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Corresponding author. E-mail: jjfoo@segi.edu.my

IMPROVEMENT OF A SOLAR HEATING PANEL'S THERMAL EFFICIENCY: PARABOLIC TROUGH EFFECT COUPLED WITH A POROUS PACKED BED

Weng-Kheen Yeong[1], Yin-Ling Lai[1], *Ji-Jinn Foo[1, 2]
[1]School of Engineering, SEGi University College, Kota Damansara, Malaysia;
[2]Department of Mechanical Engineering, Sheffield University, United Kingdom.

ABSTRACT

The effects of hydrostatic, hydrodynamic, porosity and pressure drop on the heat transfer characteristics of a solar heating panel incorporating a parabolic trough collector (PTC) and porous packed bed are investigated experimentally. The results show that a solar collector installed with only a PTC is able to improve the thermal absorption of the working fluid. Through the addition of a porous media into parts of the receiver tubes, the thermal efficiency of the collector can be further enhanced. The heat transfer performance increases with the decrease in porosity and mass flow rate. It is also found that a porous medium is able to increase the rate of heat transfer during the transient hydrostatic experiment, whereas the rate of heat transfer remains constant in the hydrodynamic study where non-local-thermal-equilibrium (NLTE) becomes dominant. Lastly, it is critical to form a non-sintered porous packed bed using particles with uniform diameters to avoid extra internal pressure losses.

1.0 Introduction

Solar power is a versatile form of renewable energy that can be utilized in many applications from water distillation and power plants to food factories (Price *et. al.*, 2002; Odeh and Morrison, 2006; Dev and Tiwari, 2009). Malaysia is an equatorial country; it receives approximately six hours of daily solar radiation intensity between 410 and 830W/m^2 (Dev and Tiwari, 2009; Othman *et. al.*, 1996). Such useful natural energy can generally be used in two different applications: (i) Direct utilization to increase the working fluid temperature for further usage, for instance: in a Rankine steam cycle; and (ii) Electricity generation through photovoltaic cells (Kalogirou, 2004).

In 2009, Dev and Tiwari reported that the solar radiation intensity varies between 170W/m^2 (7 AM, morning), 820W/m^2 (12 PM, afternoon), and 180W/m^2 (17 PM, evening). Thus, the performance of a solar heating panel strongly depends on the solar radiation received throughout a day. This energy can be maximized and reutilized by using a solar light tracking concentrator and a focal receiver. Past findings proved that with the aid of PTC the thermal efficiency of a solar heating panel can be further enhanced (EI Fadar *et. al.*, 2009). The heat can be generated at a temperature between 50^{o}C and 400^{o}C, even with a light structure and using low cost technology. To construct a PTC, it is required to bend a reflective material into a parabolic shape; more importantly, the parabolic sheet has to be coupled with black metal tube enclosed within a vacuum glass tube to avoid heat losses. The last step is to adjust the receiver into the focal line (Kalogirou, 2004).

A porous medium is a material consisting of a solid matrix with many interconnected voids. A metallic porous medium with a larger surface area-to-volume ratio or a smaller porosity if filled with working fluid can further increase the heat transfer performance of a thermofluid system. It is important to note that the balance between heat transfer enhancement and the fluid pumping power is critical (Shuja *et. al*., 2009). In the numerical investigation by Mohamad (2002), it was reported that the Nusselt number of a heating porous channel is approximately 50% higher than the heat sink channel without using porous media. Such result is mainly due to the thermal dispersion effect between the solid particles and the working fluid which interact under a NLTE condition (Hsieh and Lu, 2000).

