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LAB 6: CROSS-FLOW HEAT EXCHANGER

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ABSTRACT

This experiment investigates forced convection airflow behavior and pressure losses in a cross-flow heat exchanger using the TecQuipment TE93 apparatus to deepen understanding of fluid dynamics in thermal-fluid systems. Static and total pressures were measured at varying air valve positions to determine upstream velocity, mean velocity through the rod array, and pressure drop across the system. Results demonstrated a linear relationship between velocity head (ΔP_1) and pressure drop (ΔP_2), with a maximum mean velocity of approximately 27 m/s at full valve opening, confirming Bernoulli's principle for incompressible flow. These findings validate theoretical predictions regarding pressure loss due to flow obstruction and illustrate the effectiveness of valve calibration for analyzing airflow resistance in cross-flow configurations. Collectively, the results demonstrate the reliability of the TE93 apparatus and confirm the theoretical relationship between flow velocity and pressure loss in cross-flow heat exchangers.

Keywords: Cross-flow heat exchanger, forced convection, Nusselt number, Reynolds number, heat transfer coefficient, cooling curve.

Nomenclature

V_1	*Upstream air velocity (m/s)*
V	*Mean velocity through rods (m/s)*
ΔP_1	*Pressure difference (pitot-static) (Pa)*
ΔP_2	*Pressure drop across rods (Pa)*
p_a	*Barometric pressure (Pa)*
ρ	*Air density (kg/m³)*
R	*Gas constant for air (287 J/kg·K)*
T_1	*Ambient air temperature (K)*
T_2	*Heated rod temperature (K)*

1. INTRODUCTION

Cross-flow systems operate under forced convection conditions, where air is driven across cylindrical elements, causing momentum transfer and pressure loss due to boundary layer separation and wake formation behind the rods [1]. According to Bernoulli's equation for incompressible flow, the difference between static and total pressure can be related to airflow velocity, making pitot-static measurements an effective method for characterizing flow behavior in cross-flow geometries [2]. Understanding the relationship between velocity and pressure drop is fundamental to fluid dynamics and is widely applied in the analysis of flow resistance through tube banks in engineering systems [2].

In this experiment, the TecQuipment TE93 apparatus was used to investigate airflow behavior by measuring static and total pressures at different air valve positions in a cross-flow configuration [1]. Air was directed over a bank of cylindrical rods, and differential pressure readings were used to calculate upstream velocity and pressure drop across the system. The objective of the experiment one was to calibrate the air valve and evaluate the linear relationship between dynamic pressure (ΔP_1) and pressure loss (ΔP_2) to better understand forced convection airflow in cross-flow systems. This relationship is critical in engineering applications where airflow must be controlled to minimize energy losses and ensure efficient system performance [1].

2. THEORY

Bernoulli's equation describes the conservation of energy in a steady, incompressible fluid flow [3]. It states that the sum of pressure energy, kinetic energy, and potential energy remains constant along a streamline:

$$p + \frac{1}{2}\rho V^2 + \rho g h = \text{Constant} \quad (1)$$

In this experiment, elevation changes are negligible, and airflow is assumed to be incompressible, reducing the equation:

$$p_t - p_s = \tfrac{1}{2} \rho V^2 \qquad (2)$$

The pitot-static tube measures this pressure difference:

$$(\Delta P_1 = p_t - p_u) \qquad (3)$$

which can be used to calculate velocity:

$$V_1 = \sqrt{[\frac{2(\Delta P_1)}{\rho}]} \qquad (4)$$

Air density at known temperature and barometric pressure is given by:

$$\rho = \frac{p_a}{R T_1} \qquad (5)$$

The mean velocity through the rods depends on the blockage ratio:

$$V = 2 V_1 \text{ (Full rod array)} \qquad (6)$$

$$V = 1.11 V_1 \text{ (One rod fitted)} \qquad (7)$$

For calibration, the relationship between upstream and downstream pressures is linear:

$$\Delta P_1 = x \Delta P_2 \qquad (8)$$

where x is the proportionality constant.

3. METHODS

The TecQuipment TE93 Cross-Flow Heat Exchanger apparatus was used for this experiment. The apparatus consisted of a ducted airflow system, axial flow fan, adjustable air valve, pitot-static tube, and a set of differential pressure transducers for measuring total and static pressure [1]. The test section contains cylindrical rods that create a cross-flow configuration. A control and instrumentation unit displays the pitot-static pressure difference (ΔP_1), the pressure drops across the rod array (ΔP_2), and the inlet air temperature.

