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Numerical Analysis of Exergy for Air-Conditioning Influenced by Ambient Temperature

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Abstract

The article presents numerical analysis of exergy for air-conditioning influenced by ambient temperature. The model of numerical simulation uses an integrated air conditioning system exposed in varied ambient temperature to observe change of the four main devices, the compressor, the condenser, the capillary, and the evaporator in correspondence to ambient temperature. The analysis devices of the four devices's exergy influenced by the varied ambient temperature and found that the capillary has unusual increasing exergy loss vs. increasing ambient temperature in comparison to the other devices. The result shows that reducing exergy loss of the capillary influenced by the ambient temperature is the key for improving working efficiency of an air-conditioning system when influence of the ambient temperature is considered. The higher ambient temperature causes the larger pressure drop of capillary and more exergy loss.

Keywords: exergy, ambient temperature, exergy loss, working efficiency

1. Introduction

The 21st century is not only the century of human's knowledge explosion, but also the century for human to face seriously the urgent problems of energy crisis and environmental pollution on the Earth. Due to double-quick petroleum exhausting in the beginning of 21st century, people are compelled to solve the oil crisis ahead of time.

Air-conditioning is not only one of the most modern and necessary facilities for human today, but also the system with extreme large energy consumption in the world. Recently, the Earth is growing environmental global warming and ozone depletion, so that the environmental pollution causes increasing surroundings the temperature, which is also called the greenhouse effect [1, 2]. The greenhouse effect, discovered by Joseph Fourier in 1824 and the first investigated quantitatively by Svante Arrhenius in 1896, is the process in which the emission of infrared radiation by an atmosphere warms a planet's

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surface. The greenhouse effect has already caused the surroundings temperature raising in some places on the Earth over 5°C.

The main performing process of air-conditioning is to transfer the room heat to the surrounding. The irreversible forced heat convection between air-conditioning and surrounding is the main thermodynamic process in air-conditioning.

According to the thermodynamic principle, the heat transfer in air-conditioning takes place only at a finite temperature difference which is proportional to the heat transfer rate. The previous referred greenhouse effect increases the surroundings temperature and further reduces the temperature difference between air-conditioning and surrounding, which will reduces the heat transfer rate and causes the performance of air-conditioning to degrade. Therefore, consideration of the ambient temperature to influence the efficiency of air-conditioning becomes very worthy to be done. The losses in the air-conditioning system need to be calculated by individual processes that make up the system.

Energy analysis is the most commonly used method in the analysis of thermal systems, but it gives no indication about the degraded performance of system. Exergy shows that energy having quality as well as quantity, and actual processes occur in the direction of decreasing quality of energy. Energy analysis is concerned only with the conservation of energy, but exergy analysis shows directly the working efficiency. The principles and methodologies of exergy analysis are well-established [3, 4].

An exergy analysis is usually aimed to determine the maximum performance of the system and identify the sites of exergy destruction [5]. Exergy analysis of a refrigeration system can be performed by analyzing the components of the system separately. Identifying the main sites of exergy destruction shows the direction for potential improvements. An important object of exergy analysis for systems that consume work such as refrigeration is finding the minimum work required for a certain desired result [6-8]. There have been several studies on the exergy analysis of refrigeration and heat pump systems [9-12].

Exergy is the maximum useful work during a process of a cycle system. Exergy analysis in vapor compression refrigeration (VCR) cycles has been studied in the literature. This work focuses especially on the influence for the expressions of the exergy losses for the individual processes that make up the system as well as the coefficient of performance (COP) and exergy efficiency for the entire system are obtained. Effects of ambient temperature on the exergy losses, exergy efficiency and COP are investigated.

2. Numerical Modellation

2.1. The basic vapor compression refrigeration cycle

The vapor compression refrigeration cycle is the majorly applied refrigeration cycle, which consists of a compressor, a condenser, a throttling device (capillary), and an evaporator with controls and interconnections. Fig. 1 exhibits the schema of a basic vapor compression refrigeration system, which is a general irreversible cycle model.

