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Mathematical Analysis of Energy and Exergy loss in Air Conditioning system as Affected by Ambient Temperature

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ABSTRACT: The article provides a Mathematical analysis of exergy in air-conditioning as affected by ambient temperature. The Mathematical simulation model employs an integrated air conditioning system subjected to varying ambient temperatures to monitor the changes in the four primary components: the compressor, condenser, capillary, and evaporator, in relation to ambient temperature. The examination of the exergy of the four devices revealed that the capillary exhibits an anomalous increase in exergy loss with rising ambient temperature, in contrast to the other devices. The findings indicate that minimizing exergy loss in the capillary, affected by ambient temperature, is crucial for enhancing the operational efficiency of an air-conditioning system when accounting for ambient temperature effects. The elevated ambient temperature results in a greater pressure drop in the capillary and increased exergy loss.

KEYWORDS: energy, ambient temperature, exergy loss, efficiency

1. INTRODUCTION

The current century is characterized by a significant expansion of human knowledge, as well as a critical confrontation with the pressing issues of the energy crisis and environmental damage on Earth. As a result of the rapid depletion of petroleum at the onset of the current century, individuals are necessitated to address the oil issue preemptively.

Air conditioning is not only one of the most contemporary and essential amenities for humanity today, but also a system with significant energy usage globally. Currently, the Earth is experiencing global warming and ozone depletion, resulting in environmental pollution that raises surrounding temperatures, commonly referred to as the greenhouse effect [1, 2]. The greenhouse effect, identified by Joseph Fourier in 1824 and quantitatively examined by Svante Arrhenius in 1896, is the phenomenon whereby the emission of infrared light from an atmosphere elevates a planet's surface temperature. The greenhouse effect has already resulted in temperature increases exceeding 5°C in several regions of the Earth.

The primary function of air-conditioning is to transfer heat from the room to the external environment. The primary thermodynamic process in air-conditioning is the irreversible forced heat convection between the air-conditioning system and its surroundings.

According to the thermodynamic principle, heat transfer in air-conditioning occurs solely at a finite temperature differential that is proportionate to the rate of heat transfer. The greenhouse effect elevates ambient temperatures, so diminishing the temperature differential between air conditioning and the environment, which subsequently decreases the heat transfer rate and impairs air conditioning performance. Consequently, it is essential to examine ambient temperature's impact on air-conditioning efficiency. The losses in the air-conditioning system must be assessed by each constituent process of the system. Energy analysis is the predominant method employed in the examination of thermal systems; yet it fails to provide insights into the diminished performance of the system. Exergy demonstrates that energy possesses both quality and quantity, with actual processes occurring in the direction of diminishing energy quality. Energy analysis focuses solely on energy saving, but exergy analysis explicitly illustrates operational efficiency. The ideas and procedures of exergy analysis are firmly established [3, 4].

Exergy analysis often seeks to ascertain the system's optimal performance and pinpoint locations of exergy degradation [5]. Exergy analysis of a refrigeration system can be conducted by examining the individual components of the system independently. Identifying the primary locations of exergy destruction indicates opportunities for potential enhancements. A crucial aspect of exergy analysis for work-consuming systems, such as refrigeration, is determining the lowest work necessary to achieve a specific outcome [6-8]. Numerous research has been conducted on the exergy analysis of refrigeration and heat pump systems [9-12]. Exergy represents the maximal potential work obtainable from a cyclic system during a process. Exergy analysis in vapor compression refrigeration (VCR) cycles has been examined in the literature. This study particularly examines the impact of exergy loss expressions for the different processes constituting the system, alongside the determination of the coefficient of performance (COP) and exergy efficiency for the total system. The impact of ambient temperature on exergy losses, exergy efficiency, and coefficient of performance (COP) is examined.

2. MATHEMATICAL ANALYSIS

2.1The fundamental of vapor compression refrigeration cycle

The vapor compression refrigeration cycle is the predominant refrigeration cycle, comprising a compressor, a condenser, a throttling device (capillary), and an evaporator, along with controls and interconnections. Figure 1 illustrates the diagram of a fundamental vapor compression refrigeration system, representing a typical irreversible cycle model.

