Exergy analysis on vapour compression refrigeration system using evaporative condenser

Jomy Joseph, Rijo Jacob Thomas
Industrial Refrigeration and Cryogenics department
TKM College of engineering
Kollam, India
jomybgas@gmail.com
rijojthomas@gmail.com

Abstract— Today's world is much affected by the ill effects of global warming and as a result, ambient temperature is rising significantly. Refrigeration and air- cooling systems are becoming necessary in almost all parts of India, even in places with moderate climate. Alternatively, the energy costs are shooting up day by day because of the limited availability of non-renewable types of energy. Vapour compression refrigeration system, though a century old refrigeration system, is still, the most commonly used refrigeration system. Most of the conventional refrigerating and air conditioning systems uses vapour compression refrigeration cycle, which involves evaporator, compressor, condenser, and an expansion device. However, a major drawback of conventional vapour compression refrigeration systems is that they account for a major portion of electric power consumption. A slight improvement in the performance of vapour compression refrigeration systems will have a significant influence on energy saving, considering enormous number of refrigeration and air-conditioning units globally. By using cost effective modifications like evaporative condensers instead of conventional air condensers, the performance of vapour compression refrigeration systems can be improved.

Usually COP is used as a performance index for refrigerators and air-conditioners. But COP considers only the quantity of energy and not the quality. In real practice, even though quantity of energy is conserved, its quality is always degraded. So COP alone is not a realistic measure of performance for refrigerators and air conditioners. In this work, exergy analysis is done on an experimental R22 split air conditioning system, retrofitted with an evaporative condenser. Exergy efficiency is used as a performance index to measure the improved performance of the system. By using evaporative condenser instead of conventional air condenser, about 36% improvement in exergy efficiency is obtained.

Keywords—exergy analysis, exergy efficiency, exergy destruction, evaporative cooling.

I. INTRODUCTION

Today due to the adverse effects of global warming, the atmospheric temperature has climbed-up so far that the use of air-conditioners and refrigerators has become an integral part of human life even for those in villages. These cooling devices are generally energy intensive ones and eventually, a major portion of our daily power consumption is spent for the different cooling requirements. Even though different types of machines are employed in cooling applications, one of the most widely used types is the vapour compression refrigeration (VCR) system.

A basic vapour compression refrigeration system is composed of four basic components: evaporator, compressor, condenser and expansion valve, as shown in figure below.
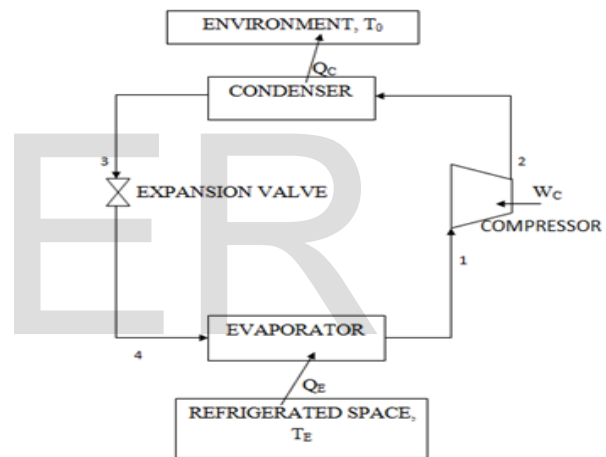

Fig.1: Schematic of basic vapour compression refrigeration system.

