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Design, Fabrication and Performance Analysis of a Subsonic Open-Circuit Wind Tunnel

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ABSTRACT
A wind tunnel is a facility that is used to investigate and analyze the aerodynamic forces acting on objects. Therefore, the wind tunnel design is critical to its successful operation in order to provide an advantageous environment. In this work, an open-circuit subsonic wind tunnel was designed, fabricated and characteristics parameters were tested. The wind tunnel consists of test section (of 0.457 m × 0.457 m × 0.457 m, contraction part of length 0.635 m and contraction ratio of 7), and diffuser having a length of 0.762 m and diffuser ratio of 1.4. From the flow characteristics analysis of the wind tunnel, the maximum air velocity was found at the mid-section of the test chamber and zero at the wall, which confirms suitability of design and construction. Moreover, the performance of a heat exchanger was tested by placing a heat exchanger inside the test chamber where hot water was flowing through copper tubes and air streams flowing across the external surface. The results showed that the water flow rate, air flow rate, and inlet water temperature had an impact on heat transfer.

Keywords: Wind tunnel design, Test section, Performance analysis, Velocity profile, Heat transfer rate.

1. Introduction

The wind tunnel is a kind of device that can be used to control the flow stream of air. The main function of a typical wind tunnel is to produce a uniform air stream around the object of interest. As from previous century science and technology has been grown much enough to provide safe and more exact design process of wind tunnel, there is no reason to degrade the performance of a conventional wind tunnel.

Leonardo Da Vinci utilized the concept of wind tunnel after acknowledging that the object situated in airflow is similar to the object flowing through the air [1]. In 1871 Great Britain got the world's first wind tunnel by the hand of Francis Wenham [2]. When scientists realized the necessity of low turbulence in the test section, from then better designs were tried to be brought into reality.

Arifuzzaman and Masud [3] fabricated and tested a subsonic open-circuit wind tunnel with minimal cost having 0.9m × 1.35m (width × length) square test chamber, a contraction section of the length 0.35m having contraction ration (*CR*) of 8, a diffuser of the length (L_D) 3.7m having divergence angle within the range of 5-7°. Arslanian et al. [4] in their undergraduate research built a low-cost laboratory-scale open-circuit wind tunnel of 0.25 m × 0.125 m (length × diameter) test chamber, a maximum contraction diameter of 0.375m, and an overall length of 1.8105 m and an overall length of 1.8105 m. Tsien [5] made a theoretical approach to design a contraction for incompressible flow through which the velocity of the fluid increases monotonically from start to end. Mikhail [6] in his work focused mainly on the optimum length of the contraction duct. He investigated the required length and optimum duct shape for maintaining the flow uniformity in the test section. Morel [7] in his research aimed to provide sufficient and proper criteria for designing a conventional wind tunnel contraction cone. He took a numerical approach considering discreet *CRs* (such as 4, 6, 9), L/D (length-diameter ratio), etc. parameters to find proper charts and design criteria. Almeida et al. [8] in their research they facilitated a wind tunnel to gain 90 m/s air velocity in the test chamber to make it reliable for research covering the area of low-speed aerodynamics, fundamental fluid mechanics, and some other flow visualization. A complete process of design and construction has been amplified.

The heat exchanger is a fundamental component that is utilized in many industrial operations involving heat transfer for thermal systems. It is crucial to examine the heat transfer rate, which is usually limited and varied for different operating conditions. Wen et al. [9] found that the heat transfer coefficient increases with the increasing of air flow rate as well as water flow rate. Karimzadehkhouei et al. [10] numerically investigate the rise of water inlet temperature increases the heat transfer rate, because a higher inlet temperature has a higher thermal entry length. Hu et al. [11] found that an increase in internal water flow rate more rapidly reduced the water outlet temperature but heat transfer rate increased. Therefore, a wind tunnel is very essential laboratory equipment for research purpose as well as for student's laboratory work related to fluid flow and heat transfer analysis. Due to the limitation of allocated budget, attention was paid for construction a wind tunnel locally by expense of minimum money in the department of Energy Science and Engineering (ESE) for general purposes of uses. The wind tunnel was fabricated using material collected from local market in Khulna city, Bangladesh. Furthermore, the heat exchanger performance test was done for the extension of the wind tunnel construction and performance.

