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Exergy Analysis of Refrigeration Cycle With Open-Cell Metal Foam Condenser

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***Abstract*—In this work, an attempt was made to replace a plate finned tube condenser of a simple vapor compression cycle by aluminum open-cell metal foams condenser. A simple vapor compression cycle, using refrigerant R134a. Many components were added to the vapor compression cycle to be suitable for studying the effect of volume flow rate of air through the condenser, condenser type, and ambient temperature on the exergy destruction, exergy efficiency of cycle components and overall exergy efficiency of foamed condenser. The obtained results compared with that obtained from finned-tube heat condenser. The finned tube condenser with 24 fins per tube, with dimensions 320×240×70 mm, was replaced by open-cell aluminum foam condenser for the study purpose. The porosity of the metal foam is 0.903 to 10 pores per inch (PPI). The results showed that replacing finned tube condenser by open-cell metal foam condenser, improving the exergy efficiency of the condenser by 120% and the exergy efficiency of the compressor by 32.25%. The exergy efficiency of the cycle is improved by 6.6%, reducing the exergy destruction in the compressor by 58.9% and increasing the exergy destruction in the condenser by 12.5%.**

Keywords—Exergy; Foam condenser; Vapor compression cycle; Second law efficiency

I. INTRODUCTION:

Today, many heat exchangers were manufactured from open cell metal foam; these heat exchangers are compact as compared with another type of heat exchangers. Many works were conducted to study the performance of metal foam as heat exchangers. Mansour studied the effect of some operational and geometrical design parameters for an air-cooled finned-tube condenser on the entire cycle exergy destruction, Musa and Hassan in 2007 [1], the finned tube condenser were a part of a vapor compression cycle for a rooftop bus air-conditioning system at a specified cooling capacity. Kurtbaş Nevin and Dinçer (2010) [2] investigated the heat and exergy transfer characteristics of forced convection flow through a horizontal rectangular channel where open-cell metal foams of different pore densities such as 10, 20 and 30 PPI were situated. All of the bounding walls of the channel subjected to various uniform heat fluxes. Six types of heat exchangers; three of them were aluminum foam heat exchangers, and the other three were aluminum fin heat exchangers were investigated by Sertkaya, Altınısık, and Dincer in 2012 [3]. The open-cell aluminum foam heat exchangers were of PPI 10, 20, 30 features and dimensions of 300×100×200 mm. The aluminum fin heat exchangers were of the same dimensions as the open-cell aluminum heat exchangers and with fin intervals of 1.6, 3.2, 4.8 mm. In 2013 Tian and Zhao [4] has been proposed a metal foam-enhanced cascaded thermal energy storage (MF-CTES), to solve the problem of poor heat transfer during the heat exchange process, which caused the unavoidable decrease of temperature differences. The work conducted a theoretical study examining the overall thermal performance of (Single-stage thermal energy storage, cascaded thermal energy storage and MF-CTES, with both heat exchange rate and exergy efficiency being considered. The thermal performance of open-cell aluminum foam heat exchangers was modeling using experimental data for the aluminum featuring with 10, 20 and 30 PPI were studied by Sertkaya et al. In 2016 [5]. Modeling based on the Artificial Neural Networks method. In this work, an attempt was made to replace a plate finned tube condenser of a simple vapor compression cycle by aluminum open-cell metal foams condenser. The experimental results were used to analyze the effect of key variables; on the exergy destruction of the cycle, components using finned tube and metal foam condensers. The key variables are volume flow rate of air through the condenser, ambient temperature.

II. THEORY

The obtained data from a simple vapor compression cycle produced by Gunt Company used for exergy analysis. The vapor compression cycle modified by adding many components to be suitable for studying the exergy performance of foamed condenser and compared the obtained results with that of the finned-tube heat exchanger. Fig.(1) shows

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the experimental test rig and the locations of temperature and pressure measurements. The cycle consists of a hermetic reciprocating compressor, working on R134a, of a capacity of 386 W. The condenser was Plate-finned tube condenser with 24 fins per tube, of dimensions of 320×240×70 mm. Two open cell foam sheets were used, each of 320 mm height, 240 mm width, and 35 mm thickness, the two sheets were collected together to form the condenser thickness. The porosity of the metal foam is 0.903 with 10 pores per inch (PPI). As in the old plate finned condenser, there were nine copper tubes of 12.3 mm in diameter per row and two tubes per column, while the distance between two neighbored pipes is 36.3 mm.

