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International Journal Of Modern Engineering Research (IJMER)

Development and Experimental Analysis of Waste Heat Recovery of Heat Pump

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ABSTRACT : *In vapor compression machine (VCM), heat generated in condensation of refrigerant is wasted. In proposed model, heat generated from condenser coil in refrigeration cycle is used to heat water. Besides circulating cool air in constrained area, there is also one more innovative way to create potable water from environment by collecting condensed water from evaporator coil. By working on evaporator heat exchanger, it is made possible to condense considerable amount of moisture present in moist air into useful water (5 kg/day). The scaled down prototype has been developed to conduct experiments. Experiment is conducted and theoretical calculations were validated with experimental values. Hence, computational simulation is not carried out. Thus, an efficient way is developed to use waste heat from refrigeration cycle by end output as, hot water, cool air and potable water.*

Keywords: *Atmospheric water generator, multipurpose heat pump, space cooling, total coefficient of performance, water extraction*

I. INTRODUCTION

In hotels and hospitals, there is requirement of hot water for cleaning and sterilization of equipments or utensils. There is also requirement of cool air for space cooling. This space cooling may be a room or hall or a close refrigeration unit to preserve contents of product (similar to refrigerator). They use dedicated heating source such as heater or liquid petroleum gas to heat the water. Also, for space cooling they use dedicator freezers, air conditioning unit or a chiller. Therefore, it is essential to make a machine which fulfils or combines both requirements of heating of water and space cooling. Also, it is possible to collect the condensed water droplets from evaporator heat exchanger thus making it atmospheric water generator. Generation of water is beneficial as water scarcity is increasing day by day. Therefore, this work focuses on development of a multipurpose heat pump to recover waste heat with vapour compression cycle and experimentally tests it according to requirements.

II. LITERATURE SURVEY

M. Kumar and M. Chougale [1] presented a paper on use of heat pump with multi utilities functions. The primary objective of this paper is to identify practically by experimentation, efficient mode of operation for multi utility heat pump. The operating modes were air conditioning only; Water heating + air conditioning mode; water cooling + air conditioning mode and water heating + water cooling + air conditioning mode. The finding of this research is heat pump operates most efficiently in air conditioning + water heating mode. The COP was 2.86, also percentage reduction in power consumption highest at 24.06%. The possibility of tapping potable water from air is explored in this paper.

R. Vali and V. Reddi [2] presented a research paper on experimental and performance investigation of refrigeration system with helical geometry type condenser heat exchanger coil by using R-134a and R-410a refrigerants; objective of this research was to identify best coil geometry for efficient heat transfer in condenser. Primary objective is to develop helical coil, manufacture it and lab tests it with existing refrigerator. The result was encouraging to use R-410a than R-134a due to its superior properties viz. high refrigeration effect and thus better C.O.P. Comparison of this modified system with original system showed that performance of refrigerant helical coil is better than old refrigerant coil.

U. Kongre, P. Dhumatkar, A. Chiddarwar and A. Aris [3] studied air conditioner cum water dispenser system. Experimental setup is build for heat pump which can deliver hot and cold water, hot and cold air. Thus making it the multi functional machine. Heat pump is experimentally tested and assessed its performance behavior. It is concluded that utilizing combination of air conditioner and heating of water is best way in terms of efficiency in multi functional heat pump. It is noted that cooling COP first increases and then decreases. While heating efficiency remains constant after certain time.

M. Kim and J. Chung [4] presented a paper on Transient thermal behavior of a water system driven by heat pump. Objective of this research is to identify and minimize heat losses in heat pump to robust heat pump water heater design. Finite volume method was applied to describe heat exchangers and consolidated parameter models were utilized to examine the compressor and hot water reservoir. The result of simulation showed that, the smaller size of the water reservoir had higher transient performance degradation and the larger size of the water present in tank caused additional heat loss due to storage of hot water over a time. Since hot water storage requires heat to maintain its temperature, causes consumption of additional heat power. Therefore, the reservoir size should be optimized in a design phase to minimize both performance degradation and heat losses.

