PERFORMANCE SIMULATION OF A DOUBLE-EFFECT WATER-LITHIUM BROMIDE SOLAR-ASSISTED COOLING SYSTEM INTEGRATED WITH A STORAGE SYSTEM

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ABSTRACT

Most of the heating, ventilation, and air conditioning (HVAC) systems used to provide comfort in residential, commercial, and industrial buildings are electric vapour compression type. These systems consume considerable amounts of electrical energy, mostly generated from fossil fuels such as coal, oil, and natural gas. The continuous burning of fossil fuels contributes significantly to global warming due to the greenhouse effect in the ozone. Consequently, more energy-efficient and cleaner cooling options are required. Absorption chiller appears to be an attractive alternative for cooling as it operates primarily with heat energy. The heat is obtainable from various sources such as solar, geothermal heat, or waste heat. The use of solar-assisted absorption chiller for space cooling is limited to the availability of solar radiation, hence, energy storage is crucial to achieving extended hours of cooling operation. Therefore, the main goal of this research is to evaluate the performance of a solar-assisted double-effect absorption cooling system integrated with absorption energy storage (AES) and study its economic feasibility. This thesis simulated and evaluated the operational and economic performance characteristics of a solar-assisted cooling system. The solar-assisted cooling system consists of a parabolic trough solar collector (PTC), parallel-flow double-effect water-lithium bromide (H_2O-LiBr) absorption chiller, and absorption energy storage (AES). The thermodynamic model of the system is developed, validated, and simulated using the Engineering Equation Solver (EES) software package. The economic feasibility of the system is evaluated based on the annuity method. The simulation is carried out in four stages. Firstly, a detailed parametric analysis of the system is performed without the AES, considering a reference double-effect absorption chiller by Broad air conditioning company (USA) for determining the area of the PTC. Secondly, the system without AES is optimized using the genetic algorithm technique, where the system exergy efficiency is maximized. The optimization parameters considered are the mass flow rates of the external working fluids and solution distribution ratio of the parallel-flow double-effect absorption chiller. Thirdly, the solar-assisted cooling system is then integrated with AES and simulated, where its performance and the storage charging and discharging characteristics are discussed. Fourthly, the economic potential of the solar-assisted cooling system with and without AES is evaluated considering a reference commercial building. The results show an overall coefficient of performance (COP) of the integrated solar cooling system of 0.99 and an exergy efficiency of 6.8%. The energy storage density of the AES for typical climatic conditions of Dhahran, Saudi Arabia, is found to be 444.3 MJ/m^3. The energy storage density from the integrated solar-assisted cooling system is higher by 13 - 54% compared to other integrated systems based on single-effect configuration. The economic analysis indicates a reasonable payback period of five years to recover the initial investment of the solar-assisted system with AES. A specific solar collector area of 1.16 m^2/kW of cooling is obtained. This could be applied in sizing the solar collector field and evaluating the performance of similar systems under various climatic conditions with minimum solar radiation of around 500 W/m^2.

