Experimental Investigation of Forced Convective Heat Transfer in Circular Pipe with Wire Mesh Porous Media

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Abstract. This experimentation aims to study Nusselt number (Nu) and Friction factor (f) deriving from the forced flow of fluid inside a circular pipe under a uniform heat flux condition. Porous media used in this study is made of stainless-steel wire mesh 304 which has the number of pores per inch (PPI) of 8. Reynolds number (Re) ranges from 3000–15000. Distance between two plates of wire mesh (p), ranges from 10-50 mm. The results of the experiment indicate that the Nu figure tends to be higher when there is a rise in Re and a decrease in length of p, resulting in an increase in mass of material. The increasing mass of material enables it to store a large quantity of energy from hot air causing heat to be transferred toward the pipe wall in a higher rate. The value f tends to decline when the Re and p grow up. This phenomenon rather conforms to the general principles of nature, namely that a barrier against the flow will lead to a higher friction factor (f). The Performance Evaluation Criteria (PEC), recorded across the whole Reynolds number range, reaches a maximum where the p is 40 mm since the ratio of Nu to f is the most appropriate figure.

1. Introduction
Heating system and cooling system often involve heat transfer within fluid flowing through a pipe. This kind of flow is regarded as internal flow, such as the flow of cold air through the air duct, the flow of cooling water through the pipe. Enhancement to the heat transfer can be made by inserting porous media into the pipe because the prominent feature of porous media is having a higher ratio of surface area to volume than general opaque materials [1, 2]. With such characteristic, the heat transfer both in a pattern of heat conduction and in a pattern of heat convection of any device using the porous media will be much enhanced [3]. Researchers have consistently endeavored to conduct both the experimental study and theoretical analysis in order to apply the porous media for enhancing the heat transfer, particularly in a form of the forced convection within fluid flowing through the pipe. The related research studies have been presented as follows. Al-Nimr and Alkam [4] created the mathematical model to investigate the influence of inserting the porous media in the cylinder tube on the heat convection with transient flow of a fluid. The results were found that the Nu increased by a
factor of 12, compared to a situation without the porous media inserts. Later, Alkam and Al-Nimr [5] developed their research and broadened scope of the study by analyzing the numerical calculations. The finding suggested that the enhancement to heat convection could reach a maximum level when the proper layer thickness was applied. Angirasa and Peterson [6] demonstrated an experiment and a numerical calculation representing the effect of fibrous porous media on heat transfer. In addition, Angirasa [7] performed the experiment by inserting open-cell metal foam in the pipe. The porosity (ε) of the open-cell foam consisted of 0.97 and 0.93. It was observed that the Nu taking place in the pipe with the porous media tended to be higher than that of the pipe with a flat opaque material. The open-cell foam with porosity of 0.97 had a lower value of Nu than the open-cell foam with porosity of 0.93. Mohamad [8] examined the enhancement to the heat transfer of the flow inside the pipe and compared between fully and partially filling the pipe with porous media. The porous media was inserted in the core of the pipe while the laminar flow was set. The influence of the layer thickness on the heat transfer and the pressure drop emerging within the Darcy number range of 10^{-6} to 10.0 was found that the pipe partially fitted with the porous media had a higher transfer rate and a lower degree of pressure drop than the pipe fully fitted with the porous media. Pavel and Mohamad [9] studied the effect of metallic porous material on heat transfer. The test section had a constant heat flux and wall temperature with the Reynolds numbers that ranged from 1000 – 4500. The study was conducted to analyze the influence of porosity and the layer thickness on the heat transfer rate and the pressure drop. A comparison between the flow through the pipe with porous media and the flow through a smooth pipe was found that the heat transfer rate with porous media would increase in line with the pressure drop. Chatchawan Phuemsud and Surachai Sanitjai [10] experimentally studied the effect of porous media on enhancement to the forced convection in a circular pipe. The porosity (ε) of material used ranged from 0.72 to 0.86. The result of the experiment indicated that the heat was transferred from the pipe wall to the air flowing through the pipe with the amount increased by a factor of 1.2 – 3.2, compared to smooth pipe. Sarada et al. [11] investigated the heat transfer enhancement of the turbulent flow in a circular pipe. The wire mesh porous media with porosity ranging from 99.73 to 99.88 was inserted. Compared to the blank pipe, filling the pipe with the porous media would help improve the heat transfer performance, whereas the pressure drop was found to merely increase by 1.45 times. Huang et al. [12] conducted the experiment and numerically calculated what the effect of copper wire mesh inserted in the pipe on heat transfer rate could be. A comparison between the smooth pipe and the pipe with porous media pointed to the conclusion that the pipe fitted with the porous media would achieve substantial levels of heat transfer enhancement. The level of heat transfer enhancement of the pipe with the copper wire mesh increased by 5 times, compared to the smooth pipe, where the laminar flow was set with the porosity of 0.951. Renju et al. [13] experimentally studied vertical heat transfer by using wire mesh porous media. The research result suggested that the heat transfer coefficient deriving from the vertical heat transfer in the pipe with the wire mesh would double its number, compared to the blank pipe, at same flow velocity. Based on a review of previous studies, there are some noticeable issues concerning the heat transfer using wire mesh that have not been adequately examined. The present research, thus, uses the stainless steel wire mesh 304 with the number of pores per inch of 8 (PPI = 8) as porous media to enhance the forced convective heat transfer within fluid flow in a pipe. The effects of the distance between wire mesh plates (P) on the heat transfer rate are researched. The knowledge acquired from this study will be advantageous for improving the performance of tube heat exchanger.

