STUDIES ON LIQUID DESICCANT COOLING SYSTEMS USING INDIRECT CONTACT HEAT AND MASS EXCHANGER

RAJAT SUBHRA DAS

DEPARTMENT OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY DELHI

JUNE 2015

STUDIES ON LIQUID DESICCANT COOLING SYSTEMS USING INDIRECT CONTACT HEAT AND MASS EXCHANGER

by

RAJAT SUBHRA DAS

DEPARTMENT OFMECHANICAL ENGINEERING

Submitted

in fulfilment of the requirements of the degree of

DOCTOR OF PHILOSOPHY

to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI

JUNE 2015

CERTIFICATE

This is to certify that the thesis entitled **"Studies on liquid desiccant cooling systems using indirect contact heat and mass exchanger"** being submitted by **Mr. Rajat Subhra Das** to Indian Institute of Technology , Delhi for the award of the degree of ***Doctor of Philosophy*** is a record of bonafide research work carried by him under my supervision. This thesis has been prepared in conformity with the rules and regulations of Indian Institute of Technology Delhi, New Delhi. I further certify that the thesis has attained a standard required for a degree *Doctor of Philosophy*. To the best of our knowledge, the research reported and results presented in the thesis have not been submitted, in part or full to any other institute or university for award of any degree or diploma.

Date:

Place:

Dr. Sanjeev Jain
Professor
Mechanical Engineering Department
Indian Institute of Technology, Delhi
New Delhi-110016, India

ACKNOWLEDGEMENTS

It gives me great pleasure and honour to express my deep sense of gratitude to my supervisor, Prof. Sanjeev Jain for his keen interest, timely help, valuable suggestions, inspiration, encouragement, illuminating discussions and unwavering support for the successful completion of this thesis. I would like to thank the Chairman of my Student Research Committee (SRC), Prof. P.M.V. Subbarao for his valuable suggestions and critical review. I would also like to extend my thanks to other SRC members Prof. S.C. Kaushik and Dr B. Premachandran for their useful suggestions.

Sincere thanks are for Mr. Pratik Saha, Mr. Kundan Singh and Mr. Sunil Kumar who contributed significantly to the fabrication and other experimental work in the project. I commend the support of Mr. Sagun Tripathy during the initial days of the research work. I specially thank Mr. Vaibhav Gupta for his support and encouragement for the theoretical work. I would also like to heartily acknowledge the assistance and support provided by the lab staff K.D. Khurana, Shambhu Prasad, Prem Singh. I am thankful to my friends and fellow research scholars, especially Mr. Pranab Das and Mr. Gezahegn Habtamu for their encouragement and support. I sincerely extend my gratitude to all of those, who were directly or indirectly involved with this research work. Last but not the least, I am especially thankful to my family members (Late Shri Ratish Ranjan Das, my father; Smt Sabita Das, my mother; Smt Sucharita Das, my sister; Smt Anwesha Roy my wife) for their boundless love, patience, sacrifices and moral support. My doctoral thesis is indeed a dream of my father late Shri Ratish Ranjan Das coming true and I am sure he would be the most happiest and proud person for my title of PhD. At the end I thank God for showering his blessings and bestowing upon me moral strength to carry out my work.

Rajat Subhra Das

ABSTRACT

Solar energy driven air-conditioning systems has garnered much attention worldwide, owing to the growing energy demands and environmental issues. Liquid desiccant cooling systems (LDCS), can operate on low grade heat which can easily be catered to by solar energy. The major drawback of liquid desiccant systems is the carryover of desiccant droplets into the supply air. Membrane based indirect contact heat and mass exchanger designs tend to eliminate the carryover of liquid desiccant, thus reducing the risk of health hazard and corrosion. In the dehumidifier, membranes act as barrier between desiccant and air streams allowing only water vapour but not desiccant to pass through. In the present work a two-dimensional mathematical model has been developed in MATLAB to study the heat and mass transfer in the air-liquid membrane contactor acting as dehumidifier. The model can predict the air and desiccant parameters inside the dehumidifier and the outlet parameters for given input parameters. Seven different membrane contactors with different designs have been manually fabricated using various commercially available membranes like polypropylene, polyvinylidenefluoride etc. Series of experiments have been carried out on the membrane contactors to find the suitable membrane. Aqueous solution of lithium chloride has been used as desiccant. The numerical model is validated with the experimental results. The maximum deviations between experimental and predicted values are within $\pm 10\%$ for outlet specific humidity and outlet enthalpy of air, $\pm 15\%$ deviation in dehumidification effectiveness and $\pm 20\%$ deviation in enthalpy effectiveness.