ABSTRAK

Sebilangan besar sistem pemanasan, pengudaraan, dan penyaman udara (HVAC) yang digunakan untuk memberikan keselesaan di bangunan kediaman, komersial, dan perindustrian adalah jenis pemampatan wap elektrik. Sistem ini menggunakan sejumlah besar tenaga elektrik, kebanyakannya dihasilkan dari bahan bakar fosil seperti arang batu, minyak, dan gas asli. Pembakaran bahan api fosil secara berterusan menyumbang kepada pemanasan global kerana kesan rumah hijau di ozon. Oleh itu, pilihan penyejukan lebih cekap tenaga dan bersih diperlukan. Penyejuk penyerapan nampaknya menjadi alternatif yang menarik untuk penyejukan kerana ia beroperasi terutamanya dengan tenaga haba. Haba dapat diperoleh dari pelbagai sumber seperti suria, haba bumi, atau haba terbuang. Penggunaan penyejuk penyerapan berbantukan suria untuk penyejukan ruang terhad kepada ketersediaan sinaran suria, oleh itu, penyimpanan tenaga sangat penting untuk mencapai operasi penyejukan yang berpanjangan. Oleh itu, tujuan utama kajian ini adalah untuk menilai prestasi sistem penyejukan penyerapan kesan berganda dengan bantuan suria yang disatukan dengan penyimpanan tenaga penyerapan (AES) dan mengkaji kesauran ekonominya. Tesis ini mensimulasi dan menilai ciri-ciri prestasi operasi dan ekonomi sistem penyejukan berbantukan suria. Sistem penyejukan berbantukan suria terdiri daripada pengumpul suria parabolik (PTC), penyejuk penyerapan air-lithium bromida (H_2O-LiBr) kesan selari, dan penyimpanan tenaga penyerapan (AES). Model termodinamik sistem dibangunkan, disahkan dan disimulasi menggunakan pakej perisian *Engineering Equation Solver* (EES). Kebolehlaksanaan ekonomi sistem dinilai berdasarkan kaedah anuiti. Simulasi dijalankan dalam empat peringkat. Pertama, analisis parametrik terperinci sistem dilakukan tanpa AES dengan menimbangkan penyejuk penyerapan kesan berganda oleh syarikat penyaman udara Broad (USA) untuk menentukan kawasan PTC. Kedua, sistem tanpa AES dioptimumkan menggunakan teknik algoritma genetik, yang mana kecekapan eksergi sistem dimaksimumkan. Parameter pengoptimuman yang dipertimbangkan adalah kadar aliran jisim cecair kerja luaran dan nisbah taburan larutan penyejuk penyerapan kesan berganda aliran selari. Ketiga, sistem penyejukan berbantukan suria kemudian disatukan dengan AES dan disimulasikan, yang mana prestasi dan ciri-ciri pengisian dan pelepasan penyimpanan dibincangkan. Keempat, potensi ekonomi sistem penyejukan berbantu suria dengan dan tanpa AES dinilai dengan menimbangkan satu rujukan bangunan komersial. Hasilnya menunjukkan keseluruhan pekali prestasi (COP) sistem penyejukan suria bersepadu adalah 0.99 dan kecekapan eksergi 6.8%. Ketumpatan simpanan tenaga AES untuk keadaan iklim khas Dhahran, Arab Saudi, didapati 444.3 MJ/m^3. Ketumpatan simpanan tenaga dari sistem penyejukan berbantukan suria bersepadu adalah lebih tinggi sebanyak 13% sehingga 54% berbanding sistem bersepadu lain berdasarkan konfigurasi kesan tunggal. Analisis ekonomi menunjukkan tempoh pembayaran balik yang munasabah selama lima tahun untuk mendapatkan semula pelaburan awal sistem bantuan suria dengan AES. Kawasan pemungut suria tertentu dengan penyejukan 1.16 m^2/kW diperolehi. Ini dapat diterapkan dalam ukuran medan pengumpul suria dan menilai prestasi sistem yang serupa dalam berbagai keadaan iklim dengan radiasi suria minimum sekitar 500 W/m^2.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ABS	-	Absorber
ACH	-	Absorption Chiller
AES	-	Absorption Energy Storage
AUD	-	Australian dollar
CFCs	-	Chlorinated Fluorocarbon Compounds
CON	-	Condenser
CPC	-	Compound Parabolic Concentrator
CRF	-	Capital Recovery Factor
CSP	-	Concentrated Solar Power
D4	-	Octamethylcyclotetrasiloxane
D5	-	Decamethylcyclopentasiloxane
DE	-	Double-effect
DMAC	-	N,N’-dimethylacetamide
DMETEG	-	Dimethyl ether tetraethylene-glycol
DMEU	-	Dimethyl-ethyleneurea
DS	-	Direct Search
E181	-	Tetraethylene glycol dimethyl ether
EES	-	Engineering Equation Solver
EMISE	-	1-ethyl-3-methylimidazolium ethylsulfate
ESP	-	Energy Savings Percentage
ETC	-	Evacuated Tube Collector
EVA	-	Evaporator
FLR	-	Linear Fresnel Collector
FPC	-	Flat Plate Collector
GA	-	Genetic Algorithm
GE	-	Generator
HE	-	Heat Exchanger
HFC	-	Heliostat Field Collector
HTG	-	Hight Temperature Generator
HVAC	-	Heating, Ventilation, and Air Conditioning

