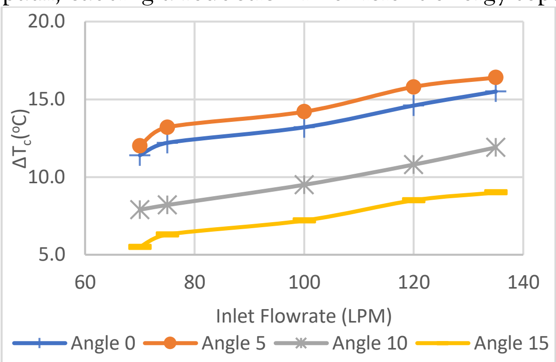

Figure 14. The Connection between the Air Intake Flow Rate and Cold Air Outlet Difference (ΔTc) For a Different Inclination Nozzle Angle

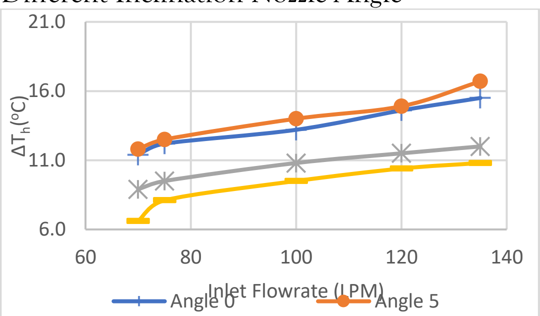

Figure 15. The Connection between the Air Inlet Flow Rate and Hot Air Outlet Difference (ΔTh) For a Different Inclination Nozzle Angle

The cold and hot coefficients of performance (COPc and COPh) were theoretically calculated using equations number (7 and 8) and based on the experimental results.

Figures (16 and 17) illustrate that the COPc and COPh of the vortex tube at a nozzle inclination angle of 5° is optimal compared to other angles (0°, 10°, and 15°). This is due to the high effectiveness of the airflow vortex inside the hot tube, which enhances energy separation efficiency and consequently the overall performance.

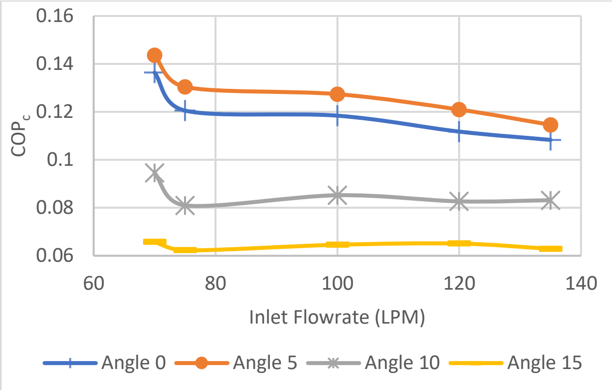

Figure 16. The Connection between the Air Inlet Flow Rate and Cold Air Outlet Difference (ΔTc) For a Different Inclination Nozzle Angle

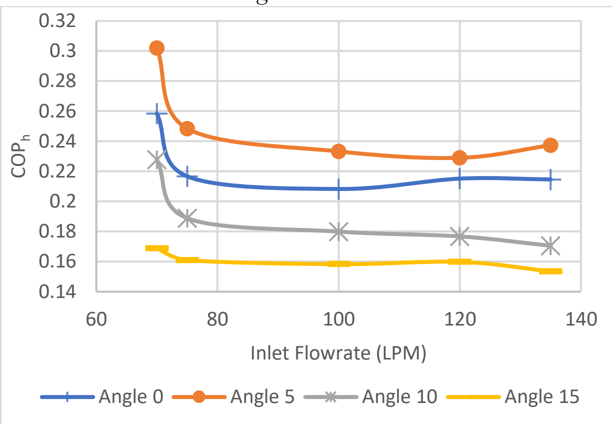

Figure 17. The Connection between the Air Inlet Flow Rate and Hot Air Outlet Difference (ΔTh) For a Different Inclination Nozzle Angle

The calculations showed that the optimum average performance coefficients for the variable flow rate values for cold and hot sides are (0.127) and (0.250) at the nozzle inclination angle of (5°).

While it was noted that the average COPc and COPh improved by (6.97% and 12.29%) respectively when the nozzle inclination angle was changed from the base angle (0°) to an inclination angle of 5°. Also, it has been noted that the COPc and COPh rise in tandem with the rise in airflow rates for all cases.