Due to the higher value of air pressure drop through metal foam condenser, the old axial fan that used to deliver air to through the air cooled condenser replaced by a variable speed centrifugal made by Edison Company, Spain. PC can control the speed of the fan up to 3000 rpm. The exergy balance equation can be written as [6]:

$$\frac{d\psi}{dt} = \sum \dot{Q}_{CV}.\left(1-\frac{T_0}{T}\right) - \sum \dot{W}_{CV} + P_0\frac{dV}{dt} + \sum \dot{m}_i.\psi_i - \sum \dot{m}_e.\psi_e - T_0.\dot{S}_{gen.} \quad (1)$$

The work input to compressor is:

$$\dot{W}_{comp.} = \dot{m}_r(h_2 - h_1) \quad (2)$$

And the exergy destruction and exergy efficiency of compressor are [7]:

$$\Psi_{dest.comp.} = \dot{m}_r.(\psi_1 - \psi_2) + \dot{W}_{comp.} \quad (3)$$

$$\eta_{ex_{comp}} = \frac{\dot{m}_r.(\psi_2-\psi_1)}{\dot{W}_{comp.}} \quad (4)$$

The heat rejected from condenser is:

$$\dot{Q}_{cond.} = \dot{m}_r.(h_2 - h_3) \quad (5)$$

The exergy destruction and exergy efficiency of condenser are [8]:

$$\Psi_{dest.cond.} = \dot{m}_r(\psi_2 - \psi_3) + \dot{m}_{air}(\psi_9 - \psi_{10}) \quad (6)$$

$$\eta_{ex_{cond}} = \frac{\dot{m}_{air}(\psi_{10}-\psi_9)}{\dot{m}_r(\psi_2-\psi_3)} \quad (7)$$

The exergy destruction and exergy efficiency of the adiabatic expansion valve are [9]:

$$\Psi_{dest.exp} = \dot{m}_r(\Psi_3 - \Psi_4) = T_o\dot{S}_{gen.} \quad (8)$$

$$\eta_{ex.exp} = \frac{\Psi_4}{\psi_3} \quad (9)$$

The heat received in the shell and coil evaporator is:

$$\dot{Q}_{evap.} = \dot{m}_r.(h_1 - h_4) \quad (10)$$

While the exergy destruction and exergy efficiency of evaporator are [10]:

$$\Psi_{dest.evap} = T_o\dot{S}_{gen.} = \dot{m}_r(\Psi_4 - \Psi_1) + \dot{m}_w(\Psi_5 - \Psi_6) \quad (11)$$

$$\eta_{ex.evap} = \frac{\dot{m}_w(\psi_6 - \psi_5)}{\dot{m}_r(\psi_4 - \psi_1)} \quad (12)$$

The overall exergy destruction of the refrigerant system can be calculated by assuming the overall vapor compression cycle as a control volume [9], and apply the exergy flow equation to the control volume as shown in Fig. (2).

$$\Psi_{dest.tot.} = Q_{cond}\left(1-\frac{T_o}{T_{cond}}\right) + Q_{evap}\left(1-\frac{T_o}{T_{evap}}\right) - \dot{W}_{comp.} - \dot{W}_{fan.} - \dot{W}_{pump.} \quad (13)$$

Then the overall exergy efficiency of the vapor compression cycle is:

$$\eta_{ex,overall} = 1 - \frac{\Psi_{dest.tot.}}{\dot{W}_{comp.}+\dot{W}_{fan.}+\dot{W}_{pump.}} \quad (14)$$

