EXPERIMENTAL INVESTIGATION OF THE PERFORMANCE OF VORTEX TUBE SYSTEM USED FOR CONTROL PANELS COOLING

Hussein S. Sultan[1], Khalid B. Saleem[1], Ammar A. Ojimi[2], Lioua Kolsi[3]

1 Department of Mechanical Engineering, College of Engineering, University of Basrah, Basrah, Iraq; hussein.sultan@uobasrah.edu.iq; khalid.saleem@uobasrah.edu.iq

2 Department of Petroleum Engineering, College of Engineering, University of Basrah, Basrah, Iraq; ammar.ojimi@uobasrah.edu.iq

3 Department of Mechanical Engineering, College of Engineering, University of Ha'il, Saudi Arabia; lioua_enim@yahoo.fr

ABSTRACT

To meet the urgent need for effective cooling solutions in a manufacturing setting, the effectiveness of a vortex tube system for cooling electrical control panels is carefully investigated in this experimental study. This paper presents a novel strategy to improve cooling efficiency in industrial settings by investigating the creative use of a vortex tube for panel cooling. The main goal of this work is to extend the cooling procedure for the electronic control panel and the method of impacting different pressures (1 to 7 bar) on the system's performance. This work offers core information on the activity and capability of using the vortex tube for cooling purposes by performing some tests in Basrah / Iraq for three days during June 2023. Detecting perfect operation conditions enhances the cooling performance and reduces power consumption. The finding confirms that air pressure at the entrance has an impact on the allocate the ability of the system on the cooling. This confirms that the coefficient of performance (COP) of 0.12 is produced by 4 bar internal air pressure. Achieving solutions for high performance cooling is critical for the control panel of the manufactural field. This study helps lower energy consumption, improve equipment reliability, and lessen environmental effects by examining the operation of a vortex tube system and optimizing cooling efficiency.

KEYWORDS

Vortex tube; Control panels; Compressed air-cooling; Ranque-Hilsch tube, COP.

1. INTRODUCTION

While manufacturing a piece of material, most energy is transformed into heat due to the shear stresses. Hence, the heat produced in the cutting area plays a crucial role in determining the workpiece's efficiency and quality during machining. While the utilization of cutting liquids enhances cooling efficiency, it also raises production costs and has detrimental effects on the environment. The need to discover various cooling strategies is steadily growing for these reasons. The research on sustainable manufacturing has notably surged in recent years. An example of a cooling method is the vortex tube cooling system. The vortex tube is a straightforward, compact, lightweight, and silent apparatus that can divide an identical-temperature compacted gas flow into two streams: a stream colder than the incoming flow. The division of the gaseous fluid stream into two distinct streams with varying temperatures is known as the temperature (energy) separation effect. Ranque is credited with inventing the vortex tube and documenting the energy separation process. Subsequently, Hilsch reported methodical experimental findings about this phenomenon. Subsequently, this occurrence has garnered the attention of numerous scientists. Experimental, analytical, and numerical studies have proposed various theories to elucidate this phenomenon. An expansion of air from a high-pressure area close to the wall to a low-pressure area close to the axis, as suggested by Hilsch, would produce a radial velocity gradient. Viscosity acts upon this gradient, transferring kinetic energy from the fluid's inner to outer layers (Choi *et al.*, 2001; Dutta *et al.*, 2010). The following components comprise a Ranque-Hilsch Vortex Tube (RHVT): a tube, a cold-end orifice, a vortex chamber, and a hot-end control valve. A fast and robust rotation is produced by the peculiar internal arrangements of the vortex chamber, which efficiently uses the combined forces of pressure and pushed air (Xue and Arjomandi, 2014). Examples of the many industrial uses for the vortex tube include heating operations, cooling suits, refrigeration, and CNC machines. There is no need to worry about repairs or replacements because this gadget is impervious to wear and tear and has no moving parts (Yüksel and Onat, 2015). The vortex tube is the most basic energy-and gas-free mechanical device known to man. As seen in Figure 1, the compressed air enters the tube, which then flows into the nozzles organized in a vortex, producing hot air and cold air, according to this tube's operation principle. The device is also called the Ranque-Hilsch tube.

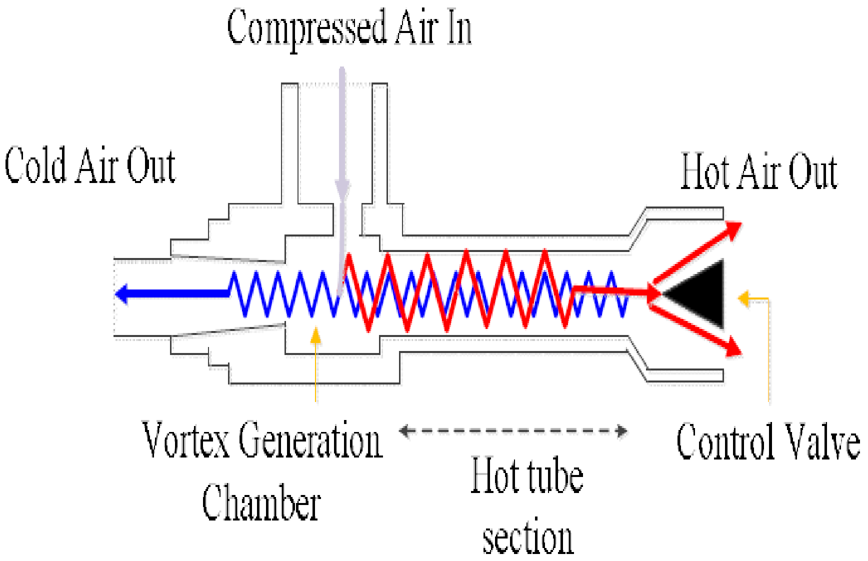

Fig. 1. Counter-current flow vortex tube.