Figures 18 and 19 illustrate the experimental results of the air outlet temperatures for varying values of compressed airflow supplied by the compressor (70, 75, 100, 120, and 135 LPM) and for a varying number of the nozzle manifolds.

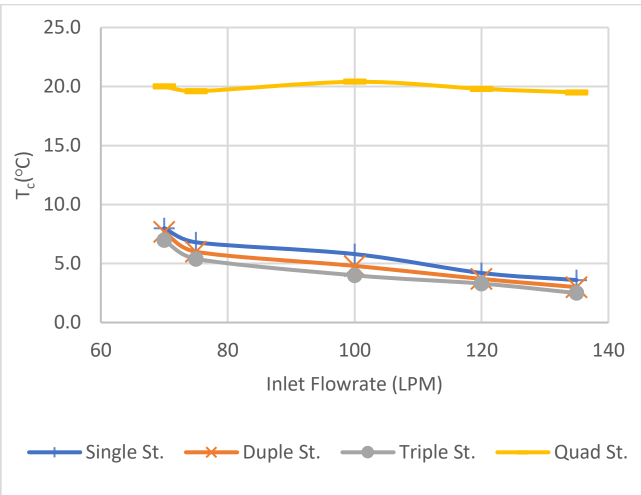

Figure 18. The Connection between the Air Inlet Flow Rate and Cold Air Outlet temperature (Tc) For a Different Nozzle Stage Number

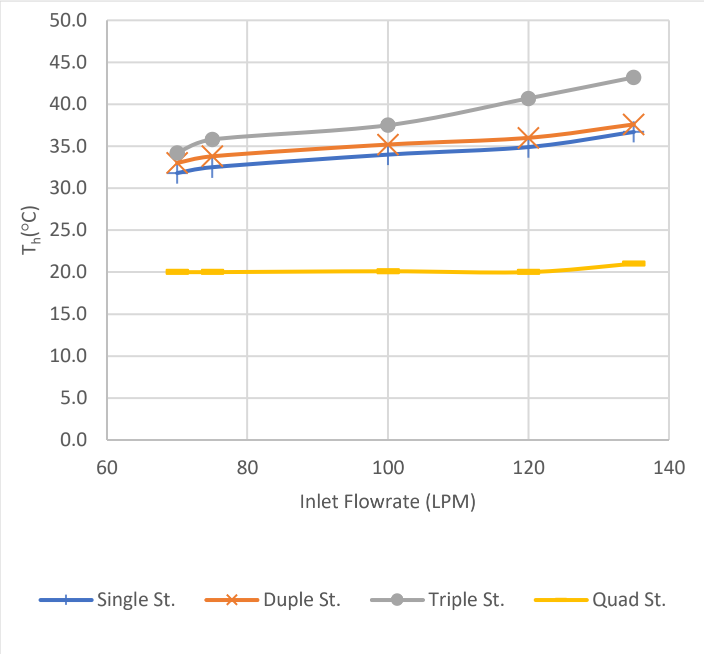

Figure 19. The Connection between the Air Inlet Flow Rate and Hot Air Outlet temperature (Th) For a Different Nozzle Stage Number

The result showed the temperatures at the cold outlet drop as the number of manifolds increases, while the temperatures at the hot outlet increase, up to a certain number of manifolds.

The outlet temperatures of the vortex tube improved when the number of manifolds increased from one to two for both the cold and hot sides at different airflow rates, with improvement rates of (11.27%) and (3.35%), respectively.

Additionally, the temperatures improved by (21.83%) and (12.65%) for the cold and hot outlets, respectively, when operating with a triple manifold compared to the single manifold.

While the improvement rate for the triple against the double nozzle stage in the cold and hot outlet temperatures is (11.90%) and (9%) respectively.

However, when a quadruple manifold was installed, a significant decrease in the device's performance was observed, with almost the input and output air are identical temperatures. Due to the lack of centrifugal force generation, prevented the formation of the vortex, which is essential for energy separation.

The impact of the number of the nozzle manifold on the temperature differences (ΔTc and ΔTh) were illustrated in fig. 20 and 21 on variable air flow rates.