The Arabic numerals in Fig. 1, ranging from 1 to 8, illustrate the various states of the vapor compression refrigeration cycle, with the Mathematical sequence denoting the refrigerant flow direction, commencing with the compressor's suction, so facilitating the explanation of the process. The refrigerant is initially drawn in and compressed by the compressor from state 1 to state 2. At state 2, the refrigerant is under exceedingly high pressure and is superheated. The compressed refrigerant vapor transitions from state 2 to state 3. The refrigerant vapor in state 3 will enter the condenser to undergo condensation and engage in heat exchange with the environment. The heat released by the refrigerant during condensation in the condenser is dissipated into the environment via forced convection. The condensed refrigerant at the condenser outlet, designated as state 4, is directly sent to the capillary input and flows through the capillary into the evaporator. The refrigerant's evaporation process in the evaporator absorbs heat from the cooling space. Following the evaporation of refrigerant in the evaporator, the vapor is reabsorbed by the compressor, so completing the refrigeration cycle.

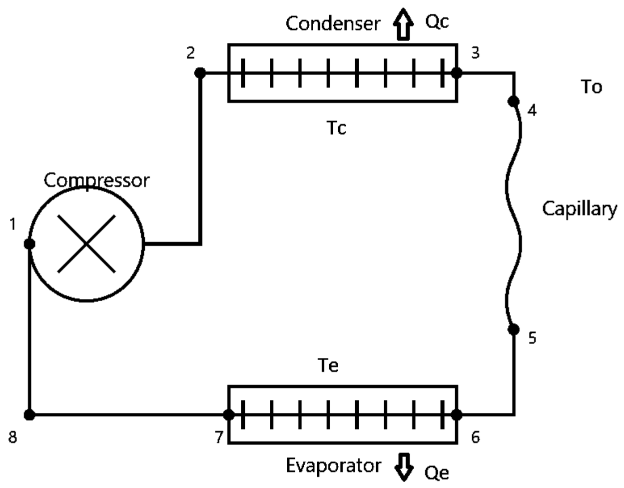

Fig. 1: Schema of a basic vapor-refrigeration cycle

2.2 Exergy Analysis

The exergy analysis is based on the fundamental vapor compression refrigeration system illustrated in Fig. 1. Mathematical modeling examined the entire system and its four primary components individually. The implemented vapor compression refrigeration system is characterized by the following four assumptions:

(1) Steady-state, steady-flow operation,
(2) minimal pressure dips in the evaporator, condenser, and junctions,
(3) adiabatic compression process,
(4) isenthalpic expansion in the capillary,
(5) negligible kinetic and potential energy.

Table 1 presents the design parameters of the implemented system. The efficiency of a vapor compression refrigeration cycle is represented by the coefficient of performance (COP), defined as the ratio of cooling energy to the work input. The coefficient of performance (COP) of a vapor refrigeration cycle is represented by equation (1).

Table 1 Design parameters of the applied vapor compression refrigeration system

Parameter	Value
Refrigerant	R-417A
Refrigerating capacity	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

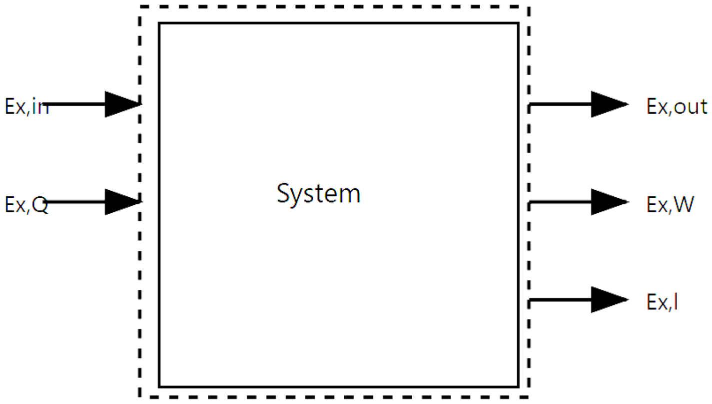

Fig. 2: The general exergy balance of a steady thermal system.

