Heat transfer enhancement of flow insulator by combined stainless steel fibrous and wire net porous materials

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Abstract. The present research article aims to propose the heat transfer enhancement of the flow insulator using combined fibrous and wire net stainless steel porous material. The stainless fibrous plate with porosity of 0.9292 was combined to the stainless steel wire net having pore per inch (PPI) of 16 and total thickness of 30 mm. Two models of the arranging porous plates were prepared, which were model BA and model AB. Each porous plate segment had the same thickness. The examined porous plate model have porosities of 0.8452. The porous plate was placed normal to the flow direction. The air was used as working fluid heated by 5 kW electric heater, which was controlled by the automatic temperature control. Type-K thermocouples were employed to measure the air temperatures. The temperature at front of the porous plate was varied to be 350, 450, and 550℃. The air flow rate was varied in the range of 4-12 m³/hr. The experimental result showed that the temperature drop across the porous plate and the thermal efficiency increase with the inlet temperature. The air velocity slightly affects the temperature profile inside the test section at the upstream side of the porous plate but greatly affects temperature inside the porous plate. In consideration of the arranging porous plate, placing of the stainless steel wire net at the upstream side and placing the stainless steel fibrous at downstream side (model BA) results in the highest temperature drop and the highest thermal efficiency. At Re 733 and inlet temperature 550℃ for model BA at 30 mm thickness, the thermal efficiency was 50%. It was shown that the combined stainless steel fibrous and stainless steel wire net porous material could be a good flow insulator.

1. Introduction

Over the past two decades, heat transfer in the porous media has been studied both experimentally and theoretically. Because the porous media features large areas for heat transfer, it has high heat transfer coefficient at the surface. Many high temperature facilities were done by highly porous material, for example, a gaseous core nuclear reactor, plasma, combustion burner [1-3] and high temperature heat exchanger [4]. These applications could be done by using a multiphase medium consisting of fluid phase (gas) and particulate phase (solid) [5-8] of the porous media. Owing to the advantage of the porous media on high efficiency heat transfer, the energy of the flowing fluid flow through the porous element was recovered leading to the temperature difference between the upstream and downstream sides. This so-called novel concept was called flow insulation because the porous could act as a thermal insulator.

The concept of flow insulation system was presented by Echigo [9] in 1982. He placed a high-porosity steel porous material normal to the gas flow direction in an exhaust duct. It was found that the
temperature dropped more than 60% across 15-mm-thick porous plate. When the porous media receives the thermal energy, it emits the thermal radiation into both upstream and downstream sides. In 2009, Viskanta [10] proposed a high-porosity porous material and its application. He showed that high-porosity porous materials could emit, absorb, and radiate the thermal radiation due to its large surface area for heat transfer. Several researchers [11-18] studied this both numerically and experimentally. They illustrated the recovering thermal energy from flowing fluid using the porous materials which involve with the flow insulation concept. Khantikomol et al. [19-20] proposed the numerical and experimental study on the flow insulation system using open-cellular porous material. They indicated that the upstream radiation temperature strongly affected the quantity of the gas temperature drop across the porous plate.

As mentioned above, the high-porosity porous material has significant characteristics in heat transfer. Preecha et al. [21] reported that the stainless steel fibrous material could be a good heat transfer recovery. However, the fluid flow was quite difficult through the fibrous due to complicated structure. In the present work, therefore, the enhancement in heat transfer characteristics of the flow insulation system using combined stainless steel fibrous and wire net material have been investigated. Three average porosities and three thickness were examined. Heat transfer characteristics were presented in terms of heat recovery, temperature drop and the thermal recovery efficiency.

2. Experimental Setup

Figure 1 shows the experimental apparatus diagram. The experimental apparatus was made of the steel tube with 130-mm inner diameter. To make sure that it is perfectly insulated (adiabatic), the ceramic fiber was insulated on both inner and outer sides. Therefore, the experimental tube had the inner diameter of 120 mm. Air was used as a working fluid moved by the blower through the electric heater controlled by the PID temperature controller. The combined porous plates made of stainless steel fibrous and wire net were placed normal to the hot air flow at the top of the experimental tube at a distance of 300 mm from the electric heater. The air temperatures in front of the porous plate (inlet temperature) were varied from 350-550 °C and volume flow rate from 4-12 m³/h. Several type-K thermocouples were used to measure the temperatures of the flowing air at inlet of the heater (T₁), outlet of the heater (T₂), inlet of the porous plates (T₃) and out of the porous plate (T₄). Moreover, the ambient temperature (Tₓ) was also measured during the experiment.