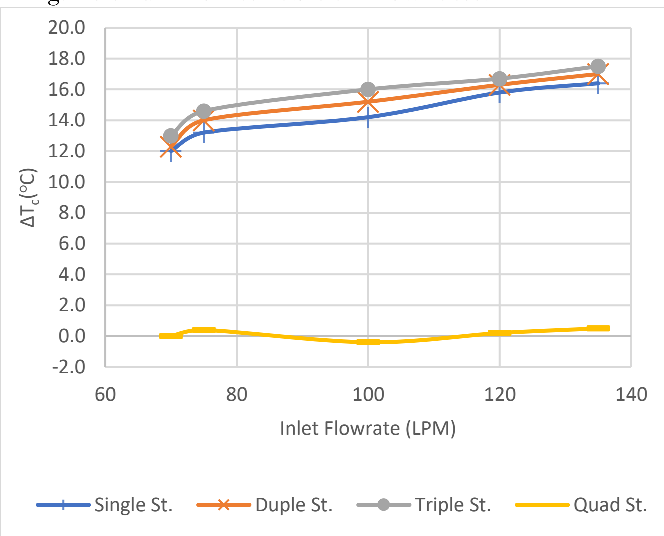

Figure 20. The Connection between the Air Intake Flow Rate and cold Temperature Difference for Multistage Nozzle Manifolds

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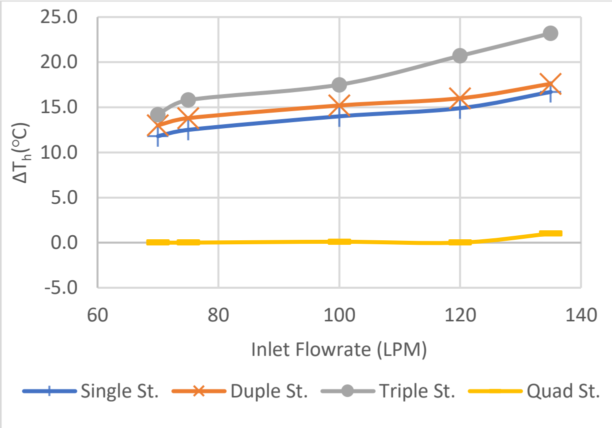

Figure 21. The Connection between the Air Inlet Flow Rate and Hot Temperature Difference for Multistage Nozzle Manifolds

The results shown in the figures above indicate a noticeable improvement in the temperature difference values for the cases of dual and triple nozzle manifolds. The improvement percentages reached (4.47%) and (8.15%) for the (ΔTc and ΔTh) respectively for the dual nozzle manifold compared to the single one. Meanwhile, the improvement percentages were (8.66%) and (30.76%) for the triple nozzle manifolds compared to the single nozzle manifold. These improvement percentages were due to the increase in the amount of air entering the vortex tube. But there is no change between the air inlets and the outlets temperatures for the quadruple nozzle manifolds.

The COP was calculated based on Equation (7) and (8) using experimental results to assess the performance of the manufactured laboratory device

Figures 22 and 23 explain the connection between the inlet air flow rate and the COPc and COPh respectively.

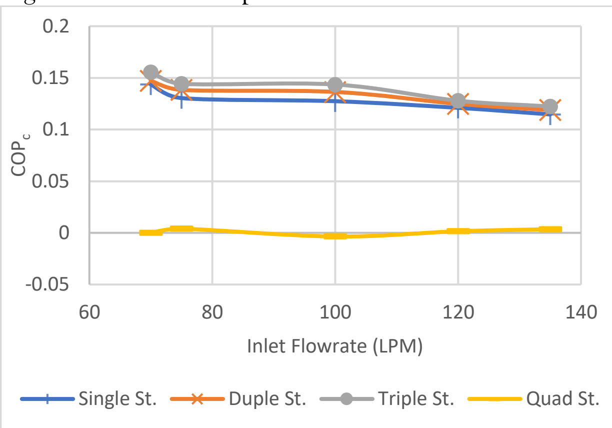

Figure 22. The Relationship between Air Inlet Flow Rate and Cold Coefficient of Performance for Multistage Nozzle Manifolds

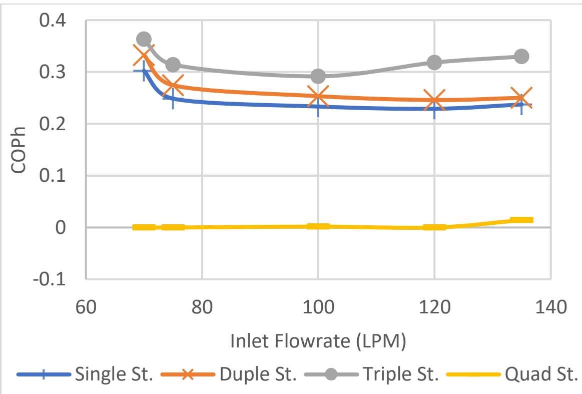

Figure 23. The Relationship between Air Inlet Flow Rate and Hot Coefficient of Performance for Multistage Nozzle Manifolds

