EXPERIMENTAL STUDY ON USING WASTE HEAT FROM SOLAR PHOTOVOLTAIC COOLING FOR LIQUID DESICCANT REGENERATION IN A SOLAR AIR-CONDITIONING SYSTEM

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ABSTRACT

The utilization of a desiccant cooling system presents a remarkable resolution to address forthcoming energy demand issues, all the while prioritizing human comfort through its ability to effectively control temperature and humidity levels. The typical vapour compression cooling and air conditioning systems may be replaced or supplemented by liquid desiccant cooling systems that are powered by solar photovoltaic (PV) waste heat. This study aims to investigate the utilisation of solar photovoltait cooling waste heat for liquid desiccant regeneration in a solar air conditioning system. The experimental setup incorporates accurate measuring instruments specifically designed to facilitate a wide range of precise observations during the experiment. The performance evaluation of the system was conducted using a regenerator that utilized a desiccant solution consisting of up to 40% concentrated Calcium Chloride ($CaCl_2$). The waste heat from the desiccant, reaching temperatures of up to 60°C, was utilized in a liquid spray towers system for regeneration. The maximum calculated output power for a solar photovoltaic (PV) system with heat recovery was 185.6 W with an efficiency of 26.54%. At 1:00 p.m. the system's maximum temperature was 70°C. The experiment's findings show that the desiccant held in the reservoir can reach a temperature of 65°C. The regenerator modifies the air's specific humidity as the solution's inlet temperature and mass flow rate increase. The rate of water evaporation increases as air flow rates and desiccant solution inlet temperatures increase.

ABSTRAK

EKPERIMEN PENGGUNAAN HABA BUANGAN DARIPADA PENYEJUKAN SOLAR FOTOVOLTAIK UNTUK PENJANAAN SEMULA CECAIR DISECCANT DALAM SISTEM PENYAMANAN UDARA SOLAR

Penggunaan sistem penyejukan bahan pengering memberikan resolusi yang baru untuk menangani isu permintaan tenaga yang akan datang, dimana ia mengutamakan keselesaan manusia melalui keupayaannya mengawal tahap suhu dan kelembapan dengan berkesan. Sistem penyejukan mampatan wap dan penyaman udara biasa boleh digantikan atau ditambah dengan sistem penyejukan bahan pengering cecair yang dikuasakan oleh haba sisa fotovoltaik suria. Kajian ini bertujuan untuk mengkaji penggunaan haba sisa penyejukan fotovoltait suria untuk penjanaan semula bahan pengering cecair dalam sistem penyaman udara solar. Persediaan ujikaji menggabungkan alat pengukur yang direka khusus untuk memudahkan pemerhatian semasa eksperimen. Penilaian prestasi sistem telah dijalankan menggunakan penjana semula yang menggunakan larutan pengering yang terdiri daripada Kalsium Klorida ($CaCl_2$) dengan kepekatan sehingga 40%. Haba buangan daripada bahan pengering, mencapai suhu sehingga 60°C, telah digunakan dalam sistem menara semburan cecair untuk penjanaan semula. Kuasa keluaran maksimum untuk sistem PV solar dengan pemulihan haba ialah 185.6 W dengan kecekapan 26.54 peratus. Pada jam 1.00 petang, suhu maksimum sistem ialah 70 °C. Dapatan eksperimen menunjukkan bahan pengering di dalam takungan boleh mencapai suhu 65°C. Penjana semula mengubah suai kelembapan khusus udara apabila suhu masuk larutan dan kadar aliran jisim meningkat. Kadar penyejatan air meningkat apabila kadar aliran udara dan suhu masuk larutan bahan pengering meningkat