In 2009, Sopian *et*. a*l*. conducted an experimental study on a double pass air solar collector with and without a porous medium in the second channel. Their group reported that solar collector heat transfer performance increases with the addition of a porous medium in the second channel. Kumar and Reddy (2009) performed a numerical analysis of a solar PTC with a porous disc receiver using Therminol VP1 as the working fluid. They found that by comparing with a tubular receiver without a porous disc the Nusselt number increases 64.3% for the receiver with the addition of a porous disc at a pressure drop of 457Pa. A curved channel solar collector was built to investigate the heat transfer enhancement (Rababi and Mismar, 2003). When coarse aluminum chips of porosity 0.1453 were filled into the system for extra thermal storage capability, it was found that the instantaneous thermal efficiency was higher for a channel filled with a porous medium. The measured outlet temperature was 73.3^{o}C for collector without a porous medium at 70*l*/h of flow rate and 60.2^{o}C for collector with a porous medium at 50*l*/h.

The main objective of this study is to develop a solar heating panel by incorporating a PTC with the addition of a porous medium in order to enhance the thermal absorption of the working fluid hydrostatically (without fluid motion, natural convection) and hydrodynamically (with fluid motion, forced convection). An experimental study is performed to measure the inlet and outlet water temperature and pressure drop of the solar heating panel. More importantly, three different arrangements of the solar collector's thermal absorption performance are investigated. The effects of non-sintered packed bed porosity as well as the corresponding hydraulic power are observed. Lastly, the overall system efficiency is also discussed.

2.0 Experimental Setup and Methods

Figure 1(a) shows the schematic experimental setup. The solar heating panel is constructed using plywood as the shell with six tube passes. The diameter of the steel metal tube is 12.5mm with a total tube length of about 4640mm. All the pipes are painted in black. The solar collector is covered with a glass to avoid further heat losses due to the greenhouse effect. During the experiment, the amount of water flowing out is collected within a constant period of time in order to measure the mass flow rate. A *K*-type thermocouple thermometer (HANNA Instruments, USA) is used to measure the inlet and outlet water temperature. Furthermore, by measuring the static head of water at the inlet and outlet of the solar collector, the pressure at both locations can then be determined using the general hydrostatic equation,

$$P = h\rho g \quad (1)$$

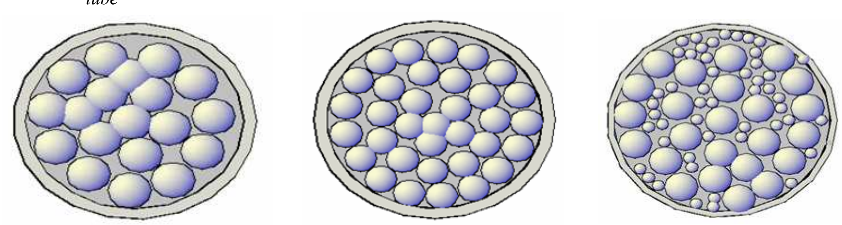
where P is the hydrostatic pressure, h is the measured static head of water, ρ denotes water density, and g is the gravitational acceleration. All the experiments are carried out on a sunny day between 11.30AM to 1.00PM.

(a) (b) (c)

Figure 1(a): Schematic Drawing of the Current Solar Heat Panel; (b) Solar Heating Panel with a PTC installed; and (c) Mild Steel Particles used in the Study

Three different experimental setups are studied in this investigation: (i) A control solar heating panel without the addition of a PTC and a porous medium; (ii) solar collector with a PTC installed beneath every pipeline where the aluminum foil is folded onto all the parabolic surfaces as well as the whole surrounding walls [except the cover glass, see Figure 1(b)]; and (iii) solar heating panel with the addition of a PTC and a porous medium using mild steel particles [Figure 1(c)]. Three different porosities are selected to determine the heat transfer performance of case (iii) (see Figure 2), which are: 0.0628 (using 6mm diameter particles), 0.0348 (a combination between 4mm and 6mm of particles of equal volume), and 0.0068 (using 4mm diameter particles). It is important to note that a porous medium is only added into the two centre tubing, as circled in Figure 1(b). The porosity is defined as follow,

$$\varepsilon = \frac{V_{tube} - V_{particles}}{V_{tube}} \qquad (2)$$



(a) (b) (c)

