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Exergy Analysis of a Vapour Compression Chiller at Elevated Chilled Water Outlet Conditions

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In the pursuit of efficient energy use, decoupling the sensible and latent loads of a Mechanical Vapour Compression Chiller system with the use of a Dehumidifier has been of great interest to society. Focusing purely on the sensible load allows the supply chilled water to be elevated to temperatures above the standard of 7°C. This paper focuses on using prior research on an elevated chilled water chiller system to carry out an exergy analysis, in order to identify the contribution of each and individual component to the total exergy destruction as well as the exergetic efficiency. Varying the temperature of the chilled water outlet conditions between 7-17°C provides valuable insight into how the total exergy destruction increases at a rate of 1.2% per degree Celsius of chilled water supply whilst the exergetic efficiency decreases at a rate of 1.4% per degree Celsius. The largest contributor to the exergy destruction is identified to be the compressor, whilst the evaporator and condenser show similar exergy destructions and the expansion valve has the lowest exergy destruction. These findings highlight the irreversibilities occurring within the system when the operation conditions of the chilled water are varied above the standard.

Key words: *Chiller, Exergy, Sensible Cooling, Second Law Efficiency*

Nomenclature

COP	coefficient of Performance [-]
q_{Evap}	cooling effect [kW]
$\dot{m}_{Ch}$	chilled water flow rate [kg/s]
C_p	specific heat capacity [kJ/kgK]
$T_{Ch,In}$	chilled water inlet temperature [°C]
$T_{Ch,Out}$	chilled water outlet temperature [°C]
q_{Cond}	condenser heat rejection [kW]
$\dot{m}_{Cw}$	cooling water mass flow [kg/s]
$T_{Cw,In}$	cooling water inlet temperature [°C]
$T_{Cw,Out}$	cooling water outlet temperature [°C]
E_{cv}	exergy of control volume [kW]
t	time [s]
T_0	dead state temperature [°C]
T_j	temperature of i[th] component [°C]
$\dot{Q}_j$	heat transfer of i[th] component [kW]
$\dot{W}_v$	shaft work [kW]
p_0	dead state pressure [bar]
V_{cv}	volume of control volume [m^3]
$\dot{m}$	mass flow rate [kg/s]
e_f	flow exergy [kW]
$\dot{E}_D$	exergy destruction rate [kW]
h	specific enthalpy [kJ/kg]
s	specific entropy [kJ/kgK]
η_{Ex}	exergetic efficiency [%]
P_{Comp}	compressor power [kW]

Subscripts

In	inlet
Out	outlet
Evap	evaporator
Cond	condenser
Comp	compressor
Exp	expansion valve
Ch	chilled water
Cw	cooling water
Suc	suction
Disch	discharge

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1. Introduction

Attaining comfort conditions for habiting indoor environments is of major importance in everyday life. In most tropical countries and during summer seasons, the warmer outside air temperatures require to be conditioned in order to attain cooler temperatures and lower relative humidity values within indoor spaces. This has boosted the demand and use of air conditioners, especially within tropical countries[1]. In the case of many office buildings and industrial applications, chillers with water as the secondary working fluid are utilized due to the ease in the distribution of chilled water within the building. However, chillers are very energy intensive and can consume up to 50% of a building's electrical energy demand[2]. Therefore, they contribute indirectly to adverse effects such as global warming which humanity is currently trying to control. Since the basic invention of the chiller by Willis Carrier in 1902, both sensible and latent loads have been handled together[3]. This dual load controls the temperature of the air as well as the relative humidity or water content, both of which are considered to be important factors in determining thermal comfort[4]. In order to handle both sensible and latent loads, chilled water is required to be cooled down to temperatures below the dew point of the outdoor air, which removes moisture whilst simultaneously cooling the supply air. Cooling the chilled water to such low temperatures in order to handle the latent load of the air requires more energy than in the case of pure sensible load[5].