Fig.2 and 3 respectively shows temperature – entropy and pressure-enthalpy diagram of a basic VCR system.
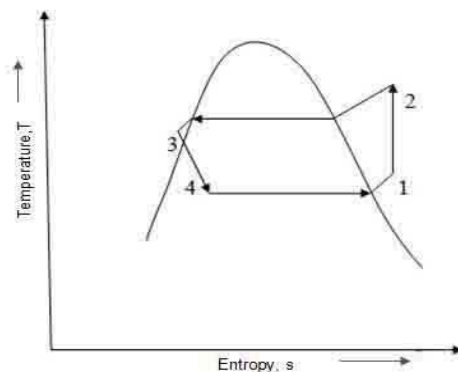

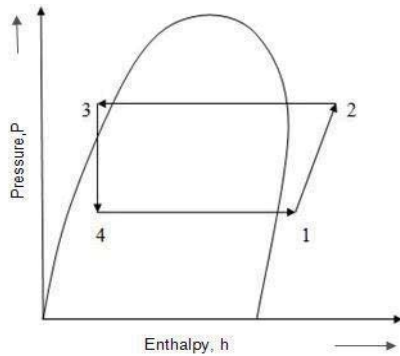Fig.2: Temperature-entropy diagram of a basic VCR system.

Fig.3: Pressure- enthalpy diagram of a basic VCR system.

In VCR system, the refrigerant vapour alternatively undergoes a change of phase from vapour to liquid and vice versa during a cycle. Even though VCR system is a century old refrigeration system ,there are only slight changes from the basic one, on today's actual system The performance of a conventional VCR cycle can be improved either by enhancing the performance of any one of the components or all of them. Using evaporative condenser instead of conventional air condenser can be considered as energy efficient, environment friendly and cost-effective method to enhance the performance of VCR systems.

When the ambient air temperature increase and approach 50^0C or higher, as it happens in many Middle East countries, the performance of air condenser drops down. In such situations, VCR system work improperly since the temperature and the pressure of the condenser increase and the compressor is forced to work under greater pressure ratio, which results in more power consumption. The simple and cheapest remedy for this problem is to cool the ambient air temperature by employing evaporative cooling system.

Usually, evaporative condensers are used in air-conditioning systems to enhance their performance. There are 2 methods for evaporative cooling in condensers namely direct and indirect method. In direct method water is directly injected on the condenser and provides cooling effect. This method has many side effects including mineral deposits and corrosion of the condenser coils. Therefore, this method has rarely been used in air conditioning systems. In the indirect method water is injected on the evaporative media pad which is located in the way of air over the condenser and provides cooling effect by evaporation of water. Evaporative condensers are ideally suited for operation in dryer climates.

Several researchers reported that the use of evaporative condenser in place of conventional condensers resulted in performance improvement of refrigerators and air-conditioning systems. Some of the prominent works are mentioned below.

Goswami et al. (1993) retrofitted an evaporative cooler on the existing 2.5ton air conditioning system by using an evaporative media pad and reported 20% power saving for the modified system when the ambient air temperature was 34^0C. Zhang et al. (2000) investigated on the evaporative cooler filled with corrugated holed aluminium foil and presented correlations to predict the performance, pressure drop and temperature outlet of the cooler. They used correlations to predict the improvement of an air-cooled chiller by comparing the exit temperature of evaporative cooler with performance curve of the chiller and reported that COP of the chiller could be improved about 39%.

Hosoz et al. (2004) conducted experiments on a refrigeration system employing 3 types of condensers, namely, the air-cooled, the water-cooled and evaporative condensers and compared the performance characteristics of the system in 3 cases. Experimental studies revealed that the refrigeration capacity and C.O.P. of the unit with evaporative condenser were higher than those of the one with air-cooled condenser by 31 and 14.3% respectively. Yu and Chan (2005) conducted simulation studies on an air- cooled chiller equipped with a direct evaporative cooler and showed up to 14.4% reduction in power consumption and up to 4.6% increase in the refrigeration effect. Youbi- Idrissi et al. (2007) proposed a water spraying system in front of the air-cooled condenser to reduced air temperature and developed a semi-local numerical model for a sprayed air-cooled condenser coupled with a refrigeration system. By using the model, they predicted that COP of the refrigeration system could be improved up to 55%.