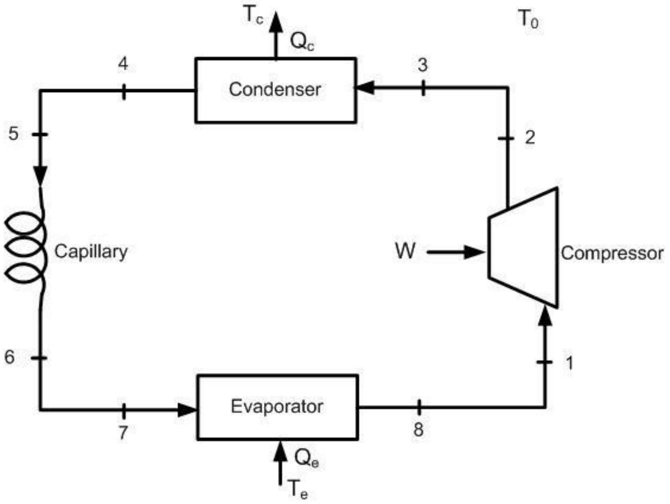


Fig. 1 Schema of a basic vapor-refrigeration cycle

The arabic numbers in Fig. 1 from 1 to 8 show the different state of the vapor compression refrigeration cycle and the number sequence indicates the flow direction of the refrigerant cycle from the begin with suction of compressor, which is convenient to explain the procedure. In process, the refrigerant is firstly sucked and compressed by the compressor from state 1 to state 2. At state 2, the refrigerant is with extremely high pressure and superheated. The compressed refrigerant vapor runs from state 2 to state 3. The refrigerant vapor at the state 3 will influx into the condenser to be condensed and takes place the heat exchange with the surroundings. The emitted heat of refrigerant during condensing in the condenser is transferred into the surroundings through the forced convection. The condensed refrigerant in the condenser outlet at state 4 is directly lead to the inlet of the capillary and runs through the capillary into the evaporator. The process of the evaporation for refrigerant in the evaporator will receive heat from the cooling space. After the evaporation of refrigerant in the evaporator, the refrigerant vapor is sucked again by the compressor and built the refrigeration cycle.

2.2. Exergy analysis

The exergy analysis bases on the basic vapor compression refrigeration system shown in Fig. 1. Numerical modellation discussed the complete system and its four main devices separately. The applied vapor compression refrigeration system is defined to fit the following four assumptions:

(1) Steady state, steady flow operation,
(2) negligible pressure drops in the evaporator, condenser, and intersections,
(3) adiabatic compression process,
(4) isenthalpic expansion in capillary,
(5) negligible kinetic and potential energies.

Table 1 exhibits design parameters of the applied system. The efficiency of a vapor compression refrigeration cycle is indicated by the coefficient of performance (COP), which is defined by the amount of cooling energy per supplied work. The COP of a vapor refrigeration cycle is expressed as equation (1).

$$COP = \frac{Q_e}{W} \tag{1}$$

where Q_e is the cooling energy and W the input energy.

Table 1 Design parameters of the applied vapor compression refrigeration system

Parameter	Value
Refrigerant	R-22
Refrigerating apacity	4 kW
Condenser capacity	4.95 kW
Isentropic efficiency	0.91
Evaporating temperature	267 K
Condensing temperature	313~328 K
Ambient temperature	303~318 K
Room temperature	277 K

The relationship of exergy balance for a general open system is illustrated graphically in Fig. 2, which describes the general exergy balance of a steady thermal system.