Willy Adriansyah [5] extensively studied combined air conditioning and tap water heating, using CO_2 as a refrigerant. Author have designed the system, developed a computer program and experimentally proved all data. Study has been done on Ratio of hot water load and heat rejected by air conditioning system, cold water temperature, hot water temperature, evaporator temperature, discharge pressure and suction pressure of compressor and presence of intermediate heat exchanger. Further, optimum pressure is found out on the basis of Coefficient of performance (COP) and cooling capacity. It concludes that as water temperature increases, system performance decreases and COP increases when intermediate heat exchanger is deployed and system performance deteriorate when refrigerant cooling media temperature rises (condenser temperature).

D. Eriksson and R. Hashemi [6] presented research paper on evaluation of suitable methods for water generation. Primary objective is to explore possibility of water generation through vapor compression cycle. The model is conceptualized and then builds the prototype to check its feasibility. It is concluded that, low relative humidity leads to poor performance of machine.

V. Gao and F. Chen [7] had presented a paper on CFD analysis and experimental testing of buoyancy-driven convection caused due to condensers submerged in a water tank of HPWH. The primary objective of this paper is trace temperature distribution of HPWH tank. The result showed that when condenser coil in tank was in vertical-shape, there was a temperature difference of 160^0C from top to bottom. But, when the coil was in L-shape, the temperature differential was null.

A. Hepbasli and Y. Kalinci [8] reviewed heat pump water heating systems, the main objective of this study is to review every study published in a period of 1976 to 2007 associated with HPWH. Motivation behind research was that the energy analysis method was used in most of researches, while the number of researchers who conducted study on exergy analysis was very low. Therefore, energy and exergy analysis is presented for the performance assessment of the HPWH machines. Suitable balance (mass, energy and exergy) equations are developed for steady state, constant-flow controlled volume systems and parts.

B. Aye and D. Wu [9] researched on drinking water sourced from air, its modeling and computational simulation of a solar power driven atmospheric water generator. The primary objective of this study is setting up a heat pump powered by electricity generated by solar PV panels with measurement devices across system. They chose Kasaragod district in Kerala for research due to superior atmosphere to conduct experiment. Kasaragod is classified under hot and humid conditions throughout the year. The experiment was operated for complete one year, and reading of each day was noted. The maximum water extraction efficiency is 9.3% for the month of July and August.

S. White and D. Cleland [10] had presented a paper on heat pump for concurrent refrigeration and water warming. The objective of this research is to produce refrigeration and hot water, specifically required for food industry with optimization of specific parameters to make it practically feasible and costs compelling with low capital cost for New Zealand market. Refrigerant used is CO_2. It is concluded that, combining operations in a single machine reduces energy costs by 33%. COP is also increased by 10% stands at 3.00. It is proved that optimum operating temperature of condenser as 60^0C. Methodology was simulation of thermodynamic properties of CO_2 with boundary condition as: Evaporator temperature was set at -5^0C and Hot water temperature varied from 15^0C to 90^0C. Additional cycle is performed at 65^0C to verify optimum operating conditions of heat pump.

Water can also be generated from Solar chilling. Simulation model of solar chilled drinking water is developed and simulated with one year data collected at Kasaragod, Kerala. Efficiency of water extraction from moist air with the help of solar energy, is noted as only 7% [9]. Heat pump is designed for New Zealand climate for food process industries; however achieved COP is close to 3 with carbon dioxide as a refrigerant6. Also it is proved that reduction in hot water temperature leads to increase in COP.

Performance evaluation has been carried out to prove helical geometry is better than U shape geometry in domestic refrigerator context. R134a leads to 25% decrease in compressor power consumption [2]. Results are encouraging to use helical coil geometry for condenser heat exchanger. It is also proved that R134a is better than

R410a in terms of compressor power consumption, heat rejection and low cost of refrigerant. R134a is developed to substitute R12. In low cooling capacity machines, mostly R134a is used. Examples can be given as refrigerators, automobile air conditioning systems etc. R134a have less global warming potential than R410a hence it is more eco- friendly than R410a.

It is also evident that helical geometry type coil have better uniform heat flux distribution in water tank. Potable water from evaporator can be extracted by calculating dew point temperature from relative humidity and ambient temperature provided that evaporator temperature is lower than dew point temperature so water molecules from moist air can condensate on evaporator fins. Extraction of water depends more on air speed over evaporator rather than its area. From the literature survey, it is evident that although combined heating and cooling application heat pump is developed, it is not eco-friendly due to its refrigerant (R410a). Hence, the efforts are made to make the eco-friendly heat pump for heating and cooling applications with R134a since R410a is have higher global warming potential.