III. Result and Discussions

Fig. 3 shows the exergy destruction through both open-cell aluminum foam and finned tube condensers; it can be seen from the figure that the exergy destruction through foam condenser is much more than that for finned tube condenser, this is due to that foam condenser dissipated more heat as compared with the finned tube condenser. As well as, the foam condenser exergy destruction affected positively with the increasing of volume flow rate of air, while finned tube condenser shows an insignificant effect on the volume flow rate of air because the capacity of this type of condenser is limited to a given volume flow rate of air. The exergy destruction of aluminum foam condenser is approximately 1.15 times of plate-fin condenser. Since the objective of a condenser in a vapor compression cycle is to dissipate heat, therefore the more dissipation of heat means the more exergy destruction, or in the other word, means the more exergy efficiency, as shown in Fig. 4.

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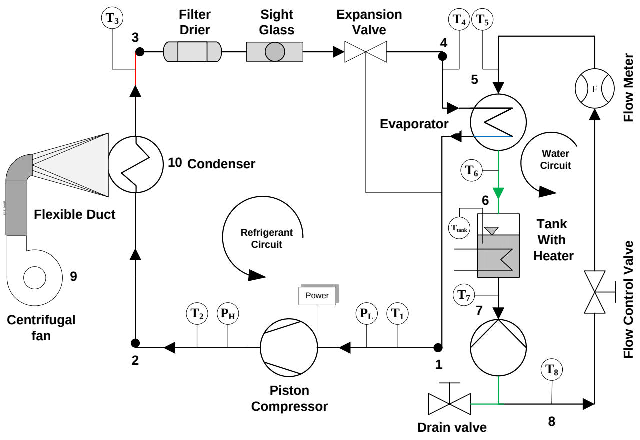

