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Experimental Study of Thermal Performance of Air-Cooled Cross-Flow Heat Exchanger

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***Abstract* - This study aims to evaluate the effect of variations in Re_D and heating power on the thermal characteristics of a tube bundle. Tests were conducted using a test model with a channel cross-section of 150 mm × 150 mm and a length of 1540 mm, equipped with an air-driven fan and heating elements with varying power of 10 W, 20 W, and 30 W. The main parameters analyzed were the convection heat transfer coefficient (h) and the Nusselt number (Nu) as a function of Re_D and P. The results showed that increasing Re_D significantly increased h and Nu at all power levels, especially at high Re_D which produced maximum heat transfer due to the strengthening of turbulence effects. Increasing heating power also contributed to the increase in h and Nu, but the effect of Re_D was more dominant on the thermal performance of the system. The combination of high flow rates and large heating power was proven to maximize heat transfer efficiency in the tube bundle configuration.**

Keywords: heat exchanger, tube bundle, Reynolds number, Nusselt number, heat transfer coefficient.

I. INTRODUCTION

Heat exchangers play a vital role in various thermal systems such as power generation, air conditioning, and electronic cooling, and with the increasing energy demand, improving the efficiency of heat exchangers has become a priority [1]. In various applications, tube bank heat exchangers are the most widely used and they represent the largest market share of heat exchangers [2][3]. Tube bank heat exchangers are widely used in various industrial fields due to their high effectiveness and simplicity [4]. Improvement of heat exchanger performance can be achieved through optimizing the tube configuration which affects the fluid flow pattern and heat transfer coefficient [5].

Flow conditions within a tube bank are dominated by boundary layer phenomena, including turbulence, flow separation, and wake interaction, which influence convective heat transfer [6]. Furthermore, the Reynolds number plays a crucial role in heat exchanger design [7]. Turbulent flow is often used to enhance heat transfer. A high Reynolds number (Re) can improve efficiency, although it can also increase friction, which can increase system load [8].

Research by Shih [9] discusses the importance of tube spacing in a heat exchanger. Results show that closer tube spacing can enhance heat transfer. Research by Wang [10] concludes that more complex tube configurations can improve heat transfer but increase pressure losses in the system. Another study by Yang [11] discusses the effects of transverse and longitudinal tube arrangements on improving heat transfer performance and reducing energy consumption in a heat exchanger. In a study by Kumar [12], an experimental evaluation of various tube configurations was conducted to understand their importance in maximizing heat transfer rates in a heat exchanger under low-pressure conditions.

The shape of the tube can affect the heat transfer coefficient performance. Research by Zhang [13] showed that the use of helical tubes can increase flow turbulence, which can increase the heat transfer rate. However, this is often accompanied by increased pressure losses. Meanwhile, research by Kumar [14] showed that the use of tubes with spiral wires can significantly increase the heat transfer coefficient in low-turbulent flows. Furthermore, research by Ibrahim [15] showed that a combination of different tube configurations, such as flat and curved tubes, can increase the effectiveness of a heat exchanger under various operating conditions. Saini [16] in this study stated that heat exchanger with non-cylindrical tube configurations such as multi-fin tubes can increase thermal efficiency in industrial cooling applications.

This study aims to test various tube bundle models as a representation of the tube model of a heat exchanger with a Re factor and heating power. Test data were measured in an open-circuit wind tunnel as an air mover for the cooling medium.

II. METHODOLOGY

2.1 Test Model

This study uses a tube bundle test model as shown in Figure 1. The heating elements used in this test equipment are arranged in several configurations. The tube bundle

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arrangement in this experiment is specifically designed to represent the real conditions in heat exchanger equipment. This arrangement consists of several tubes arranged regularly in a certain pattern to influence the air flow pattern and heat transfer characteristics that occur. The arrangement and placement of the tubes in this configuration are shown in Figure 2. This serves as the main reference in the implementation of testing and thermal performance analysis in this study.