Figure 2 graphically depicts the exergy balance relationship for a generic open system, illustrating the overall exergy balance of a stable thermal system.
The total exergy entering a steady flow system in all forms must equal the exergy exiting plus the exergy destroyed, as articulated in equation (2).

Based on the primary cycle loop illustrated in Fig. 1, in accordance with the first law of thermodynamics and equation (2), a general relationship for a cyclic process can be expressed as equations (3) through (8).

Coefficient of Performance (COP)

$$COP=Q_e/W \quad (1)$$

General Exergy Balance

$$\sum Ex,in=\sum Ex,out+\sum Ex,Q,out+\sum Ex,W,out+\sum Ex,l,out \quad (2)$$

Exergy Loss on Compression Process

$$Ex,l,cp=Ex,1-Ex,2 \quad (3)$$

Exergy Loss on Condensation Process

$$Ex,l,cd=Ex,3-Ex,4 \quad (4)$$

Exergy Loss on Throttling Process

$$Ex,l,th=Ex,5-Ex,6 \quad (5)$$

Exergy Loss on Evaporation Process

$$Ex,l,ev=Ex,7-Ex,8+Ex,Qe \quad (6)$$

Exergy Flow Rate

$$Ex,i=\dot{m}\,si \quad (7)$$

General Relation for a Cyclic Process

$$\dot{m}\sum \Delta si=0 \quad (8)$$

Exergy Efficiency

$$\eta_{ex}=E_x/W \quad (9)$$

Exergy Loss in Compression Process (Expanded)

$$Ex,l,cp=-W+Ex,1-Ex,2 \quad (10)$$

$$Ex,l,cp=\dot{m}\,T_0(s_2-s_1) \quad (11)$$

Exergy Loss in Condensation Process

$$Ex,l,cd=\dot{m}\,[(h_3-h_4)-T_0(s_3-s_4)] \quad (12)$$

Exergy Loss in Throttling Process

$$Ex,l,th=\dot{m}\,[(h_5-h_6)-T0(s_5-s_6)] \quad (13)$$

$Ex,l,th = \dot{m} T_0 (s_6 - s_5)$ (14)

Generalized Relationship for Enthalpy Change

$dh = Tds + vdp$ (15)

Partial Derivative of Enthalpy

$(\partial h \partial p)T = v$ (16)

Exergy Loss in Throttling Process (Pressure Drop Dependency)

$Ex,l,th = \dot{m} T_0 \Delta p$ (17)

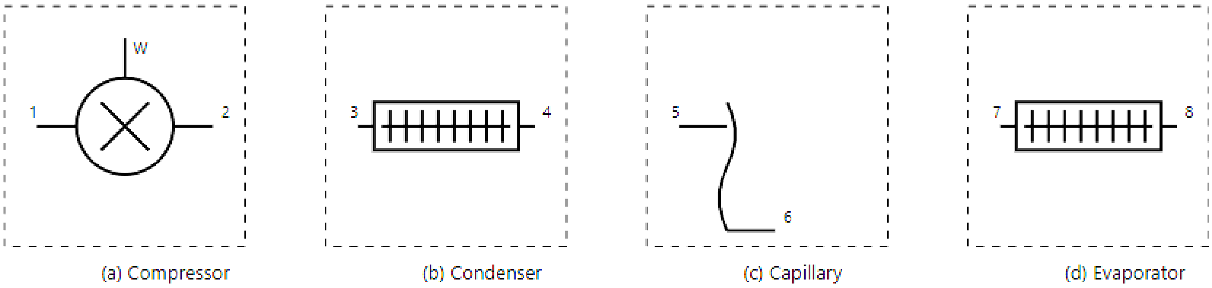

Fig. 3: Schemas of control volumes for the four main devices of a vapor compression refrigeration system:

3. RESULTS AND ANALYSIS

The Mathematical analyses concentrate on the correlation between exergy loss and ambient temperature, examining each of the four primary devices separately. The concept of heat transfer states that the rate of heat transfer is proportionate to the temperature differential, resulting in a reduction in heat convection between devices and their environment as the temperature difference diminishes. The heat transfer rate influences the operational efficiency of the system or the exergy loss in an air-conditioning unit. Typically, a greater heat transfer rate correlates with enhanced system efficiency or reduced exergy loss. The heightened exergy losses of the system not only indicate a reduction in the system's operational efficiency but also signify an escalation in energy wastage. Figure 4 illustrates the exergy losses for each component related to vapor compression refrigeration (VCR) as a function of ambient temperature.

Figure 4 demonstrates that the variation in exergy loss relative to ambient temperature for the capillary exhibits an anomalous rise compared to the other three primary devices. This outcome is a crucial insight for developing a new energy-saving system, particularly when accounting for the impact of ambient temperature. Reducing the exergy loss of the capillary at elevated ambient temperatures will enhance the system's operational efficiency. The behaviors depicted in Fig. 4 can be elucidated both physically and mathematically. The compressor, condenser, and capillary are initially affected by ambient temperature by heat convection with the environment during operation. The rising ambient temperature will result in a diminishing temperature differential between devices and their environment. The evaporator transfers heat to the cooled room, contingent upon the system's operational efficiency and indirectly affected by the ambient temperature. The heat transfer rate diminishes as the temperature differential decreases with the rising ambient temperature.

The physical rationale for the anomalous escalation of exergy loss in the capillary may be as follows. The rate of forced heat convection in tubes is similarly contingent upon the contact surface area. With a constant temperature differential, an increase in contact surface area results in an enhanced forced heat convection rate. The contact surface of the capillary is significantly greater than that of the other three primary devices. The impact of ambient temperature on the capillary is far greater than that on the other three primary devices. The mathematical impact of ambient temperature on the compressor, condenser, and evaporator is of one order as a function, however the capillary exhibits an influence greater than one order. The pressure differential across the capillary rises with an increase in ambient temperature, as seen in equation (16).

The observed pattern of exergy loss in the capillary rising with ambient temperature can be attributed to the increase in the average pressure differential between the condenser and the evaporator when ambient temperature rises, as illustrated in Fig. 5. Figure 5 illustrates that the pressure drops in the capillary grow with rising ambient temperature. Two parameters influence the products on the right side of equation (16).

The impact of ambient temperatures on the coefficient of performance (COP) and exergy efficiency, together with the relationship between COP and input exergy of the refrigeration cycle, is illustrated in Figures 6-8.

The coefficient of performance (COP) of the refrigeration cycle diminishes as the ambient temperature rises, as depicted in Fig. 6. The trends in Figures 6 and 7 are fundamentally identical, with the coefficient of performance (COP) fluctuating between 2.8 and 4.2 as a function of ambient temperature. The Coefficient of Performance (COP) is determined by dividing the heat extracted from the cold area by the actual work input of the compressor.

In Fig. 8, the percentages of exergy efficiency per unit input exergy diminish as the ambient temperature rises. Within the temperature ranges depicted in Fig. 8, the exergy efficiency diminishes from 42% to around 29%. The declining trend corresponds with the computed results.