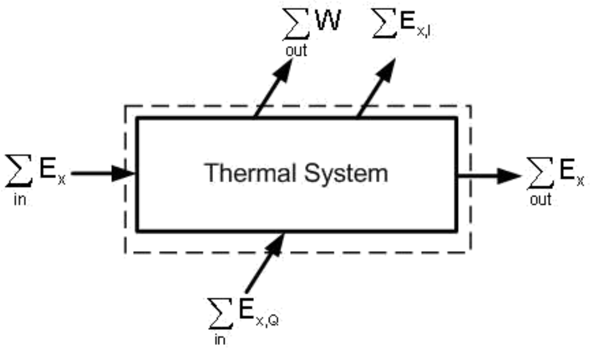


Fig. 2 The general exergy balance of a steady thermal system

The amount of exergy entering a steady flow system in all forms must be equal to the amount of exergy leaving plus the exergy destroyed, which is described as equation (2).

$$\sum_{in} E_x + \sum_{in} E_{x,Q} = \sum_{out} E_x + \sum_{out} E_W + \sum_{out} E_{x,l}, \tag{2}$$

where $\sum_{in} E_x$ is the total input exergy, $\sum_{in} E_{x,Q}$ the total input exergy from heat, $\sum_{out} E_x$ the total output exergy, $\sum_{out} E_W$ the total input exergy from work, and $\sum_{out} E_{x,l}$ the total exergy loss.

Referring to the main cycle loop in Fig. 1 from the first law of thermodynamics and equation (2), a general relation for a cyclic process can be written as equations (3)~(8).

$$E_{x,l,cp} = E_{x,1} - E_{x,2} \tag{3}$$

$$E_{x,l,cd} = E_{x,3} - E_{x,4} \tag{4}$$

$$E_{x,l,th} = E_{x,5} - E_{x,6} \tag{5}$$

$$E_{x,l,ev} = E_{x,7} - E_{x,8} + E_{x,Qe} \tag{6}$$

$$E_{x,i} = \dot{m} \times s_i, i = 1 \sim 8 \tag{7}$$

$$E_{x,Qe} = \dot{m}(1 - \frac{T_0}{T_e})Q_e, \tag{8}$$

where $E_{x,l,cp}$ is the exergy loss on the compression process, $E_{x,l,cd}$ the exergy loss on the condensation process, $E_{x,l,th}$ the exergy loss on the throttling process, $E_{x,l,ev}$ the exergy loss on the evaporation process, and $E_{x,Qe}$ the exergy loss from heat Q_e.

The efficiency of exergy η_{ex} is defined by a refrigeration cycle as the ratio of the available exergy requirement (E_x) to the actual work input(W). That is

$$\eta_{ex} = \frac{E_x}{W}, \tag{9}$$

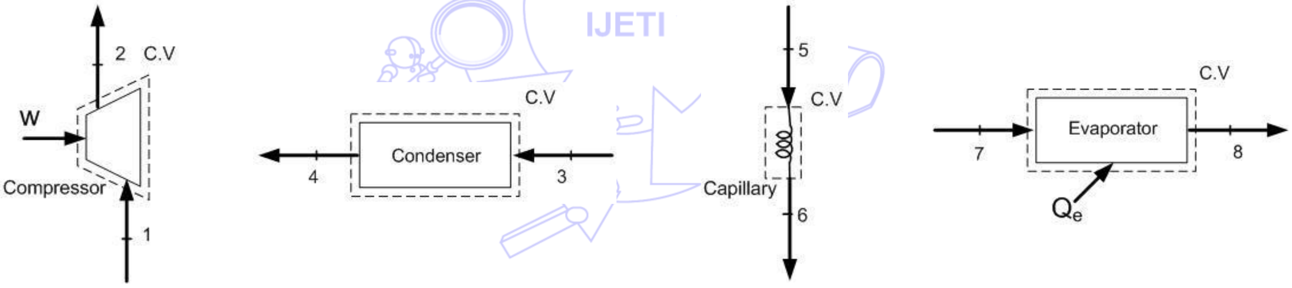
where E_x is equal to W - $E_{x,l}$. Further descriptions for each component will be detailed in the following sections.

2.2.1. The compression process

Fig. 3 exhibits the four main devices, where the dash lines show the control volume. The compression process is illustrated in Fig. 3(a) with input exergy from point 1 and work W, output exergy to point 2. Mathematical representation can be written as follow:

$$\begin{aligned} E_{x,l,cp} &= -W + E_{x,1} - E_{x,2} \\ &= -W + \dot{m}[(h_1 - h_2) - T_0(s_1 - s_2)] \\ &= \dot{m}T_0(s_2 - s_1) \end{aligned} \tag{10}$$

with W = $\dot{m}$(h1 − h2).