III. MULTIPURPOSE HEAT PUMP OPERATION

3.1 Problem Statement

System design parameters are as follows:

i. Hot water temperature: Above 55^0C
ii. Cool air temperature: Below 26^0C
iii. Water extraction rate: 5 kg/day

3.2 Operation

3.2.1 Water extraction and space cooling

Refrigerant evaporates in evaporator by absorbing latent heat from surrounding forced air (fig. 3). Therefore, air is cooled & refrigerant becomes warm. This cooled air can be used to space cooling. In this process, the moisture present in moist air gets condensed on evaporator heat exchanger due to temperature of evaporator which is less than dew point temperature and thereby water gets collected in water extraction tank by gravity (fig. 1). This water is extracted from air hence, it may be potable. Thus, this process may be termed as atmospheric water generator by vapor compression cycle. Two temperature sensors are attached across evaporator refrigerant coil and one at just outside of evaporator heat exchanger.

3.2.2 Water heating

The warm refrigerant suctioned in compressor from evaporator and discharged at high temperature and at high pressure to condenser. Refrigerant gives up its latent heat to water present in condenser around refrigerant coil. Thus, refrigerant loses its latent heat and it gets condensed. In this process, water gets heated. In this model, condenser is considered as a water tank (fig. 2). Helical coil maximizes heat rejection therefore refrigerant flows through helical coil in condenser. Then, condensed refrigerant passes through capillary tube. This device lowers pressure of refrigerant and hence, temperature also gets lowered. This refrigerant again goes to inlet of evaporator and thus the cycle continues. Two temperature sensors are attached across condenser on refrigerant coil and two in condenser water tank (one at top surface and other at bottom surface). 15 kg water holding capacity condenser is designed for experimentation. Complete experimental setup can be found in (fig. 4).

IV. DESIGN CALCULATIONS

At, Ambient room temperature T_0= 31.4^0C and relative humidity, R.H=74%, therefore, 12 gm of water is present in 1 kg of dry air by mass [11].

Assume water extraction efficiency by vapor compression cycle as 40%. Therefore, to extract 5 kg water per day considering efficiency, air required to extract water is given by,

$$\text{Re}\,quired\,air\,quanity = \frac{Water\ \ to\ be\ Extracted\ \ (kg)}{Efficiency\ \ x\ Humidity\ \ Ratio\ \ of\ \ moist\ air\ \ by\ \ mass(kg/kg)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Eq.(1)$$

$$Condenser\ work = \dot{m}_w\,x\ C_{p_{(w)}}x\ \Delta T_w \ldots\ldots\ldots \text{Eq. (2)}$$

Where,

$\dot{m}_w$ = mass of water
$C_{p(w)}$ = Specific heat of water
ΔT_w = Temperature difference of water in condenser

Nusselt number for free convection-external flow is given by Churchill and Chu correlation ($Ra < 10^9$) as (for condenser side water calculation) [12],

$$N_u = \left\{ 0.68 + \frac{0.67\ x\ R_a^{1/4}}{\left[1 + \left(\frac{0.492}{P_{r_{avg}}}\right)^{\frac{9}{16}}\right]^{\frac{4}{9}}} \right\}$$

Nusselt number for forced convection for tube flow geometry with restrictions as ($0.6 < Pr < 100$) and ($1.5 < Re < 1.25 \times 10^5$), the relation is given by, (for condenser side refrigerant calculation) [12],

$$Nusselt\ Number, N_u = 0.023\ x\ \mathrm{R_e}^{0.8}\ x\ P_r^{0.3}$$

We know that,
Heat absorbed by water = Heat rejected by refrigerant

$$m_w\ C_{p_w} \Delta T_w = U\ A_c\ \Delta T_r$$

$$Area\ of\ coil, A_c = \frac{m_w\ C_{p_w} \Delta T_w}{U\ \Delta T_r}$$

Where,
U = Overall heat transfer coefficient for condenser
ΔT_r = Temperature difference of refrigerant in condenser
To decide length (L) and number of turn of condenser coil (N),
We have,

$$A_c = \pi\ d\ L$$

$$L = \pi\ D\ N$$

$$Coefficient\ of\ Performance, C.O.P. = \frac{\mathrm{Re}\ frigeation\ \ Effect\ (W)}{Electrical\ \ power\ input\ to\ compressor\ (W)} \text{..................................} Eq.(2)$$

$$Coefficient\ of\ Performance, C.O.P. = \frac{\mathrm{Re}\ frigeation\ \ Effect\ (W) + Heating\ \ Capacity(W)}{Electrical\ \ power\ input\ to\ compressor(W)} \text{..............................} Eq.(3)$$

