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Assessment of next generation refrigerants for air conditioning systems integrated with air-membrane heat and mass exchangers

Fahad A. Al-Sulaiman

Center of Research Excellence in Renewable Energy (CoRERE), Research Institute, and Mechanical Engineering Department, King Fahd University of Petroleum & Minerals, (KFUPM), Dhahran 31261, Saudi Arabia

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ABSTRACT

Thermodynamic analysis was conducted, in detail, to compare the performance of an air conditioning system with and without an air-membrane heat and mass exchanger. The study evaluated the performance of the system considering four promising new refrigerants: R1234yf, R1234ze, R32, and R423A. To evaluate the performance of the system, key performance parameters were used, including, coefficient of performance (COP), exergy destruction rate, second law efficiency, compressor work, irreversibility ratio, fuel depletion ratio, and productivity lack. In addition, the effect of varying the compressor pressure ratio, effectiveness of the membrane, and the relative humidity of fresh air on the performance of the system were evaluated for both configurations. The performance of an air conditioning system significantly improves when an air-membrane heat and mass exchanger is used. The main reason of this improvement is the significant drop in the cooling load and, consequently, the compressor input power. Furthermore, the study showed that COP as a measure of performance is not enough to have an appropriate comparison for the performance and further detailed analysis is needed, such as exergy analysis. Therefore, exergy analysis was also conducted to fully assess the advantages of using a membrane with an air conditioning system. From thermodynamics point of view, the study showed that R1234ze has the best performance while R32 has the lowest performance.

1. Introduction

As air conditioning systems consume a tremendous amount of energy, the electricity consumption to cool buildings is more than 50% of the total consumption in some countries with hot weather [1,2]. Therefore, even a minor improvement in the performance of air conditioning systems will result in substantial saving of electricity. Air-membrane heat and mass exchangers can be integrated with conventional air conditioning systems to reduce their electricity consumption. The performance of air conditioning systems can be further enhanced by using next-generation high-performance refrigerants, which have the added benefit of being environment friendly. In this study, the performance of an air-membrane heat and mass exchanger coupled with air conditioning systems based on four next-generation refrigerants is examined.

Several studies have been conducted to study the effects of reducing the humidity of fresh air entering an air conditioning system. Tu et al. [3] conducted an exergy analysis to assess the performance of a desiccant wheel for a cooling system and found that the COP of the system is 5.0 and the exergy efficiency is about 18.3%. Angrisani et al. [4] compared the performance of an air-conditioning system with and without a desiccant subsystem. They found that the performance of a hybrid desiccant cooling system with a micro-generator is better than using thermally activated technology. Purge angle analysis for desiccant wheel was investigated by Mandegari et al. [5]. They developed a new model that could optimize the purge angle of the desiccant wheel, which will be reflected positively on the COP of the cooling system. Li et al. [6] analyzed the performance of an ejector-expansion refrigeration cycle operated with the refrigerant R1234yf and found that the maximum COP is 5.91. Ahmed et al. [7] presented a new configuration of air conditioning system that avoids some of the loses of the energy in the weak desiccant solution and moisture content of the scavenging air. They found that the performance of the proposed system performed 11.25% better than the conventional system. Huang et al. [8] tested a new heat recovery device that heats the refrigerant and thus could improve the performance. They observed that the temperature of the fluid in the suction side increased by 25 degrees. Another recent technology to improve the performance through heat recovery was in investigated by Ali et al. [9]. They demonstrated that the COP could be improved by 60% as compared to conventional CO_2 cooling system when the heat is recovered from the compressed CO_2 to drive adsorption subsystem.

E-mail address: fahadas@kfupm.edu.sa.

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Nomenclature

AC	air conditioning
C_p	specific heat, J kg^{-1} K^{-1}
EE	enthalpy exchanger
ex	specific exergy, J kg^{-1}
Ex	exergy rate, W
$\dot{E}x_d$:	exergy destruction rate, W
h	enthalpy, J kg^{-1}
g	gravity, m s^{-2}
IP	exergetic improvement potential
$\dot{m}$	mass flow rate
NEE	without enthalpy exchanger
P	pressure, kPa
P_{low}	the lowest pressure value in the AC cycle
$\dot{Q}$	heat rate, W
R	gas constant
s	specific entropy, J kg^{-1} K^{-1}
T	temperature (°C)
v	velocity, m s^{-1}
w	constant, 1.6081
$\dot{W}$	input power, W
y	fraction of mass flow rate
z	elevation