Hajidavalloo (2007) investigated the effect of using evaporative cooler in the window-air- conditioner by injecting water on the evaporative media pad installed in front of the condenser entrance and reported 16% reduction in power consumption and 55% improvement in total performance. Hajidavalloo et al. (2010) investigated the effect of using indirect evaporative cooling in split air-conditioning system under variable ambient conditions. Experimental studies revealed that at ambient temperature of 35^0C, refrigeration capacity and COP improved by 16.4% and 31.7% respectively. At ambient temperature of 49^0C, refrigeration capacity and COP improved by 20.1% and 50.6% respectively. Tissot et al. (2013), carried out an experimental and numerical study, for improving the energy performance of refrigerating machine, using a water spray upstream of the condenser. The experimental setup is based on a reversible heat pump used in cooling mode. Their results showed that water spraying upstream of the condenser may increase the

global COP of the system (refrigerating machine plus spraying system) up to 28.9% for relatively hot and dry air conditions.

Usually COP is used as a performance index for refrigerators and air-conditioners. But COP considers only the quantity of energy and not the quality. In real practice, even though quantity of energy is conserved, its quality is always degraded.COP alone is not a realistic measure of performance for refrigerators and air conditioners. So in this work, exergy analysis of an experimental R22 split air conditioning system(Hajidavalloo et al.(2010)), retrofitted with an evaporative condenser is carried out and performance improvement is evaluated in terms of exergy efficiency.
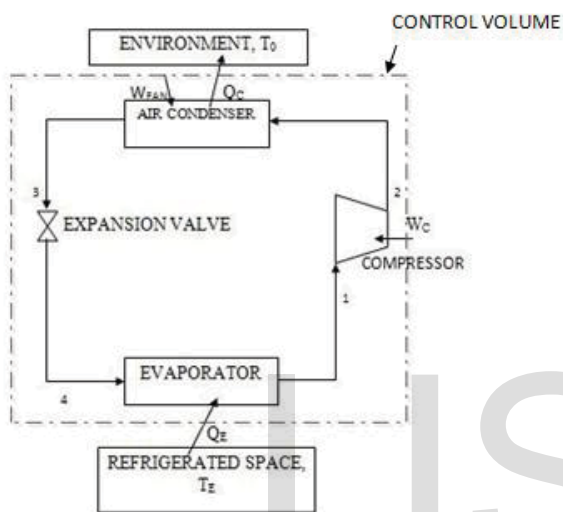
II. EXERGY ANALYSIS

Fig.4: Vapour compression refrigeration system using air condenser.
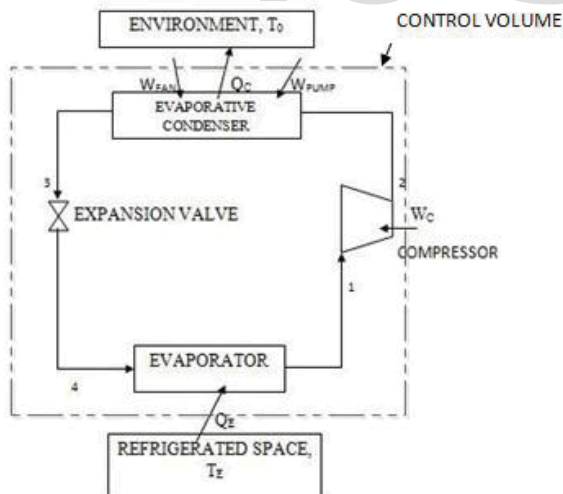

Fig.5: Vapour compression refrigeration system retrofitted with evaporative condenser.

In this section exergy analysis of experimental R22 split air conditioning system (Hajidavalloo et al. (2010)) is carried out. Figure 4 and 5 represent the control volumes for the base system (i.e., vapour compression refrigeration system using air condenser) and modified system (i.e., vapour compression refrigeration system retrofitted with evaporative condenser).

The magnitude of specific exergy at every state is determined from the following equation,

$$e = e_{ph} + e_k + e_p + e_{ch} \tag{2.1}$$

where,

e_{ph} - Physical exergy,
e_k – Kinetic exergy,
e_p – Potential exergy,
e_{ch} – chemical exergy.