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2. Design Methodology

Generally, a typical wind tunnel has certain segments including the settling chamber, contraction part, test chamber, diffuser part, etc. Description of each part and several considerations to design a wind tunnel are given below.

2.1 Test Chamber

The size of the test section must be determined by the wind tunnel's main application, including operating speed and desired flow quality. A square cross section is recommended for civil and industrial applications. [12] For this case, an 0.457 m width square cross-section test section has been chosen optimally. The length of the test chamber has to be 0.5 to 3 times its hydraulic diameter [13]. Hereby, the length has been selected as 1 time the hydraulic diameter which is 0.457 m. This length has to be maintained as small as possible, as the pressure loss coefficient starts to increase with the increase of the test section length.

2.2 Wind tunnel contraction

According to previous research work, *CR* need to be within the range of 6 to 10 for small-scale low speed wind tunnels [12]. In addition, with that range the cross-sectional area of the test section needs to be below 0.5 m^2 and velocity of the free stream need to be below 40 m/s [14]. Considering these factors *CR* = 7 has been chosen. Design parameters such as length, wall curvature profile and Reynolds number decides the overall performance of the tunnel [15]. However, flow separation occurs at the exit while having too long contraction length. In case of too short contraction length boundary layer separation occurs close to the inlet. Fifth order polynomial defined curve fulfils most of the requirements by providing minimum and the flow separation happens when contraction length/contraction intel height (L_C/H_i) goes beyond the range of 0.667 to 1.79 [14]. For our case minimum ratio leads to a contraction length of 0.813 m. The contraction profile in figure 1 has been found out.

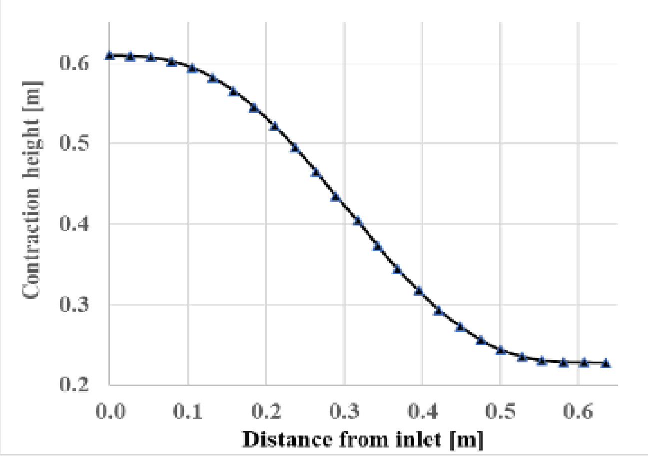

Fig. 1 Contraction profile of the fabricated wind tunnel.

2.3 Wind tunnel diffuser

The diffuser serves as the connection between the fan section the test section. The purpose is to lessen the velocity and convert it to an optimum exit pressure by using the smallest diffuser length possible. Already 0.61 m diameter of the fan and the 0.457 m × 0.457 m square inlet section of the diffuser are fixed. These led to diffuser area ratio (A_R) = 1.4 which satisfies the condition of below 2.5 area ratio. Again, the diffuser angle ($a_{1/2}$) has to be within the range of 5˚ – 7˚ [16]. The minimum diffuser length can be obtained from the following equation,

$$a_{1/2} = arc\ tan \frac{(\sqrt{A_R}-1)}{2\ L_D/D_h} \quad (1)$$

From this equation, L_D = 0.762 m leads to $a_{1/2}$=3.15˚ which is within the conditional range (5˚ – 7˚).

2.4 Honeycomb

In case of honeycomb design, there are key parameters that need to be considered e.g., length (L_h), cell hydraulic diameter (D_h), and the porosity (β_h). The ratio of exact flow area to the total cross-sectional area can be defined as porosity.

$$\beta_h = \frac{A_{flow}}{A_{total}} \quad (2)$$

There are two main criteria for honeycomb design and these are $6 \leq \frac{L_h}{D_h} \leq 8$ and $\beta_h \leq 0.8$. [17] For optimum design condition these criteria should be maintained and also it is considered to be convenient to have about 150 cells per settling chamber diameter.