IEA	-	International Energy Agency
KSA	-	Kingdom of Saudi Arabia
LF	-	Levelized Factor
LTG	-	Low Temperature Generator
MDM	-	Octamethyltrisiloxane
MD2M	-	Decamethyltetrasiloxane
MD4M	-	Tetradecamethylhexasiloxane
MCL	-	N-methyl ε-caprolactum
MM	-	Hexamethyldisiloxane
[MMIM][DMP]	-	1,3-dimethylimidazolium dimethylphosphate
NMP	-	N-methy1-2-pyrrolidone
PCM	-	Phase Change Material
PTC	-	Parabolic Trough Collector
PV	-	Photovoltaic
PYR	-	2-pyrrolidone
RST	-	Refrigerant Storage Tank
SE	-	Single-effect
SEC	-	Saudi Electricity Company
SNL	-	Sandia National Laboratories
SST	-	Solution Storage Tank
STES	-	Sorption Thermal Energy Storage
TES	-	Thermal Energy Storage
TFE	-	2,2,2-trifluoroethano
TEGDME	-	Tetraethylene glyeol dimethyl ether
TESS	-	Thermal Energy Systems Specialist
TRNSYS	-	Transient Systems Simulator
USD	-	United State Dollar
V	-	Valve
VC	-	Vapour Compression

LIST OF SYMBOLS

A_c	Solar collector area (m^2)
A_{ri}	Inner surface area of receiver tube (m^2)
A_{ro}	Outer surface area of receiver tube (m^2)
A_{co}	Outer surface area of receiver glass cover (m^2)
CC	Capital cost (USD)
CES	Cost of energy saving (USD)
COP	Coefficient of performance
Cp	Specific heat capacity (kJ/kg K)
C_{tot}	Levelized total annual cost of investment (USD)
D_{co}	Outer diameter of glass cover (m)
D_r	Solution distribution ratio
$D_{r,i}$	Inner diameter of receiver tube (m)
$D_{r,o}$	Outer diameter of receiver tube (m)
D_o	Outer diameter of heat exchanger tube (m)
D_i	Inner diameter of heat exchanger tube (m)
E	Electric energy (kWh)
Elc	Electricity cost (USD)
$\dot{E}_s$	Radiation exergy rate of solar collector (kW)
$\dot{E}_u$	Exergetic output of solar collector (kW)
f	Friction factor
f_o	Fouling factor of outer surface of heat exchanger tube
f_i	Fouling factor of inner surface of heat exchanger tube
f_r	Amount of solution/refrigerant from storage tanks (%)
g	Gravitational acceleration (m/s^2)
h	Enthalpy (kJ/kg)
h_{co}	Convective heat transfer coefficient, outer glass cover (W/m^2-K)
$h_{r,i}$	Convective heat transfer coefficient, inner receiver tube (W/m^2-K)
h_o	Outer convective heat transfer coefficient of heat exchanger tube (W/m^2-K)
h_i	Inner convective heat transfer coefficient of heat exchanger tube (W/m^2-K)
h_{fg}	Latent heat of condensation (kJ/kg)
HTHX	High temperature heat exchanger
IC	Installation cost (USD)
i	Average annual interest rate (%)
I_G	Incident solar radiation (W/m^2)
k	Thermal conductivity (W/m-K)
LMTD	Logarithmic mean temperature difference
LTHX	Low temperature heat exchanger
M	Mass (kg)
Min	Minimum