Figure 2: Schematic Diagram showing the Current Porous Medium within the Steel Pipes: (a) 6 mm diameter, (b) 4 mm diameter, and (c) mixed between 4 and 6 mm Spherical Particles

where ε denotes the porous medium porosity, V_{tube} is the volume before inserting the porous medium, and $V_{particles}$ represents the total volume occupied by spherical particles. The thermal efficiency η of the solar collector can be determined using the following equation,

$$\eta = \frac{\dot{m}c_p(T_{out} - T_{in})}{A \cdot I} \qquad (3)$$

where $\dot{m}$ is the mass flow rate, c_p is the specific heat capacity of the working fluid, T_{in} and T_{out} are the inlet and outlet water temperature, respectively, A is the projected area of the solar heating panel, and I is the solar radiation intensity of about 820 (W/m^2) at 12.00PM. The hydraulic power P_h needed to overcome the pressure difference across the solar heating panel is given defined as follow,

$$P_h = Q\Delta P \qquad (4)$$

where Q is the volumetric flow rate, and ΔP is the pressure drop across the system. Thus, by taking into account the heat transfer performance and power consumption, the overall system efficiency can be determined using the following equation (Rababi and Mismar, 2003),

$$\eta_{overall} = \frac{\dot{m}c_p(T_{out} - T_{in})}{P_h + A \cdot I} \qquad (5)$$

The Reynolds number *Re* can be expressed as,

$$Re = \frac{4\dot{m}}{\pi D \mu} \qquad (6)$$

where D is the pipe diameter and μ is the viscosity of water. The Reynolds numbers chosen in the present investigation are 126 and 146, which correspond to the mass flow rate of 1.38gs^{-1} and 1.60gs^{-1}. Lower flow velocities within the laminar flow regime are preferred in order to ensure a better thermal absorption as the working fluid flow passes through the system. It is important to note that all the experiments are repeated three times, with a maximum standard deviation of not more than 0.7^{o}C.

3.0 Results and Discussion

The present study aims to improve the solar collector thermal absorption performance by incorporating a PTC with a porous medium. Five different set of experiments are carried out, namely: (i) conventional solar heating panel (the control experiment), (ii) solar collector with a PTC added, and (iii) solar collector coupling between a PTC and a porous medium with three different porosities ε. In Figure 3, the measured water temperature distributions under hydrostatic condition are shown. Temperatures are measured at every 10 minutes intervals after direct exposure under the sun (from 11.30AM to 1.00pm). Clearly the water temperature increases with time of exposure. The water temperature of the control experiment increases 8.7^{o}C in the first 10 minutes and to 22.8^{o}C after 60 minutes, the measured temperature distribution is found to slowly reach a plateau of 52^{o}C. For solar collector with only a PTC installed, it is observed that there is a 14.3^{o}C increase in temperature at the first time step, and the temperature is still increasing after one hour of observation (to 69°C). Since the whole chamber within the solar collector are fully covered by reflective aluminum foils, most of the solar energy within the chamber are trapped and being reflected back to the system. Secondly, the parabolic reflective surfaces are able to redirect the solar intensity to every steel pipe. Thus, more energy can be absorbed by the working fluid.