Many researchers have studied this device, (AYDIN and BAKI, 2006) delved into the relationship between the vortex tube length, the nozzle diameter, and their effects on nitrogen, air, and oxygen. (Liu and Kevin Chou, 2007) utilized the cold air produced by the vortex tube in cutting machines to achieve a reduction in cutting temperature of up to 20 °C. (Eiamsa-ard and Promvonge, 2008) explored the Ranque-Hilsch vortex tube, highlighting its potential in various industrial applications. Their study assessed geometric and thermophysical parameters and scrutinized pressure, velocity, and temperature fields. (Rattanongphisat and Thungthong, 2014) used a thermoelectric module operated by hot air from the vortex tube to produce electricity at 1.5 bar. Using experimental and computational research, investigated the actions of microscale vortex tubes. They gained insights into optimizing refrigeration power and isentropic efficiency using computational fluid dynamics to solve the energy separation phenomena. Using a vortex tube,(Fazel Bakhsheshi *et al.*, 2016) established a new method for cooling the brain selectively. Their research confirms that using a vortex tube to bring cold air into the nasal cavities is safe and effective, as it efficiently lowers and maintains brain temperature before bringing it back up to normal levels. The performance of the vortex tube was experimentally investigated by (Hamdan *et al.*, 2018), who looked at some geometrical parameters, including the tapering angle, diameter, and length of the tube. They also measured the effect of input pressure on vortex efficiency.

(Ganugapenta *et al.*, 2018) designed a vortex tube made of Delrin material. Their study focused on enhancing the COP by investigating how cooling and heating impact the orifice diameter and inlet pressure. (Xue *et al.*, 2019) conducted an experiment exploring the flow dynamics within a closed cylindrical system, mimicking the genuine flow conditions in a vortex tube with diverse settings. (Li *et al.*, 2019) designed and constructed a large-scale vortex tube using a five-hole probe and thermocouples to measure internal parameters. They analyzed cold mass fractions (0.2, 0.4, 0.6, 0.8) and discussed their impact. Their study identified the tangential velocity as a steady Burgers vortex form, revealing a backflow boundary that varied with conditions and axial positions. (Hu *et al.*, 2020) extensively reviewed the development of energy separation in vortex tubes, focusing on principles, design criteria, and applications. They discussed factors influencing vortex tube performance and highlighted its widespread use in refrigeration, heating, and mixture separation. (Kim *et al.*, 2020) investigated the potential of a vortex tube as a refrigerant-free solution for vehicle air conditioning, addressing environmental concerns. They studied temperature variations and characteristics and designed a simulation device for air conditioning systems using indirect and direct heat exchange methods. (Sarifudin *et al.*, 2020) conducted experiments to enhance the vortex tube efficiency, comparing it to a traditional heat pump engine using Freon refrigerants. They analyzed data, considering various parameters like temperatures, heat transfer, and efficiency. Measurements were collected under controlled conditions, ensuring instrument consistency. (Tempiam *et al.*, 2020) designed and tested a vortex tube to cool the intake air of a 7.5 kW piston air compressor. They conducted experiments with three nozzle sizes, identifying the most effective one. Their outcomes showed a temperature decrease of 8.3 °C, optimal energy-saving settings yielded a 2.3% improvement, and increasing pressure to the vortex tube enhanced energy efficiency.

(Fadhli Suhaimi *et al.*, 2020) selected the Vortex tube to cool the jacket at diverse cold mass flow rate 30 to 90 L/min and inlet pressure of 200 to 500 kPa. (Vignesh *et al.*, 2020) studied the geometrical parameter role (L/D ratio) at various inlet pressures to the tube. Based on their results, the vortex tube's tube length and diameter ratios affect a cooling system's performance. (Parker and Straatman, 2021) explored the impact of pressure parameters on temperature differentials by conducting a practical investigation on the Ranque-Hilsch vortex tube. Their study draws on a substantial body of prior research and highlights the importance of considering dynamic temperature components in the analysis. (Alsaghir *et al.*, 2022) used numerical simulations to analyze energy separation in vortex tubes, employing various working fluids. They focused on specific fluid properties that were unattainable through experiments and assessed their impact on performance. (nejad *et al.*, 2022) studied a hybrid system using a vortex tube to reduce natural gas pressure at stations. The system converts gas into hot and cold streams, generating electricity through thermoelectric generators (TEGs). Their study focused on energy, exergy, and environmental performance, optimizing the system for the Kermanshah pressure reducing station's conditions. More recent papers on vortex tube implementation on numerous refrigeration systems can be found in (Abed and Ghaydh, 2024; Ambedkar and Dutta, 2023a, 2023b; Khrebish and Sultan, 2021; Li *et al.*, 2023; Oberti *et al.*, 2023).