2.5 Screens

Screen porosity need to be within 0.58 to 0.8 to obtain an efficient operation where values lower than 0.58 could result in instability. [18] It's convenient to install screens on a removable frame for cleaning and maintenance easily. Screen porosity can be calculated by the following equation,

$$\beta_s = \frac{A_{flow}}{A_{total}} \quad (3)$$

Ratio of mesh wire number (n_w) and cross section side of the chamber can be defined as screen mesh density,

$$\rho_m = \frac{n_w}{l} \quad (4)$$

Screen mesh divisions (w_m) can be indicated as,

$$w_m = \frac{1}{\rho_m} \quad (5)$$

Porosity can also be expressed in terms of mesh density,

$$\beta_s = (1 - d_w\, \rho_m)^2 \tag{6}$$

The selected measurement of the wind tunnel after considering the design criteria is given below,

• Open circuit wind tunnel.
• Square inlet sections of contraction and testing chamber.
• *CR* 7.
• 0.457 m wide test section.
• Fan inlet diameter 0.61 m.

3. Fabrication

The parts of the designed wind tunnel namely contraction, diffuser, test section, fan blower, or total wind tunnel assembly supporting structure were made with the materials and services available in the local market.

An open-circuit, subsonic type laboratory-scale wind tunnel with a total length of 2.34 meter was fabricated. Table 1 shows the specifications of the fabricated wind tunnel and figure 2 shows the total wind tunnel assembly.

Table 1 Specifications of the fabricated wind tunnel

Parts	Specification	Material
Contraction	Inlet: 1.22 m x 1.22 m outlet: 0.457 m x 0.457 m CR: 8; L_C: 0.635 Contraction profile: fifth-degree polynomial	Stainless Steel sheet
Test Chamber	Height: Width: Length = 0.457 m : 0.457 m : 0.457 m	Acrylic sheet
Diffuser	Inlet: 0.457 m x 0.457 m Outlet circular diameter: 0.61 m L_D: 0.762 m	Stainless Steel sheet
Flexible Connection	Circular inlet and outlet: 0.61 m	Flat rubber-gasket
Blower	Motor: Phase – 3 phase Voltage- 380-440 V Maximum current- 5.16 A Frequency – 50 Hz Capacity – 3 HP Maximum speed- 1430 rpm Connection – Y Weight: 31 Kg Propeller: No of blade -10 Blade arrangement: Inclined	–
support	–	Cast iron angle-bars

4 Experimental Setup

In this work, a fin and tube heat exchanger was placed in the wind tunnel. Heat transferred between the hot water flowing within the tube and the ambient air moving cross-section to the tube panel. The airflow rate across the heat exchanger varied from 1.66 kg/s to 2.88 kg/s and was measured by a pitot tube with a micro manometer having ±1% accuracy. The water flow rate also varied from 0.01207 kg/s to 0.0238 kg/s. water velocity was measured using Arduino based water flow meter of ±10% accuracy.

Water inlet temperature varied using water bath from 38.1℃ to 55.7 ℃ with ±2% accuracy when the ambient air temperature was kept at almost 30℃. K-type thermocouple was used to measure the water and air temperature with 0.75% accuracy.

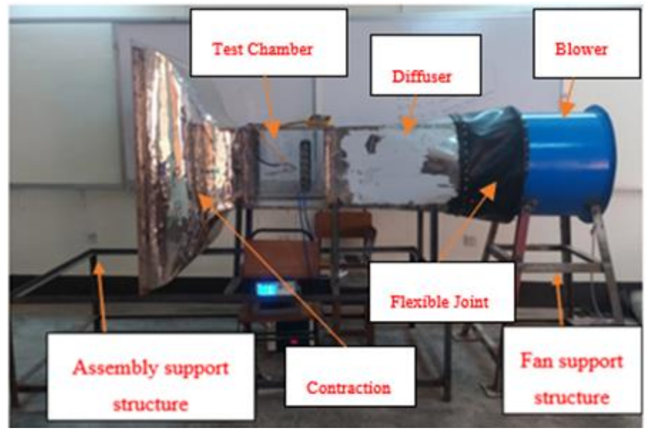

Fig. 2 Total wind tunnel assembly.