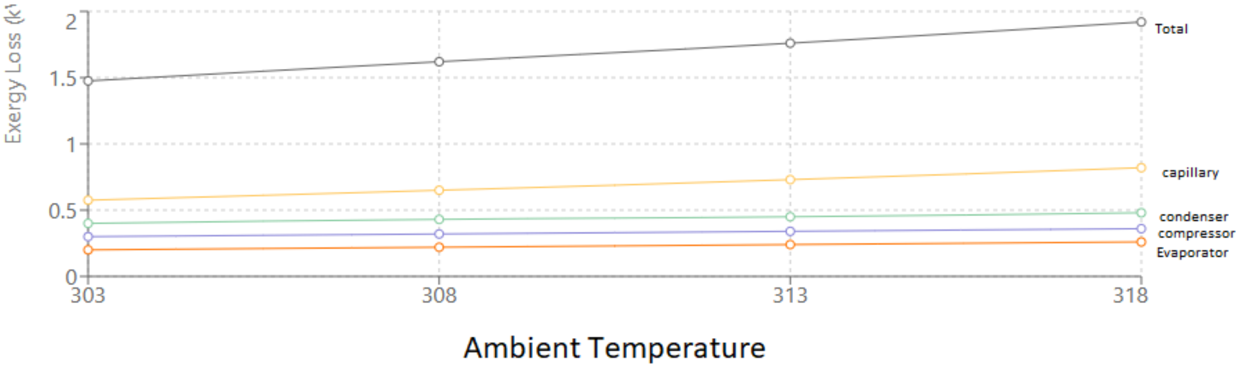

Fig. 4: Exergy losses (kW)vs. ambient temperature(K) for the four main devices and the total exergy loss.

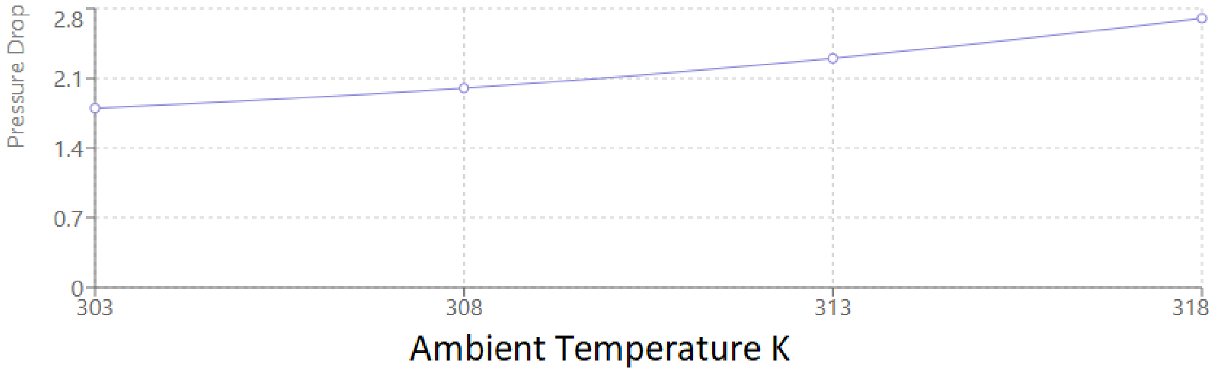

Fig. 5: Pressure drops (kPa) of the capillary during operation.

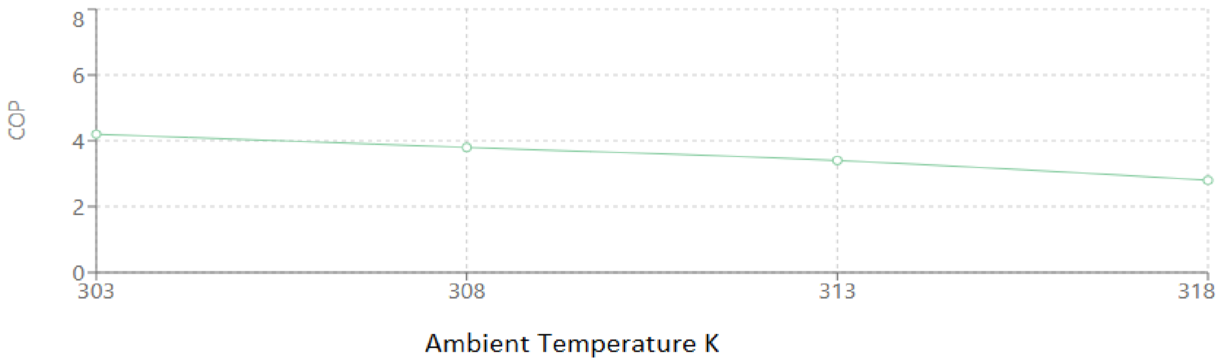

Fig. 6: COP of the refrigeration cycle vs. ambient temperature (K).