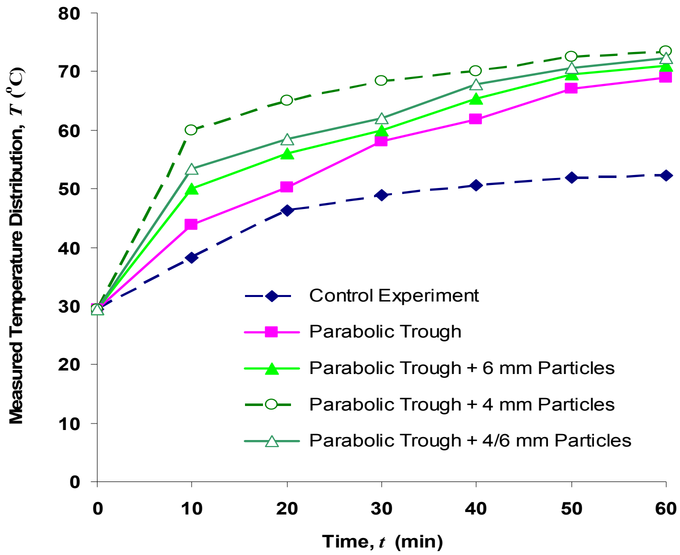


Figure 3: Measured Outlet Water Temperature Distributions for Different Arrangements of Solar Heating Panels performing hydrostatically

Starting from the third experiment, a porous medium is added into the receiver pipes. It is important to note that only two selected sections of approximately 1.22m in length are fully occupied by spherical metal particles [see Figure 1(b)]. It is found that the heat transfer performance increases with the decrease of porosity. Results show that solar collector of $\varepsilon = 0.0068$ can greatly enhance the thermal absorption of the system. The outlet water temperate increases by 40.5% compared with the control experiment, and is 6.5% higher for the solar collector with only using a PTC, after one hour of direct exposure beneath the sun.

The transient responses of the above hydrostatic solar heating panels heat transfer performance are shown in Figure 4. The temperature difference is non-dimensionalized as follows,

$$\Delta \overline{T} = \frac{T_{out,\max} - T_{in}}{T_{out,t} - T_{in}} \qquad (7)$$

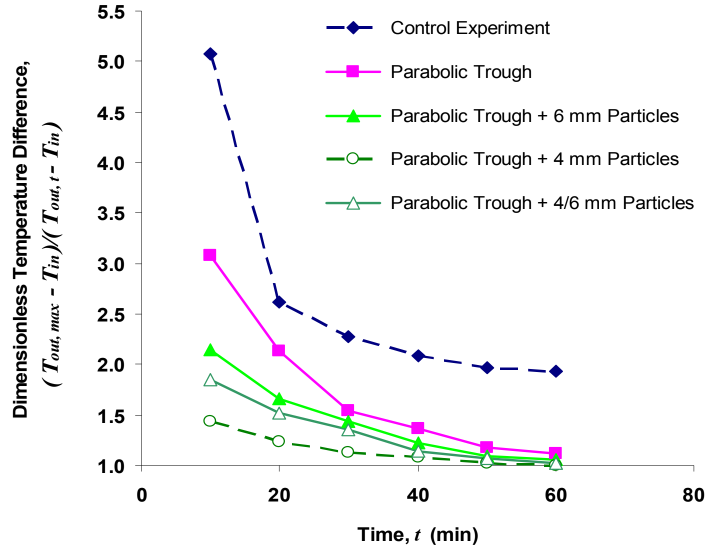


Figure 4: Calculated Dimensionless Temperature Difference for Different Arrangements of Solar Heating Panels performing hydrostatically: The Time Response of the Solar Collector

where $T_{out,t}$ is the measured outlet water temperature at every single time interval, and $T_{out,\max}$ represents the maximum outlet water temperature obtained from the solar collector having the highest thermal absorption. It is found that the solar collector coupled with a PTC and a porous medium of porosity $\varepsilon = 0.0068$ is able to provide the optimum heat transfer performance. The highest temperature achieved within 60 minutes of observation is 73.5°C. Thus, in the present hydrostatic study $T_{out,max} = 73.5^{o}C$. Clearly the smaller the dimensionless temperature difference $\Delta\overline{T}$, the better the heat transfer performance. It is also important to note that the porous medium plays a critical role during the initial transient state of the heat transfer performance where the working fluid temperature increases drastically. Such effect is due the increase of internal surface area to volume ratio that allows a direct thermal conduction from the pipes into the channel and being removed by the water that flows through the interconnected voids. As a result, in the first 10th minutes of the experimental measurement on the solar collector coupling with a PTC and a porous medium of porosity $\varepsilon = 0.0068$, the thermal energy that transferred into the tubes is approximately $1\times$ higher than the solar collector with only a PTC installed, and about $2\times$ higher than the control experiment (data not shown). The maximum energy stored in this system reaches 100kJ after one hour of observation.