The results indicate that the COPc and COPh increases with the number of the nozzle manifolds, except for the Quadrupole nozzle manifold, due to the interference in the airflow paths.
It is observed that the average improvement in the COPc and COPh was (3.65%) and (5.38%), respectively, for the double nozzle manifold compared to the single nozzle manifold. Meanwhile, the improvement percentages were (6.70%) and (38.92%) for the triple nozzle manifolds compared to the single nozzle manifold.
The improvement of the performance of the vortex tube with the rise in the number of stages is attributed to the enhanced efficiency of the energy separation process.
It is worth mentioning that the maximum flow rate was set at 135 liters per minute (equivalent to a supply line pressure of 7 bar because of the constant area of the cross-section of the flow path), despite the capability of supplying 178 liters per minute (equivalent to 11 bar pressure). This limitation was imposed to ensure stable supply pressure during each test until a steady-state condition was reached.
It can be observed that, in all cases studied, the properties of the vortex tube improved with the rise in the airflow rate supplied.
The effect of increasing the airflow rate on the coefficient of performance studied separately due to its unique behavior in one of the studied cases.
A decrease in COPc and COPh values is observed with an increase in airflow rate (and supply air pressure), despite the improvement in temperature values (higher hot outlet temperature and lower cold outlet temperature). This decline is attributed to the logarithmic relationship in the denominator of the COP calculation equations (7 and 8), which involves the ratio of supply pressure to atmospheric pressure. Since the atmospheric pressure remains constant, a rise in the supply pressure results in a larger denominator in the COP equations, leading to a reduction in COPc and COPh values as the airflow rate (or supply pressure) increases.

6. RESULT VALIDATION:

Validation is a necessary step in scientific research to ensure the accuracy of experimental results. A validation test was conducted by comparing the results with those from study by [40]. This required manufacturing a single nozzle only shown in fig.24, along with a 675 mm tube length, to match the dimensions used in the referenced study (L/D=45).

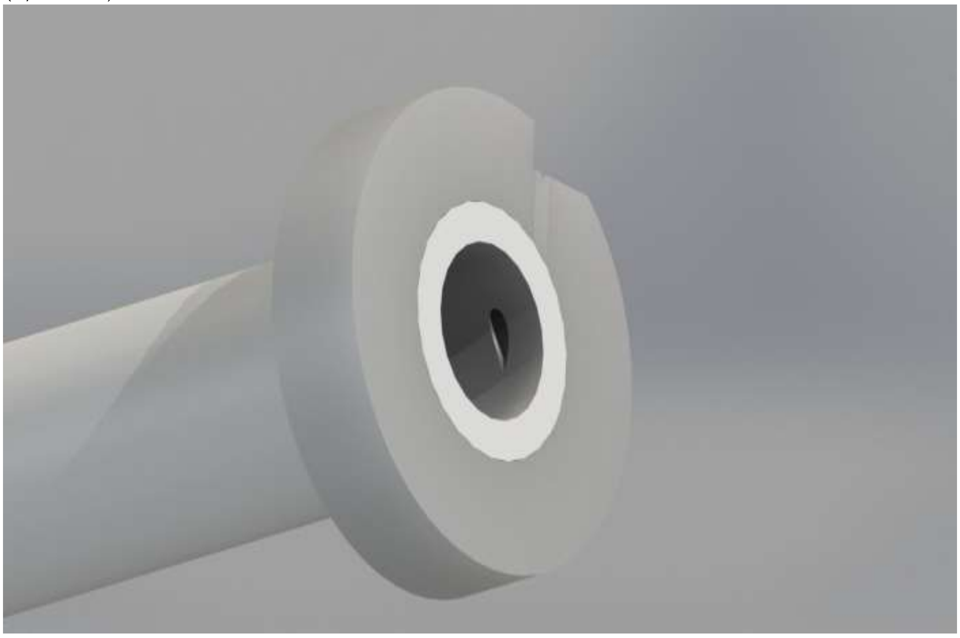

Figure 24. single nozzle (validation case)

Figure (25) presents the experimental results from the referenced experimental study alongside the laboratory readings obtained from the validation test setup.
The control valve (conical valve) was adjusted and optimized to determine the ideal position, ensuring similar conditions to those in the comparative study (ε = 0.2, 0.3, 0.4, 0.5, 0.6 and 0.7).
The validation results showed that the average agreement between the experimental readings and study by [40] was 96.9% (3.1% error percentage).