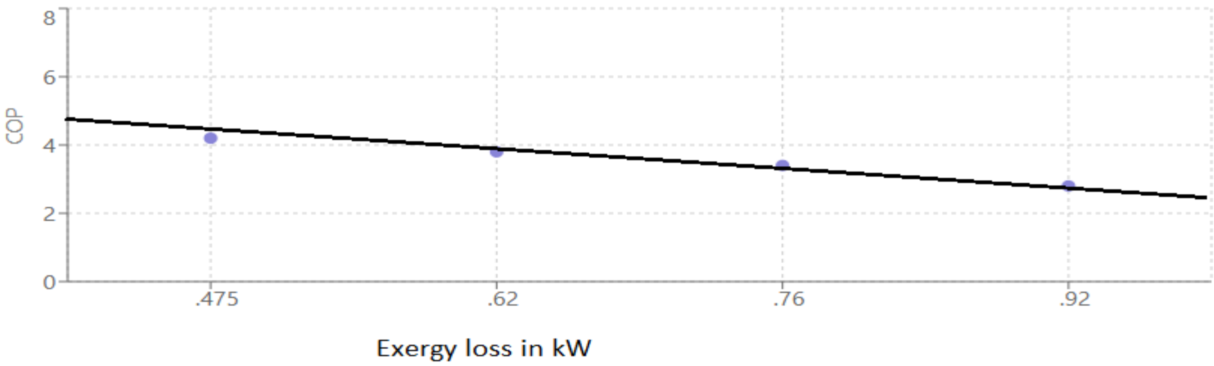

Fig. 7: COP vs. exergy loss (kW) of the cycle.

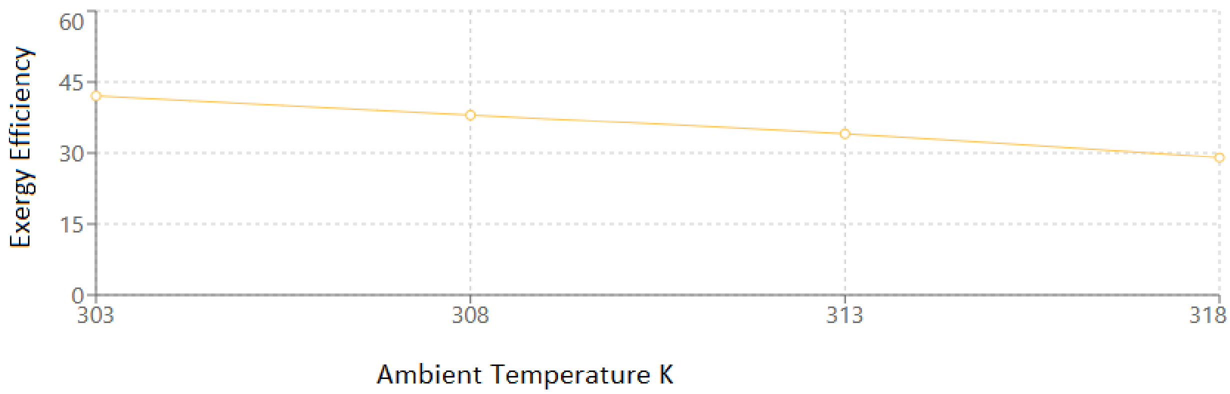

Fig. 8: Exergy efficiency vs. ambient temperature (K).

4. CONCLUSIONS

The investigations into the impact of ambient temperatures on exergy losses, exergy efficiency, and the coefficient of performance (COP) of a vapor compression refrigeration cycle by Mathematical analysis have been effectively conducted. The capillary is most significantly affected by ambient temperature, while the other three primary devices exhibit less influence. The rising pressure drops in the capillary due to elevated ambient temperatures result in a significant alteration in exergy loss for the capillary, whereas the pressure drops in the condenser and evaporator are disregarded. As the ambient temperature rises by 1˚C (from 303 to 304 K), the exergy loss escalates from approximately 0.575 to 0.6 kW, reflecting an increase rate of about 4.35%, while the coefficient of performance (COP) of the refrigeration system diminishes from about 4.2 to 4.08, indicating a decline rate of approximately 2.86%.