5. Data Reduction

For force convection, the tube side and air-side heat transfer of fin and tube heat exchanger would be calculated, Water heat loss,

$$Q_w = m_w \times C_{pw} \times \Delta T_w \tag{7}$$

Air heat gain,

$$Q_a = m_a \times C_{pa} \times \Delta T_a \tag{8}$$

Where, Q_w water heat loss, Q_a air heat gain, m_w water flow rate, m_a air flow rate, and C_{pa} specific heat of air and water respectively, ΔT_w temperature difference between the water inlet and outlet, ΔT_a temperature difference between air outlet and inlet. Average heat transfer (Q) can be expressed as,

$$Q = 0.5(Q_w + Q_a) \tag{9}$$

The relation between heat transfer rate and overall heat transfer coefficient of the heat exchanger is,

$$Q = U \times A_s \times \Delta T_{LMTD} \tag{10}$$

Where, U is the overall heat transfer coefficient, A_s is the surface area and ΔT_{LMTD} is the log mean temperature that could be calculated from,

$$\Delta T_{LMTD} = \frac{(T_{w,i}-T_{a,o})-(T_{w,o}-T_{a,i})}{\ln\left(\frac{T_{w,i}-T_{a,o}}{T_{w,o}-T_{a/i}}\right)} \tag{11}$$

Where, $T_{w,I}$ and $T_{w,o}$ are water inlet and outlet temperature, $T_{a,i}$ and $T_{a,o}$ are the air inlet and outlet temperature.
The effectiveness could be calculated by using this equation,

$$\varepsilon = \frac{C_h \times (T_{h,i}-T_{h,o})}{C_{min}(T_{h,i}-T_{c,i})} \tag{12}$$

Where, C_h heat capacity of hot fluid and C_{min} is the lowest heat capacity between hot and cold fluid.

6. Result and Discussion

6.1 Flow Characteristics

A hole was drilled into the edge of the test chamber. Pitot tube was inserted to the test chamber through the hole and the value of the blowing wind was measured at different positions of the chamber. Figure 3 illustrates different position of pitot tube in the test chamber. A set of data was collected from different positions of the test chamber along the horizontal axis by varying motor speeds of the blower from 715 rpm to 1430 rpm to observe the velocity profile of air into the test chamber. Figure 4 was plotted from the collected data.

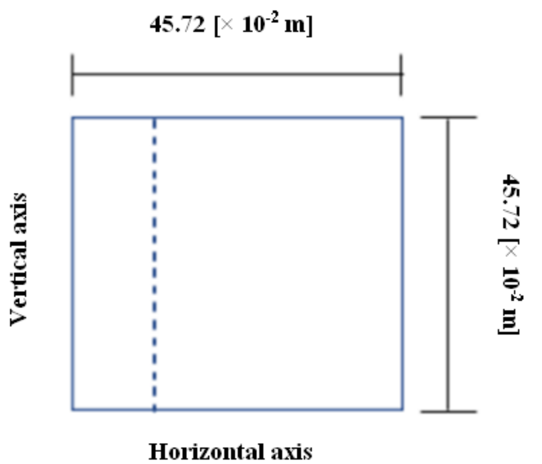

Fig. 3 Different positions of the test chamber.

It depicts the relationship between air velocity and various positions of test chamber along the horizontal axis, and the change in air velocity as a function of motor speed. It can be seen that adjacent layer of the wall slow down the velocity of air as a result of shear stress or friction. To overcome the velocity deduction, the velocity of the mid-section of the test chamber was increased to maintain a constant mass flow rate. As a result, a velocity gradient was occurred.
The velocity of air at different positions along the vertical axis of the test chamber for different motor speed of the blower was also observed and figure 5 is plotted by using the observed data. Figure 5 depicts that viscous effect and shear stress between the adjacent layer of the wall cause boundary layer and this type of result is obtained.

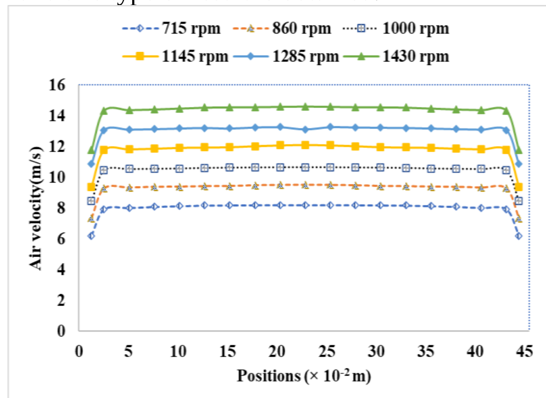

Fig. 4 Air velocity at different position of the test chamber for different motor speed. (Horizontal Axis).