The hydrodynamic effect on different solar heating panels' heat transfer performance is also studied. Figure 5 shows the measured outlet water temperature distributions for the control experiment, the solar collector with a PTC installed, and the solar collector with the addition of both a PTC and a porous medium of $\varepsilon = 0.0068$. The experiments are conducted at two different mass flow rates of $1.38gs^{-1}$ (Re = 126) and $1.60gs^{-1}$ (Re = 146) within 30 minutes of direct exposure under the sun. Clearly a lower mass flow rate is preferred to ensure a higher thermal absorption of the solar energy into the working fluid. In order to further increase the outlet water temperature, it is critical to optimize and balance the rate that solar energy enters the receiver tubes and the rate of thermal energy transferred into the working fluid. Thus, a PTC is responsible to increase the rate of solar energy entering the pipes, and the porous medium focuses on an increase of the interstitial flow velocity of working fluid and in the meantime supports direct heat conduction from the surroundings into every specific control systems (i.e. view through Lagrangian observation). It is found that the thermal efficiency [Equation (3)] is highest for a solar collector coupled with a PTC and a porous medium. The calculated thermal efficiencies are of approximately 43.7% and 42.6%, at Re=126 and 146, respectively (please refer to Table 1). Therefore, there is an average of 24% improvement in thermal efficiency compared with the control experiment, and of about 6% better than a solar heater only using a PTC.

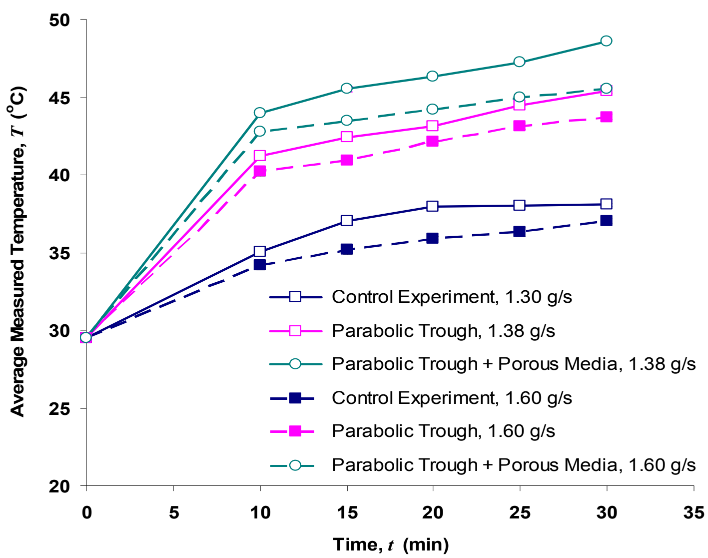


Figure 5: Measured Outlet Water Temperature Distributions for Solar Collectors running hydrodynamically, A Porosity of 0.0068 is selected in the Porous Media Heat Transfer Study

Table 1: Calculated Temperature Difference and Thermal Efficiency at the 30th Minute of Measurement: The Effects of a PTC and a Porous Medium

Flow rate, g/s	Control		PTC		PTC + Porous (4 mm)	
	$\Delta T, ^oC$	η, %	$\Delta T, ^oC$	η, %	$\Delta T, ^oC$	η, %
1.3 – 1.38	8.6	18.5	15.9	36.5	19.1	43.7
1.6	7.5	20.0	14.2	37.8	16.0	42.6

Table 2: Calculated Temperature Difference and Thermal Efficiency at the 30th Minute of Measurement: Porosity Effect