Seven potential liquid desiccant cycles have been identified and analysed to select the suitable configuration for achieving thermal comfort. A computer simulation model has been developed in Engineering Equation Solver (EES) software platform to evaluate the performance of all the cycles at selected ambient conditions. Supply air conditions, cooling capacity, COP and circulation rate (CR) per unit cooling capacity and hot water temperature requirement have been used as a measure for analyzing the performance of the different cycles. The effect of hot water temperature on the performance of the cycles has been evaluated at ARI conditions. The performances of the cycles have also been evaluated for cities selected from each of the climatic zone of India that represent typical tropical climates. Although all the cycles are feasible at ARI and hot and dry conditions, only two cycles can achieve the selected indoor conditions in the peak humid conditions. A complete solar energy driven liquid desiccant cooling system (LDCS) with an indirect contact dehumidifier has been developed and tested in the laboratory. Solar water heating systems (SWHS) have been installed to harness solar energy and generate hot water. The SWHS consists of water-in-glass evacuated tube collectors (ETC) and heat pipe based ETCs connected both in series and parallel arrangements on the rooftop. Typical efficiencies of ETC and heat pipe collectors at an irradiation of 800 W/m^2 have been found to 50%. The hot water from SWHS has been used to heat the desiccant solution in a plate heat exchanger and the hot desiccant has been concentrated in the regenerator. Liquid desiccant concentration of 36% to 40% has been achieved using hot water in the range of 60 to 70^0C. The dehumidifier effectiveness mostly lies between 25 to 55%, which seems to be limited by the additional mass transfer resistance due to the indirect contact between air and desiccant in the dehumidifier. The capacity and COP of the system varies depending on the operating ambient and the desired supply conditions along with the selected configuration.

Keywords: Liquid desiccant, Solar Cooling, Dehumidification, Membrane contactor, Desiccant cycles.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

Symbol	Description	Units
A	area	m^2
AAHX	air-air heat exchanger	
AWHX	air-water heat exchanger	
a	thermodynamic activity	
atm	atmosphere	
B	breadth of the contactor	m
C	concentration	$kmole/m^3$
CC	cooling capacity	kW
c_p	specific heat capacity	J/kg-K
COP	coefficient of performance	
CR	circulation rate	kg/s-TR
CT	cooling tower	
$C_{lm,so}$	logarithmic mean solute concentration difference	$kmole/m^3$
C_t	total concentration of the solution	$kmole/m^3$
c_p	specific heat capacity	J/kg-K
D	diffusion coefficient	m^2/s
DBT	dry bulb temperature	^oC
DEC	direct evaporative cooler	
DHX	dehumidifier heat exchanger	
DOAS	dedicated outdoor air system	
DPT	dew point temperature	^oC
d_a	width of air channel	m
d_h	hydraulic diameter	m
d_p	pore diameter	m
EA	exhaust air	
ETC	evacuated tube collector	
EX	enthalpy exchanger	
G’	mass flow rate unit area	kg/m^2s

H	height of the contactor	m
HX	heat exchanger	
h_t	heat transfer coefficient	W/m^2K
h	specific enthalpy	kJ/kg
h_{T_d}, h_{fg}	latent heat of vaporization	W/m^2K
I	irradiation	W/m^2
IAQ	indoor air quality	
IEC	indirect evaporative cooler	
J	mass flux	kg/m^2-s
K	mass transfer coefficient	m/s
Kn	Knudsen number	
k	thermal conductivity	W/mK
L	length of contactor	m
Le	Lewis number	
LDCS	liquid desiccant cooling system	
M_w	molecular mass of water	kg/kmole
m	mass flow rate	kg/s
m_h	Henry's constant	$kg\text{-}m^2/kmole\text{-}s^2$
NTU	number of transfer unit	
Nu	Nusselt number	
n	number of liquid channels	
P	pressure	Pa
P_l	partial pressure of solution	Pa
Pr	Prandtl number	
R	heat transfer resistance	m^2K/W
R_u	Universal Gas Constant (8.314)	kJ/kmole-K
Re	Reynolds number	
REC	regenerative evaporative cooler	
RHX	regenerator heat exchanger	
RSHF	room sensible heat fraction	
SSHX	solution-solution heat exchanger	
SEM	scanning electron microscopy	
Sc	Schmidt number	

Sh	Sherwood number	
T	temperature	^oC
TR	ton of refrigeration	
t	time	s
U_h	overall heat transfer coefficient	W/m^2K
U_m	overall mass transfer coefficient	
V	velocity	m/s
VAS	vapour absorption systems	
w	specific humidity	g/kg of dry air
WBT	wet bulb temperature	^oC

Greek letter

ε	effectiveness	
ξ	desiccant concentration	
ρ	density	kg/m^3
δ	membrane thickness	m
μ	dynamic viscosity	$N\text{-}s/m^2$
λ	mean free path	m
ϕ	mass transfer resistance	m^2s/kg
τ	membrane tortuosity	
η	fraction of room air	
η_{sc}	efficiency of the solar collectors	

Subscripts

a	air
abs	absorber
atm	atmosphere
cc	cooling capacity
cl	cooling load
col	collector

d	desiccant
deh	dehumidifier
dil	dilute
e	equilibrium
in	inlet
k	Knudsen
lm	logarithmic mean
lam	laminar
lat	latent
mem	membrane
o	ordinary
OA	outside air
out	outlet
p	pore
RA	room air
sen	sensible
sol	solution
st	strong
SA	supply air
lat	latent
tot	total
turb	turbulent
v	water vapour
w	water