V. Experiment Test Setup

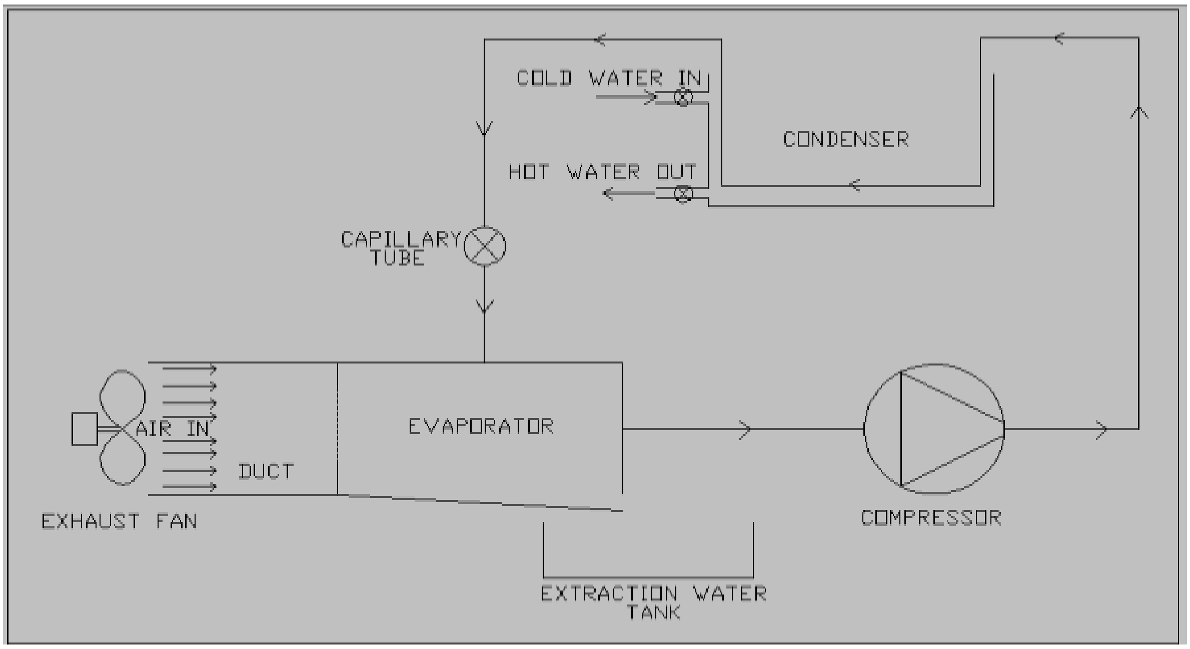

Fig.1: Schematic diagram of test setup

Fig. 2: Condenser

Fig 3: Evaporator

Fig. 4: Complete test setup

Experimental setup consists of compressor (97 W), water tank, capillary tube, evaporator, refrigerant (R134a), water collection tub, exhaust fan, temperature and humidity sensors (fig. 4).