$\dot{m}$	Mass flow rate (kg/s)
N	Number of collectors
n	System lifetime (year)
Nu	Nusselt number
OMo	Operating and maintenance cost in first year (USD)
OM	Operating and maintenance cost (USD)
OMR	Operating and maintenance cost reduction (USD)
P	Pressure (kPa)
PBP	Payback period (year)
Pr	Prandtl number
$\mathrm{P_R}$	Electricity unit price (USD/kWh)
Q	Heat quantity (MJ)
$\dot{Q}$	Heat transfer rate (kW)
Re	Reynolds number
REV	Refrigerant expansion valve
rho	Density (kg/m^3)
r_i	Average inflation rate (%)
r_n	Nominal annual escalation rate (%)
s	Entropy (kJ/kg-K)
t	Time (h)
T	Temperature (°C or K)
T_{sky}	Sky temperature (K)
T_{sun}	Sun outer surface temperature (K)
U	Overall heat transfer coefficient, (kW/K-m^2)
UA	Overall heat transfer coefficient – area product, (kW/K)
V	Volume (m^3)
V_a	Wind speed (m/s)
V_{cf}	Volume flow rate of collector fluid (m^3/s)
$\dot{W}$	Work (kW)
X	Mass fraction of LiBr in solution
Z_k	Purchased equipment cost (USD)
η	Efficiency
ε	Emittance
ρ	Density (kg/m^3)
μ	dynamic viscosity (kg/m-s)

Subscripts

a	Absorber, air
abs	absorbed
c	Collector, condenser, glass cover
cf	Collector fluid
co	Outer glass cover surface

conv	Conventional system
ct	Cooling tower
e	Evaporator
Elc	Electricity
ex	Exergy
G	Global
HTG	High temperature generator
HTHX	High temperature heat
i	Inner, State points 1, 2, 3, 4,…….
icas	Integrated chiller-absorption storage
l	liquid
L	Lower limit, levelized
LTG	Low temperature generator
m	Mean
max	maximum
n	nominal
o	outer
opt	Optical
OM	Operation and maintenance
p	Pump
r	Receiver, ratio
ri	Absorber inner surface
ro	Absorber outer surfce
ref	Reference
RST	Refrigerant storage tank
s, sol	Solar
SST	Solution storage tank
sas	Solar absorption system
spc	specific
sys	System
tot	Total
u	Useful
U	Upper limit
v	vapour
w	wall

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Problem Background

The demand for air conditioning is ever increasing in many parts of the world, mainly due to population growth, industrialization, urbanization, and global climate change (Xu et al., 2018). Vapour compression systems have been widely used to provide comfort in buildings. These systems are powered by electricity that is mostly generated from fossil fuels such as coal, oil, and natural gas. The continuous usage of fossil fuels contributes largely to global warming (Sarbu & Sebarchievici, 2013a). Moreover, the electric vapour compression air conditioning systems consume considerable electrical energy. About 55% of the world's annual energy consumption in residential buildings is attributed to cooling (Harvey et al., 2014). Santamouris (2016) reported a comprehensive detail on energy consumption by air conditioners worldwide. For example, energy consumption by cooling systems in the residential sector in the Kingdom of Saudi Arabia (KSA) is about 60% (Alaidroos & Krarti, 2016). This is due to high ambient temperatures, which prevail throughout the long summer seasons. Similar statistics indicate that the operating cost of air conditioners contribute to about 30% of the total electricity bills in Malaysian residential sector (Yau & Pean, 2014). Moreover, the energy consumption by air-conditioning systems in the Malaysian building sector is expected to grow by 56% by the year 2040 (Yau & Amir, 2019).