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ɳel	-	Electrical efficiency
ɳth	-	Thermal efficiency
Apvt	-	Collector area [m^2]
εdeh	-	Dehumidifier effectiveness
Fw	-	Fraction of total area available for mass Transfer
Fh	-	Fraction of total area available for heat Transfer
G	-	Irradiance [W/m^2]
Im	-	Current of PV Module at max. Power
Vm	-	Voltage of PV Module at Max. Power.
To	-	Outlet Water Temperature [°C]
Ti	-	Collector Inlet Water Temperature [°C]
ṁ	-	Mass Flow Rate [kg/s]
Cp	-	Specific Heat of Water [J/kg K]
Qc	-	Cooling Capacity [kJ/h]
ma	-	Air Flow Rate [kg/s]
Cpa	-	Specific Heat of Air [J/kgK]
Twb	-	Wet bulb temperature, °C
wa	-	Humidity ratio of inlet air [g/kg of dry air]
ma	-	Mass flow rate of inlet air [kg/s]
T	-	Temperature
F*	-	Feasibility index
Pd	-	Partial pressure of dry air [kpa]
Pv	-	Partial pressure of water vapour [kpa]
Psat	-	Partial pressure of saturated air [kpa]
ha	-	Enthalpy of inlet air
Ha	-	specific enthalpy
ṁs	-	mass flow rate of the air
ṁa	-	Mass flow rate of desiccant solution
Cs	-	desiccant concentration
Hs	-	Specific enthalpy
Tsi	-	Temperature of solution inlet
SE	-	Saturation effectiveness
L	-	Length
n	-	Number of steps
Iroc	-	Current at ROC (A)
Istc	-	Current at STC (A)
Vroc	-	Voltage at ROC (V)
Vstc	-	Voltage at STC (V)
FF	-	Fill Factor (decimal)
Voc	-	open circuit voltage (V)
Vmp	-	voltage at maximum power (V)
Isc	-	short circuit current (A)
Imp	-	current at maximum power (A)
Tcell	-	cell or module temperature
ρ	-	Density of the air [kg/m^3]

ε	-	Effectiveness [Dimensionless]
ω	-	Specific humidity [kg/kg of dry air]
dω	-	Change in specific humidity [kg/kg of dry air]
ξ	-	Uncertainty [Dimensionless]
φ	-	Relative humidity
ω_o	-	Specific humidity
v	-	Velocity of air (m/s)
a	-	Dry air
ai	-	Inlet of air
ao	-	Outlet of air
as	-	Air to solution
av	-	Average
atm	-	Atmospheric
d	-	Dehumidifier
eq	-	Equilibrium
evap	-	Evaporation rate
i	-	Inlet max
o	-	Outlet
p	-	Partial pressure
r	-	Regenerator
s	-	Solution
si	-	Inlet of solution
so	-	Outlet of solution

LIST OF ABBREVIATIONS

A	-	Ampere
$CaCl_2$	-	Calcium chloride
CFC	-	Chlorofluorocarbon
COP	-	Coefficient of Performance
CPVC	-	Chlorinated polyvinyl chloride
CSLD	-	Cost-Effective Liquid Desiccant
DBT	-	Dry bulb temperature
DEG	-	Diethylene Glycol
H2O/KCOOH	-	potassium
HVAC	-	heating, ventilation, and air-conditioning
I	-	Current
IAQ	-	Indoor air quality
KCOOH	-	Non-Corrosive Potassium
LDAC	-	Liquid desiccant air conditioning
LDCS	-	Liquid Desiccant Cooling System]
LDD	-	Liquid Desiccant Dehumidification
LDDC	-	Liquid desiccant dehumidification cooling
LDEC	-	Liquid Desiccant Evaporative Cooler
LiBr	-	Lithium Bromide
LiCl	-	Lithium chloride
LPH	-	Litres per hour
MEG	-	Monoethylene-Glycol
MRR	-	Moisture Removal Rate
NTUm	-	Nephelometric Turbidity
P	-	Power
PV	-	Photovoltaics
PV/T	-	Photovoltaics/Thermal
PVC	-	Polyvinyl Chloride
SIE	-	Solar-Driven Interfacial Evaporation
TEG	-	Triethylene glycol
TR	-	Ton of refrigeration
UMS	-	University Malaysia Sabah
V	-	Voltage
VCS	-	Vapor Compression System
W	-	Watt
WBT	-	Wet bulb temperature

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CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter presents an introduction to the research topic, which is focused on the experimental investigation of utilizing waste heat from solar PV cooling for the regeneration of desiccant in a liquid desiccant evaporative cooler. The chapter provides background information on the reasons behind selecting this research title and how the problem arose. It discusses the problem statements, aims, parameters, and potential benefits of the study. Additionally, the chapter outlines the study plan, which contains crucial information that will influence the progression of this project.