This study addresses a research gap by conducting an experimental examination of using a Vortex Tube system to cool electronic control panels. The research centers on real-world contexts using compressed air, particularly in the environment of Iraq's Basrah metropolis. This study introduces a novel approach to effectively cooling electronic control panels in the harsh Iraqi metropolis of Basrah using a Vortex Tube unit in combination with compressed air-cooling technology. The goal of this project is to reduce carbon dioxide output and electric energy utilization. With a focus on the impacts on the heat removal rate (Q) and coefficient of performance (COP), this study set out to assess the Vortex channel cooling unit's efficiency under various operating pressures and weather scenarios. An important reason why this study is noteworthy is that it addresses a growing need for environmentally friendly cooling solutions in manufacturing. In addition to being an affordable and eco-friendly option, it offers a practical answer. It also has real-world consequences for making cooling units for electronics more efficient.

2. EXPERIMENTAL METHOD AND VORTEX TUBE DESCRIPTION

The vortex channel utilized in this experiment is an excellent example of a device that successfully separates temperatures without using mechanical parts. The work of the vortex tube can be understood by breaking it down into its three primary components and then examining the airflow route. The chamber that creates vortices is the first component. Essentially, it's just a cylindrical duct with an entry nozzle placed at an angle. The purpose of this nozzle is to create a whirling vortex flow by introducing compressed air into the chamber at an angle. When temperatures separate, this vortex is a necessary component. Nozzle design (including the presence or absence of specific holes or shapes) substantially impacts the vortex channel's efficiency and the temperature fluctuation it achieves (as seen in Fig. 2).

The second element comprises the hot air output and an achievable control valve. The vortex produces heated air expelled through a specific outlet, often positioned at the opposite side of the container from the 7.7 mm diameter entrance nozzle. The warm air flow usually removes substantial heat from the compressed air. A control valve, either mechanical or electrical, can be incorporated into the pathway through which hot air is discharged. This valve controls the movement of hot air, which can be adjusted to control and affect the temperature of the emitted cold air.

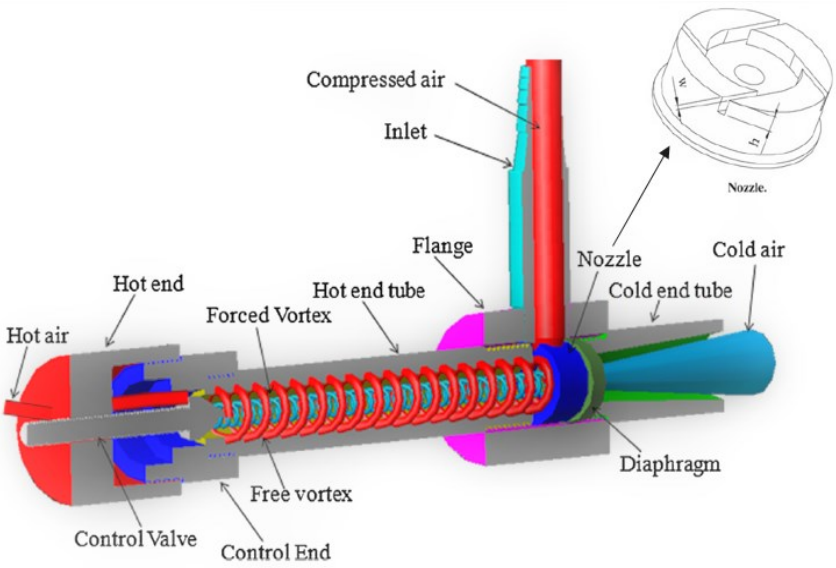

Fig. 2. Schematic for the vortex tube including the main parts.

The last part is the chilled air outlet. This is essential for achieving the required cooling impact. The outlet is located inside the vortex chamber, usually near the entrance nozzle at the same end. As a result of the vortex dynamics, the cold air gathers in this central area. Figures 3 and 4 demonstrate using a specialized pipe with a smaller diameter (12.8 mm in this experiment) to direct the cold air stream for external use, separate from the hot air outflow. The diameter of this pipe is a crucial design component that directly impacts the pressure gradient and, consequently, the attainable chilly air temperature.

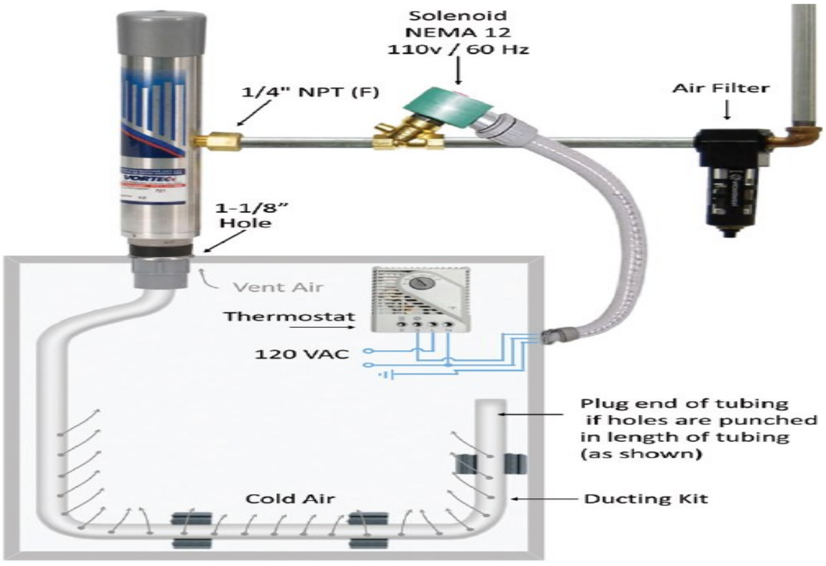

Fig. 3. Vortex tube with control panel.