Furthermore, most of the electric vapour compression systems operate with chlorinated fluorocarbon compounds (CFCs), which, when exposed to the atmosphere through leakages contributes to the depletion of the ozone layer and hence, the global warming. Therefore, more energy-efficient and greener cooling systems that utilize renewable energy are needed. Solar energy is regarded as a promising alternative source as it is clean and abundantly available in most regions of the world (Hepbasli & Alsuhaibani, 2011). Solar energy is continuously becoming a subject of interest for cooling due to the positive correlation between peak air conditioning load and solar radiation intensity (Bataineh & Alrifai, 2015). Mazharul et al., (2014) investigated the prospects of solar cooling in KSA, considering 21 different locations. The study revealed that most of the studied locations have solar radiation intensity more than 6-kWh/m^2/day in summer. They concluded that this is quite adequate for cooling applications. Hence, the deployment of solar energy to drive cooling systems is one of the most viable alternatives (Zhai et al., 2011).

Sorption technologies (absorption, adsorption, and desiccant) are regarded as good alternatives for vapour compression cooling systems and can be driven by renewable energy such as solar (González-Gil et al., 2011). Solar absorption technology is experiencing more attention and commercial advancement compared to other sorption technologies (Allouhi et al., 2015). In addition, absorption technology is at the forefront in terms of the number of installations worldwide (Montagnino, 2017). Techno-economic evaluation of different cooling systems; namely: vapour compression system, solar-driven absorption system and PV powered vapour compression system has been carried out (Al-Ugla et al., 2016). The results revealed that a solar absorption system is more economically feasible than a solar PV-vapour-compression system.

The deployment of solar-based thermal cooling systems is limited to available solar radiation hours. The intermittency of solar energy creates a mismatch between cooling needs and available energy supply. Energy storage is, therefore, necessary to minimize the mismatch and achieve extended cooling coverage from solar-driven cooling systems. Solar thermal energy storage (TES) is mainly classified into sensible, latent, or sorption/thermochemical heat.

Sensible storage involves storing or extracting heat in a medium by heating or cooling, without phase change. The quantity of sensible heat stored is determined by the product of specific heat, temperature change, and amount of the storage material.

The sensible heat storage materials generally can be liquids (water, thermal oil, and liquid metals) or solids (metals, minerals, and ceramics) (Leonzio, 2017). Sensible heat storage is the most commonly used for solar thermal applications compared to other thermal energy storage options (Zhang et al., 2016a). However, it is associated with low storage density, a high rate of heat loss to the ambient and requires a large volume.

In the latent thermal storage system, heat is stored and discharged at or near-constant temperature and involves phase change of the storage materials (Mohamed et al., 2017). These materials are generally called phase change materials (PCM) and examples include paraffin, ice, fatty acids, and salts, etc. The latent heat storage has better storage density compared to sensible heat, but with several drawbacks, such as low thermal conductivity, phase segregation, corrosive behaviour, and thermal instability at high temperatures (Ibrahim et al., 2017).

Sorption/thermochemical heat storage is achieved through the breaking of binding forces between the sorbent and the sorbate in form of chemical potential, where a large amount of heat can be stored (Yu et al., 2013). In other words, sorption thermal energy storage (STES) involves a reversible physio-chemical phenomenon where the energy is stored chemically. The energy is usually recovered upon supplying low-temperature heat (N'Tsoukpoe et al., 2009).

There is increasing interest in sorption thermal energy storage (STES), especially in Europe (Cot-Gores et al., 2012; N'Tsoukpoe et al., 2009; Pinel et al., 2011). This is due to the negligible heat losses associated with sorption storage because the heat is stored in the form of chemical potential. The high energy storage density of sorption storage is another good advantage over the sensible counterpart (Yu et al., 2013). Depending on the priority, cooling and heating effects can be exploited from sorption storage. While sorption thermal storage systems offer such advantages of compactness and high energy storage density, there are still drawbacks, such as complexity in systems configuration, expensive investment, and weak heat and mass transfer capacity (for chemical reaction sorption) (Yu et al., 2013).