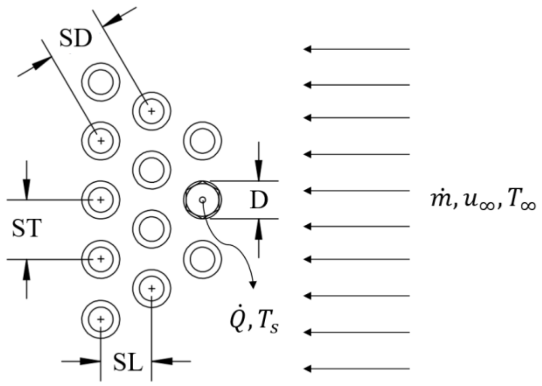

Figure 1: Test Model

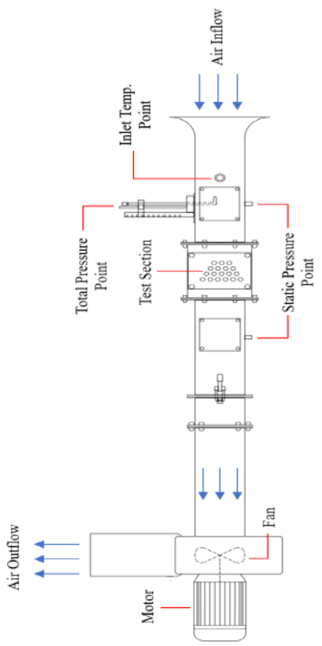

Figure 2: Experimental setup and equipment

2.2 Experimental setup and equipment

In this experiment, the test equipment used is as shown in Figure 2. This test equipment unit has a duct cross-sectional area of 150 mm × 150 mm with a length of 1540 mm. Then, this tool is equipped with an air-moving fan that has a maximum power of 1.5 kW and can produce a maximum air flow rate of 2160 m³/h.

III. RESULTS AND DISCUSSIONS

3.1 Influences of Reynolds Number (Re)

Figure 3 shows the relationship between the heat transfer coefficient and Re_D in the tube bundle configuration for the three heating power variations tested. The results show that the convection heat transfer coefficient increases with increasing Re_D and heating power. This indicates that increasing fluid flow velocity and increasing heating power will enhance the heat transfer process from the cylinder surface to the fluid. At higher Re_D values, the flow tends to transition from laminar to turbulent, resulting in better heat transfer. In addition, as the heating power increases, the tube surface temperature rises and causes an increase in the h value at each Re_D range compared to lower powers.

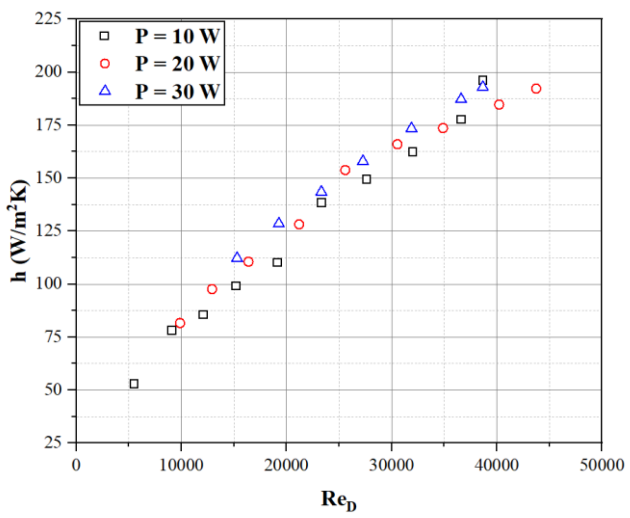

Figure3: A heat transfer coefficient (h) as a function of Reynolds Number (Re_D)

The test results of the relationship between Nu and Re_D in the test model configuration with 3 variations of heating power tested are presented in Figure 4. This plot shows that Nu increases significantly with increasing Re_D at all power levels, indicating that increasing fluid flow rates can result in better convection heat transfer. At low power P = 10 W, the Nu value is in the lowest range, but still shows an increase as Re_D increases. Medium power P = 20 W produces a higher Nu value than low P, while high power P = 30 W provides the highest Nu in almost the entire Re_D range. The difference between heating powers tends to be more pronounced at larger Re_D, indicating that the combined effect of high flow rates and large heat supply is able to maximize heat transfer process in the tube bundle configuration.

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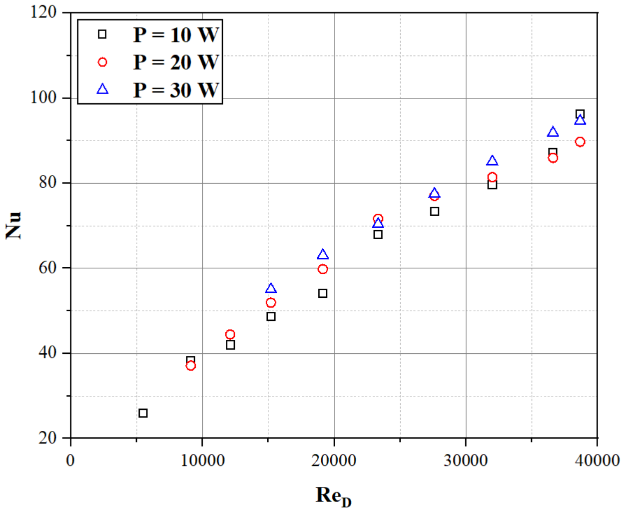