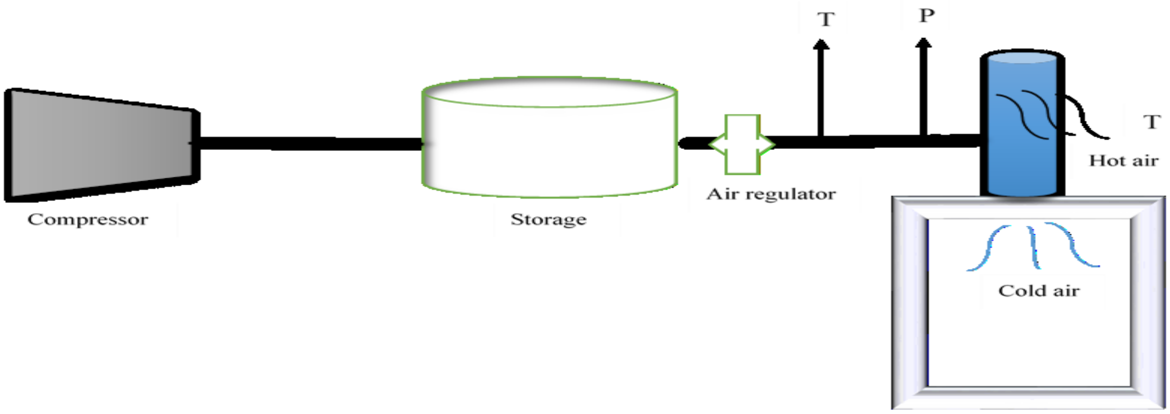

Fig. 4. Vortex tube installation system including the compressor, storage area, and air regulator.

The actual vortex tube with conditioned control panel is shown in Fig. 5.

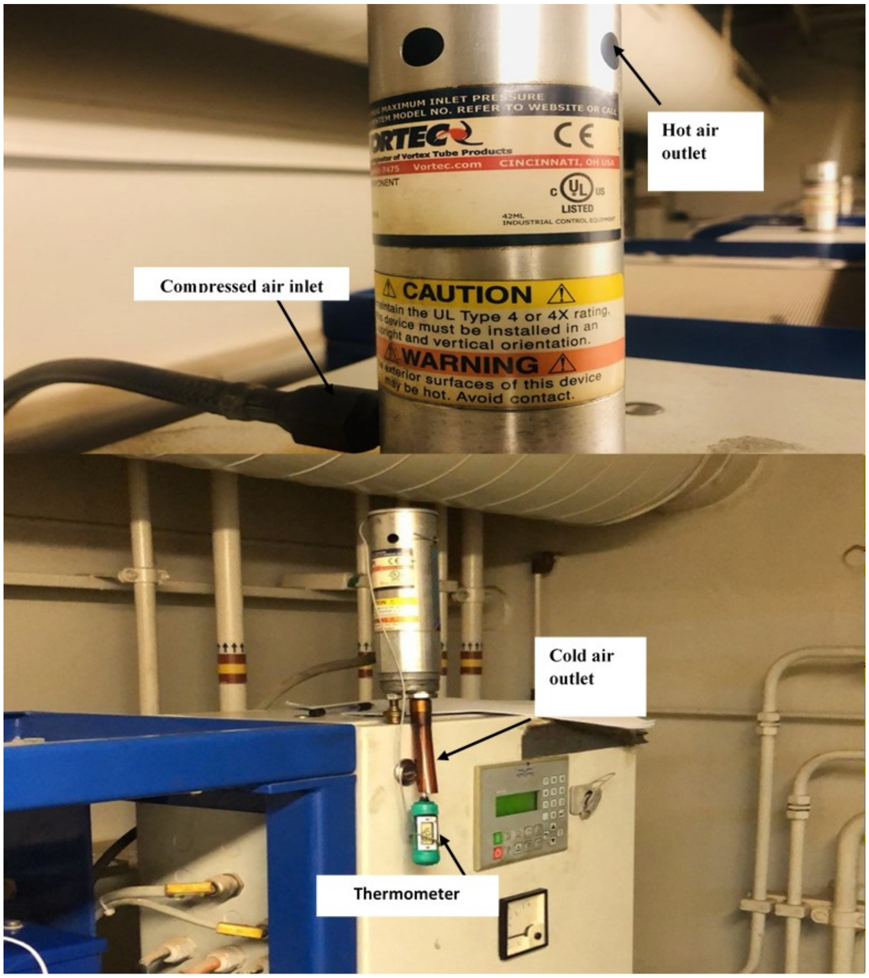

Fig. 5. Actual vortex tube with a control panel system.

The pressure was measured using a pressure gauge placed on a pressure regulator, through which a variable pressure is applied, as depicted in Fig. 6.