Turning back to the sorption cooling technologies, absorption chillers are more commercially available; constituting about 82% market distribution of the sorption technologies worldwide (Allouhi et al., 2015). Hence, coupling absorption energy storage with an absorption chiller while sharing the same working fluid worth further consideration and this is the focus of the present research. The term *absorption energy storage* (AES) is also referred to as liquid sorption storage (Scapino et al., 2017). The common working fluid used in commercial absorption chillers are H_2O-LiBr (water-lithium bromide) and NH_3-H_2O (ammonia-water) but with different configurations and applications. The NH_3-H_2O absorption chiller is more complicated as it requires an additional component called a rectifier used to separate droplet carryover of water from the solution after desorption. Chillers working with NH_3-H2O produce sub-zero temperatures (Sun et al., 2012), hence, are widely used for refrigeration. In H_2O-LiBr absorption chillers, water, which is environmentally safe, is used as the refrigerant, and this restricts the application to above 0 °C, hence, are mostly used for comfort cooling. The H_2O-LiBr absorption chillers are already in the market as single-effect and double-effect. Single-effect absorption chillers require operating temperature in the range of 80 °C to 100 °C, achieving a thermal coefficient of performance (COP) of around 0.7 – 0.8 while double-effect chillers operate at higher driving temperatures up to around 180 °C, with COP up to 1.4 (Shirazi, et al., 2018). Integration of H_2O-LiBr absorption chiller with absorption energy storage is advantageous over NH_3-H_2O absorption chiller due to higher enthalpy of evaporation of water compared to other liquids (Li & Sumathy, 2000).

1.2 Problem Statement

Electric vapour compression systems have been used in many facilities for comfort cooling (Ibrahim et al, 2017). However, the contribution of these systems in the total energy consumption in buildings is very high, which causes additional stress in the generation and distribution of electric systems (Aman et al., 2018). One alternative for cooling is the solar air conditioning based on absorption technology (Hirmiz et al., 2018). The variability of solar energy is the main concern in the real deployment of solar-driven absorption chillers as an alternative for air conditioning and refrigeration. Hence, energy storage is necessary to bridge the gap between the energy supply and its demand. Despite the significant number of research activities, prototypes, and products in the field of solar air conditioning, there is still a need for more innovative and technological advancement to make the process more efficient, economical, cost-effective, and sustainable.

Although sensible heat storage has been widely used in the application of solar thermal energy, its law storage density, high thermal losses, and large storage volume requirement are the major drawbacks. Research focus on sorption storage is recently increasing due to its low heat losses and high capability of energy storage. Since absorption cooling systems are already commercial; constituting about 82% market distribution of absorption chiller technologies (Allouhi et al., 2015), coupling this matured technology with absorption energy storage deserves further attention and research focus. Mugnier & Goetz, (2001) emphasized that integration of sorption energy storage into continuous sorption systems seems to be realistic in the future based on their comparative study of different thermal storage options. Based on the literature survey, many studies on absorption energy storage focused on long-term (seasonal) heating applications. Hence, the use of this technology on existing absorption chillers for cooling is yet, not well investigated and this is the focus of the present study.

The main goal of the present study is to address the problem of intermittent utilization of solar energy for air conditioning applications through proper system integration with absorption energy storage and driven by solar thermal energy. The problem is to model, simulate, and evaluate the performance and operational characteristics of a solar-assisted double-effect H_2O-LiBr absorption chiller integrated with absorption energy storage. The integrated chiller-absorption energy storage system can provide simultaneous cooling and charging of the storage unit for the cooling application.