With the emergence of new dehumidification technology, there is a possibility of decoupling the sensible and latent loads. Research carried out by Oh et al. have shown that there is great promise in using dehumidifier technology with solid desiccants in order to control water vapour concentrations of air[6]. There has also been the application of liquid desiccant cooling which have been studied by Peng et al. using exergy analysis[7]. Wang et al. have also used model based optimization for a liquid desiccant system which have helped further improvement in possible operating conditions[8]. Much of these findings are summarized by Jani et al. where details regarding the use of solid desiccants and their benefits are reiterated[9]. It has also been shown that there exist many alternative ways of assisting this dehumidification process, such as the use of solar assisted dehumidification in order to treat fresh air[10]. Thus with the possibility of utilizing dehumidification systems with chillers, the cooling load can be decoupled such that the chiller handles only the sensible load whilst the dehumidifier handles the latent load. To provide an idea on the benefits as well as feasibility of adapting such a process, an important analytical tool is exergy analysis. In system analyses, exergy technique has been utilized often in order to provide an accurate and realistic representation of the efficiency of a process as well as its deviations from the ideal conditions[11]. These deviations are a result of irreversibilities within the system, which are important to both engineers and designers for assessing the improvement and optimization of machines and processes. It is quite commonly seen that exergy analysis is applied by many researches, such as in the case of comparing alternative refrigerants for replacing ones with higher Global Warming Potential (GWP) or Ozone Depletion Potential (ODP) in domestic refrigeration systems[12.14]. These studies justified their findings using exergy analysis since it allows the performance of the refrigeration systems to be compared even if the capacities and refrigerant used are different. Adsorption chillers and cooling systems have also been analysed due to their ability to utilize waste heat or solar thermal energy and further reduction in the environmental impact[15-18]. Ahamed et al. carried out a review on the use of exergy analysis of vapour compression (VC) refrigeration systems which points out that factors such as evaporator temperature and condenser temperature affect the overall exergetic performance of the chiller[19]. It is also mentioned that the use of alternative refrigerants and utilizing nanofluids as lubricants can reduce the exergy loses in some components.

Although exergy analysis is an important method which is utilized for the study of Refrigeration Systems, Adsorption Chillers and Vapour Compression (VC) Chillers, there has been little work which explores the exergetic relation of operating Mechanical Vapor Compression (MVC) Chillers at elevated chilled water temperatures above the standard of 7°C. Therefore, based on experimental works carried out by Thu et. al. regarding a MVC chiller at elevated chilled water temperatures, a second law exergetic analysis is presented in this paper[20].

2. Experiment

2.1 Experimental Method

A water cooled Mechanical Vapour Chiller with a capacity of 10kW is employed as the experimental set up[20]. In order to make the gathered data and presented results internationally comparable, AHRI Standard 551/591[21] is utilized. AHRI Standard 551/591 requires that the supply chilled water be maintained at 7°C with a mass flow rate of 0.0478 L/(s-kW) whilst the cooling water supplied to the condenser is maintained at 30°C[22]. The chilled water supply which is elevated above the standard of 7°C, is raised up to 17°C, whilst the cooling water supply is varied between 28-32°C. The operation conditions of full load and part load are also studied with a temperature difference of both 4°C and 5°C being assigned to the cooling liquid. In order to achieve these required set points, the chiller system incorporated mixing tanks, which allowed both chilled water, cooling water from the cooling tower and from the condenser to be mixed in required rates using PID controllers for the valves. The measuring instruments for temperature and flow volume allowed the accuracy of the system to be maintained at ±0.3°C and ±0.45 LPM respectively. During the data collection, the system was allowed to reach steady state conditions for at least 45 minutes and the superheat conditions were maintained at 6.5 ±0.5°C and sub-cooling at 3.5±0.5°C.

2.2 Exergy

In order to calculate the cooling capacity of the evaporator and the heat rejection of the condenser the secondary fluid or chilled water and cooling water is utilized by applying an energy balance to the heat exchangers[20].

$$q_{Evap} = \dot{m}_{Ch} \times C_p \times (T_{Ch,In} - T_{Ch,Out}) \quad (1)$$

$$q_{Cond} = \dot{m}_{Cw} \times C_p \times (T_{Cw,Out} - T_{Cw,In}) \quad (2)$$

Energy conservation is applied for the heat exchangers and any heat leaks are neglected. The compressor power input is directly recorded from a power meter which measures the electrical power usage of the compressor through the duration of the experiment.