VI. RESULTS AND DISCUSSIONS

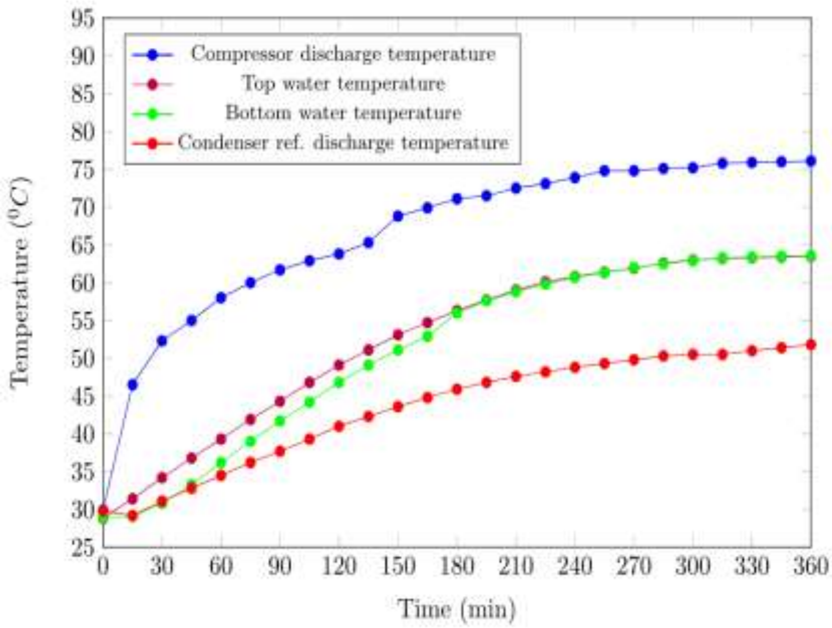

Fig. 5: Temperature profiles across condenser

The experiment observations are carried out in transient state and discontinued when steady state is achieved. The temperature profile is drawn across condenser tank where refrigerant temperature and water temperature is noted down. It is concluded that from fig. 5, water temperature almost equal to average temperature of refrigerant temperatures across condenser. Also, both water temperature (top and down) coincides at 175 minute. Meaning, 15 kg of water is heated from 28^0C to 55^0C in 175 minutes.

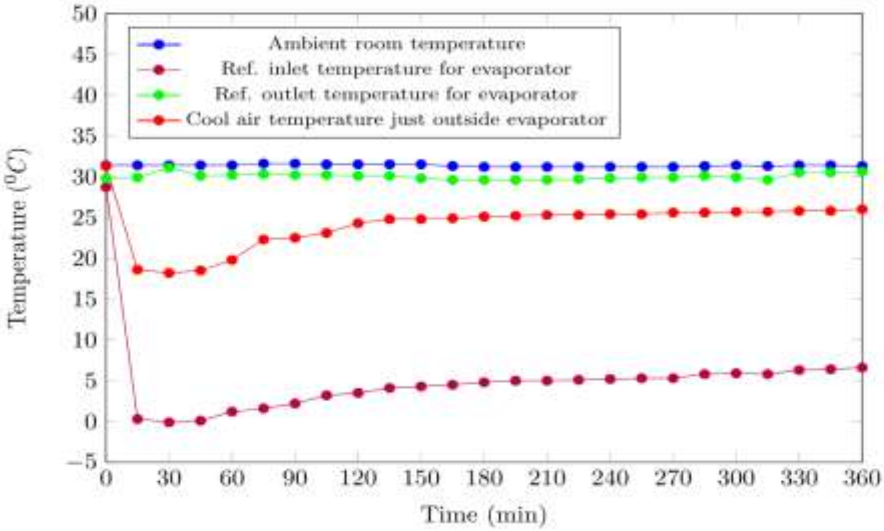

Fig. 6: Temperature profiles across evaporator

From fig. 6, the temperature profile is drawn across evaporator where refrigerant temperature and cool air temperature is noted down. It is concluded that cool air temperature is below dew point temperature (26.3^0C) which was calculated according to relative humidity and ambient room temperature at the time of performing experiment. Therefore, moisture from moist air gets condensed on evaporator heat exchanger. Water extracted in 6 hours of experimentation is 1.2 kg.