Kinetic, chemical and potential exergies are neglected. Therefore, specific exergy at each arbitrary state can be assumed to be equal to the physical exergy.

$$e = e_{ph} = (h - h_0) - T_0 (s - s_0) \tag{2.2}$$

After finding out the specific exergy at each state point in the system, the general exergy flow equation is applied to each component in the system, assuming the system to be in steady state.

The general exergy flow equation for each component is defined as below:

$$0 = \sum_j (1 - \frac{T0}{Tj})Qj - Wcv + \sum_i (me)in - \sum_i (me)out - Ed \tag{2.3}$$

Where,

Q_j – Time rate of heat transfer in the jth component.
T_j – Temperature at which heat transfer takes place.
T_0 – Dead state temperature.
W_{cv} – Time rate of energy transfer rate by work other than flow work.
m – Mass flow rate
e – Specific exergy
Ed – Exergy destruction in the component.

In order to find out exergy destruction in different components of the split a.c. system, equation (2.3) is applied to each component of the split a.c. system.

Thus, applying equation (2.3) for the compressor gives,

Exergy destruction in compressor,

$$(Ed)_{comp} = me_1 - me_2 - W_c \tag{2.4}$$

Now, for the split a.c. system using air condenser (base system)

Exergy destruction in condenser,

$$(Ed)_{cond} = me_2 - me_3 - W_{fan} \tag{2.5(a)}$$

For the split a.c. system retrofitted with an evaporative condenser (modified system)

Exergy destruction in condenser,

$$(Ed)_{cond} = me_2 - me_3 - W_{fan} - W_{pump} \tag{2.5(b)}$$

Where W_{fan} is the fan work and W_{pump} is the pump work required for the recirculation pump used to spray water in an evaporative condenser.

While calculating exergy destruction in condenser, the term associated with heat transfer in condenser is neglected because, the magnitude of the term will be very small considering the temperature difference between ambient and average surface temperature of the condenser[8], [9].

Exergy destruction in expansion valve,

$$(Ed)_{exp} = me_3 - me_4 \qquad (2.6)$$

Exergy destruction in evaporator,

$$(Ed)_{evap} = Q_{evap}\left(1 - \frac{To}{Tj}\right) + me_4 - me_1 \qquad (2.7)$$

$$\text{Exergetic efficiency, } \varepsilon = 1 - \frac{(Ed)}{ExIN} = \frac{Ex\ out}{ExIN} \qquad (2.8)$$

Where,

E_d – Exergy destruction,

E_{xIN} – Exergy input.

$Exout$ –Exergy output.

Exergy analysis was conducted by considering the following assumptions:

1. Dead state pressure and temperature are assumed as 1atm and 308 K respectively.

2. Heat rejection in the condenser and compressor are assumed to take place at near ambient conditions.

3. Exergy losses in the suction line, discharge line and other pipelines are neglected

III.   RESULTS AND DISCUSSIONS

Exergy analysis of the experimental split a.c. system (Hajidavalloo et al. (2010)) using air condenser and evaporative condenser is carried out separately and performance of both the systems is compared on the basis of percentage increase in exergy efficiency.
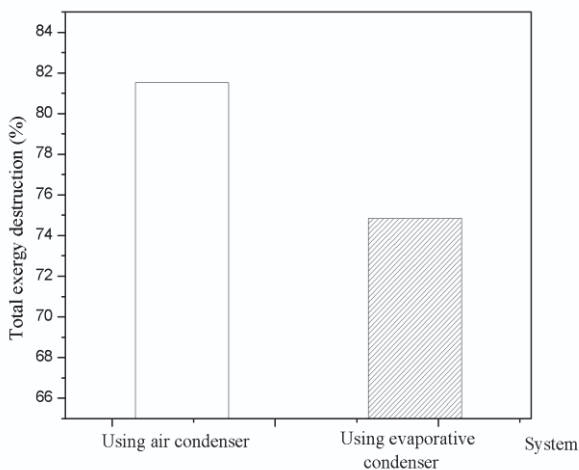