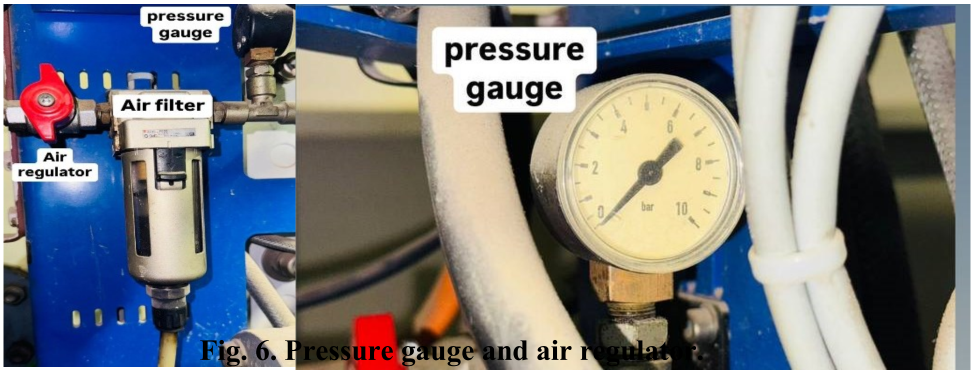

Fig. 6. Pressure gauge and air regulator.

The air compressor used is the reciprocating type. It provides a maximum mass flow rate of 30 m^3/hr and a maximum pressure of 30 bar to air storage, as shown in Fig. 7.

Fig. 7. The air compressor.

The cold air velocity was measured using a speed meter, as illustrated in Fig. 8.

Fig. 8. The speed meter.

3. THEORETICAL ANALYSIS

The thermal cooling load of the vortex tube is calculated using the subsequent equation, which is the amount of heat energy removed from the entering compressed air by the cold air stream:

$$\dot{Q}_c = \dot{m}_c C_p (T_c - T_{in}) \tag{1}$$

The mass flow rate ($\dot{m}_c$) can be estimated as:

$$\dot{m}_c = \rho A V \tag{2}$$

where ρ is the air density, A is the area, V is the air speed. The $\dot{m}_c$ is the amount of cold air being produced by the vortex tube per unit time, C_p is the specific heat capacity and $(T_c - T_{in})$ is the change in temperature between the compressed air entering the tube and the cold air exiting it.
The COP of the vortex tube can be estimated according to (Simões-Moreira, 2010).

$$COP_R = \varepsilon \frac{k}{k-1} \frac{(1 - T_c/T_{in})}{\ln(P_{in}/P_o)} \tag{3}$$

where ideal gas constant (k) is a property of the gas being used, which is taken as 1.4 in this case. $\ln(P_{in}/P_o)$ is the natural logarithm of the ratio of the inlet pressure to the atmospheric pressure, indicating the expansion process occurring within the vortex tube. Cold air fraction (ε) represents the proportion of air that is cooled and given as (nejad *et al.*, 2022):

$$\varepsilon = \frac{T_H - T_{in}}{T_H - T_C} \tag{4}$$

In Eq. (3), the cold air temperature is denoted by ($T_{C.}$), compressed air temperature (T_{in}), compressed air pressure (P_{in}), and atmospheric pressure (P_o).

4. RESULT AND DISCUSSION

This study explored the possibility of cooling an electrical control panel in Basrah, Iraq, using a vortex tube. Examining how input air pressure and other environmental factors affect the vortex tube's operation was the primary goal of the experiment. The trials were conducted over three days in June 2023, with the current meteorological conditions in Basrah considered. Consistent with ambient temperatures (39–41 °C), the researchers carefully adjusted the input air pressure from 1–7 bar while maintaining a constant compressed air temperature. The compressed air's relative humidity levels were 10% to 20%.

The study found that the vortex tube's cooling effectiveness directly relates to the intake air pressure. From 1 bar up to a certain threshold, the vortex tube's cooling effect became significantly stronger. Two primary causes are responsible for this. A more efficient separation of the hot and cold air streams is achieved by raising the pressure, improving the vortex formation within the chamber. Cooler air collects in the center and is used for cooling, while hot air, which contains a lot of thermal energy, is expelled outward. A vortex tube's ability to reduce temperatures directly relates to the pressure differential between the inflowing and outflowing streams. The cold air stream's temperature drops precipitously when the intake pressure rises because the pressure ratio also rises. The results showed that the vortex channel's efficiency dropped when crossing a certain pressure threshold. Many people believe that the compressed air causes this effect. The airflow out of the nozzle could get blocked at very high intake pressures. This hampers the establishment of a steady whirlpool, impeding the efficient separation process and eventually diminishing the cooling impact. The discovered patterns correspond to well-established principles that control the operation of vortex tubes. The Ranque-Hilsch effect governs the temperature differentiation inside the vortex chamber. Rising the inlet pressure improves the vortex, causing better separation effectiveness and a colder exiting air stream. Nevertheless, surpassing a specific threshold of pressure can disturb the creation of a swirling pattern caused by restricted airflow, thereby diminishing the overall effectiveness.