Fig. (1) Schematic Diagram of the test rig

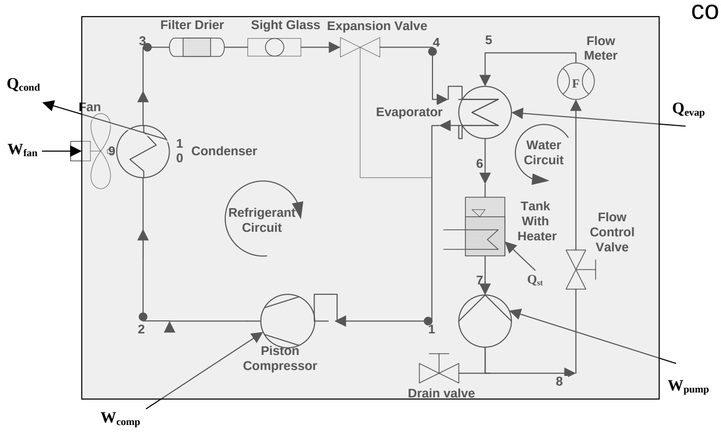

Fig. (2) Vapor compression cycle as a control volume

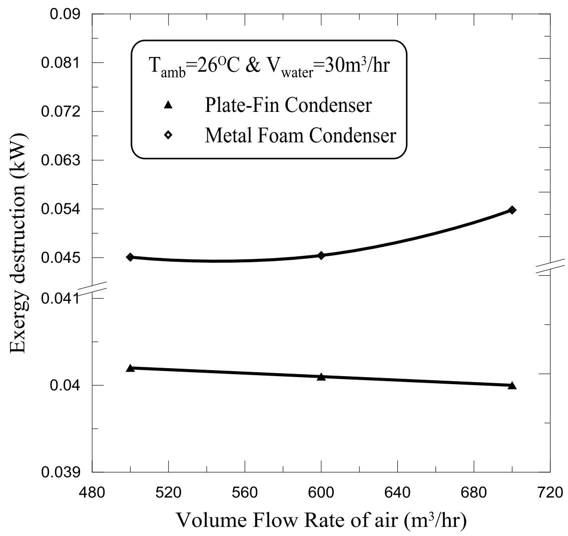

Fig. 3 Effect of volume flow rate of air on the condenser exergy destruction

Fig. 5 show the variation of the exergy destruction for each cycle components. It can be seen that the exergy destruction in compressor for plate-fin condenser unit is more than that for the compressor in metal foam condenser cycle, due to increasing the degree of superheating of refrigerant vapor leaving compressor, the improve in compressor exergy destruction is about 12.5% as plate finned condenser is replaced by metal foam condenser. The same trends can be seen for the water pump, due to reducing in refrigeration effect when using finned tube condenser instead of foam condenser, which reflects on the specific volume of water through the water pump. As mentioned in Fig. 3, that the exergy destruction in metal foam condenser is greater than that for finned tube condenser. The exergy destruction the expansion valve is insignificant compared with other components due to an increase of the degree of sub-cooling of refrigerant leaving the foam condenser [11]. The exergy destruction in the evaporator for the plate-fin condenser cycle is more than metal foam condenser. The exergy destruction in the storage tank decreases from 0.031 to 0.027 kW. It can be noted the exergy destruction in the plate-fin condenser is more than metal foam condenser.

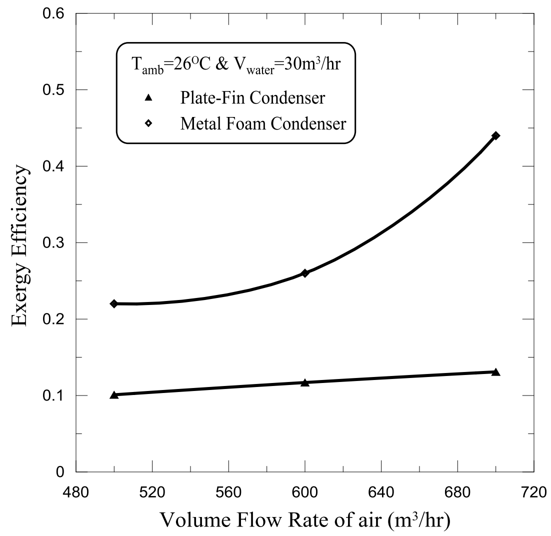

Fig. 4 Effect of volume flow rate of air on the condenser exergy efficiency

Fig. 6 shows the exergy efficiency for each component of the system. The using metal foam condenser can lead to the following improve; increasing the exergy efficiency of the compressor from 0.62 to 0.82, condenser from 0.1 to 0.2, and water pump from 0.61 to 0.66. While decrease exergy efficiency of expansion valve from 0.93 to 0.92, evaporator from 0.33 to 0.26 and storage tank from 0.97 to 0.82.