Fig.6: Variation of total exergy destruction with system modification
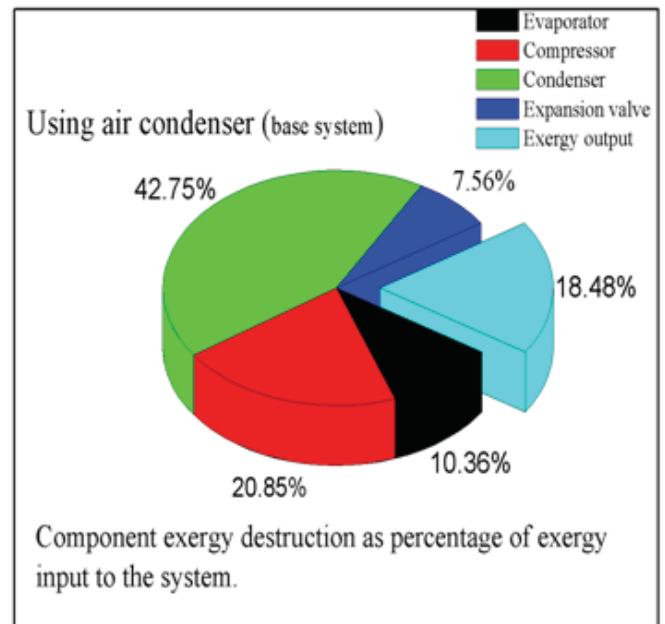

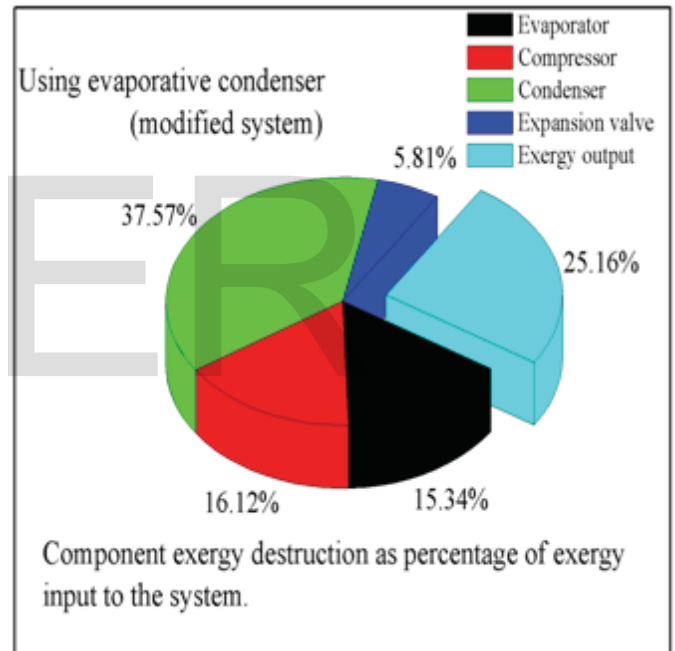Fig.7a: Exergy destruction when air condenser is used.

Fig.7b: Exergy destruction when evaporative condenser is used.