The exergy analysis of this MVC Chiller is carried out with the aid of p-h diagram and derived equations for individual exergy destruction within each component. Figure 1 displays the p-h diagram of both 7°C and 17°C Chilled Water Outlet Temperature (T_{ChOut}) conditions at Condenser Inlet Temperature (T_{CondIn}) 32°C. The displayed points from 1-9 represent the green colour 7°C cycle whilst the points a-i represent the purple colour 17°C cycle;

$$1/a = Compressor\ \ Suction$$
$$2/b = Compressor\ \ Discharge$$
$$3/c = Condenser\ \ Inlet$$
$$4/d = Condenser\ \ Saturated\ Vapour\ State$$
$$5/e = Condenser\ \ Saturated\ Liquid\ Stage$$
$$6/f = Condenser\ \ Outlet$$
$$7/g = Exapnsion\ Valve\ Inlet$$
$$8/h = Evaporator\ \ Inlet$$
$$9/i = Evaporator\ \ Saturated\ Vapour\ Sate$$

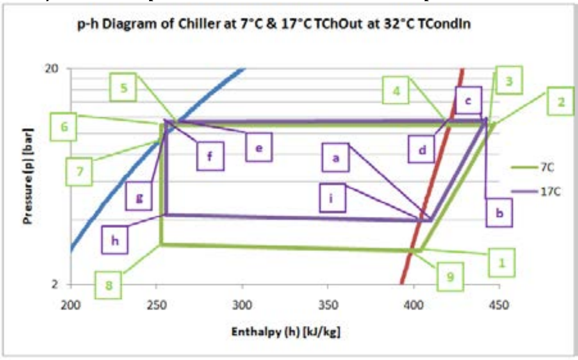

Fig. 1 p-h Diagram of Chiller at 7°C & 17°C T_{ChOut} at 32°C T_{CondIn}

It is also noted that data for a constant ambient condition or Condenser Inlet Temperature (T_{CondIn}) 32°C with varying T_{ChOut} 7-17°C will be solely utilized for the analysis in this paper, since the mechanical vapour compression chillers are often operated and are considered to be more beneficial during higher ambient temperatures in order to achieve comfort conditions for occupants within indoor spaces. The exergy analysis will be based on the following equations, Eqn .3 to Eqn. 9. With the assumption of steady state conditions, the rate of exergy change within the control volume is zero and heat leaks are also assumed to be zero.

Exergy Balance Equation

$$\frac{dE_{cv}}{dt} = \sum_{j=1}^{n} \left(1 - \frac{T_0}{T_j}\right) \dot{Q}_j + \left(\dot{W}_v + p_0 \frac{dV_{cv}}{dt}\right) + \sum_i \dot{m}_i e_{fi} - \sum_e \dot{m}_o e_{fe} - \dot{E}_D \quad (3)$$

Flow Exergy

$$e_f = (h_i - h_0) - T_0(s_i - s_0) \quad (4)$$

Evaporator

$$\dot{E}_D = \dot{m}_{ref}(e_{fEvap,In} - e_{fSuc}) - \dot{m}_{Ch}(e_{fCh,in} - e_{fCh,out}) \quad (5)$$

Condenser

$$\dot{E}_D = \dot{m}_{ref}(e_{fDisch} - e_{fCond,out}) - \dot{m}_{Cw}(e_{fCw,in} - e_{fCw,out}) \quad (6)$$

Compressor

$$\dot{E}_D = P_{Comp} + \dot{m}_{ref}(e_{fSuc} - e_{fDisch}) \quad (7)$$

Expansion Valve

$$\dot{E}_D = \dot{m}_{ref}(e_{fCond,out} - e_{fEvap,in}) \quad (8)$$

Exergetic Efficiency

$$\eta_{Ex} = COP\left(\frac{T_0}{T_{Evap}} - 1\right) \quad (9)$$

3.1 Results and Analysis

3.1.1 Exergy Destruction

With the increase in T_{ChOut}, there are mainly two characteristics visible as shown in Fig. 2 and Fig. 3. The two heat exchangers (evaporator and the condenser) show an increasing exergy destruction trend, whilst the compressor and expansion device show a decreasing trend. Both the evaporator and condenser are the heat exchanging components of this system and with increasing T_{ChOut}, they also exhibit increased quantities of heat exchanged[20]. Thus the major contributor to the increased exergy destroyed would be this increased rate of cooling effect at the evaporator and heat dissipation rate at the condenser.

