International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 – 5161
Available at http://inpressco.com/category/ijcet

Research Article

Experimental Study the Performance of Aluminum Foams Condensers in the Vapor Compression Cycle

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Accepted 14 April 2016, Available online 16 April 2016, **Vol.6, No.2 (April 2016)**

Abstract

This work aims to study the improvement in thermal performance of vapor compression cycle due to replace finned tube condenser by aluminum open-cell metal foams one. For the study purpose, a simple vapor compression cycle was modified by adding many components. The traditional finned tube condenser of 24 fins per tube, with dimensions 320×240×70 mm, was replaced by an open-cell aluminum foam condenser that designed for this work and manufactured by China Beihai Building Material Co., Ltd. The porosity of the metal foam is 0.903 with 10 pores per inch (PPI). The variation of air-side heat transfer coefficient, compressor, fan power consumption, cycle COP and pressure drop were studied under the volume flow rate of air through condenser in the range of 500 to 700 m3/hr, in step of 100 m^3/hr and ambient temperature in the range of 20 to 35°C, in step of 3°C. The experimental results showed that, the average enhancement in the air-side heat transfer coefficient was 542%, the improvement in the heat reject from condenser was 5.79%, saving in compressor power consumption was 16.9%, and the average enhancement in COPref was 33%. Metal foam increases air pressure drop through condenser by 1117%, in addition to the increase in fan power consumption was 1088%. Depending on the volume flow rate of air through the condenser, the beneficent factor for this work was in the range of 0.41 to 0.47.

Keywords: *Aluminum Foams, Vapor compression cycle, Foam condenser, heat transfer coefficient*

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1. Introduction

Open cell foam is characterized by its descriptive name, meaning that the cells are not closed off from one another, and that material may flow freely through one cell to another. This type of foam is created during the foam manufacturing by removing the intercellular membranes of closed cell foam. Open cell metal foam is manufactured with different pores per inch (PPI) ranging from 10 to 100 PPI. (Ashby *et al*, 2000; Gibson and Ashby, 1999; Hipke and Poss, 2007). The heat transfer coefficient in forced convection of air through aluminum foams was measured by(Kim and Kang, 2000), they reported many experiments with six type of forms, namely: foams with a porosity of (φ=0.92) at (10, 20 and 40PPI), and the other three foams had 20 PPI and varying porosity. The used of finned metal foam was investigated by (Bhattacharya and Mahajan, 2002), the finned metal foam was used as a heat sinks for electronic equipment. Cooling applications for metal foam was investigated by (Boomsma and Zwic, 2003), they found that the compressed aluminum foams showed a significant improvement in the efficiency of several commercially available heat exchangers. The interstitial heat transfer coefficients for Cu foams with 5.4, 5.6 and 12.8 PPI and Fe Cr Alloy were measured experimentally by (Giani and Tronconi, 2005). An assessment on the forced convection through metal foams was investigated experimentally and analytically by (Mancin and Rossetto, 2012), the results executed air heat transfer out of nine copper foam models and twelve aluminum foam models. The effects of the PPI on the heat transfer and fluid flow performance for a constant porosity of 0.93 open-cells copper foam samples was investigated by (Diani *et al*, 2013). The performance of five foam wrapped tubes to a finned tube as a benchmark were studied by (Chumpia, and Hooman, 2014), after the results were compared, they found that a foam wrapped tube provides more heat transfer, while keeping the pressure drop at the same level as that of the finned tube, if the proper foam thickness is selected. Heat transfer coefficient and the pressure drop under a flow of forced humid air was investigated by (Guarino *et al*, 2015), three different types of aluminum alloy foams, (5, 10 and 20 PPI).

In this work a traditional condenser of a simple vapor compression cycle was replaced by aluminum metal foam condenser of 10 PPI, 0.903 porosity. The improvement in the condenser air side heat transfer coefficient, due to the replacement of condenser was studied under the variation of volume flow rate of air

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*Corresponding author: **Abdul Hadi N. Khalifa** through condenser, at different ambient temperature were studied. The improvement in the vapor compression cycle performance were studied also.