Figure 9 illustrates the changes in the COP of the vortex tube cooler in relation to the inlet air pressure on three different days in June 2023 (18th, 20th, and 21st). Consistent patterns in the data throughout all trial days suggest that the vortex tube system's COP is mostly unaffected by environmental variables. According to the results, the COP increases at first with rising inlet air pressure and peaks at 4 bars. After this point, the COP drops as the pressure increases. Investigating how the vortex's strength interacts with the airflow limitation might shed light on this occurrence. A more efficient separation of the hot and cold air streams is achieved by increasing the input pressure, improving the production of a vortex inside the chamber. This, in turn, leads to a higher COP at lower pressures. Excessive pressures can lead to air choking at the nozzle, which disrupts the vortex and hampers effective separation, ultimately decreasing the COP. Remarkably, the consistent trend in the COP obtained over three days indicates that environmental conditions such as temperature and humidity have negligible influence on the performance of the vortex tube within the range of testing. The vortex tube's ability to provide consistent cooling under varying environmental circumstances can benefit practical uses. Additional research could delve into the precise factors contributing to the limited impact on the environment identified in this study. Furthermore, further research could focus on improving the vortex tube's design, precisely the nozzle's shape, to possibly improve the COP at higher pressure levels and reduce the occurrence of air choking.

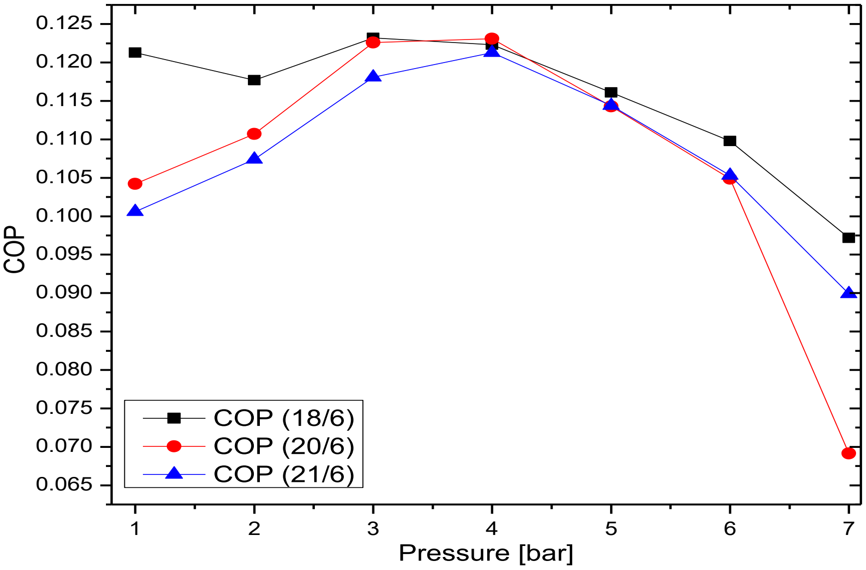

Fig. 9. Alteration of COP with pressure for three different days (18th, 20th, and 21st of June-2023).

Figure 10 demonstrates the impact of the entrance air pressure on the cold air temperature exiting the vortex tube on three specific testing days (June 18th, 20th, and 21st, 2023). The data indicates a correlation between pressure and cold air temperature and a possible impact of environmental factors. As the inlet air pressure rises, stronger and more consistent vortices are formed within the chamber. This initially causes a drop in the temperature of the cold air that exits as the separation of the hot air stream improves. The trend approaches its lowest point when the inlet pressure is 4 bar. Nevertheless, additional pressure rises beyond this threshold can result in a marginal elevation in the temperature of the cold air. This increase can be ascribed to two possible factors: the obstruction of airflow at the nozzle, which hampers the creation of swirling patterns at extremely high pressures, and the limited ability of the cold air flow to absorb heat energy despite the enhanced separation at higher pressures. Notably, the data also indicates that external variables, while not specifically measured, could influence the temperature of the cold air as it exits. The thermal exchange mechanisms within the vortex channel can be affected by the ambient temperature and humidity, which in turn may influence the desired cold air temperature. Additional inquiries could investigate the precise environmental variables that impact the low air temperature and accurately measure their impact. Furthermore, further study could focus on optimizing the layout of the vortex channel, namely the shape of the nozzle and the size of the chamber, to potentially improve the cooling effect of the cold air at greater pressure levels and reduce the negative impact of air choking.

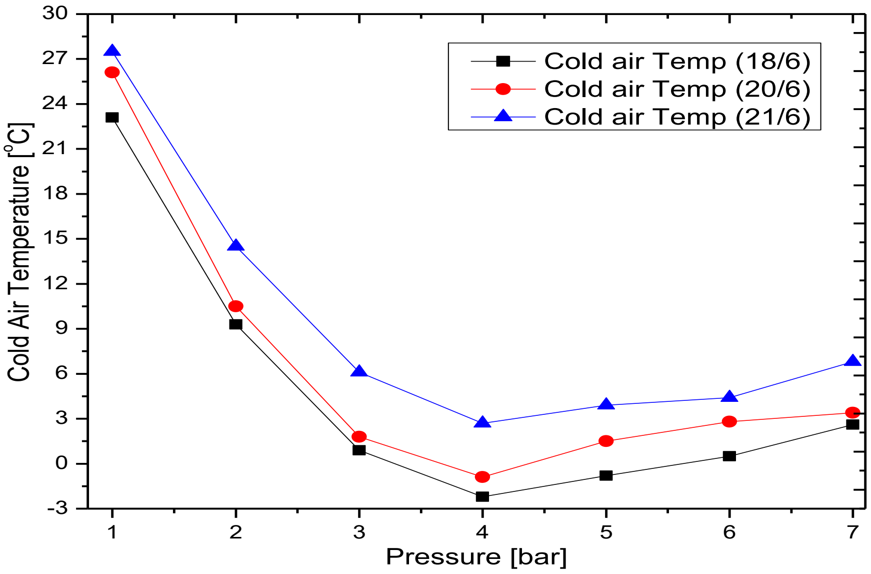

Fig. 10. Variation of cold air temperature with pressure.