From fig.6, it may be observed that, by using evaporative condenser instead of conventional air condenser total exergy destruction of the system is reduced. As a result the exergy efficiency of the modified system using evaporative condenser is very high compared to the system using conventional air condenser. In fig.7a and fig.7b, the exploded portion of the graph shows the percentage of exergy input converted into useful work or exergy output, which is same as the exergy efficiency. On comparing fig.9a and 9b, we can see that by using evaporative condenser exergy

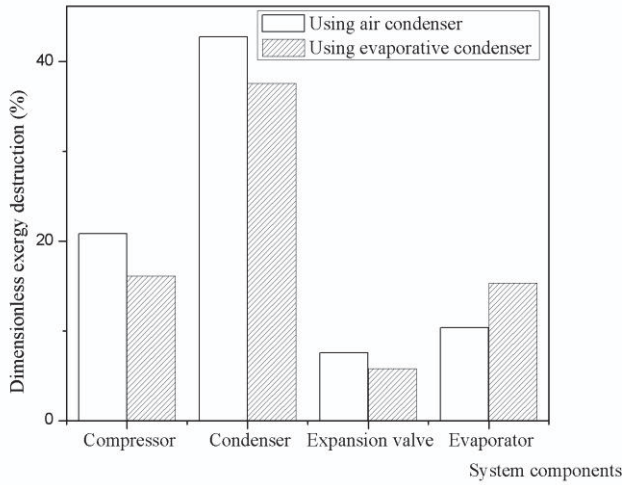efficiency increased from 18.48% to 25.16% i.e., about 36% increase in exergy efficiency is observed.

Fig8: Exergy destruction in various components

From fig.8, it may be inferred that maximum exergy destruction occurred in condenser and is followed by compressor, evaporator and expansion valve. By using evaporative condenser, the condensing pressure and temperature decreases. As a result the approach temperature in the condenser reduced and hence the exergy destruction in the

condenser decreased. As the condensing pressure drops due to the use of evaporative condenser, the compressor discharge pressure will also be less, resulting in a lower compressor pressure ratio and hence the exergy destruction in compressor also decreases. The pressure difference between the condenser and evaporator side reduced and hence the exergy destruction in the expansion valve also decreased. The mass flow rate through the evaporator is found to be increased and as a result the load on evaporator is increased, which resulted in increase of exergy destruction in the evaporator.

Exergy analysis is conducted on the experimental work by Hajidavallo et al. (2010) and based on the results of exergy analysis Grassmann diagrams are drawn for both base and modified systems.Fig.9and 10 given below respectively, shows the Grassmann diagram or exergy flow diagram for the split a.c. system (Hajidavalloo et al.(2010) ,when air condenser is used (base system)and when evaporative condenser is used(modified system). Grassmann diagram or exergy flow diagram is a graphical representation of the flow of exergy in any system. It gives an idea about how the input exergy supplied to a system is destroyed or utilized in different components of the system. So Grassmann diagram is drawn for the base system using air condenser and for the modified system using evaporative condenser.
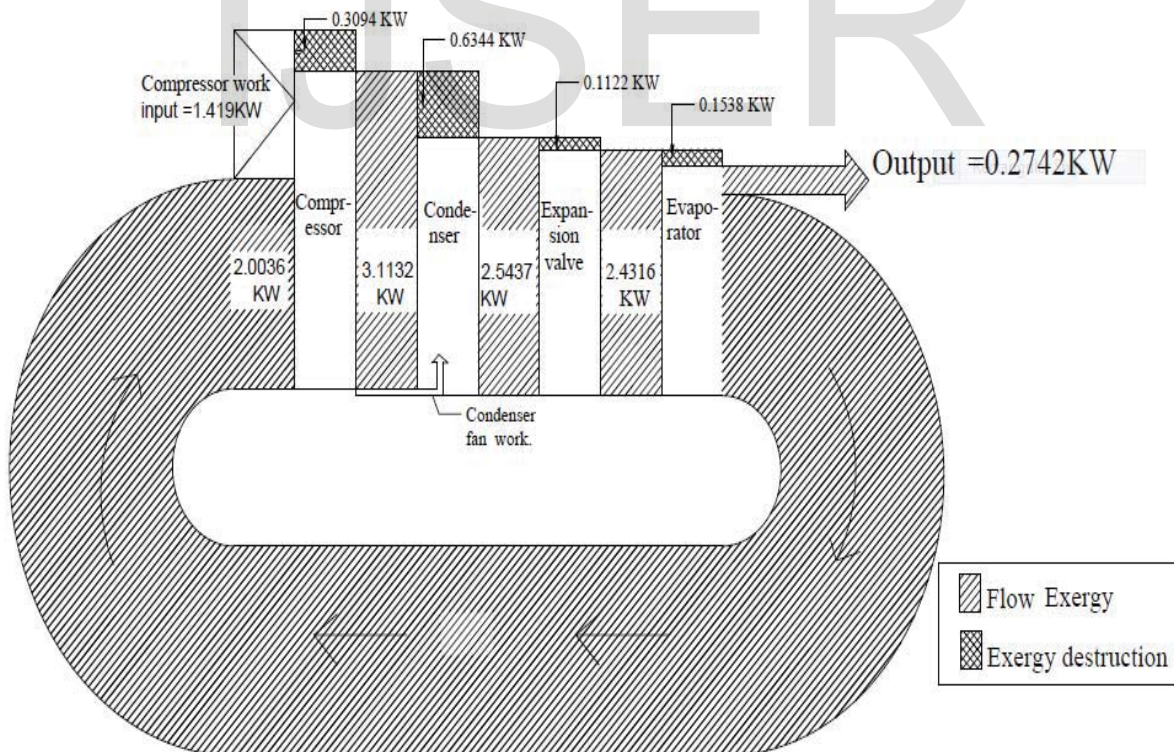