REFERENCES

1. Jian Sun, Wenhua Li, Borui Cui, Energy and exergy analyses of R513a as a R134a drop-in replacement in a vapor compression refrigeration system, International Journal of Refrigeration, Vol 112,2020, Pages 348-356, https://doi.org/10.1016/j.ijrefrig.2019.12.014.
2. J.M. Belman-Flores, V.H. Rangel-Hernández, S. Usón, C. Rubio-Maya, Energy and exergy analysis of R1234yf as drop-in replacement for R134a in a domestic refrigeration system, Energy, Volume 132,2017,Pages 116-125, https://doi.org/10.1016/j.energy.2017.05.074.
3. Miguel Padilla, Rémi Revellin, Jocelyn Bonjour, Exergy analysis of R413A as replacement of R12 in a domestic refrigeration system, Energy Conversion and Management, Volume 51, Issue 11, 2010, https://doi.org/10.1016/j.enconman.2010.03.013.
4. Gang Yan, Chengfeng Cui, Jianlin Yu, b Energy and exergy analysis of zeotropic mixture R290/R600a vapor-compression refrigeration cycle with separation condensation, International Journal of Refrigeration, Volume 53, 2015, https://doi.org/10.1016/j.ijrefrig.2015.01.007.
5. Mahmood Mastani Joybari, Mohammad Sadegh Hatamipour, Amir Rahimi, Fatemeh Ghadiri Modarres, Exergy analysis and optimization of R600a as a replacement of R134a in a domestic refrigerator system, International Journal of Refrigeration, Volume 36, Issue 4, 2013, https://doi.org/10.1016/j.ijrefrig.2013.02.012.
6. Mehdi Rasti, SeyedFoad Aghamiri, Mohammad-Sadegh Hatamipour,Energy efficiency enhancement of a domestic refrigerator using R436A and R600a as alternative refrigerants to R134a,International Journal of Thermal Sciences,Volume 74,2013,Pages 86-94, https://doi.org/10.1016/j.ijthermalsci.2013.07.009.
7. Muthuraman Subbiah, Saravanan N, Sivaraj M, Kumar A. Implementation of a solar-thermal hybrid air conditioning system in Muscat for energy conservation. Building Engineering. 2024; 2(1): 1380. https://doi.org/10.59400/be.v2i1.1380
8. Muthuraman Subbiah, Sharif, H. Z., Murugan, S., and Ayyappan, K. (2024). Net zero energy analysis and energy conversion of sustainable residential building in Muscat, Oman. Building Engineering, 2(1), 1231. https://doi.org/10.59400/be.v2i1.1231
9. Muthuraman Subbiah, Natarajan, S. and Murugan, S., Analyze the Effects of Implementing a Solar Thermal Hot Water System on Oman's Economy and Environmental Factors. Open Access Library Journal, 11: e11127.January-2024, https://doi.org/10.4236/oalib.1111127
10. Chen, J., Chen, X., & Wu, C. 2001. Optimization of the rate of exergy output of a multistage endoreversible combined refrigeration system. Exergy, An International Journal, 1(2), 100-106.
11. D. Sánchez, R. Cabello, R. Llopis, I. Arauzo, J. Catalán-Gil, E. Torrella, Energy performance evaluation of R1234yf, R1234ze(E), R600a, R290 and R152a as low-GWP R134a alternatives,

International Journal of Refrigeration, Volume 74,2017, Pages 269-282, https://doi.org/10.1016/j.ijrefrig.2016.09.020.

12. Y. Heredia-Aricapa, J.M. Belman-Flores, A. Mota-Babiloni, J. Serrano-Arellano, Juan J. García-Pabón, Overview of low GWP mixtures for the replacement of HFC refrigerants: R134a, R404A and R410A, International Journal of Refrigeration, Volume 111,2020, https://doi.org/10.1016/j.ijrefrig.2019.11.012.