Flow rate, g/s	Control		6 mm Particles		4 mm Particles		Mixed 4/6 mm	
	$\Delta T, ^oC$	η, %	$\Delta T, ^oC$	η, %	$\Delta T, ^oC$	η, %	$\Delta T, ^oC$	η, %
1.3 – 1.38	8.6	18.5	17.4	39.8	19.1	43.7	18.0	41.3
1.6	7.5	20.0	14.6	38.8	16.0	42.6	15.0	39.9

Figure 6 shows the porosity effect on solar heating panels. The measured outlet water temperature increases with the decrease of mass flow rate and porosity. In the present study the Lagrangian energy absorption is rather more important than the observation through an Eulerian method. Thus, water that runs slower in the system will then have sufficient time to receive more external solar energy. In all cases, the thermal efficiency for a solar collector incorporating with a PTC and a porous medium performs better than a solar collector with only a PTC (thermal efficiency of average 37.2%), which are of average: 39.3% for $\varepsilon = 0.0628$, 40.6% for $\varepsilon = 0.0348$, and 43.2% for $\varepsilon = 0.0068$ (see Table 1 and Table 2).

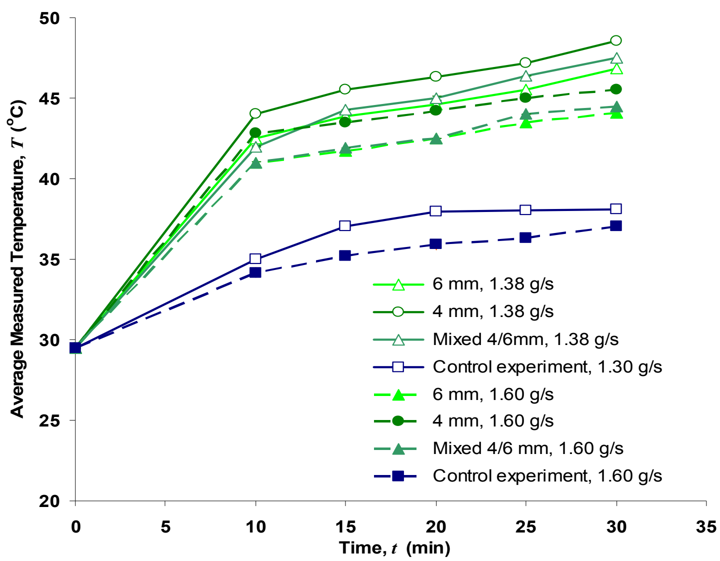


Figure 6: Measured Outlet Water Temperature Distributions at Different Porosities and Mass Flow Rates

The transient responses of the corresponding hydrodynamic experiments at $Re = 126$ are shown in Figure 7. It is clear that the smaller the porosity the faster the thermal absorption to the working fluid. Moreover, it is important to note that the rate of change of the dimensionless temperature difference $\Delta\overline{T}$ almost remains constant for either using a PTC alone or coupled with a PTC and a porous medium. These results are different if compared with the hydrostatic study. The rates of change of the dimensionless temperature differences for hydrostatic studies decrease with time of exposure for a solar heating panel coupled with a porous medium. This differences is due to the fact that porous medium heat transfer in the hydrostatic condition is slowly approaching from NLTE toward a local-thermal equilibrium (LTE) condition; whereas the rate of heat transfer for a solar heating panel will always remain under NLTE in the hydrodynamic operation. It can also be observed that the dimensionless temperature difference $\Delta\overline{T}$ is about 2.2× larger between the control experiment and the solar collector having $\varepsilon = 0.0068$, after thirty minutes of observation. Similar results can be obtained for a solar collector performing under $Re = 146$.