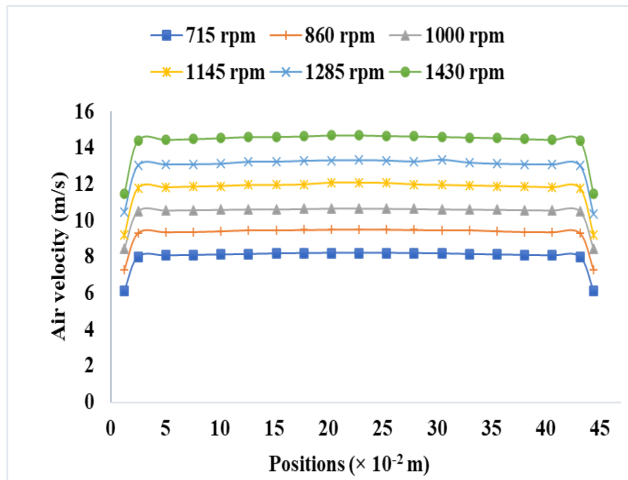

Fig. 5 Air velocity at different position of the test chamber for different motor speed. (Vertical Axis)

6.2 Performance Test of Heat Exchanger

The performance of the heat exchanger was determined for different operating conditions such as variation of air flow, variation of water inlet temperature and variation of water flow rate. The effect of factors on heat transfer are described below.

6.2.1 Effect of air flow rate

Air flow rate was varied from 1.66 kg/s to 2.88 kg/s and it observed that the heat transfer between the water and air was changing with respect to air flow rate. Figure 6 depicts the relationship between heat transfer rate and air outlet temperature as a function of air velocity. The heat loss of water which flowing at constant speed of 0.02 kg/s though the tube, losses more heat since air flow rate was increased.

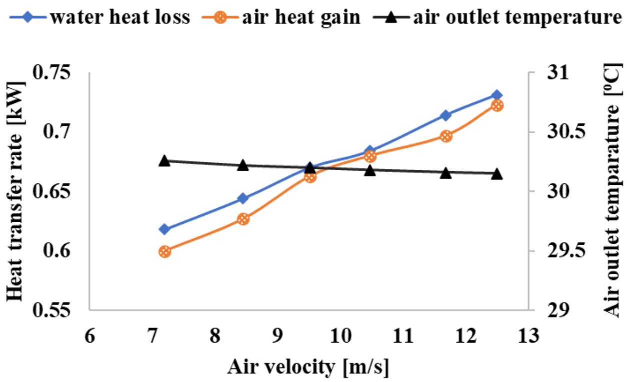

Fig.6 Variation of heat transfer rate and air outlet temperature for varying air velocity at water flow rate of 0.02 kg/s.

From figure 6, it can be seen, when air speed was increasing then outlet temperature of air decreased because the air got less time to contact with hot water. Figure 7 shows the effect of air velocity on the overall heat transfer coefficient and effectiveness of heat exchanger as well as indicates that the effectiveness of heat exchanger was increasing with the rise of air velocity. At a water flow rate of 0.02 kg/s and water inlet temperature maximum effectiveness was found 57.54. In this boundary conditions the effectiveness of the heat exchanger could be higher, but this did not happen due to bad condition of the compact heat exchanger. Besides air leakage might be a cause of lower effectiveness.

6.2.2 Effect of inlet temperature

By adjusting the water bath's temperature, the effect of water inlet temperature was observed. Figure 8 depicts the relationship between the temperature of the air outlet and the heat transfer rate as a function of the temperature of the water inlet. Since the temperature of the flowing water raised, the amount of heat transfers between air and water increased. Due to constant airflow the air outlet temperature of air enhanced with increasing of water inlet temperature.

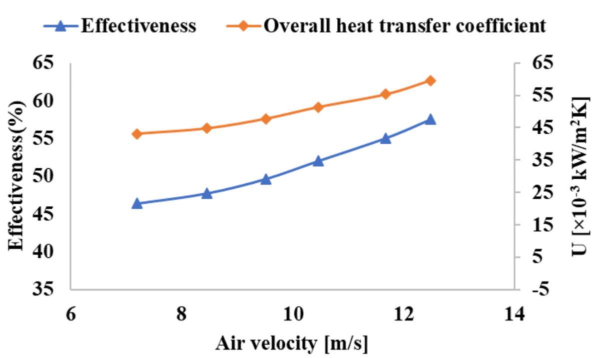

Fig.7 Variation of effectiveness and overall heat transfer coefficient for varying air velocity at water flow rate of 0.02 kg/s.