Figure 11 illustrates the inverse correlation between the vortex tube's entrance air pressure and the output hot air temperature. The data were collected on three specific test days in June 2023 (18th, 20th, and 21st). The data demonstrates a distinct correlation between higher air temperature and rising pressure, with only minor effects from external factors. The explanation for this phenomenon lies in the amount of effort needed to counteract the effects of frictional losses occurring within the vortex tube. Increased input pressure requires the compressed air to exert more effort to overcome friction when generating a vortex. This increased labour results in an augmentation of the heat transferred by the warm air flow, resulting in a warmer fluid at the exit. Remarkably, akin to the findings regarding low air temperature (Fig. 10), the data indicates that ambient variables have minimal impact on the warm air output temperature. The influence of ambient temperature and humidity on the heat transfer mechanisms in the vortex tube's hot air stream is minimal. Although the examined range of environmental variables has shown limited impact, subsequent research could investigate their influence under more extreme temperatures and humidity levels. In addition, investigations could focus on optimizing the vortex tube's design, namely the nozzle's shape and the characteristics of the surfaces inside the chamber. This might decrease losses due to friction and decrease the temperature increase of the warm air at higher pressure levels.

Figure 12 demonstrates a strong direct relationship between the pressure of the incoming air and the velocity of the cold air that exits the vortex channel. The data indicates a substantial increase in the speed of cold air, rising from 3 m/s at 1 bar to 30 m/s at 7 bar. This phenomenon can be elucidated using the theory of energy conservation. Increasing the input air pressure results in a higher flow energy for the air under pressure that enters the vortex channel. This heightened energy is evident in the accelerated speed of the cold air stream as it exits. The method of generating vortices within the chamber is of utmost importance. A more robust and energetic vortex is generated with a rise in the inlet pressure. The strengthened vortex increases the momentum of the cold air gathering in the center, leading to a higher speed when it exits. Nevertheless, it is crucial to consider the compromise with other performance characteristics. Although increasing pressure might enhance cooling air velocity, overly high pressure can cause air choking and potentially reduce the cooling performance of the vortex tube (see Fig. 9). Hence, further investigation could focus on enhancing the vortex tube's configuration, specifically the nozzle shape, in order to strike a harmonious equilibrium between maximizing the speed of cold air and preserving effective vortex generation within elevated pressure levels.

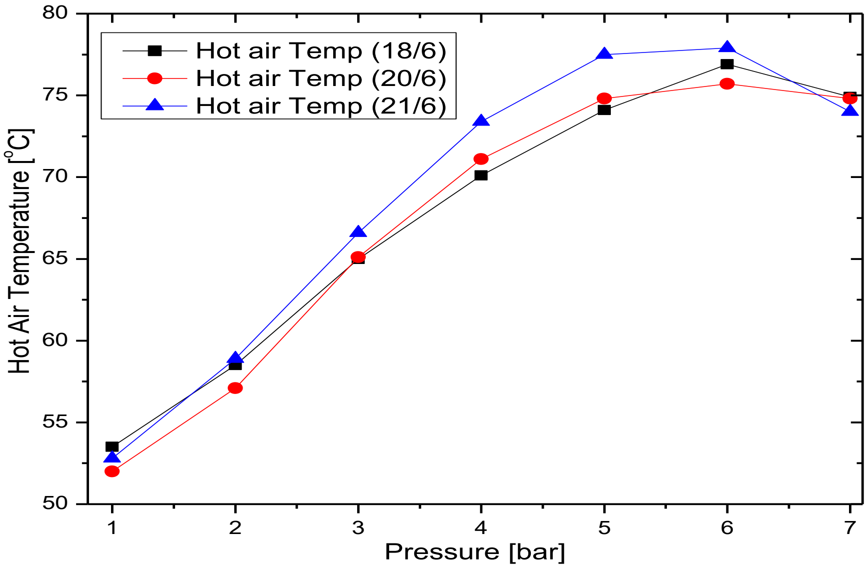

Fig. 11. Variation of hot air temperature with pressure.