(a) The compressor (b) The condenser (c) The capillary (d) The evaporator

Fig. 3 Schema of control volume for the four main devices of vapor compression refrigeration system

2.2.2. The condensation process

The condensation process is illustrated in Fig. 3(b). Mathematical representation can be written as follow:

$$\begin{aligned} E_{x,l,cd} &= E_{x,3} - E_{x,4} \\ &= \dot{m}[(h_3 - h_4) - T_0(s_3 - s_4)] \end{aligned} \tag{11}$$

2.2.3. The throttling process

The throttling process is illustrated graphically in Fig. 3(c) as follow:

$$\begin{aligned} E_{x,l,th} &= E_{x,5} - E_{x,6} \\ &= \dot{m}[(h_5 - h_6) - T0(s_5 - s_6)] \\ &= \dot{m}T0(s_6 - s_5) \end{aligned} \tag{12}$$

with $h_5 = h_6$. The generalized relationship for enthalpy change is as follows:

$$dh = T\,ds + vdp \tag{13}$$

$$\left.\frac{\partial s}{\partial p}\right|_h = -\frac{\upsilon}{T} \tag{14}$$

The partial derivative by equation (14) yields

$$\left.\frac{\partial E_{x,l,th}}{\partial p}\right|_h = \dot{m}\left.\frac{\partial s}{\partial p}\right|_h = -\dot{m}\frac{T_o}{T}\upsilon \tag{15}$$

$$E_{x,l,th} = -\Delta E_{x,l,th} = \dot{m}\frac{T_o}{T}\upsilon(p5 - p6) \tag{16}$$

2.2.4. The evaporation process

The evaporation process is illustrated in Fig. 3(d). Mathematical representation can be written as follow:

$$\begin{aligned} E_{x,l,ev} &= E_{x,7} - E_{x,8} + E_{x,Qe} \\ &= \dot{m}[(h_7 - h_8) - T_o(s_7 - s_8) + (1 - \frac{T_o}{T_r})Q_e] \end{aligned} \tag{17}$$

3. Results and Discussion

The numerical calculations focus on the relationship between exergy loss and ambient temperature by keeping observation on the four main devices individually. According to the principle of heat transfer, the heat transfer rate is proportional to the difference of temperature, which causes the heat convection between the devices and the surroundings to become slower while their temperature difference is decreased. The heat transfer rate determines the system's working efficiency or the exergy loss of an air-conditioning. Normally, the larger the heat transfer rate is, the higher the system's working efficiency or the smaller the exergy loss is. The increased exergy losses of system does not only represent that the system's working efficiency is decreased, but also show that the energy wastage is increased. Fig. 4 shows the exergy losses for each component associated with vapor compression refrigeration (VCR) as function of the ambient temperature.

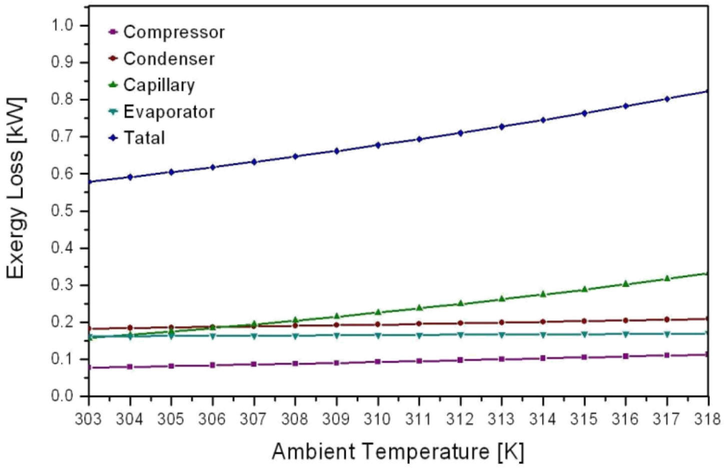


Fig. 4 Exergy losses vs. ambient temperature by keeping observation on the four main devices and the total exergy loss

Fig. 4 exhibits that the change of the exergy loss vs. the ambient temperature for the capillary increases unusually in comparison with the other three main devices. This result offers a greatly significant key point for making a new energy saving system when the influence of ambient temperature is considered. In other words, to decrease the exergy loss of the capillary at the higher ambient temperature will be able to increase the system's working efficiency.