2. Experimental Rig

A simple vapor compression cycle (VCR), produced by Gunt Company, was modified by adding many components. The modified VCR was used to study the cycle performance with finned tube condenser and foamed condenser. The schematic diagram for the test rig is shown in Fig. 1 The VCR consist of R-134a hermetic compressor of 386W capacity, of model (BP1632H), the condenser is a plate-finned tube condenser of with dimensions 320×240×70 mm dimensions, with specification shows in Table 1.

Table1. Condenser specifications

Geometric	Specifications	
	Finned tube	Open-cell aluminum foam
Height	320mm	320mm
Width	240mm	320mm
Thickness	70mm	70mm
Outer tube diameter	12.3 mm	12.3mm
Inner tube diameter	10.9 mm	10.9mm
Number of tubes per row	9	9
Number of rows	2	2
Vertical spacing between tubes	36.3 mm	36.3 mm
Horizontal spacing between tubes	35.3 mm	35.3 mm
Number of fins per tube	24	-
Fin thickness	0.33 mm	-
PPI (Pore per inch)	-	10
Porosity	-	0.903

While the evaporator is a coaxial coil evaporator of cooling capacity of 245W. The new condenser was foam condenser that designed for this work and manufactured by China Beihai Building Material Co., Ltd. Two metal sheets foam, of dimensions of 320 mm height, 240 mm width and 35 mm thickness, were gathered together manufactured to form the condenser. The foam sheets of porosity of 0.903 with 10 pores per inch (PPI), Table 1 shows the specifications foam condenser . The performances of foam and finned plate heat exchangers were examined under many key variables, for each key variable under study, other variables were set as constant. The variables affecting the performance of condenser were: outdoor temperature in the range of 20 to 35°C, in step of 3°C, volume flow rate of air through condenser in the range of 500 to 700 m^3/hr, in step of 100 m^3/hr and the effect of load imposed on the evaporator, that simulated by varying the mass flow rate of hot water through the evaporator, in the range of 30 to 50 lit/min, in the step of 10 lit/min.

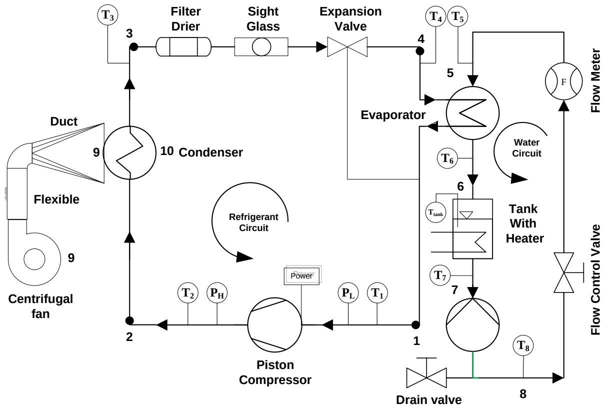

Fig. 1 Schematic Diagram of the test rig

3. Results and discussions

Fig. 2 shows the effect of volume flow rate of air through condenser on the air-side heat transfer coefficient for both finned and foam condensers. The figure shows that, as the volume flow rate of air increases the heat transfer coefficient increases for both types of condensers. Also, the figure shows that, the heat transfer coefficient for metal foam is greater than that of finned tube condenser, due to the increases in heat transfer surface area per unit volume, which is equal to 1185m^2/m^3, while it is equal to 230.9 m^2/m^3 for finned tube condenser. the average percentage enhancement in the air-side heat transfer coefficient is 542% in the range of air flow under study namely 500, 600 and 700 m^3/hr.

Fig. 3 shows the effect of volume flow rate of air on the heat transfer coefficient ratio (the ratio of foam condenser air side heat transfer coefficient to that for finned condenser), the figure shows that as the volume flow rate of increases the heat transfer coefficient ratio decreases, which means that the improvement of air side heat transfer coefficient of finned tube condenser, due to variation of volume flow rate of air, is better than that for foam condenser.