Figure 4: Nusselts Number (Nu) as a function of Reynolds Number (Re_D)

3.2 Effects of Heater Element Power

Figure 5 shows the relationship between heating power and heat transfer coefficient in a tube bundle configuration for three different Re_D= 12,000, 23,000, and 36,500. From the plot, it can be seen that the heat transfer coefficient increases with increasing heating power, where for each Re_D value, the h value tends to increase as P increases. In addition, the h value also increases significantly with increasing Re_D value, indicating that increasing fluid flow velocity increases the effectiveness of heat transfer. This trend is consistent for all tested heating power levels, where the highest Re_D produces the largest h value.

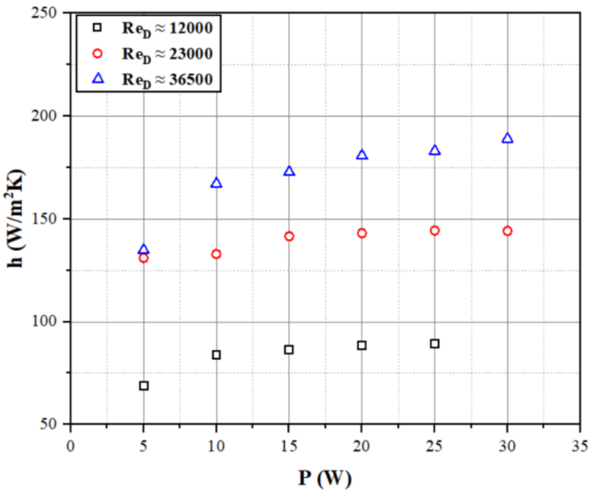

Figure 5: A heat transfer coefficient (h) as a function of heater element power (P)

The plot of the relationship between Nu and heating power in the test model configuration for the 3 variations of Re_D tested is shown in Figure 6. The plot results show that the Nusselt number increases with increasing heating power, indicating an increase in convection heat transfer. For Re_D≈12,000, the Nu value is relatively small and the increase is slow with P. At Re_D≈23,000, the Nu value is higher than low Re_D, and shows an increase with increasing P. Meanwhile, Re_D≈36,500 produces the highest Nu value across the P range, with a more significant increase at low to high P. This indicates that the flow rate represented by Re_D has a dominant influence on heat transfer compared to heating power, where the flow with high Re_D triggers greater turbulence, thereby increasing the heat transfer efficiency in the tube bundle configuration.

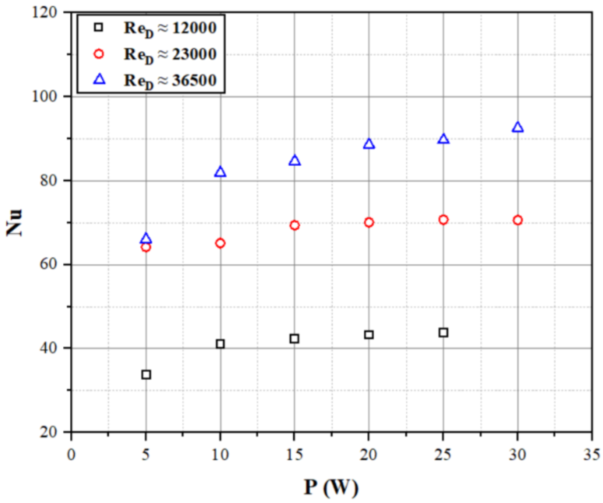

Figure 6: Nusselts Number (Nu) as a function of heater elemet power (P)

IV. CONCLUSION

Some important results of this experiment can be noted as follows: the thermal characteristics of the tube bundle configuration are significantly influenced by the Re_D value and heating power. Increasing Re_D causes the flow transition to turbulence, thus strengthening the convective heat transfer. Similarly, increasing the heating element power increases the cylinder surface temperature which contributes to the increase in the heat transfer coefficient and Nu number throughout the Re_D range. In addition, it can also be noted that the influence of Re_D on heat transfer is more dominant than P. High Re_D values consistently produce large h and Nu values. The combination of high flow rates and large heat supply is proven to maximize the thermal performance of the tube bundle.

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