The explanations of the previous phenomena in Fig. 4 can be cited physically and mathematically. At first, the compressor, the condenser, and the capillary are directly influenced by the ambient temperature due to their heat convection with the surroundings during operation. The increasing ambient temperature will cause the decreasing temperature difference between devices and surroundings. The evaporator exchanges the heat with the cooled room, which depends on the system's working efficiency and is indirectly influenced by the ambient tempeature. The heat transfer rate is decreased by the decreasing temperature difference due to the increasing ambient temperature. The physical explanation for the unusual increasing exergy loss of the capillary could be as follow. The forced heat convection rate of tubes depends also on the contact surface. At the same temperature difference, the larger the contact surface is, the bigger the forced heat convection rate is. The contact surface of the capillary is extremely larger than the other three main devices relatively. This causes the influence of ambient temperature on the capillary is extremely larger than the other three main devices relatively. On the mathematical side, the influence of ambient temperature for the compressor, the condenser, and the evaporator is one order as function, but the capillary is higher than one order. The pressure drops across the capillary also increases as the ambient temperature increases, which is shown in equation (16).

The trend of the exergy loss in the capillary increasing with the ambient temperature can be explained by the fact that the average pressure difference between the condenser and the evaporator increases with increasing ambient temperature, which is shown in Fig. 5. Fig. 5 shows the pressure drops on the capillary is increased with the increased ambient temperature. There are two influenced parameters in products at the right side in equation (16).

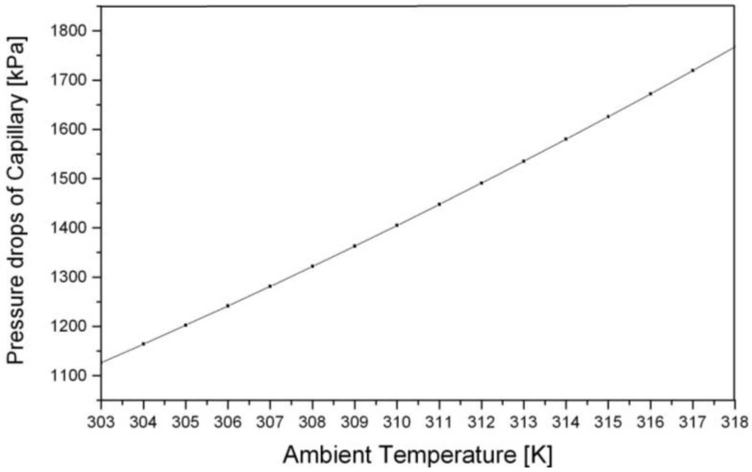


Fig. 5 Pressure drops of the capillary during operation

Effects of ambient temperatures on COP and the exergy efficiency as well as COP vs. input exergy of the refrigeration cycle are plotted in Figs. 6~8.