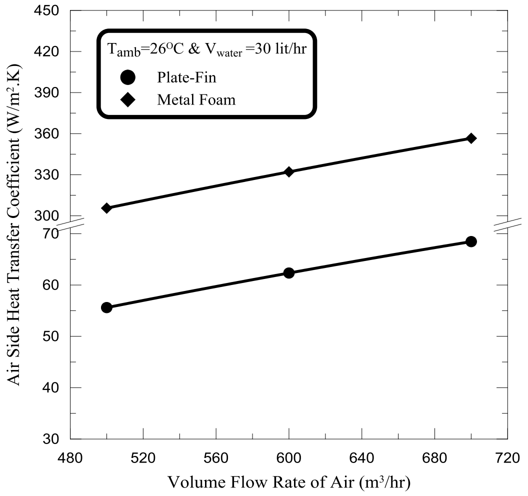

Fig. 2 Air-side heat transfer coefficient vs. volume flow rate of air through condenser

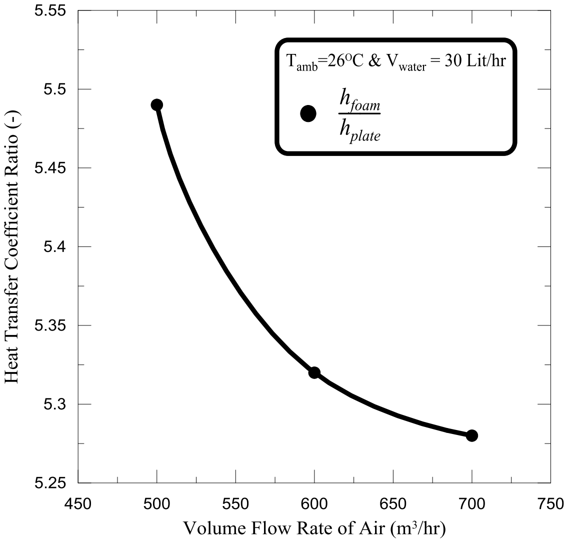

Fig. 3 Air-side heat transfers coefficient ratio vs. volume flow rate of air through Condenser

Fig. 4, shows the effect of ambient temperature on the air-side heat transfer coefficient, the figure shows that, as the ambient temperature increases the air-side heat transfer coefficient decreases slightly. This is because that the dissipated heat rate decreases as a result of a reduction in the temperature difference between the condenser surface temperature and outside air temperature. Also, it can be seen that the air-side heat transfer coefficient for metal foam condenser is much large than that for finned tube condenser.As the volume flow rate of air through condenser increases the rate of heat rejected from condenser increases also, as shown in Fig. 5, and, since the air side heat transfer coefficient for metal foam is greater than that for finned tube, the heat rejected from metal foam condenser increases significantly as compared with that rejected from finned tube condenser.

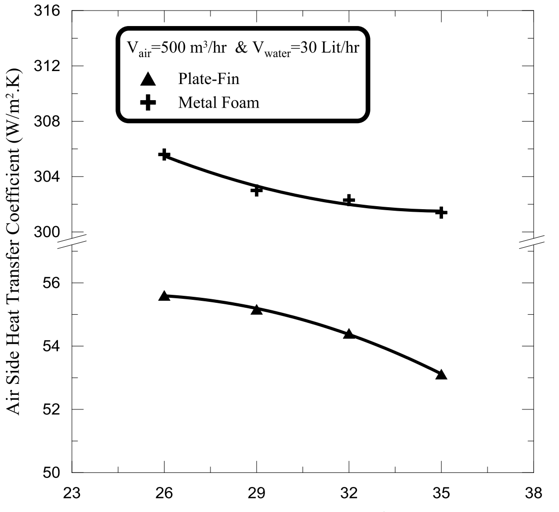

Fig. 4 Air-side heat transfer coefficient vs. ambient temperature through condenser

The increases in ambient temperature reflects negatively on the heat rejected from both foam and finned tube condensers, as shown in Fig. 5.

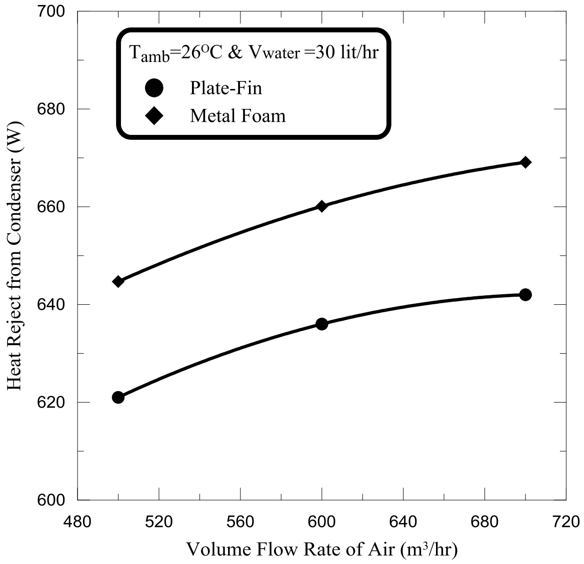

Fig. 5 Condenser heat transfer rate vs. volume flow rate of air through condenser