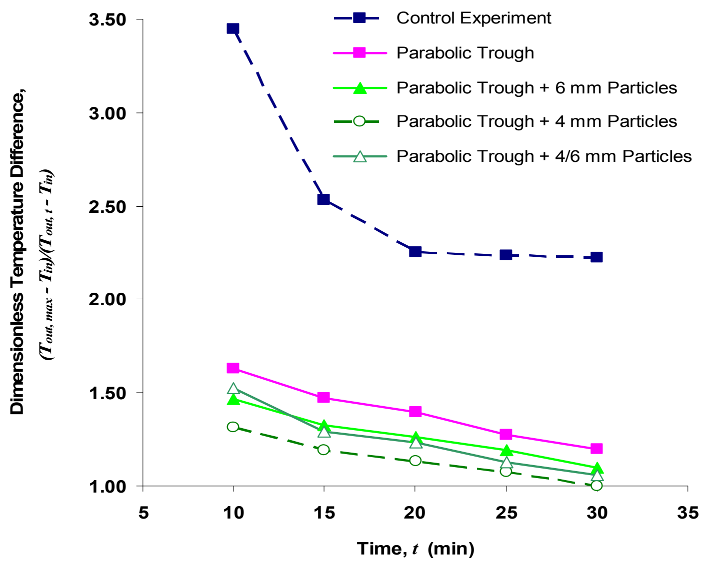


Figure 7: Calculated Dimensionless Temperature Difference for Solar Collectors performing hydrodynamically: The Time Response of a Solar Heat Panel at *Re* = 126

The calculated dimensionless inlet pressure distributions $\overline{P}$ are given in Figure 8. The inlet pressure is non-dimensionalized as follow,

$$\overline{P} = \frac{P_{in}}{P_{in,control}} \qquad (8)$$

where P_{in} is the inlet pressure, $P_{in,control}$ is the inlet pressure for control experiment measured under the same flow rate. As shown in Figure 8 the dimensionless inlet pressure $\overline{P}$ increases with the decrease of porosity and mass flow rate. The existence of a porous medium that occupies about 33% of the whole steel pipes is able to cause an average of 1.4× of increment on the inlet pressure. Therefore, it is important to understand the hydraulic power P_h required to work against the internal losses within each solar collector piping system. As shown in Figure 8, it is found that the hydraulic power increases when a porous medium is added, the larger the Reynolds number *Re* the higher the hydraulic power.

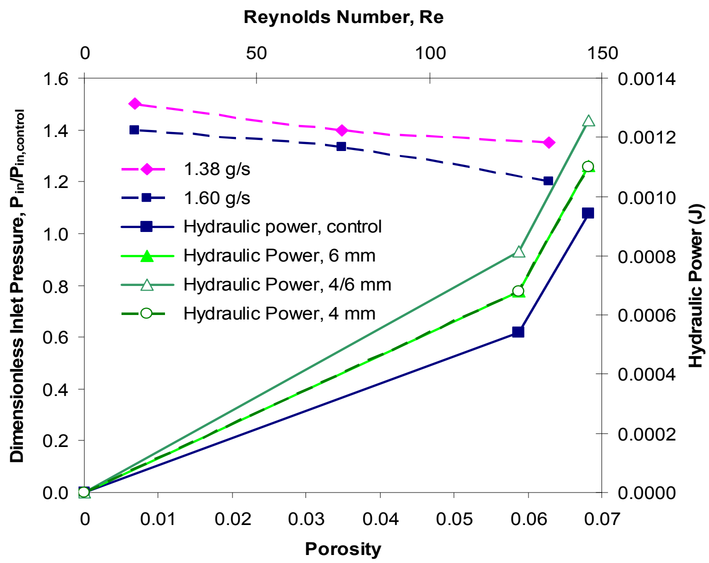


Figure 8: Calculated Dimensionless Inlet Pressure and Hydraulic Power at Different Porosities and Reynolds Number, respectively

It is interesting to note that the hydraulic power increases for $\varepsilon = 0.0348$ (a mixed condition), instead of $\varepsilon = 0.0068$ and 0.0628. This might due to the reason that the porous packed bed is randomly arranged using two different sizes of spherical particles of 4mm and 6mm in diameter. As a result, it affects the permeability and inertia effects of the working fluid that flows through the pipes (Hwang and Chao, 1994). As a result, uniform particle size is suggested to construct the porous packed bed to avoid such extra pressure losses inside the system.