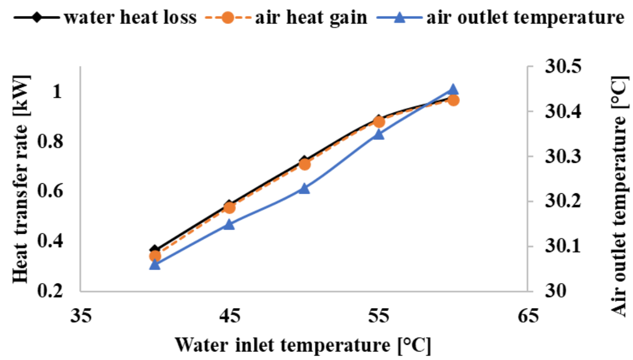

Fig.8 Variation of heat transfer rate and air outlet temperature with water inlet temperature at water flow rate of 0.02 kg/s and air flow rate of 2.14 kg/s.

In that study, the inlet temperature was changed from 38.1 °C to 55.7 °C, and the highest heat transfer rate was attained at 55.7 °C with a value of 0.975 kW. The water flow rate was 0.02 kg/s and the air flow rate was 2.14 kg/s. According to conservation of energy, the heat loss of water and heat gain of air should be equal, but it did not happen due to air leakage through the test chamber

6.2.3 Effect of water flow rate on heat transfer

Varying the water flow rate set of data was collected. Using the collected data figure 9 is plotted. During this process, airflow rate was at 2.13 kg/s and the inlet temperature of the water was kept around 47.5℃. Figure 9 illustrates the change of heat transfer rate and water outlet temperature with the variation of flow rate of water as well as it can be said that heat transfer rate increases with rises of water flow rate. It almost a linear curve but some deflection occurs at some point this may happen due to air leakage of test chamber as well as ambient conditions affecting the performance of heat exchanger. This figure also shows that with the higher of water flow rate the temperature of the water outlet increases because water got less time to reject heat to the surroundings.

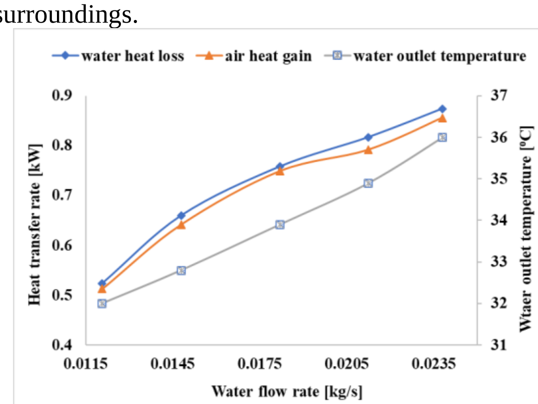

Fig.9 Variations of heat transfer rate and water outlet temperature with the change of water flow rate at an air flow rate of 2.13 kg/s.

7. Conclusion

In this work, a laboratory-scale, open circuit and subsonic wind tunnel was designed and fabricated for dept. of ESE, KUET. 0.457 m × 0.457 m × 0.457 m test chamber was chosen for designing the wind tunnel. Based on this the other parts of the wind tunnel had been designed and fabricated. It had been tried to synchronize the spatial limitation by optimizing the size and shape of the contraction and diffuser duct. Air velocity at the different point of the test chamber was measured at different speed of blower. When the blower air speed was increased the velocity difference between the mid-section and boundary wall was increased. The air velocity at the mid-section of the wind tunnel was maximum. The impact of air flow rate, water flow rate and inlet temperature of water on heat transfer between water and air were observed. It showed that hear transfer rate was increasing with the change of airflow rate, water flow rate as well as inlet water temperature. But it could say from work, air flow rate was more impactful than the other factor in this set up. The following conclusions may be drawn from the experimental findings:

- The maximum velocity of air 14.62 m/s was found at the 22.86 cm depth of the test chamber at 1430 rpm of the motor.
- For a water flow rate of 0.02 kg/s and an air flow rate of 2.14 kg/s, the maximum heat transfer rate of 0.967 kW was found within the experimental limit.
- The maximum effectiveness 57.54 % was found

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