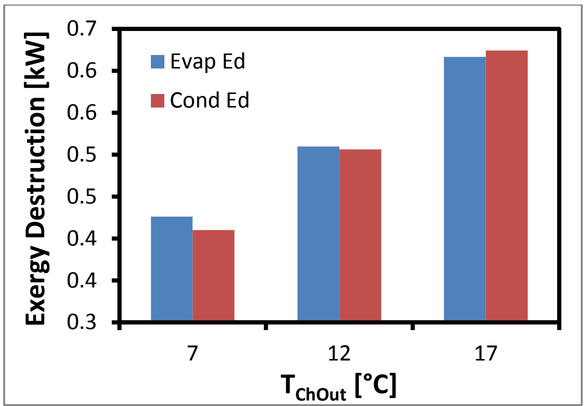

Fig. 2 Exergy destruction vs. T_{ChOut} at 32°C T_{CondIn} for evaporator and condenser

Furthermore, with the increase in the chilled water temperature, the p-h diagram (Fig. 1) shows the evaporator pressure increase from 8-9-1 to h-i-a, which would also result in the larger exergy destruction than at lower evaporator pressures. The evaporator shows an exergy destruction increase rate of 4.1% per °C of T_{ChOut}, whilst the condenser increases at a rate of 5.0% per °C of T_{ChOut}.

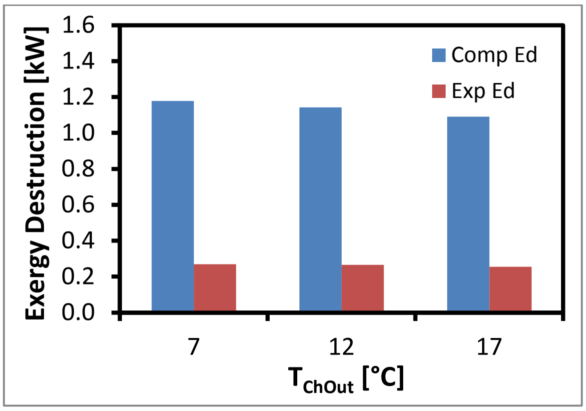

Fig. 3 Exergy destruction vs. T_{ChOut} at 32°C T_{CondIn} for compressor and expansion valve

The compressor and expansion valve which involve no heat transfers are affected by the change in the compression ratio which is clearly seen in Fig. 1 as the difference between the condenser and evaporator pressures signified by the decrease in the vertical span between the two horizontals of 6-5-4-3 and 8-9-1 to the smaller gap of f-e-d-c and h-i-a. The reduced compression ratio at the elevated T_{ChOut}, will result in lesser exergy destruction within the compressor due to the lower work input, and lower pressure drop when passing through the expansion valve will also result in a similar observation. Respectively, the exergy destruction rates reduce by 0.6% per °C of T_{ChOut} and 0.4% per °C of T_{ChOut} within the Compressor and Expansion Valve.

3.1.2 Exergetic Efficiency

The exergetic efficiency of the system is shown in Fig. 4. It is observed that the efficiency decreases with increasing chilled water outlet temperature at a rate of 1.4% per °C of T_{ChOut}.

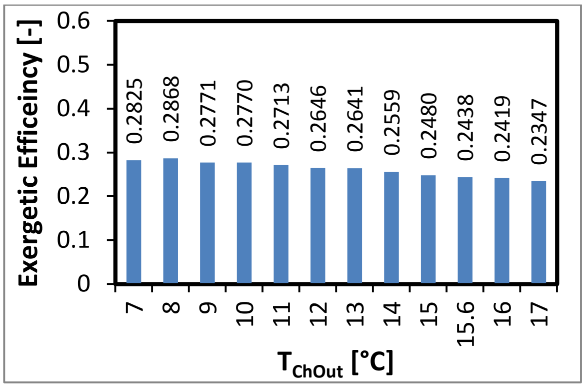

Fig. 4 Exergetic efficiency vs. T_{ChOut} at 32°C T_{CondIn}

This trend is expected as the chilled water temperature is raised, the pressure of the evaporator increases. As the evaporator temperature reaches T_0, the exergetic efficiency will reach zero.