Greek symbols

β	productivity lack
χ	irreversibility ratio
ε_L	latent effectiveness
ε_s	sensible effectiveness
η	efficiency
δ	fuel depletion ratio
ω	absolute humidify
ξ	productivity lack
φ	relative humidity

Subscripts

0	surrounding condition
a	air
c	compressor
e	exit
eV	evaporator
i	inlet
j	a property at a given state
r	relative or refrigerant
v	vapor
w	water

Several studies on membrane-based heat and mass exchangers for air were, also, conducted [10–15]. El-Dessouky et al. [10] analyzed the performance of an air evaporative cooling system and concluded that a substantial amount of energy can be saved when a membrane is used. However, they found that the performance of the system is sensitive to the properties of the incoming air. Nada et al. [11] performed an energy analysis of an air conditioning system integrated with a desalination system and an air heat exchanger for heat recovery. They found an increase in freshwater production as the air temperature is increased. Al-Waked et al. [12] modelled a membrane using CFD and found that a membrane in the counter-flow configuration is more sensitive to its geometry than parallel- or cross-flow configurations. Zhang [13] published a review on the advances of using membranes with air conditioning systems and found that membranes can increase the COP up to 5.8, resulting in substantial energy savings. Sebai et al. [14] numerically modelled an air membrane in the cross-flow configuration under both balanced and unbalanced flow conditions and identified the best operating conditions for each case. Furthermore, they report that the energy demand can be reduced under optimized unbalanced flow conditions. Liang [15] examined the performance of a membrane heat and mass exchanger for an air conditioning system and identified the relationship between the sensible effectiveness and the latent effectiveness under selected operating conditions.

In a different study, Zhang et al. [16] conducted exergy and entransy analyses for an air handling process between the air and the liquid desiccant. They found that during the heat and mass transfer processes, entransy dissipation and exergy destruction occurred owing to the limited transfer capability and unmatched properties. Nasir and Kim [17] conducted energy analysis of an air conditioning system driven by organic Rankine cycle considering different refrigerants for the air conditioning system. The refrigerants analyzed are R245fa, R123, R134a, R1234yf, R1234ze (E), Butane and Isobutane. They found that R134a the best refrigerant.

Several other studies were conducted to assess the performance of a membrane heat and mass exchanger [18–24]. Zhang and Niu [18] conducted an energy analysis of air conditioning systems with a membrane exchanger and report that savings of about 58% can be achieved. For a tropical climate Zaw et al. [19] studied the performance of an air-membrane exchanger for dehumidification, without coupling it to an air conditioning system. Das and Jain [20] compared different desiccant types and selected the best for the climatic conditions of India. Xing et al. [21] assessed the performance of an exchanger with a zeolite membrane for air conditioning applications and they suggested a separation factor of more than 200 to improve the performance of an air conditioning system. Zhang et al. [22] evaluated the performance of a membrane exchanger coupled with an air conditioning system and demonstrated that up to 33% of energy savings can be achieved. Zhang [23] further improved the design of the membrane exchanger and achieved substantial savings in energy reaching 42%. Liang et al. [24] compared air conditioning systems integrated with a membrane exchanger and a conventional dehumidification system and showed that the system based on a membrane exchanger provides better results. In a different study Al-Sulaiman [25] conducted performance analysis of an air-membrane heat and mass exchanger for air conditioning applications using refrigerant R134a and demonstrated that significant exergy destruction, reaching 50%, can be obtained when the membrane is used.

The following refrigerants have high potential as potential refrigerants in the future and, therefore, they were selected in this study: R1234yf, R1234ze, R32, and R410A. R1234yf and R1234ze are synthetic HFO refrigerants which have very low global warming potential and will be used to replace other refrigerants, such as R134a; R32 will replace R410A and R 22; and R423A will replace R12. An air-membrane heat and mass exchanger can be used as a heat recovery device and additionally reduces the moisture contents in the air. Consequently, improves significantly the performance of an air conditioning system.

Even though membrane heat and mass exchangers coupled with air conditioning systems have the potential of providing substantial energy savings, they were not investigated well enough. In the study reported here, a membrane heat and mass exchanger integrated with an air conditioning system using the next generation refrigerants R1234yf, R1234ze, R32, and R423A, was investigated in detail. Key performance indicators of the system including the coefficient of performance, second law efficiency, exergy destruction rate, compressor work, irreversibility ratio, productivity lack, and fuel depletion ratio were also determined. To the best of author's knowledge, energy and exergy analyses were not performed for such a system using these next-generation refrigerants.