As the heat rejected from condenser increases, the power consumed by VCR compressor reduces, the more increases in heat rejected from condensers, mean less power consumed by compressor, as shown in Fig. 7, the figure shows that the compressor of VCR with metal foam condenser consumed less power as compared with that consumed by the compressor of finned tube condenser VCR. When the volume flow rate of air through both condensers equals 500m^3/hr, the saving in power consumption by compressor is 16.9%. Fig. 8 shows that the power consumption by the compressor increases with the increasing of ambient temperature, due to the reduction in heat rejected from condenser.

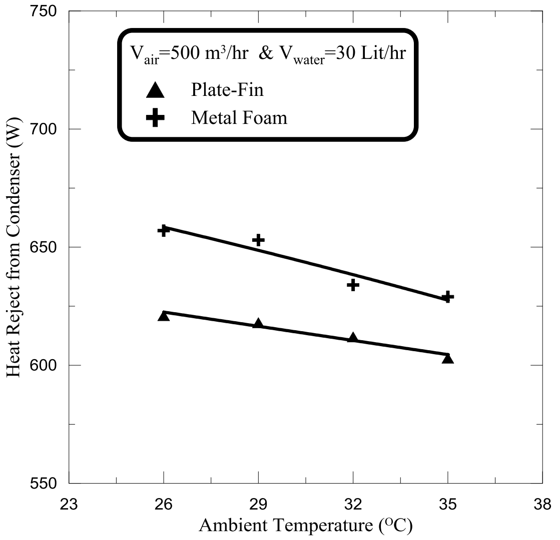

Fig. 6 Air-side Heat Transfer Rate vs. Ambient Temperature through condenser

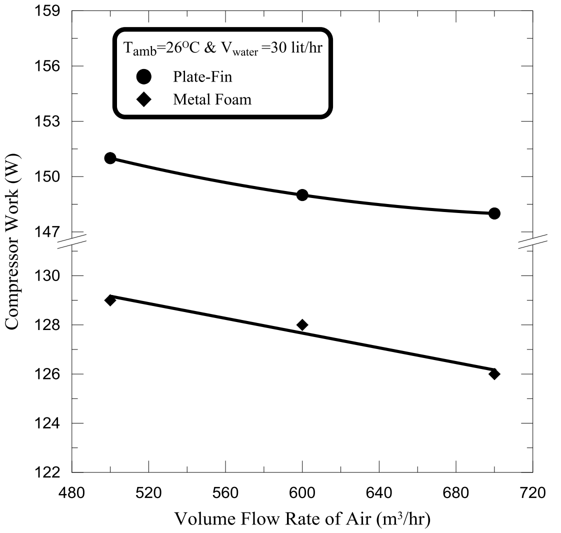

Fig. 7 Compressor work vs. volume flow rate of air through condenser

The coefficient of performance of vapor compression COP_{ref}, is defined as the ratio between the cycle capacity and compressor power consumption without including the power consumption by the fan. Fig. 8 shows the effect of volume flow rate of air through condenser on the COP_{ref}. It can be seen from the figure that, as the volume flow rate of air increases the COPref increases also, this is due to improvement in condenser performance as well as due to the reduction in compressor power consumption.

The COP_{ref} in finned tube improves from 3.09 to 3.33 as a result of increasing volume flow rate of air from 500 to 700 m3/hr. While COP_{ref} for metal foam increases from 4.11 to 4.29. Also, It is evident the COP_{ref} in metal foam condenser is much better than finned tube condenser at the same geometrically and operation condition. The COP_{ref} improve from 3.09 to 4.11, due to replacing finned tube condenser by 10 PPI aluminum metal foam condenser. The average percentage enhancement in COP_{ref} is 33%.