Nomenclature

- $\dot{Q}$: heat transfer rate (W)
- $\dot{m}$: mass flow rate (kg/s)
- $A$: surface area of pipe (m²)
- $c_p$: specific heat capacity (J/kg.K)
- $h$: convective heat transfer coefficient (W/m².K)
- $T_s$: surface temperature of a pipe (K)
- $T_i$: inlet temperature (K)
2. Experimental Materials and Methods

Figure 1. represents a schematic diagram of the experimental materials for investigating the forced convective heat transfer in a circular pipe with wire mesh porous media under a uniform heat flux condition. The mechanism to conduct the experiment is started off by blowing the air with the blower through the valve and measuring flow rate of the air by using rotameter. Later, the air flows through the flow straightener used to straighten the air flow before getting into the developing flow pipe and then into test section. The test section is a stainless steel pipe with inner diameter of 82.55 mm, and the length of 500 mm, and it is heated up by 200-watt electric coil. The outer surface of the test section is covered with fiberglass with the thickness of 100 mm. The thermocouple is installed by attaching 7 wires to the wall of test section and 2 wires to the inlet and outlet for measuring temperature. The wire-net porous media is at the iron core then insert into the core of the test pipe with the similar distance between each plate under the experimental condition as shown in Figure 2. In addition, this study measures the pressure drop of the test pipe by using micro manometer at the inlet and outlet of the test section.
With reference to the Figure 1., the experimental methods are started off by (1) inserting the porous media in the test section, (2) adjusting and releasing the air into the test section with the Reynolds number (Re) ranging from 3000 – 15000, (3) enabling the electric coils to heat up the pipe wall and waiting until the inlet and exit temperatures of the air stay constant or are in a steady state, and (4) then recording the experimental results, including the surface temperature, the inlet/exit temperatures, and the pressure drop inside the test section.

3.3. Data analysis
The convective heat transfer coefficients (h) of the forced convection in the circular pipe with a uniform heat flux [14] are calculated by

\[ h = \frac{\dot{Q}}{A(T_s - T_m)} \]  
\[ \dot{Q} = \dot{m}c_p(T_o - T_i) \]  
\[ T_m = (T_o + T_i)/2 \]

The convective heat transfer coefficients taking place in this study are represented by the dimensionless number, called Nusselt number (Nu) that can be defined as follows.

\[ Nu = \frac{hD_n}{k} \]  
\[ f = \frac{2\Delta PD}{\rho v^2L} \]

The Performance evaluation criteria (PEC) is a parameter using to evaluate the value of energy consumption [15]. The PEC that is greater than 1 refers to the enhancement to the heat transfer (Nu) which is able to control the negative effects caused by the increased flow resistance or pressure drop (\( \Delta P \)). PEC is calculated by

\[ PEC = \frac{Nu/Nu_{\text{ref}}}{(f/f_0)^{1/3}} \]
Where

- \( \text{Nu} \) Nusselt number of the pipe with porous media.
- \( \text{Nu}_s \) Nusselt number of the smooth pipe.
- \( F \) Friction factor of the pipe with porous media.
- \( f_s \) Friction factor of the smooth pipe.