1.3 Research Gaps

Absorption cooling systems are classified based on the working fluid type. These are water-lithium bromide (H_2O-LiBr) and ammonia-water (NH_3-H_2O) absorption chillers. The two have different configurations as highlighted in the background, Section 1.1, with NH_3-H_2O chiller having more components and requires higher heat input. The current work is concerned with the integration of absorption energy storage with the H_2O-LiBr absorption cooling system using the same working fluid. Based on the literature review on integrated H_2O-LiBr chiller-absorption energy storage, the following research gaps are summarized:

- There is no clear rule yet on sizing solar collector field for a given absorption chiller cooling capacity as indicated in CHAPTER 2, Section 2.2.5.
- Several simulation-based studies related to solar-driven single-effect absorption chiller coupled with absorption storage are reported in the literature. However, to the best of the author's knowledge, there are scarce attempts of integrating absorption storage with double-effect H_2O-LiBr absorption chillers. Since a double-effect absorption chiller requires heat source at high temperature (up to about 180 ºC), utilization of sensible hot storage at this temperature to drive the chiller during the period of non-available solar energy may suffer significant heat loss. Therefore, it is more suitable to integrate absorption energy storage with a double-effect absorption chiller. In addition, the double-effect absorption chiller has a better performance compared to a single-effect chiller (COP in the range 1.0 – 1.4). Therefore, this study attempts to bridge the gap and open a new direction towards integrating double-effect chiller with absorption energy storage and evaluating its performance.
- Economic evaluation of the integrated chiller-absorption energy storage is limited even for single-effect based systems. This needs to be performed to evaluate the economic potential of the solar cooling system integrated with absorption energy storage.

1.4 Research Objectives

The objectives of the research are:

1. To develop a thermodynamic model of a solar-assisted H_2O-LiBr double-effect chiller integrated with absorption energy storage.
2. To conduct a detailed parametric analysis and optimization of the base solar-assisted system without the storage for the purpose of sizing the solar collector field.
3. To evaluate the performance and operational characteristics of the integrated solar-assisted double-effect absorption system with storage, such as cooling effect, COP, exergy efficiency, and energy storage density.
4. To study and evaluate the economic feasibility of the integrated solar system with absorption energy storage.

1.5 Research Scopes

The research work is conducted within the following scopes:

1. Modelling of the solar-assisted double-effect H_2O-LiBr absorption chiller with storage was carried out based on the first and second laws of thermodynamics (energy and exergy).
2. The model involves sub-models of solar collector, double-effect H_2O-LiBr absorption chiller, and absorption energy storage.
3. The thermodynamic model is validated with experimental/catalogue data available in the literature.
4. The software package Engineering equation solver (EES) (Klein & Alvarado, 2017) is used for simulating the models in this study, similar to the following studies (Bagheri et al., 2019; Bellos et al., 2017; Qiao, 2004). This has been discussed in detail under the ‘selection of software package’ in CHAPTER 3, Section 3.2.

v. Application of the studied system for cooling was investigated considering a reference commercial building and weather conditions of the Eastern region of Saudi Arabia as a case study.

1.6 Significance of the Research

Integrating absorption energy storage with the existing solar-driven absorption chillers can provide enhanced performance and sustainability in certain applications such as commercial and residential buildings. The storage volume requirement for absorption energy storage is less than half of that required for sensible heat storage according to the literature (Yu et al., 2013). Hence, integrating absorption energy storage to a solar driven absorption chiller system will save a reasonable portion of space, reducing the cost of the initial investment. Moreover, using H_2O-LiBr absorption systems for the storage is more advantageous because water is used as the refrigerant, which is environmentally safe compared to ammonia (NH_3). The published work from this research will contribute to the world's academic literature and will be a reference source for future research in this area.

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LIST OF PUBLICATIONS

ISI Journal Papers:

1. **Ibrahim, N.I.,** Al-Sulaiman, F.A., Saat, A., Rehman, S., Ani, F.N., (2020) “Charging and discharging characteristics of absorption energy storage integrated with a solar driven double-effect absorption chiller for air conditioning applications” *Journal of Energy Storage,* 29, 101374. https://doi.org/10.1016/j.est.2020.101374. **(Q2, IF: 3.762)**

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