In the present experimental study, the stainless steel fibrous and wire net material were combined in two models, called model AB and model BA as shown in figure 2, where A and B indicated the fibrous and wire net stainless steel, respectively. In model AB, the fibrous plate was placed upstream and the wire net plate was placed at downstream side. Here, the fibrous plate having porosity φ = 0.9292 and wire net having pore per inch (PPI) 8, 12, and 16 were examined. The total combined porous plate thickness were 10, 20, and 30 mm, with each type having the same thickness.
Flow meter

Data logger

Electrical heater

Porous plates

Blower

Temperature controller

Type-K thermocouples

T₁
T₂
T₃
T₄

Figure 1. The schematic diagram of the experimental apparatus.

Model AB

Model BA

B
A

B
A

Flow (a)

Flow (b)

Figure 2. Combined porous plate model: (a) model AB and (b) model BA.

3. Data Analysis

When the fluid moves through the porous element, the heat is exchanged between the fluid and the solid element of the porous material by both convection and radiation. Some of energy is transferred by convection to the solid element and some is transferred by fluid element. Therefore, the energy transfer from the fluid to the solid element of the porous was called the heat recovery by the porous. For flowing fluid, the velocity would be presented in term of Reynolds number based on the tube diameter, $Re_D$. To investigate the heat transfer between the flowing fluid and the solid element of the porous plates, the heat recovery or heat transfer from the fluid to the porous plate was conducted. Here, the temperature drop ($ΔT$) and the thermal recovery efficiency of the flow insulator ($η_r$) were investigated. The flow
condition (Reynolds number, \( Re_D \)), the inlet temperature of hot gas \( (T_{in}) \), the porosity \( (\phi) \), porous thickness were considered as independent parameters.

The Reynolds number \( (Re_D) \) based on the tube diameter is given by

\[
Re_D = \frac{\rho \omega V D}{\mu_c} .
\]  

(1)

where \( \rho \) is the ambient air density \((1.225 \text{ kg/m}^3) \), \( \mu \) is the atmospheric absolute viscosity \((1.789 \times 10^{-5} \text{ Pa} \cdot \text{s}) \), \( V \) is the average air velocity \((\text{m/s}) \) at upstream region of the porous plate, and \( D \) is the duct diameter \((\text{m}) \).

In the present experiment, the wall of the tube with thermal insulator is assumed to be an adiabatic wall. Therefore, the gas temperature difference occurred across the porous plate is due to the exchange energy between the gas and solid phase (porous plate). The air flowing through the test tube was assumed to be a uniform flow. The present work was done under the laminar flow condition due to the fluid flow was rather low. The data was done under the steady state. The recovery energy rate \( (\dot{Q}_{\text{recovery}}) \) of the porous plate was equal to the rate heat loss of the air by convection to the solid element of porous material, which can be expressed as follows:

\[
\dot{Q}_{\text{recovery}} = \dot{m} C_p (T_{in} - T_{out}) ,
\]  

(2)

where \( \dot{m} \) is mass flow rate \((\text{kg/s}) \), \( C_p \) is specific heat of the air \((\text{J/kg.K}) \), \( T_{in} \) is inlet air temperature \((\text{K}) \) and \( T_{out} \) is outlet air temperature \((\text{K}) \).

The thermal recovery efficiency \( (\eta_r) \) of the porous plate can be evaluated by the ratio of recovery heat rate \( (\dot{Q}_{\text{recovery}}) \) and the input energy rate \( (\dot{Q}_{\text{input}}) \), as in equation (3):

\[
\eta_r = \frac{\dot{Q}_{\text{recovery}}}{\dot{Q}_{\text{input}}} = \frac{T_3 - T_4}{T_4 - T_\infty}.
\]  

(3)

where \( T_\infty \) is ambient temperature \((30 \text{ °C}) \).

4. Results and Discussions

4.1. Temperature drop

The temperature drop of flowing fluid across the porous plate \((\Delta T)\) indicates the amount of heat that the porous recover from the flowing fluid. Figures 3-6 show the temperature drops across the combined porous plates which consist of fibrous (A) and wire net (B) stainless steel. The model AB is the combined porous plates that places the fibrous at upstream side and places the wire net at downstream side. The experimental results reveal the effect of several parameters, including the inlet hot air temperature, Reynolds number, the porous plate thickness and the porosities, to the temperature drop due to the heat recovery by the porous media. Higher temperature drop of the hot air flowing through the porous plate depicted the high heat exchange between the hot air and the solid element of the porous. The experimental results revealed that the temperature drop across the porous plate increase with the inlet hot air temperature (figure 3) owing to the fact that the porous plate could act as the good radiation absorbing and emitting thermal radiation at high temperature as illustrated in figure 3. The temperature drop increases with the porous thickness (figure 4) due to the heat transfer rate increase with increasing heat transfer area by increasing porous thickness. While the temperature drop decreases with increasing Reynolds number \((Re_D = \frac{\rho \omega V D}{\mu_c})\) as shown in figure 5 and increasing porosity (figure 6). At high
Reynolds number, the heat carried by the air element is higher than the heat transfer from the hot air to the porous element by convection leading to decrease the temperature drop of flowing gas. These reasons verify the results that the temperature drop across the porous plate could be high at low fluid velocity and high inlet hot air temperature.