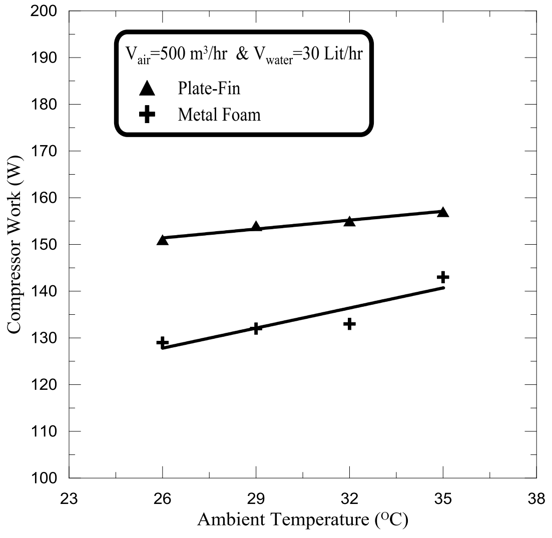

Fig. 8 Compressor work vs. ambient temperature

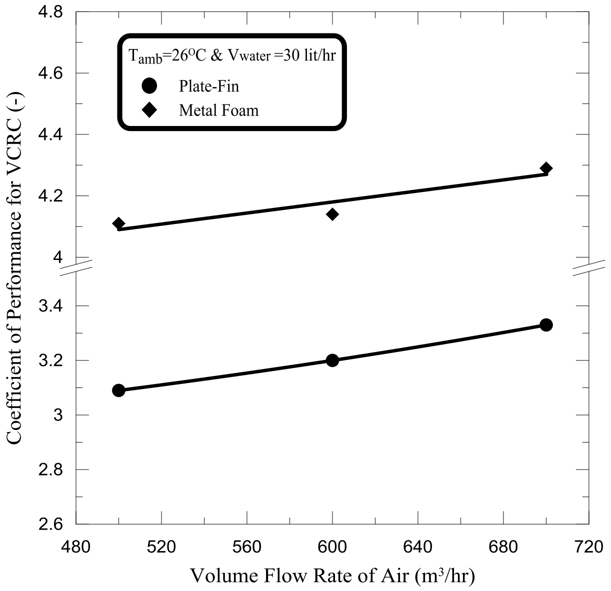

Fig. 9 Coefficient of performance for VCRC vs. volume flow rate of air through condenser

The power consumption by finned tube fan condenser is insignificant value, while when using metal foam condenser the power consumed by the condenser fan becomes significant due to increasing in pressure drop through condenser, as shown in Fig. 8. Thus, when including the fan power consumption, the coefficient of performance of the VCR (symbolized by the term COP_{sys},) reduces as compared with the COP_{ref}. Fig. 10 shows the effect of volume flow rate of condenser on the COP_{sys}, respectively, the trends of COP_{sys}, is just like for that shown in Fig. 7. The average percentage enhancement in COP_{sys}, is 19.36% as result of increasing volume flow rate of air through condenser.