1.2 Background of the Study

Air conditioning plays a crucial role in managing both sensible and latent cooling loads, especially in hot and humid regions. The primary considerations for designing air conditioning systems encompass factors such as thermal comfort, indoor air quality, energy efficiency, and their environmental impact, as noted by Vakiloroaya et al. in 2014. The commonly employed method is mechanical vapor compression, which entails cooling air to its dew point temperature to extract moisture. However, it's important to note that additional energy is required to reheat the air to the desired supply temperature, as pointed out by Xiao et al. in 2016.

Due to rising cooling loads and comfort demands, tropical countries like Malaysia are seeing an increase in the need for cooling indoor air. Air conditioning has become an indispensable cooling mechanism in all office buildings throughout

Malaysia, meeting the essential need for indoor comfort. However, it is important to note that air conditioning systems are the primary consumers of energy, accounting for approximately 40% of the total electricity consumption in office buildings, exceeding the energy consumption of lighting and other electrical appliances. Moreover, small office buildings, including shop-office buildings, represent a significant portion, comprising around 57% of the total office building inventory in Malaysia (Sopian et al., 2009). Conventional cooling methods were used by most small office buildings, often with an electrically driven compressor system that has several obvious drawbacks, including high energy consumption and high electricity peak demand. Typically, it uses refrigerants that have a harmful influence on the environment. On the other hand, mechanical vapour compression systems have several related risks that have a significant effect on indoor air quality and occupant health. These issues include water condensation on the cooling coil surface, bacterial growth, and fungus. To address these issues, several cutting-edge dehumidification cooling systems with efficient independent temperature and humidity controls and concurrently lower energy usage have been developed.

During extremely hot and humid conditions, the temperature tends to reach or hover around its maximum point. This typically occurs when the intensity of solar radiation is at its peak. The variable supply of solar energy and the demand for air conditioning are interconnected. Due to the correlation between the intensity of solar radiation and the load on air conditioning systems, there exists a potential to reduce energy consumption in air conditioning by harnessing solar energy.

Ongoing research into solar cooling technologies presents a promising avenue for mitigating the challenges posed by the peak power demand and energy consumption typically linked to conventional air conditioning systems. These innovations aim to address the substantial issues encountered with compression cooling systems, as highlighted in the 2016 report by the International Energy Agency Solar Heating and Cooling Program. Solar cooling, which utilizes solar energy to cool indoor spaces, stands out as a notable alternative to traditional vapor compression-cycle HVAC systems. Liquid desiccant air conditioning, in particular, is gaining increasing attention as a potential replacement.

The liquid desiccant dehumidification system, or LDDC system, is a hybrid air conditioning system that combines a cooling unit to manage the sensible cooling load with a liquid desiccant dehumidification unit to handle the latent cooling load (Mohammad et al, 2013). Desiccant dehumidification may be performed using solid or liquid desiccant systems (Salikandi et al, 2021). Liquid desiccant dehumidification (LDD) offers more benefits than solid desiccant dehumidification because it has a lower mass transfer resistance, a greater moisture absorption capacity, a lower airflow pressure drops, and a smaller temperature range for desiccant regeneration (SDD) (Oh et al., 2017).

A few cooling methods that can be integrated with the LDD system are evaporative cooling, vapour compression cooling, and absorption cooling. System energy efficiency can be greatly increased by using hybrid systems. (Yamaguchi et al., 2011). Due to its less expensive setup and maintenance (Heidarinejad et al., 2009), evaporative cooling has been widely used. An evaporative cooler uses about 75% less energy than a conventional cooler. (Cerci, 2003).

Liquid desiccant evaporative cooling systems integrate a liquid desiccant dehumidification system with an evaporative cooling system to enhance overall system efficiency and make use of solar energy resources. In such a hybrid configuration, the evaporative cooling system handles the sensible heat load, while the desiccant dehumidification system is responsible for removing the latent load, as detailed in Yong et al.'s work from 2006. Furthermore, because the regeneration phase of the desiccant dehumidification system only requires low-grade energy, it becomes feasible to power liquid desiccant air conditioning systems with renewable energy sources like solar energy, as discussed in Cheng et al.'s research from 2013. For this purpose, we can use the technique of utilizing waste heat from solar PV. Solar Panel waste heat refers to heat that is generated in solar panel processes and then rejected to the environment even though it could be utilized for some users. Therefore, reusing and recovering waste heat is a practical technique to significantly increase energy efficiency. Solar energy is also a clean and renewable source of energy and can generate low-grade heat.