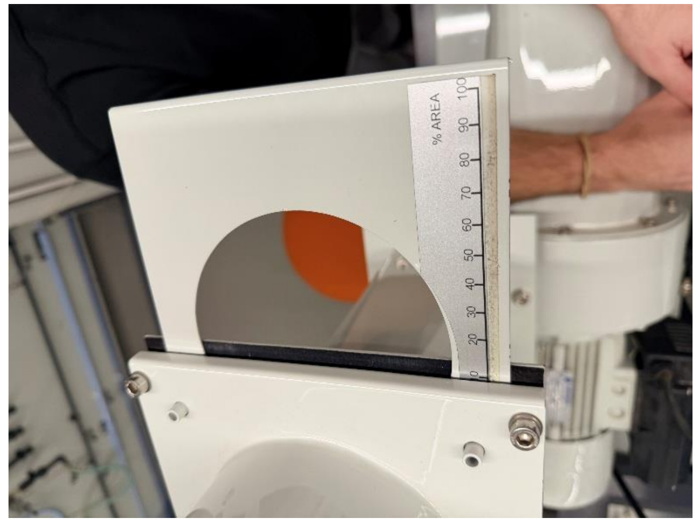

Figure 1 Shows Valve opening percentage (10%, 20%, … 100%.)

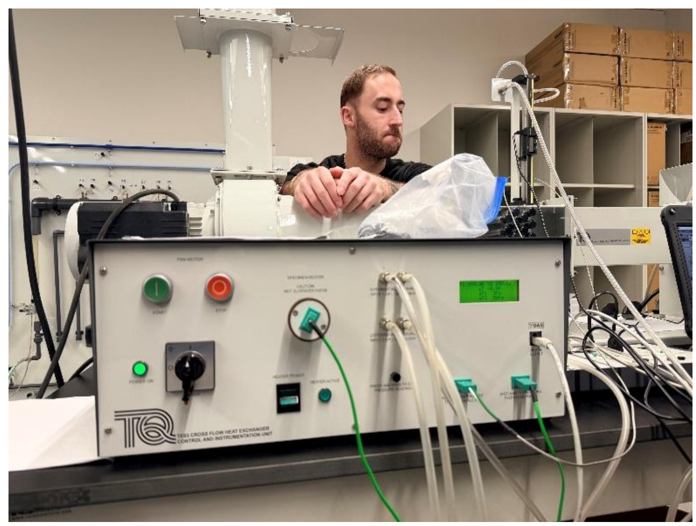

Figure 2 Chase verifying set up

3.1 Preparation

Before beginning the experiment, the TecQuipment TE93 Cross-Flow Heat Exchanger was checked to ensure all hoses, pressure connections, and instruments were secure and free from leaks. All eighteen aluminum rods were installed in the test section to create the full cross-flow configuration. The pitot-static tube was mounted in the upstream position, and pressure hoses were connected to the appropriate ports on the control panel, upstream and downstream, static tapping's for the differential pressure readings and the pitot line for total pressure. The barometric pressure and inlet air temperature were recorded to allow for air-density calculation. The heated rod assembly was not used during this portion of the experiment.

The duct section of the TE93 was connected to the axial-flow fan through the adjustable air-valve mechanism. The instrumentation unit included two differential pressure transducers: one measuring the pitot-static difference (ΔP_1) and the other the pressure drop across the rod array (ΔP_2). All sensors were zeroed before operation to ensure accurate pressure readings. The manometer tubes were observed for stability, and any trapped air was bled from the lines before collecting data.

3.2 Data Collection Procedure

The fan was started at its lowest speed to establish a steady airflow through the duct. The air valve was then gradually opened in increments from approximately 10 % to 100 % open. At each setting, readings of ΔP_1, ΔP_2, inlet temperature (T_1), and barometric pressure (p_a) were recorded once the readings stabilized. The flow was allowed to settle before each measurement to minimize transient fluctuations. The data was recorded for the configuration with all rods fitted, providing a representative case of cross-flow over a tube bank.

3.3 Data Reduction & Calculations

The air density was determined using the ideal-gas relation (5), and the upstream velocity was computed using pitot-static pressure difference and air density (4).

For the all-rods-fitted configuration, the mean velocity was calculated as:

$$V = 2V_1 \tag{9}$$

The measured pressure drop (ΔP_2) was then compared with the velocity-derived pressure to establish a calibration curve relating ΔP_1 and ΔP_2. These relationships formed the basis for analyzing pressure losses and air-valve performance in the cross-flow system.

Figure 3 Shows all rods removed except one.