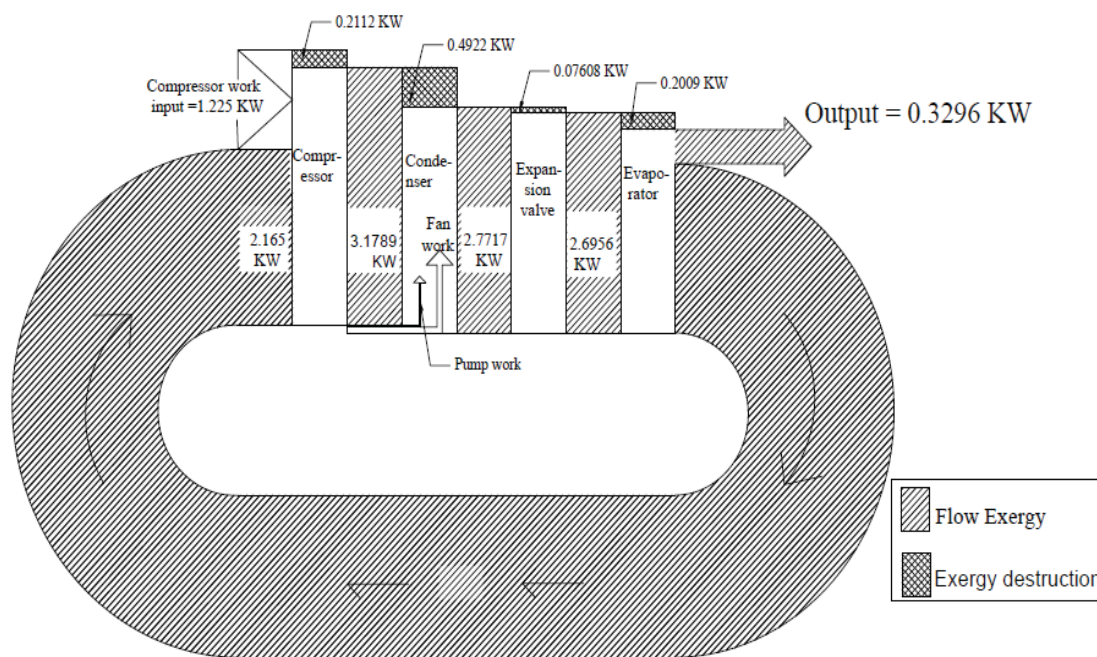Fig.9: Grassmann diagram for the split a.c. system when air condenser is used.