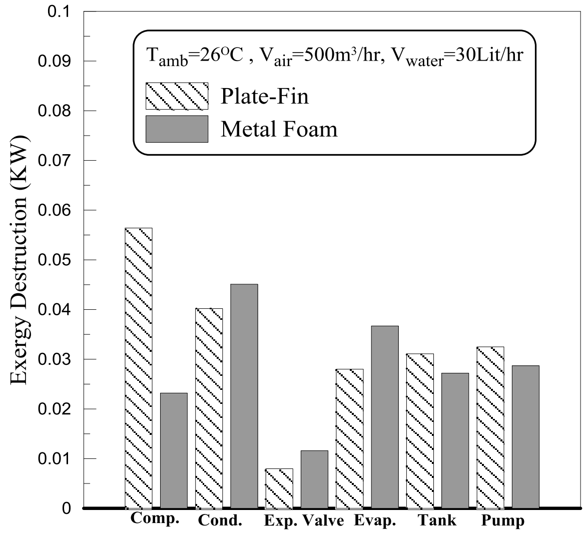

Fig.5 Exergy destruction in cycle components

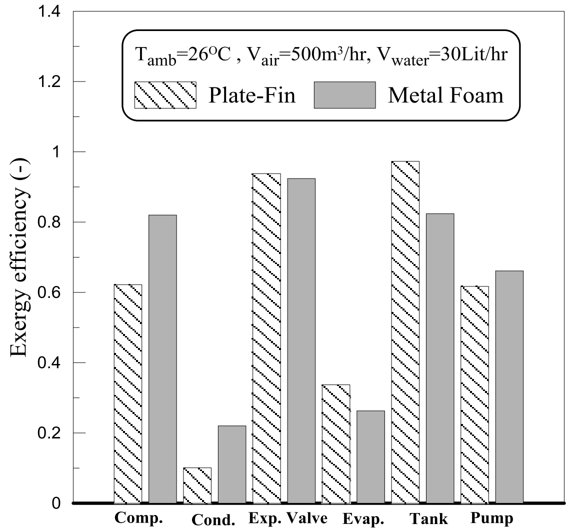

Fig. 6 Exergy efficiency of cycle components

The exergy efficiency of the refrigeration cycle is shown in Fig. 7. It can be noted seen from the figure that the improvement in the cycle condenser performance is reflected positively on the cycle exergy efficiency, the percentage of enhancing is about 28%. As the volume flow rate of air through condenser increases the exergy efficiency of the refrigeration cycle increases also.

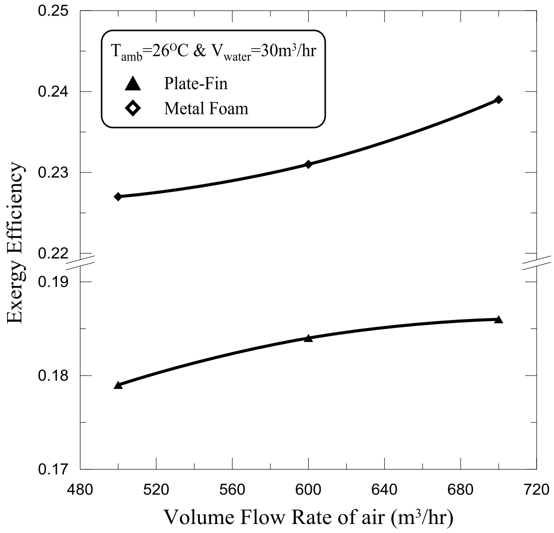

Fig. 7 Effect of volume flow rate of air on the overall system exergy efficiency

Ambient temperature affected both exergy destruction and exergy efficiency of the cycle and its components. It can be seen from the Fig. 8 that the exergy destruction of the cycle (for both condensers) increases with the increasing of ambient temperature. Increasing in exergy destruction reflects negatively on the overall exergy efficiency of the cycle, as shown in Fig.9.