3.1.3 Component and Total Exergy Destruction

It would also be beneficial to ascertain how the components rank with respect to the total exergy destruction within the system. In Fig. 5 the exergy destruction values for each of the four components are presented at 7°C and 17°C T_{ChOut}.

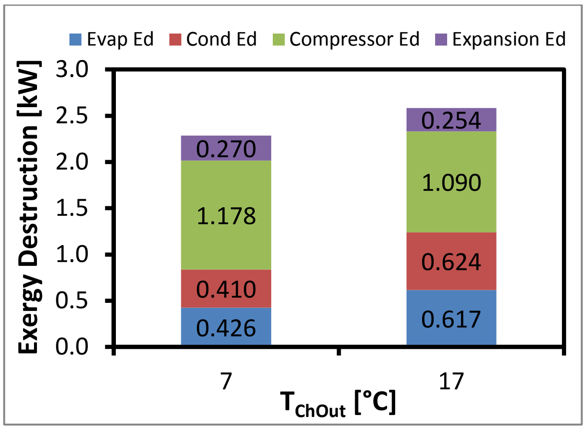

Fig. 5 Exergy destruction of individual components vs. T_{ChOut} at 32°C T_{CondIn}

The compressor clearly shows larger values in comparison to the rest of the components with 1.178 kW at 7°C and 1.090 kW at 17°C. The evaporator and condenser have almost equal values in terms of exergy destruction with 0.426 kW and 0.410 kW at 7°C and 0.617 kW and 0.624 kW at 17°C. The lowest exergy destruction occurs within the expansion valve with 0.270 kW at 7°C and 0.254 kW at 17°C.

Figure 6 presents the percentage values for exergy destruction within each individual component, which further helps visualized the impact each component has on the overall system exergy destruction. The compressor which has the largest exergy destruction with 52% and 42% at T_{ChOut} 7°C and 17°C respectively shows a decreasing trend with increasing T_{ChOut}. The evaporator and condenser show almost equal amounts of exergy destruction varying between 18-24% which increase with elevated T_{ChOut}. The expansion device has the lowest exergy destruction values between 10-12% of the whole system with a decreasing trend as T_{ChOut} is increased. Hence the compressor is the major contributor to the exergy destruction of the system, followed by the heat exchangers which show increasing exergy destruction with the rate of heat exchange.

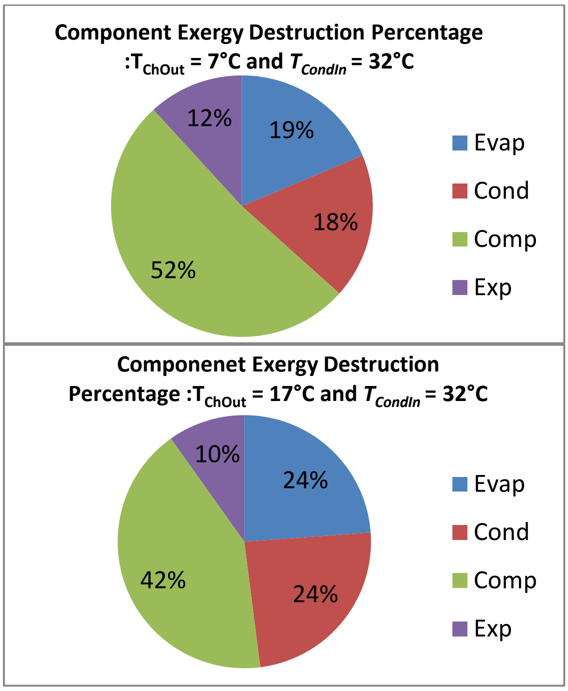

Fig. 6 Component exergy destruction percentage at T_{ChOut} = 7°C & 17°C at 32°C T_{CondIn}