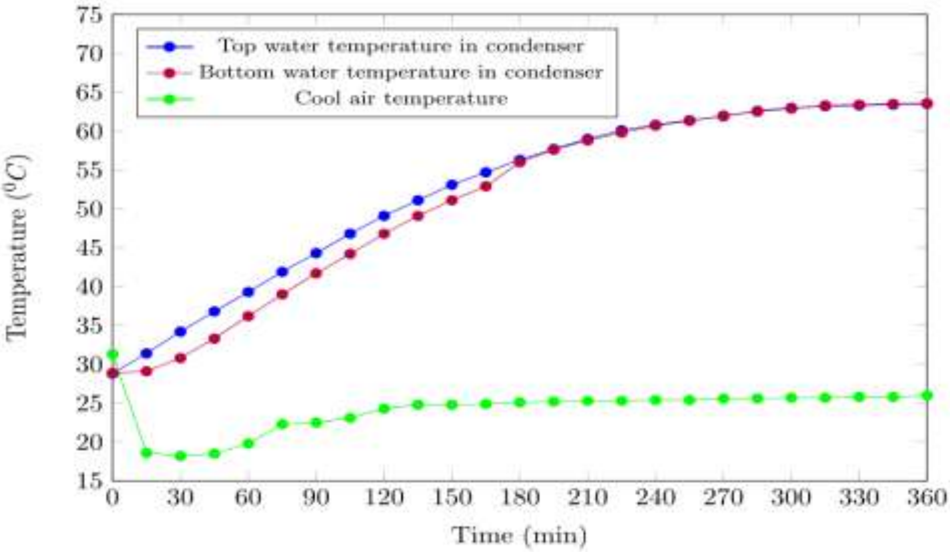

Fig. 7: Hot water and cool air temperature

From fig. 7, it is concluded that 15 kg of water is heated to 55^0C in 175 minutes and air is cooled from 31^0C to 25^0C. Thus, experiment indicates that the primary objectives are achieved. The coincidence of top and bottom water temperature is due to density of water in condenser. Since, if water is subjected to heat from top surface then density of top surface water decreases because of heat thus creates density differentials at different depths. When the density of water gets even throughout the tank then it signifies that water is at same temperature.

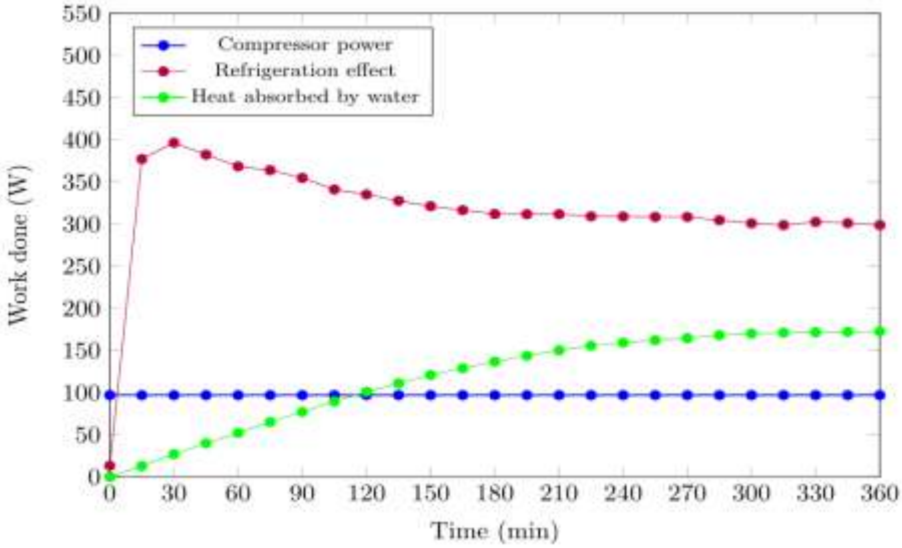

Fig. 8: Refrigeration effect and heat absorbed by condenser

From fig. 8, it is observed that initially refrigeration effect peaks up but shortly it starts to decline uniformly. But, in contrast heat absorbed by water continue to rise uniformly throughout the experimentation. Investigation reveals that, rise in refrigerant temperature from evaporator is the reason behind rise of water temperature. Meaning is that, if refrigerant's average temperature in system increases then water temperature and cool air temperature is also increases. Compressor power is constant at 97 Watts.