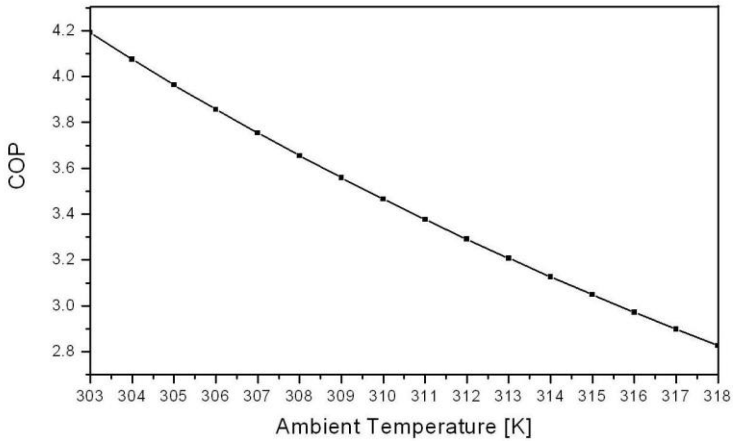


Fig. 6 COP of the refrigeration cycle vs. ambient temperature

The COP of the refrigeration cycle decreases with the increasing ambient temperature as illustrated in Fig. 6. The trend in Fig. 6 and 7 is essentially same with COP varying between 2.8 and 4.2 as a function of ambient temperature. The COP is calculated by dividing heat removed from the cold space to the actual compressor work input.

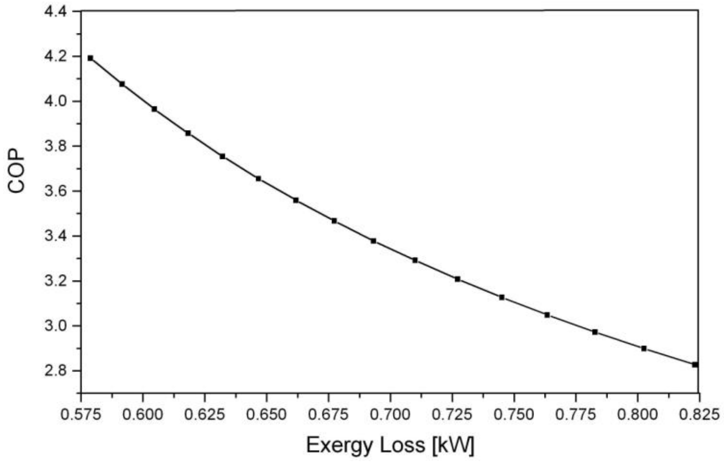


Fig. 7 COP vs. exergy loss with the cycle vs. ambient temperature

In Fig. 8, the percentages of exergy efficiency per unit input exergy decreases with the increasing ambient temperature. In the temperature ranges considered in Fig.8, the exergy efficiency degrades from 42% to ca. 29%. The decreasing trend agrees to the calculated results.

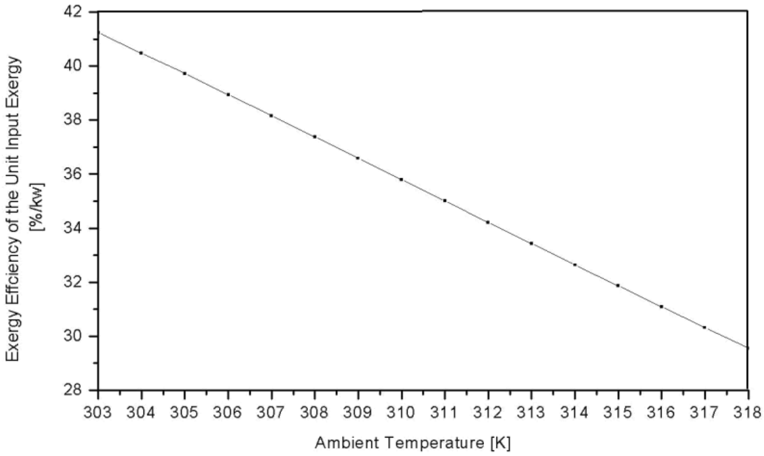


Fig. 8 Exergy efficiency vs. ambient temperature

4. Conclusions

The investigations on the effects of ambient temperatures for exergy losses, exergy efficiency, and COP of a vapor compression refrigeration cycle using numerical analysis are successfully carried out. The capillary receives the largest influence by the ambient temperature whereas the other three main devices have little effect. The increasing pressure drops of capillary with increasing ambient temperature causes the unique large change of exergy loss for capillary, while the pressure drops of condenser and evaporator is neglected. The ambient temperature increases 1˚C (from 303 to 304 K), the exergy loss increases from ca. 0.575 to 0.6 kW with increasing rate ca. 4.35% and the COP of refrigeration system decreases from ca.4.2 to 4.08 with decreasing rate ca. 2.86%.

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