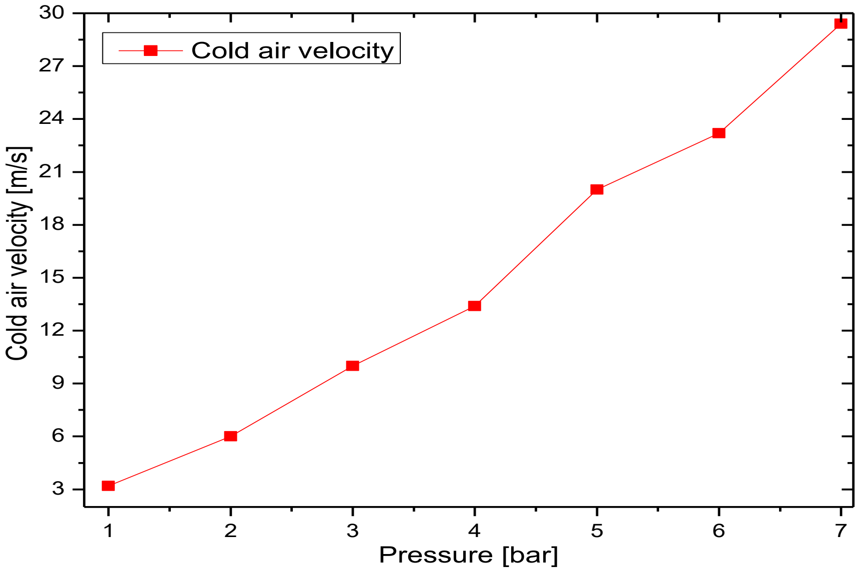

Fig. 12. Variation of cold air speed and pressure.

Figure 13 illustrates the relationship between the cooling load of the vortex canal and the inlet air pressure during the testing period. The data demonstrates a direct association, suggesting that higher inlet air pressure increases cooling capacity. For instance, on June 18th, the cooling load increases from 10 W at a pressure of 1 bar to 180 W at a pressure of 7 bar. The observed phenomenon can be attributed to the synergistic impact of both vortex intensity and low air temperature. Increasing the input pressure amplifies the generation of vortices inside the space of the vortex canal. Enhanced vortices provide a more effective division of the airflow into hot and cold portions, as depicted in Fig. 10. The hot air, which contains a substantial amount of thermal energy, is released outwardly. The colder air gathers in the middle and can be used for cooling. This enhanced separation process results in a reduction in the temperature of the outgoing cold air. The vortex tube can extract more heat from the ambiance by utilizing colder outgoing air, generating a higher cooling load. Nevertheless, it is essential to consider the possible disadvantages previously mentioned (see Figs. 9 and 11). Excessive pressure can cause air choking, which hinders the development of vortices and may decrease the cooling effect that can be achieved. Furthermore, increased hot air temperature at elevated pressures (as seen in Fig. 11) may require a larger capacity for disposing of the hot air stream.

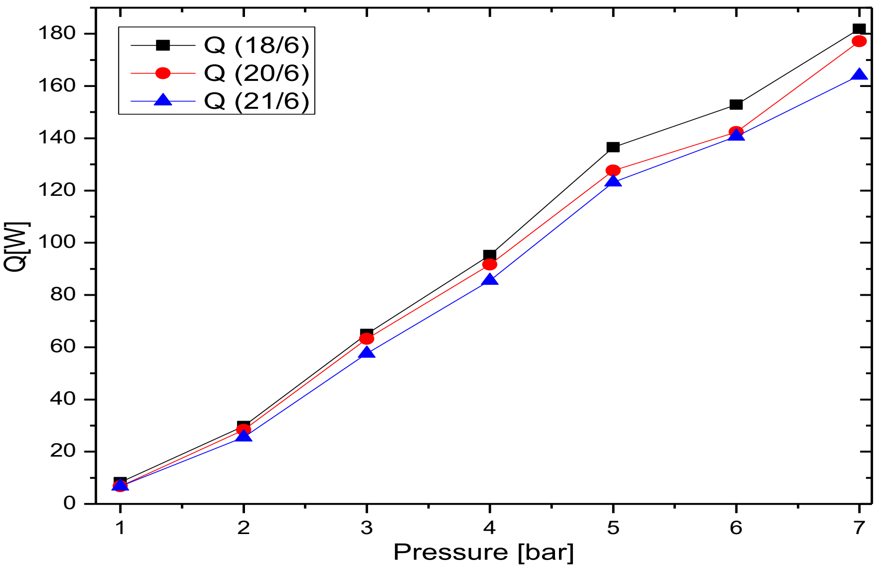

Fig. 13. Alteration of cooling load and pressure.

5. CONCLUSIONS

This study investigated the efficacy of a vortex canal unit in cooling electrical control panels, aiming to answer the demand for effective cooling solutions in industrial environments. This research focused on the utilization of a vortex tube for panel cooling, intending to maximize cooling efficiency. The primary finding of this study was the notable influence of inlet air pressure on the unit's efficiency and can be summaries as follows:

- The study determined that the best inlet air pressure is 4 bar, which leads to a COP of 0.12.
- An explicit relationship was established between the inlet air pressure and the cooling effect, where increased pressure resulted in improved cooling efficiency.
- The drop in cold air temperatures was seen as the inlet air pressure increased, eventually reaching a minimum negative value at the optimal pressure.
- The rise in inlet air pressure increased exit hot air temperatures, suggesting the occurrence of heat transfer within the system.
- The exit velocity of cold air exhibited a positive correlation with increasing inlet air pressure, illustrating the influence of pressure on the dynamics of airflow.

The effective utilization of a vortex tube system for regulating the temperature of control panels demonstrates a promising approach to improving energy efficiency and mitigating the environmental consequences of industrial processes. Future studies should prioritize refining the vortex tube configuration, examining its long-term dependability, exploring integrating intelligent control systems, assessing scalability, and evaluating its economic feasibility.

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