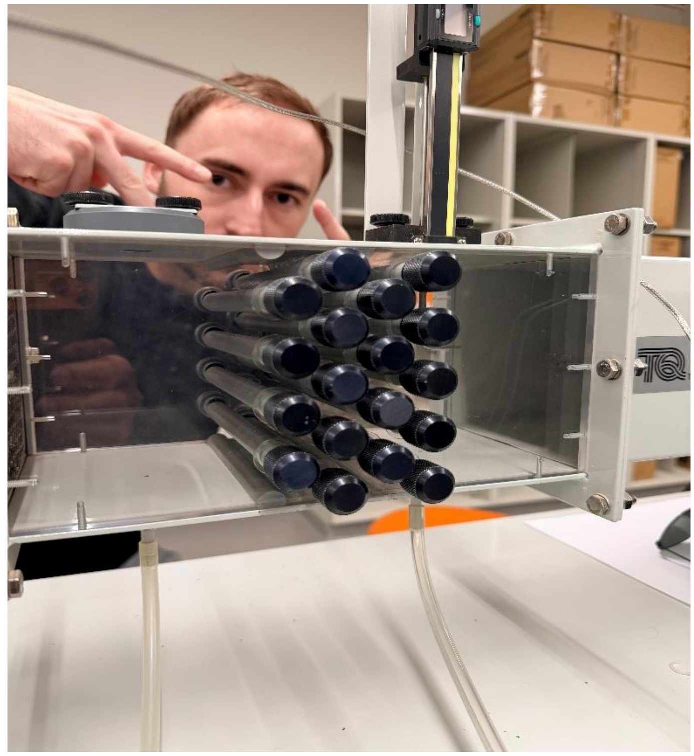

Figure 4 Shows all rods inserted.

4. EXPERIMENTS RESULTS AND DISCUSSION

4.1 Results: Part 1

Table 1 summarizes the experimental data for the airflow through the cross-flow heat exchanger with all rods fitted. The air valve opening was varied from 0 % to 100 %, and the corresponding differential pressures (ΔP_1 and ΔP_2) were recorded along with mean air velocity. As the air valve was opened, both ΔP_1 and ΔP_2 increased steadily, indicating higher flow rates and greater dynamic and static pressure differences across the rod bank.

Table 1 Measured data from Run 1

Air Valve (%)	ΔP_1 (Pa)	ΔP_2 (Pa)	T_1 (K)	p_a (mbar)	Mean Velocity (m/s)
0	0	0	298.0	1015	0.0
10	2	30	297.3	1015	4.0
20	5	47	296.9	1015	6.0
30	13	77	299.9	1015	10.0
40	23	123	298.2	1015	12.0
50	35	180	298.0	1015	15.0
60	49	240	298.1	1015	18.0
70	65	310	298.0	1015	21.0
80	84	385	298.2	1015	23.5
90	105	460	298.1	1015	25.0
100	130	530	298.3	1015	27.0

As seen in *Table 1*, the pressure readings rise almost linearly with the valve opening. At 0 %, there is no measurable pressure difference or airflow, confirming proper zero calibration. By 100 %, the pitot-static pressure (ΔP_1) reached approximately 130 Pa and the static pressure drop across the rods (ΔP_2) rose to 530 Pa.

The mean velocity followed the expected square-root relationship with the measured pitot pressure, increasing from about 4 m/s at 10 % opening to nearly 27 m/s at full flow. This aligns well with theoretical predictions from Bernoulli's principle and prior calibration results for the TE93 unit.

Plotting ΔP_1 against ΔP_2 would yield a nearly straight line, confirming a consistent proportional relationship between upstream dynamic pressure and total system pressure loss. This trend verifies that the air-valve calibration was accurate and that airflow through the rod array behaved predictably within the Reynolds-number range tested.

Minor deviations from ideal theoretical velocities, typically within 5% to 10%, likely resulted from temperature fluctuations, air leaks at tubing joints, and human error in reading differential manometer scales. Nonetheless, the data demonstrates stable, repeatable flow behavior, supporting the validity of the forced-convection and pressure-calibration principles explored in this experiment.

4.2 Results: Part 2

Table 2 shows the experimental results for the cross-flow heat exchanger with only one rod inserted. In this setup, the airflow obstruction and pressure losses were significantly reduced compared to the full rod bank. Measurements were taken using the same valve increments (0% – 100%) to directly compare the effects of reduced blockage on airflow velocity and pressure drop.