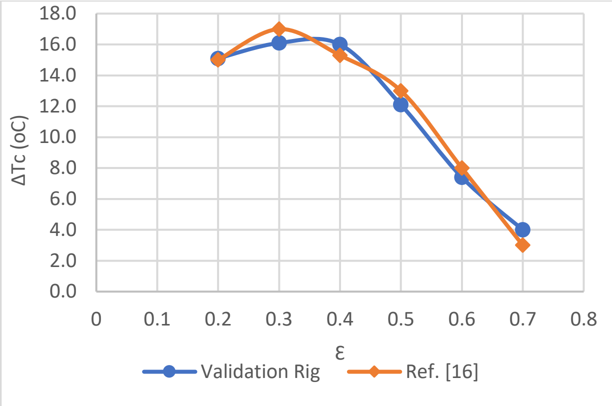

Figure 25. Validation cold temperature difference with cold flow fraction compared to study by [40]

7. CONCLUSION

The experimental results showed that the average improvement in cold and hot air outlet temperatures was 14.20% and 4.49%, respectively, when the nozzle inclination angle was increased to 5° compared to the basic 0° angle. This improvement is attributed to the fact that, up to a certain limit, the inclination of the air inlet enhances vortex formation inside the hot tube and positively influences energy separation efficiency. However, at inclination angles of 10° and 15°, this effect becomes negative.

Furthermore, at the highest airflow rate, the enhancement achieved with the 5° inclination angle compared to 0° was 4.47% and 7.03% for the cold and hot outlets, respectively. This is because increasing the nozzle inclination angle shortens the airflow path inside the vortex tube and reduces both the number of rotations and angular velocity, thereby weakening the centrifugal force responsible for energy separation. Although a 0° inclination offers a longer flow path and higher angular velocity, it causes flow disturbances at the inlet, which weaken vortex formation. Therefore, under the selected dimensions and operating conditions, the 5° inclination angle toward the hot outlet was found to be the optimal configuration.The experimental findings also verified that the cold outlet temperature (Tc) decreased as the number of manifolds increased, while the hot outlet temperature (Th) increased. The performance improved significantly when the number of manifolds was increased from one to two, with temperature improvements of 11.27% and 3.35% for the cold and hot sides, respectively. When using a triple manifold instead of a single one, the improvements reached 21.83% for the cold side and 12.65% for the hot side. Compared to the double manifold, the triple manifold offered improvements of 11.90% and 9.00% for the cold and hot outlets, respectively. However, when the vortex tube was operated using a quadruple manifold, it was observed that the intake and outlet air temperatures became nearly identical, indicating a breakdown in effective energy separation.

In terms of temperature differences, the improvements in ΔTc and ΔTh for the double nozzle manifold compared to the single were 4.47% and 8.15%, respectively. For the triple nozzle manifold, the improvements compared to the single manifold were 8.66% and 30.76%, respectively.Additionally, the results showed that both COPc and COPh increased with the number of nozzle manifolds, except in the case of the quadruple manifold. The average performance coefficients (COP) at varying flow rates for the cold side were 0.119, 0.127, 0.0850, and 0.064, and for the hot side were 0.222, 0.250, 0.188, and 0.160, corresponding to nozzle inclination angles of 0°, 5°, 10°, and 15°, respectively.The average improvement in COPc and COPh for the double manifold compared to the single was 3.65% and 5.38%, respectively. For the triple manifold, the improvement rates were 6.70% for COPc and a notable 38.92% for COPh compared to the single-stage configuration

8. Nomenclature:

T_i	Inlet Temperature °C	ΔT_c	Change in cold side
T_h	Hot outlet Temperature °C	ΔT_h	Change in hot side
T_c	Cold outlet Temperature °C	ε_c	Mass Flow rate Friction

T_i	Inlet Temperature °C	$\dot{m}_h$	Hot Mass Flow Rate (Kg/s)
$\dot{m}$	Inlet Mass Flow Rate (Kg/s)	R	The specific gas constant
$\dot{m}_c$	Cold Mass Flow Rate (Kg/s)	cp_c	Cold air specific heat
P_a	Ambient Pressure (Bar)	cp_h	Hot air specific heat
COP_h	Hot side performance coefficient	COP_c	Cold side performance coefficient
P_i	Inlet Pressure (Bar)	ω_{xi}	Standard deviation of individual parameter
W_R	The uncertainty in the result		

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