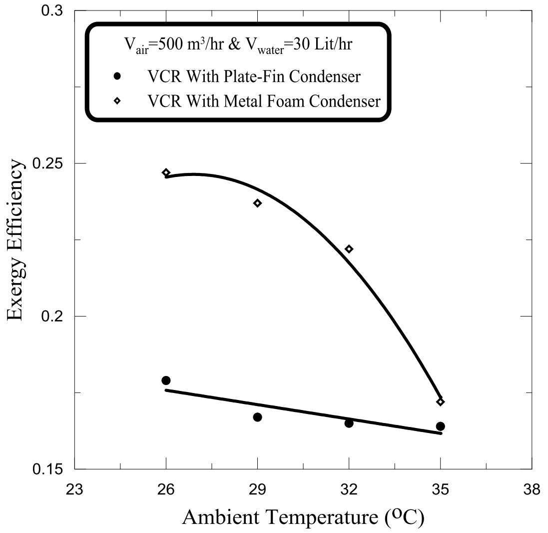

Fig. 8 effect of ambient temperature on the system exergy efficiency

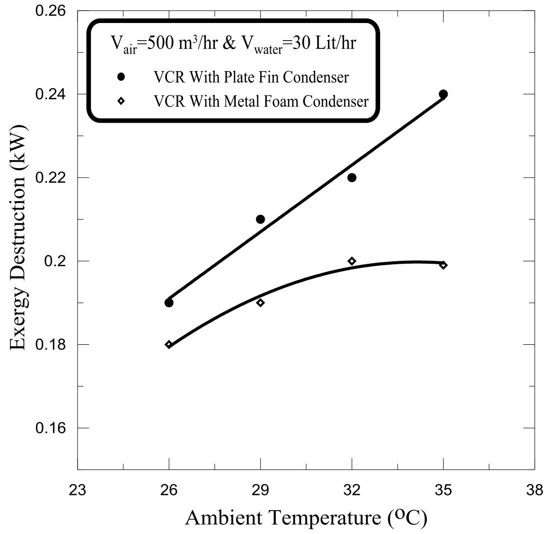

Fig. 9 Effect of ambient temperature on the exergy destruction through cycle

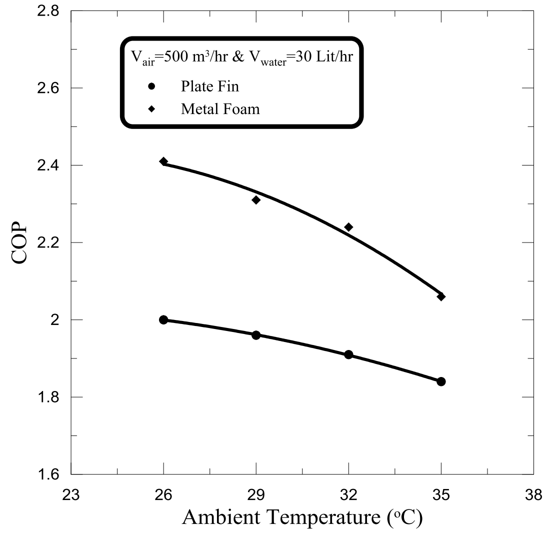

Fig. 11 Effect of ambient temperature on the COP system

Figure 10 shows the effect of volume flow rate of air on the cycle COP; it can be seen from the figure that the COP of the cycle with foam condenser is greater than that for the cycle with finned tube condenser since the increasing of heat rejected from condenser improves both refrigeration effect and compressor input work. This fact applies to the effect of volume flow rate of air through condenser on the cycle COP, as shown in the figure mentioned above. As the ambient temperature increases the amount of heat rejected from condenser decreases, which means more power consumption by the compressor and less cycle capacity, in the another word, less COP, as shown in Fig. 11.

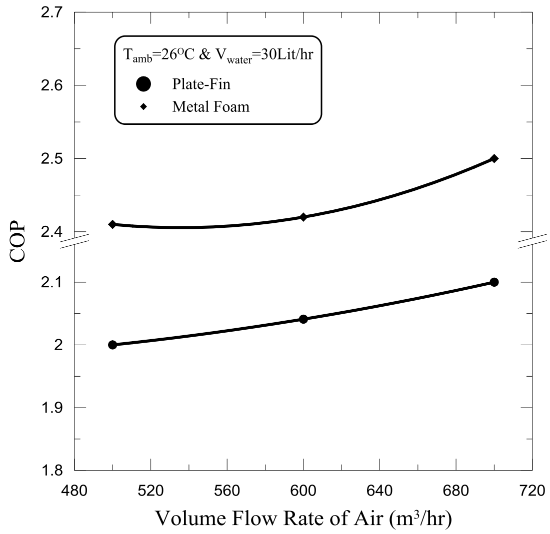

Fig. 10 Effect of volume flow rate of air on the cycle COP

IV. Conclusions:

Replacing finned tube condenser by open-cell metal foam condenser have the following effects: Improving the exergy efficiency of the condenser by 120% and the exergy efficiency of the compressor by 32.25%. Improving the exergy efficiency of the cycle by 6.6%. Reducing the exergy destruction in the compressor by 58.9% and increasing the exergy destruction in the condenser by 12.5%.

Symbols:

$\dot{m}_{air}$: mass flow rate of air through condenser (kg/s)
$\dot{m}_r$: mass flow rate of refrigerant (kg/s)
$\dot{m}_w$: mass flow rate of water through evaporator (kg/s)
P_0: Dead state pressure (kPa)
$\dot{Q}_{CV}$: heat flow from control volume (kW)
$\dot{S}_{gen.}$: Entropy generation rate (kW/K)
T: Control volume temperature (K)
T_0: dead state temperature (K)
$\dot{W}$: Power consumed (kW)
ψ: Exergy flow (kJ/kg)
$\Psi_{dest.}$: Exergy destruction (kW)

$\eta_{ex_{comp}}$: Exergy efficiency

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