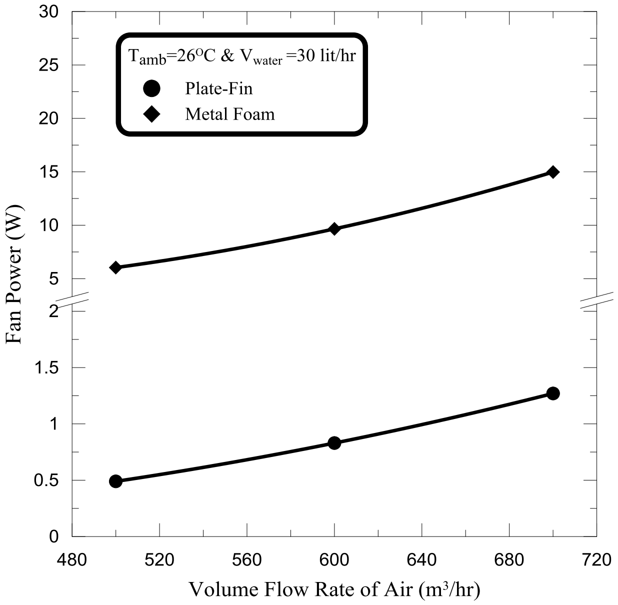

Fig. 10 Fan power vs. volume flow rate of air through condenser

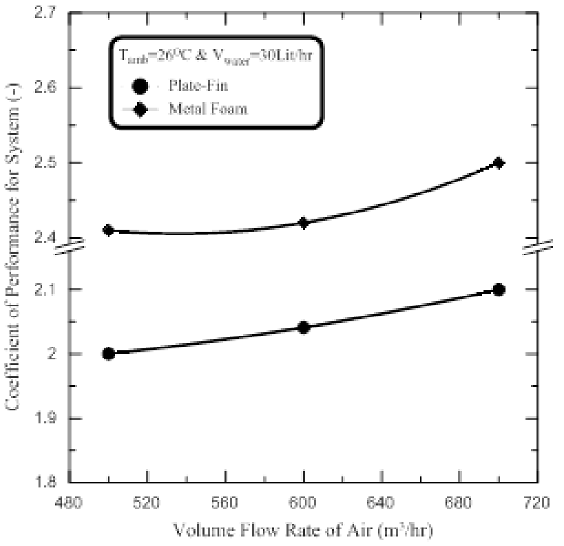

Fig. 11 Coefficient of performance for system vs. volume flow rate of air through condenser

Fig. 12 shows the variation of pressure drop versus volume flow rate of air through both finned tube and foam condensers. It observed that, the pressure drop through metal foam condenser increases rapidly with the increasing of volume flow rate of air, while pressure drop through finned tube condenser shows insignificant increases. The average percentage of losses in the pressure drop for 10 PPI metal foam condenser over the finned tube condenser is 1117% . Fig. 13 shown the variation of pressure drop ratio through metal foam condenser to that for finned tube condenser. It can be seen that, this ratio increases significantly with the increasing of volume flow rate of air, this is because the pressure loss through metal foam increases significantly with increase of volume flow rate of air as compared with the pressure drop through finned tube condenser.

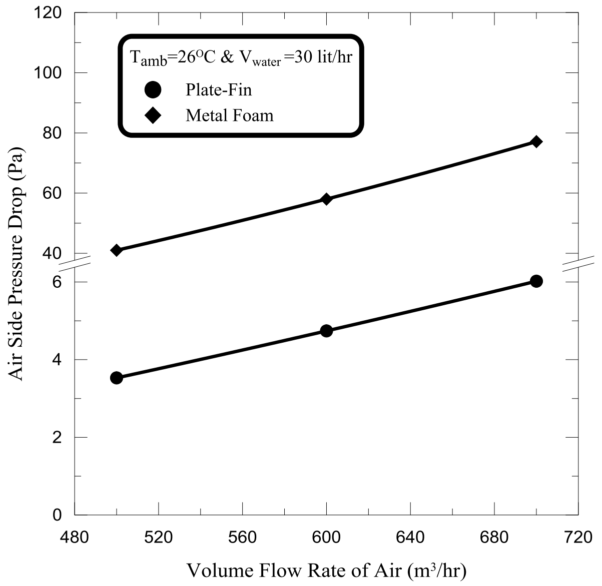

Fig. 12 Air-side pressure drop vs. volume flow rate of air through condenser

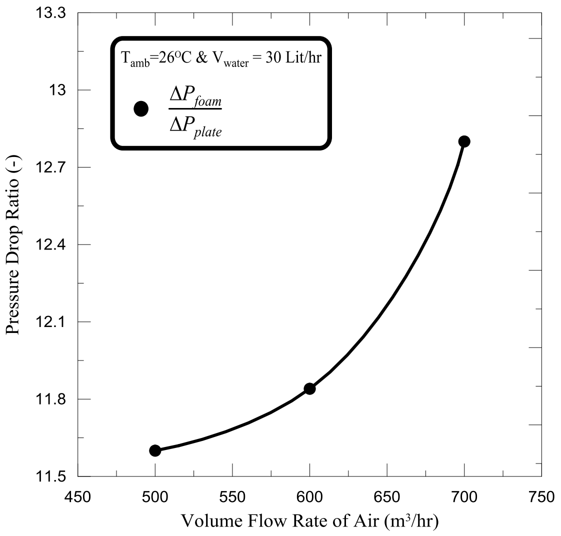

Fig. 13 Pressure drop ratio vs. volume flow rate of air through condense

In Fig. 14 it is observed that the pressure drop decreases with increase ambient temperature for both metal foam and finned tube condensers, this reduction occurs due to a reduction in air density. Again the pressure drop of the metal foam condenser is more than the finned tube condenser. Benefit Factor of the condenser (BF) is used to show the benefit of replacing the finned tube condenser by the following equation

$$BF = \frac{\frac{h_{foam}}{h_{plate}}}{\frac{\Delta P_{foam}}{\Delta P_{plate}}} \qquad (1)$$