The porosity (\( \epsilon \)) of the wire mesh used in this research is calculated based on the physical structure of the mesh. A method of calculation draws from the difference between the unit total volume and the fraction of volumetric material per unit volume (\( F_V \)). Equation for porosity can be expressed as follows. [16]

\[
\epsilon = 1 - F_V
\]

(7)

where Volume fraction (\( F_V \)),

\[
F_V = \frac{\text{Porous volume}}{\text{Total volume}}
\]

### 4. Experimental results

#### 4.1. A comparison between experimental results and correlation equations

Figure 3. represents a comparison of data from the experiment with data from the Gnielinski correlation. The Nusselt number obtained from the experiment is compared with the Nusselt number according to the Gnielinski correlation, see equation 6 [12]. For the smooth pipe, the two Nusselt numbers tend to be in line with each other and have similar values. Figure 4 represents the obtained from the experiment versus the Petukhov correlation [12] for the smooth pipe. It is evident that the obtained from the experiment tends to be in line with the calculated with Petukhov formula, see equation 7 [12]. The results lead to the assumption that the experimental materials set up in this research study are reliable since the experiment shows both quantitative and qualitative correlations.

\[
\text{Nu} = \frac{(f/8)(\text{Re} - 1000)\text{Pr}}{1 + 12.5(f/8)^{0.5}(\text{Pr}^{0.3} - 1)}
\]

(8)

Where \( f \) is friction factor in the smooth pipe

\[
f = (0.79 \ln \text{Re} - 1.64)^{-2}
\]

(9)

\[0.5 \leq \text{Pr} \leq 2000 \text{ and } 3 \times 10^3 < \text{Re} < 5 \times 10^6.\]
4.2. Effect of $p$ on $Nu$ and $f$

Figure 5. represents the relationship of Nusselt number ($Nu$) to Reynolds number of the wire mesh 304 with PPI of 8. When there are changes in the distance between the wire mesh plates, the $Nu$ is found to increase with the increasing Reynolds number at all distances. This conforms to the heat convection principles – the relationship between $Nu$ and $Re$ is direct variation. At the same $Re$, the $Nu$ increases with the reduction in the distance between the wire mesh plates. As the distance between the wire mesh plates decreases, there will be a larger quantity of the wire mesh plates leading to the storage of energy in greater amount. As a result, a larger quantity of heat is transferred from the wire mesh to the surface of the test section causing the $Nu$ to increase. On the contrary, the analysis of friction factor ($f$) in the test section brings about an observation that when there are the rises in numbers of the wire mesh plates, the $f$ tends to increase obviously, as shown in Figure 6. This is because the increasing layer thickness of the porous media will be an obstacle to the flow of the air into the test section. This is in line with the fluid mechanics theory, namely that the more obstacles cause the fluid friction to grow up. Thus, the $f$ moves upwards.
The effect of the distance between the wire mesh plates (p) suitable for arranging the wire mesh in the test section at any given Re is represented in Figure 7. The graphs illustrate the relationship of p to PEC. Where p is 40 mm, the PEC is found to be highest at any given Re. To put it another way, the ratio of Nu to f where p is 40 mm is the most appropriate figure.
5. Conclusions

- The Nusselt numbers (Nu) obtained from the smooth pipe in this research tend to be in line with the Nusselt numbers calculated according to the Gnielinski correlation. The Nu values deriving from the two methods approximate each other.
- The friction factor (f) obtained from the smooth pipe tends to be in line with the friction factor calculated according to the Petukhov correlation. The f values deriving from the two methods approximate each other.
- The Nusselt numbers (Nu) and the friction factor (f) increase with the increasing Re and the decreasing p because the increase in volume of material will enable it to store a large quantity of energy from the hot air, causing the heat to be transferred to the pipe wall in a higher rate. The increasing friction factor (f) results from the hindrance to the flow which causes the pressure drop (∆P) to go up, which conforms to the general principles of nature.
- The PEC reaches the maximum value where p is 40 mm since the ratio of Nu to f is the most appropriate figure.

6. References

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