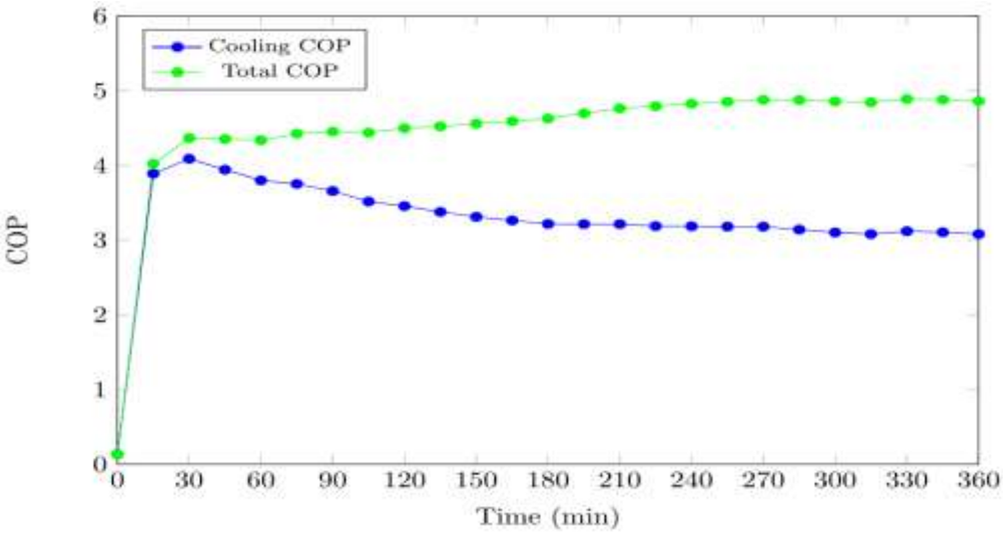

Fig. 9: Coefficient of performance of system

Coefficient of performance is defined as the ratio of refrigeration effect and compressor power. This definition particularly applies in refrigeration and air conditioning systems where cooling C.O.P. and C.O.P. is the same term. As it is observed from fig. 8, refrigeration effect is declining as time progresses. Therefore, from fig. 9, it is evident that cooling C.O.P. is also declining. Hence, to indicate coefficient of performance of a multipurpose heat pump as a whole system total C.O.P. term is introduced which includes heating efficiency also.

From eq. (3), total C.O.P. is calculated as ratio of summation of refrigeration effect and heating capacity to compressor power. So, from fig. 9, it is evident that despite falling of cooling C.O.P., total C.O.P. is uniformly increasing throughout the experiment.

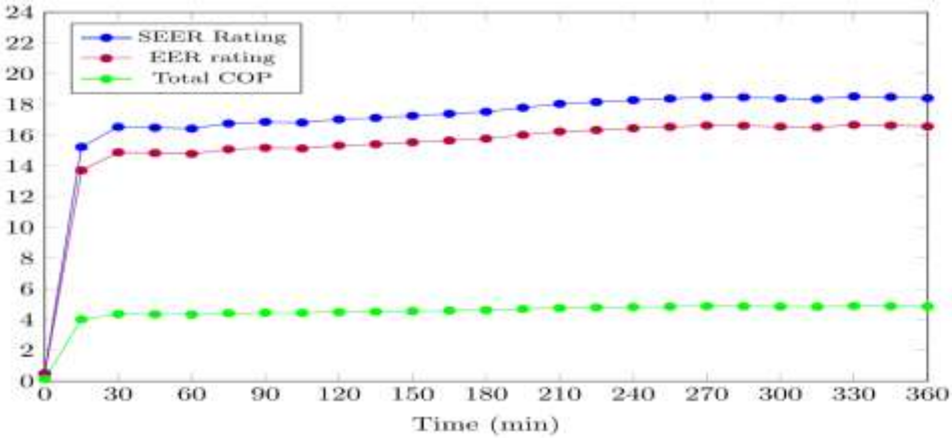

Fig. 10: EER and SEER rating

From fig. 10, Energy efficiency ratio EER, is ratio of output cooling energy (BTU) to electrical input energy (Wh). It is ratio of energies and not of power. Generally, EER is equal to 3.41 x total C.O.P. whereas, seasonal energy efficiency ratio SEER, is given by ratio of output cooling energy (BTU) over a season to electrical input energy (Wh) over same season. Generally, SEER is equal to 1.2 x EER.

VII. CONCLUSION

Multipurpose heat pump was developed to combine heating and cooling applications into single machine. Testing of prototype provided encouraging results. It is concluded that cooling COP increases at expense of lowering heating efficiency and vice versa. Also, for water extraction certain air flow over evaporator is necessary. This may causes problem when high flow of cool air is required. Because, high flow rate of air through evaporator did not allow moist particle to condensate in heat exchanger. Therefore, cooling of air and water extraction capacity are functions of air flow.

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