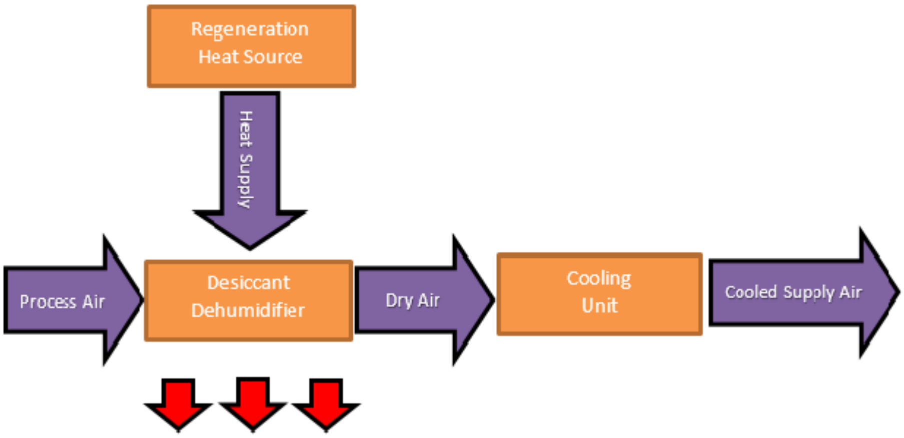

Figure 1.1 : Desiccant Cooling Principle

1.3 Problem Statement

The increasing global use of air conditioning systems necessitates improvements to address challenges related to high energy consumption and peak power demands. It is crucial to explore alternatives to chemical refrigerants to minimize the environmental impact of air conditioning systems. The development and promotion of environmentally friendly systems have become essential due to the worldwide significance of energy and environmental concerns. Renewable and waste heat sources, such as solar heat, waste steam, flue gases, and used cooling water, offer viable options as alternatives to traditional thermal or electrical energy sources due to their higher exergy and cost-effectiveness.

Evaporative cooling emerges as an environmentally friendly technology as it utilizes water as a working substance, eliminating the need for CFCs and reducing greenhouse gas emissions. Operating this technology is relatively straightforward. Evaporative cooling occurs when a liquid in contact with an object cool through evaporation, typically into the surrounding air. The cooling effect is maximized when dry air passes over a wet surface, resulting in increased evaporation and greater cooling. However, the effectiveness of evaporative cooling is reduced in hot climates with high atmospheric moisture content.

1.4 Research Objectives

This study aims to investigate the ability of heat recovered from cooling a solar PV to assist in regeneration of liquid desiccant for a Liquid Desiccant Evaporative Cooler (LDEC). The objectives of the study are:

i. To measure the maximum temperature achievable by cooling the solar PV surface, and how does this temperature impact the electricity generation efficiency of the system in terms of its performance.
ii. To evaluate the impact of various operational parameters, such as air flow rate, inlet desiccant solution concentration and inlet solution temperature on the efficiency of the regenerator and dehumidifier when utilizing waste heat recovered from solar PV cooling.
iii. To compare the performance of the LDEC, utilizing waste heat from solar PV cooling, with a traditional Direct Evaporative Cooler (DEC) in terms of cooling efficiency, temperature difference between inlet and outlet air, and humidity change.

1.5 Research Questions

The following main research questions must be answered in order to evaluate the system's effectiveness:

RQ1 - What is the maximum solution temperature achievable by cooling the solar PV surface, and how does this temperature impact the electricity generation efficiency of the LDEC system in terms of its performance?

RQ2 - What is the impact of various operational parameters, such as air flow rate, inlet desiccant solution concentration and inlet solution temperature on the efficiency of the regenerator and dehumidifier when utilizing waste heat recovered from solar PV cooling?

RQ3 - How does the performance of the Liquid Desiccant Evaporative Cooler (LDEC), utilizing waste heat from solar PV cooling, with a traditional Direct Evaporative Cooler (DEC) in terms of cooling efficiency, temperature difference between