The overall exergy destruction or the total exergy destruction of the system increases at a rate of 1.2% per °C with increasing T_{ChOut} as displayed in Fig. 7. This highlights the increase in irreversibilities of the system which results in a reduction of the exergetic efficiency at a rate of 1.4% per °C of T_{ChOut}. Even though the COP and the cooling capacity of the system is stated to have increased by Thu et al. at rates of 3.5% and 4% per °C increase in chilled water temperature[20], there still lies space for improvement of the overall system and components such as the compressor which result in large irreversibilities and hence exergy destruction.

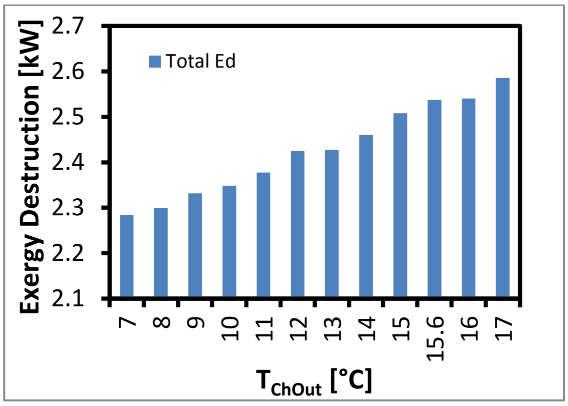

Fig. 7 Total Exergy Destruction vs. T_{ChOut} at 32°C T_{CondIn}

4. Summary and Conclusions

The exergy analysis carried out in this paper provides insight into the irreversibilities associated with the operation of a mechanical vapour compression (MVC) chiller at elevated chilled water temperatures when the condenser inlet cooling water is maintained at 32°C. Though initial findings by Thu et al. have shown the increase in COP and performance of the chiller at elevated chilled water temperatures and highlighted the possibility of using a MVC chiller coupled with a dehumidifier, the exergy destruction within the system also increases at a rate of 1.2% per degree Celsius of supply chilled water temperature, whilst the exergetic efficiency reduces at a rate of 1.4% per degree Celsius. The compressor which contributes between 42-52% of the total exergy destruction and requires the most attention in order to lessen the total exergy destruction of this system. This would help the system reach a maximum conversion of work potential during its cooling process whilst using the concept of handling sensible and latent loads separately for practical applications. The heat exchangers also show an increasing trend of exergy destruction with increasing heat transfer loads, which should be of interest to designers since this would highlight the possibility of including further measures to reduce the irreversibilities within these components. This study brings forth a better understanding to the individual efficiencies of the components of a MVC chiller system and highlights that there is a possibility to improve both the components individually and the system as a whole in order to lessen the exergy destruction at elevated chilled water temperatures, which would help reduce the large effect chillers have on the environment.