Where:h_{foam}, h_{plate}: heat transfer coefficient for metal foam and finned tube condensers respectively (W/m^2 K) and ΔP_{foam}, ΔP_{plate}: air pressure drop through metal foam and finned tube condensers respectively (Pa.).

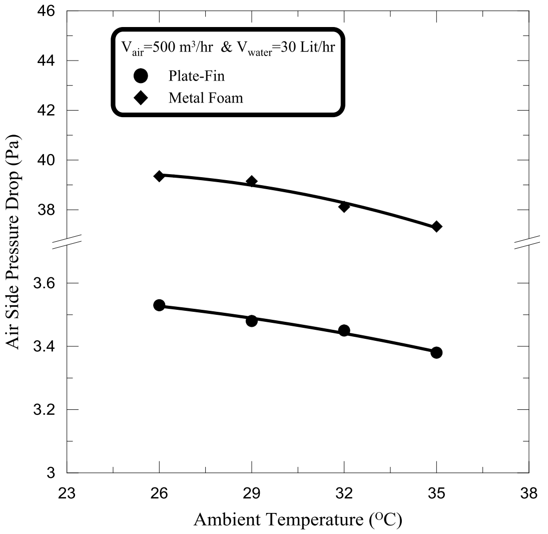

Fig. 14 Air-side pressure drop vs. ambient temperature

Fig. 15 shows the variation of benefits factor (BF) with volume flow rate of air. It is clearly that BF for all air flow rate range over condenser is less than one, which means that replacing finned tube condenser by metal foam condenser is a benefit. The BF decreases as air flow is raised, due to the loss in pressure drop through the condenser is much more than that improve in heat transfer coefficient. This means that enhancement of heat transfer is punished by pressure drop penalty.

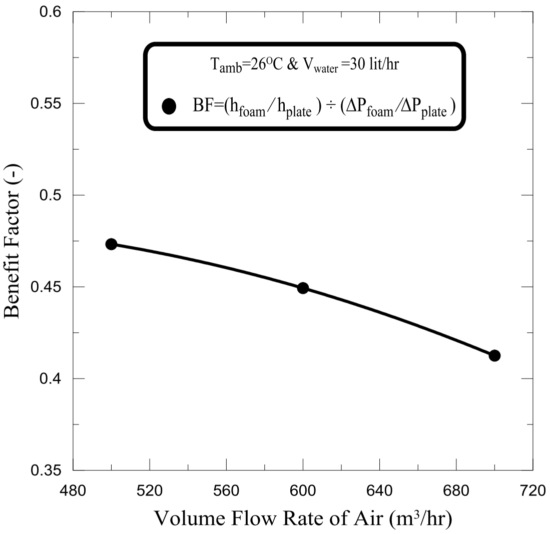

Fig. 15 Benefit factor vs. volume flow rate of air through condenser

Conclusions

Many conclusions can be derived from experimental results as follows:

1- Using metal foam can be improved the performance of metal foam condenser, the improvement in the range of air flow under study namely 500, 600 and 700 m^3/hr are as follow:
  a-The average enhancement in air-side heat transfer coefficient is 542%.
  b-The average enhancement in the heat transfer reject is 5.79%.
  c-The saving in power consumption by the compressor is 16.9%.
  d-The average enhancement in COPref is 33%.

2- Metal foam increases air pressure drop and fan power consumption as compared with that for finned tube condenser:
  a-The average percentage of losses in the pressure drop for 10 PPI metal foam condenser over the finned tube condenser is 1117%.
  b-The average percentage of increases in the fan power for 10 PPI metal foam condenser is1088%.

3- Benefit factor is a measure of the usefulness of using foam condenser on the finned tube condenser, if its value is less than one, this indicates that the feasibility of replacement finned tube by foam condenser, the BF for this work is ranging from 0.41 to 0.47, depending on the volume flow rate of air through condenser.

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