Fig.10: Grassmann diagram for the split a.c. system when evaporative condenser.

In fig.9, it may be seen that the energy input to the system are compressor work of 0.419kW, and condenser fan work of 0.065kW.

Exergy destruction values in compressor, condenser, expansion valve and evaporator are 0.3094kW, 0.6344 kW, 0.1122 kW and 0.1538 kW respectively. It may be observed that the exergy output from the system is only 0.2742 kW .Fig.10 shows the Grassmann diagram for the modified system using evaporative condenser. In Fig.10, it may be seen that the exergy input to the system are compressor work of 1.225 kW, fan work of 0.070 kW and an additional pump work (pump used for spraying water in evaporative condenser.) of 0.015kW.From experimental results, it may be said that because of the improved performance of evaporative condenser, the condensing temperature and pressure reduced slightly and as a result compressor work in the modified system is found to be less. For the modified system, exergy destruction values in compressor, condenser, expansion valve and evaporator are 0.2112 kW, 0.4922 kW, 0.07608 kW and 0.2009kW respectively. On comparing with the base system exergy destruction in all the components except the evaporator reduced. Exergy destruction in evaporator increased slightly due to increase in load on the evaporator. It may be observed that as a result of system modification exergy output increased from 0.2742 kW to 0.3296 kW. Exergy efficiency, which is the ratio of exergy output to exergy input, can be used as a realistic index to measure the improved performance of the system using evaporative condenser. From exergy analysis of the experimental work (Hajidavalloo et al.(2010) ,it is found that by using evaporative condenser instead of conventional air condenser, about 36% improvement in exergy efficiency of vapour compression refrigeration system is obtained.

IV   CONCLUSIONS

From literatures it was observed that by using evaporative condenser instead of conventional air condenser the performance of VCR systems, especially air-conditioners can be improved drastically. Most of the experimental works available in literatures rely on COP, as a measure of performance improvement. But COP considers only the quantity of energy and not the quality. In real practice, even though quantity of energy is conserved, its quality is always degraded. So COP alone is not a realistic measure of performance for refrigerators and air conditioners.

In this work exergy analysis of an experimental R22 split air conditioning system, retrofitted with an evaporative condenser (Hajidavalloo et al.(2010)), is carried out. Exergy destruction in system components such as compressor, condenser, expansion device and evaporator are found out for both the cases (i.e., by using air condenser and by using evaporative condenser.).On modifying the split air conditioning system (based on VCR system) with evaporative condenser instead of conventional air condenser, exergy destruction in all the components, except

the evaporator reduced. Exergy destruction in evaporator increased slightly due to increase in load on the evaporator.

By using evaporative condenser instead of conventional air condenser, the condensing temperature and pressure reduced slightly and as a result the approach temperature in the condenser reduced and hence exergy destruction in condenser reduced.

As the condensing pressure reduced, the compressor discharge pressure also get lowered, resulting in reduction of compressor pressure ratio and hence the exergy destruction in compressor decreased. By using evaporative condenser, compressor exit temperature and hence the compressor work also get reduced. The pressure difference between condenser and evaporator side reduced and hence the exergy destruction in expansion valve also decreased.

In this work Grassmann diagram is used as a tool to understand, how the input exergy supplied to a system is destroyed or utilized in different components of the system. From the Grassmann diagrams drawn, it may be observed that as a result of system modification exergy output increased from 0.2742 KW to 0.3296 KW. By using evaporative condenser instead of conventional air condenser about 36% improvements in exergy efficiency of VCR system is obtained. So, on the basis of exergy efficiency, which is a more realistic performance index than COP, it may be stated that the use of evaporative condenser is a cost effective and promising modification for improving the performance of conventional VCR systems. The major significance of this modification is that the use of evaporative condensers is ideally suited for operation in less humid places with high ambient temperatures, especially in Middle East countries, where the use of refrigeration and air conditioning systems are inevitable.

Acknowledgment

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