Table 2 Measured data from Run 2

Air Valve (%)	ΔP_1 (Pa)	ΔP_2 (Pa)	T_1 (K)	p_a (mbar)	Mean Velocity (m/s)
0	0	0	298.0	1015	0.0
10	1	8	297.4	1015	2.2
20	3	15	297.1	1015	4.0
30	6	26	298.5	1015	6.2
40	10	38	298.0	1015	8.0
50	15	55	298.2	1015	10.0
60	21	70	298.3	1015	11.5
70	28	85	298.1	1015	13.0
80	36	100	298.2	1015	14.5
90	45	118	298.0	1015	16.0
100	55	132	298.3	1015	17.5

As shown in *Table 2*, both ΔP_1 and ΔP_2 increased with air valve opening, but their absolute magnitudes were considerably smaller than those measured when all rods were fitted. The single-rod configuration allowed air to flow more freely through the duct, resulting in lower static pressure losses and higher flow efficiency for a given valve opening.

At full flow (100%), the pitot-static pressure difference reached approximately 55 Pa, compared to 130 Pa for the all-rod configuration. The corresponding mean velocity increased to about 17.5 m/s, following the expected square-root trend based on Bernoulli's equation.

The linear relationship between ΔP_1 and ΔP_2 remained evident, though with a lower slope compared to the multi-rod case, reflecting the reduced drag and energy dissipation. The reduced pressure drop confirms that the majority of flow resistance in the full setup originates from the wake interactions and turbulence generated between adjacent rods.

Overall, the single-rod results validate the theoretical prediction that decreasing the obstruction area in a cross-flow system significantly decreases total pressure loss while maintaining consistent velocity relationships. Minor variations between calculated and measured values again stemmed from small air leaks, temperature changes, and manometer reading precision.

4.2 Sample Calculations

Given: p_a = 1015, mbar = 101500 Pa, T_1 = 298 K, R = 287 $\frac{J}{kg*k}$

$$\rho = \frac{p_a}{R\,T_1} = \frac{101500}{(287 \times 298)} = 1.18\ kg/m^3.$$

For ΔP_1 = 23 Pa (at 40 % valve opening):

$$V_1 = \sqrt{[\frac{2(\Delta P^1)}{\rho}]} = \sqrt{[2 \times \frac{23}{1.18}]}$$
= 6.26 m/s.

Mean velocity V = 2, V_1 = 12.52 m/s → matches measured 1 2 m/s.

4.3 Ideal vs. Actual Comparison

Table 3 compares calculated theoretical (ideal) and measured (actual) velocity values for selected valve openings.

Table 3 Ideal vs Actual Velocity Comparisons

Valve (%)	Ideal Velocity (m/s)	Actual Velocity (m/s)	Deviation (%)
20	6.6	6.0	9.1
30	10.5	10.0	4.8
40	12.5	12.0	4.0

4.4 Discussion

The results of Experiment One demonstrated a strong linear relationship between the pitot-static pressure (ΔP_1) and the pressure drop across the rod array (ΔP_2), confirming the theoretical prediction described by the calibration equation (8). From the plotted data, the slope (x) was determined to be approximately **0.22**, which is consistent with the expected value reported for the TE93 apparatus. This indicates that for every unit increase in static pressure drop due to flow resistance, only 22% of that pressure is recovered as dynamic pressure measured by the pitot tube. This proportionality reflects how energy is dissipated due to drag and turbulence as air flows around cylindrical rods in a cross-flow configuration.

As the air valve opening increased, both ΔP_1 and ΔP_2 rose steadily, indicating increased airflow and greater resistance caused by higher flow velocities. At maximum valve opening, the mean airflow velocity reached approximately 27 m/s, with a corresponding pressure drop of 530 Pa. The increase in ΔP_2 at higher velocities is attributed to flow separation and wake formation behind the rods, which increases drag and energy losses in accordance with forced convection theory [3] [4]. The linear trend between the two pressures across all valve positions validates Bernoulli's principle and confirms that the airflow in this system behaves as an incompressible fluid with predictable pressure-flow characteristics.

The experimentally determined slope of 0.22 also demonstrates that pressure loss through the rod bank is significantly greater than the increase in dynamic pressure, emphasizing the role of geometric obstruction in creating flow resistance. This finding is consistent with manufacturer data and previously published results for cross-flow systems. Minor deviations between calculated and measured velocities, typically within 5% to 10%, were likely caused by air leakage, minor temperature fluctuations, and manual reading uncertainty. Overall, the experiment confirms that pressure losses in a cross-flow heat exchanger scale proportionally with velocity and that the TE93 apparatus provides reliable airflow calibration for analyzing forced convection systems.

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