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References

1) Agbemabiese, Lawrence, et al. “Air Conditioning in the Tropics: Cool Comfort or Cultural Conditioning?” 1996 ACEEE Summer Study on Energy Efficiency in Buildings: Human Dimensions of Energy Consumption, 1996, pp. 1–9.
2) “Chillers: Energy Saving Fact Sheet.” North Carolina Energy Office, 2010.
3) Huston, Mark H. “Brief History of Centrifugal Chillers.” ASHRAE Journal, vol. 47, no. 12, 2005.
4) “Human Thermal Comfort." AUTODESK: Sustainability Workshop, AUTODESK. sustainabilityworkshop.autodesk.com/buildings/human-thermal-comfort. n.d.
5) Lewis, III, G.Harriman, et al. “Dehumidification and Cooling Loads From Ventilation Air.” ASHRAE JOURNAL, November, 1997.
6) Oh, Seung Jin, et al. “Evaluation of a Dehumidifier with Adsorbent Coated Heat Exchangers for Tropical Climate Operations.” Energy, 137 (2017), pp. 441–48, doi:10.1016/j.energy.2017.02.169.
7) Peng, Donggen, et al. “Exergy analysis of a liquid desiccant evaporative cooling system” International Journal of Refrigeration, 82 (2017), pp. 495–508, doi:10.1016/j.ijrefrig.2017.06.021.
8) Wang, Xinli, et al. “Model-Based Optimization Strategy of Chiller Driven Liquid Desiccant Dehumidifier with Genetic Algorithm.” Energy, 82 (2015), pp. 939–48, doi:10.1016/j.energy.2015.01.103.
9) Jani, D. B., et al. “Solid Desiccant Air Conditioning - A State of the Art Review.” Renewable and Sustainable Energy Reviews, 60 (2016), pp. 1451–69, doi:10.1016/j.rser.2016.03.031.
10) Chen, Yi, et al. “Investigation on Solar Assisted Liquid Desiccant Dehumidifier and Evaporative Cooling System for Fresh Air Treatment.” Energy, 143 (2018), pp. 114–27, doi:10.1016/j.energy.2017.10.124.
11) Dincer, I., and T. A. H. Ratlamwala. “Importance of Exergy for Analysis, Improvement, Design, and Assessment.” Wiley Interdisciplinary Reviews: Energy and Environment, 2 (2013), pp. 335–49, doi:10.1002/wene.63.
12) Belman-Flores, J. M., et al. “Energy and Exergy Analysis of R1234yf as Drop-in Replacement for R134a in a Domestic Refrigeration System.” Energy, 132

(2017), pp. 116–25, doi:10.1016/j.energy.2017.05.074.

13) Ben Jemaa, Radhouane, et al. "Energy and Exergy Investigation of R1234ze as R134a Replacement in Vapor Compression Chillers." International Journal of Hydrogen Energy, 42 (2017), pp. 12877–87, doi:10.1016/j.ijhydene.2016.12.010.
14) Joybari, Mahmood Mastani, et al. "Exergy Analysis and Optimization of R600a as a Replacement of R134a in a Domestic Refrigerator System." International Journal of Refrigeration, 36 (2013), pp. 1233–42, doi:10.1016/j.ijrefrig.2013.02.012.
15) Ebrahimi, Masood, and Mohammad Soleimanpour. "Design and Evaluation of Combined Cooling, Heating and Power Using Micro Gas Turbine, Adsorption Chiller and a Thermal Damping Tank in Micro Scale." Applied Thermal Engineering, 127 (2017), pp. 1063–76, doi:10.1016/j.applthermaleng.2017.08.111.
16) Koronaki, I. P., et al. "Thermodynamic Modeling and Exergy Analysis of a Solar Adsorption Cooling System with Cooling Tower in Mediterranean Conditions." Applied Thermal Engineering, 99 (2016), pp. 1027–38, doi:10.1016/j.applthermaleng.2016.01.151.
17) Buonomano, Annamaria, et al. "Solar Heating and Cooling Systems by Absorption and Adsorption Chillers Driven by Stationary and Concentrating Photovoltaic/thermal Solar Collectors: Modelling and Simulation." Renewable and Sustainable Energy Reviews, 81 (2018), pp. 1112–46, doi:10.1016/j.rser.2017.07.056.
18) Stanek, Wojciech, and Wiesław Gazda. "Exergo-Ecological Evaluation of Adsorption Chiller System." Energy, 76 (2014), pp. 42–48, doi:10.1016/j.energy.2014.02.
19) Ahamed, J. U., et al. "A Review on Exergy Analysis of Vapor Compression Refrigeration System." Renewable and Sustainable Energy Reviews, 15 (2011), pp. 1593–600, doi:10.1016/j.rser.2010.11.039.
20) Thu, Kyaw, et al. "Experimental Investigation of a Mechanical Vapour Compression Chiller at Elevated Chilled Water Temperatures." Applied Thermal Engineering, 123 (2017), pp. 226–33, doi:10.1016/j.applthermaleng.2017.05.091.
21) "Standards." AHRI: Air-Conditioning, Heating and Refrigeration Institute. http://www.ahrinet.org/Standards. n.d..
22) Standard for Performance Rating of Water-Chilling and Heat Pump Water-Heating Packages Using the Vapor Compression Cycle. Vol. SI-2015, 2016, p. 74.