In consideration of the effect of porosity, the temperature drop decreases with increasing porosity because increasing porosity decreases the heat transfer area. Since all of the wire net porous plate have the same diameter, increasing of porosity leads to decrease the heat transfer area.

In comparison of the combined porous plate models AB and BA, it was shown that the temperature drop across the combined porous plate model BA (figure 4a) was higher than that of model AB (figure 4b). This indicated that placing wire net porous at upstream side increased the heat transfer from the hot gas to the porous element. Placing the wire net at upstream side increased heat radiation to the upstream region leading to an increase in the heat exchange between the porous and the flowing fluid.

![Figure 3](image1.png)

**Figure 3.** Effect of inlet temperatures to temperature drop across porous plates: (a) Model BA and (b) model AB.

![Figure 4](image2.png)

**Figure 4.** Effect of porous thickness to temperature drop across porous plates: (a) Model BA and (b) model AB.
4.2. Thermal recovery efficiency

The heat recovery efficiency ($\eta$) of the combined porous plate is defined as the ratio of energy recovery from the flowing fluid of the porous media to the supplying heat, which is equal to the heat rise in the air temperature from ambient to the temperature at downstream side of the porous plate. The experimental results are shown in figures 7-10. The results depicted that the heat recovery efficiency increases with increasing inlet temperature ($T_3$) and porous thickness. While it decreases with increasing Reynolds number (Re) and porosities ($\phi$). Note that the tendency of the heat recovery efficiency is same as the temperature drop across the porous plate due to the heat recovery have been calculated from the temperature drop. However, the heat recovery efficiency would indicate the portion of the heat that porous could recover from the flowing fluid. Clearly, placing the wire net porous plate at upstream, as opposed to the other way around, increases the amount of heat recovery significantly.
Reynolds number ($Re_D$)

Inlet temperature ($°C$)

250 300 350 400 450 500 550 600

Model BA

Thickness 30 mm

Porosity 0.8452

(a)

(b)

Figure 7. Effect of inlet temperatures to thermal recovery efficiency:
(a) model BA and (b) model AB.

Reynolds number ($Re_D$)

Thickness (mm)

5 10 15 20 25 30 35

Inlet temperature ($T_3$) 500 °C

Model BA

Porosity 0.8452

(a)

(b)

Figure 8. Effect of Reynolds numbers and porosities to thermal recovery efficiency:
(a) model BA and (b) model AB.

Reynolds number ($Re_D$)

Model BA

Inlet temperature ($T_3$) 500 °C

Porsity ($p$)

600 800 1000 1200 1400 1600 1800 2000 2200 2400

0.8452

0.8761

0.9115

(a)

(b)

Figure 9. Effect of Reynolds numbers to thermal recovery efficiency:
(a) Model BA and (b) model AB.
The present study conducted analysis of the heat transfer of flowing fluid moving through the combined porous plate made of the fibrous and wire net stainless steel porous plates. The experiment was done under the conditions according to the heat transfer characteristics of the porous media. The heat exchange between the hot air and the solid element of the porous was presented in term of temperature drop of the flowing air which indicates the amount of heat recovery. The heat recovery efficiency of the porous plate was also investigated to find conditions of heat transfer enhancement. The experimental results could conclude that the combined porous plate placed the wire net at the upstream side and placed the fibrous at downstream side rather effect to increase heat recovery of the porous plate from the flowing air. Combined porous material would enhance the heat transfer significantly.

In consideration of effect in many independent parameters to the temperature drop and the heat recovery efficiency. The result illustrated that the temperature drop (ΔT) and the heat recovery efficiency (ηr) increase with increasing the inlet hot air temperature and the thickness of the combined porous plate due to effect of increasing radiation heat transfer mode at high temperature and increasing of heat transfer area by increasing the porous thickness. While the temperature drop (ΔT) and the heat recovery efficiency (ηr) decrease with increasing the Reynolds number (ReD) and the average porosity (φ) of the combined porous plate owing to the ratio of heat recovery to the heat carried by the flowing fluid decreasing with increasing velocity although the convection heat transfer mode increase with increasing velocity. In increasing the average porosity, the heat transfer area would decrease, leading to a decrease in the heat recovery of the combined porous plate.

Acknowledgment

The authors acknowledge Rajamangala University of Technology Isan who provided the funding for the present research as well as the working space and necessary research equipment.

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