The overall system efficiency η_{total} is calculated and shown in Figure 9. Results show that overall system efficiency increases with the decrease of porosity and Reynolds number for a solar collector with a porous medium added. It is also note that the different between the thermal efficiency η and the overall system efficient η_{total} is small, due to the low hydraulic power. Overall, for system working under hydrodynamic condition, the maximum thermal efficiency achieved is 43.7% by coupling between a PTC and a porous medium.

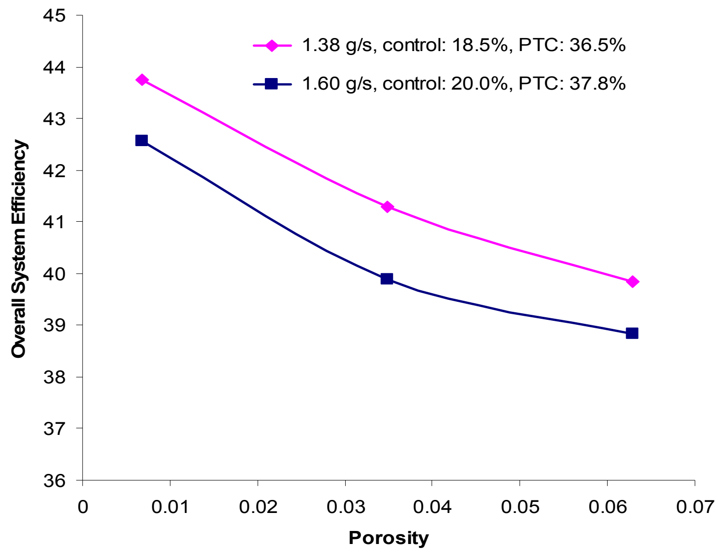


Figure 9: Calculated Overall System Efficiency at Different Porosities and Mass Flow Rate

4.0 Conclusion

The forced and natural convective heat transfer experiments on solar heating panel with and without a PTC and a porous medium effects are conducted to quantify their thermal absorption characteristics. Heat transfer performances of different sets of solar heating panels are compared with the control study. The conclusions of this study are,

1. Through the addition of a PTC alone, more solar energy can be reflected into the receiver tubes. By comparing with the control study, the outlet water temperature is 16.7^{o}C higher for solar collector performing hydrostatically, and recorded an increase of 7.3^{o}C when *Re* = 126.
2. A solar collector coupled with a PTC and a porous medium possesses an optimum heat transfer performance under hydrostatic operation. A porous medium is able to further enhance the heat transfer performance especially at the initial transient state. The system actually goes through a transition from a NLTE to a local-thermal-equilibrium (LTE) state.
3. A solar collector coupled with a PTC and a porous medium possesses the optimum heat transfer performance under hydrodynamic operation. The system always remains under NLTE condition, where the internal energy in every Lagrangian system is lower than the hydrostatic measurements, thus a lower water temperature is measured at the outlet.
4. The pressure drop across the solar collector with a porous packed bed is greater than the collector without a porous medium. Thus, more hydraulic power is necessary in order to overcome the internal pressure losses. More importantly, it is recommended to enhance the thermal absorption through using spherical particles of uniform size to lowering down the hydraulic power.

5. The overall heat transfer performance increases with the decrease in porosity and mass flow rate, the result reflects itself in the thermal efficiency of the system. The maximum thermal efficiency of the system reaches 43.7% under hydrodynamic performance by incorporating a PTC with a porous medium.

5.0 Acknowledgement
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