UNIVERSITI PUTRA MALAYSIA

DESIGN AND SIMULATION OF DUAL-PURPOSE SOLAR CONTINUOUS ADSORPTION SYSTEM USING MALAYSIAN ACTIVATED CARBON

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By

MOHAMMAD AHMED ALGHOUL

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia,
in Fulfilment of the Requirement for the Degree of Doctor of Philosophy

September 2005

DEDICATION

Especially dedicated to the man of rare integrity and radiant nobility

Prof. Dr. Mohammad Yusof Sulaiman

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

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Chairman: **Professor Mohammad Yusof Sulaiman, PhD**

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Solar adsorption refrigeration is mainly realized using activated carbon as adsorbent and methanol as adsorbate. The study tested adsorption characteristics of three types of Malaysian activated carbons *(AC-4060, AC-5060, AC-6070)* with methanol by fitting Dubinin equation to the characteristic curve of the activated carbons and thus determine the available porosity. The $P-T-X$ chart (pressure, temperature, and concentration) for each of the activated carbons was developed and the heat of adsorption was determined. A performance comparison of the activated carbons with methanol as the refrigerant for ice making was analyzed and the possibility of using the Malaysian activated carbon as adsorbent for adsorption refrigeration system was found satisfactory.

For solar intermittent adsorption system, refrigeration process takes place at night. The use of the two adsorber beds working out of phase helps maintain a continuous refrigeration cycle. Efforts have been made to commercialize the single-purpose solar adsorption refrigeration system, but has not been well received. The dual-purpose solar continuous adsorption system for domestic refrigeration and hot water is the result of a series of researches done in the field of single-purpose of solar adsorption system for refrigeration with respect to the practical needs of industries and customers.

A novel design and performance of a dual-purpose solar continuous adsorption system for domestic refrigeration and hot water is described. The system comprises of evacuated tube collectors, a water storage tank of two partitions each partition contains adsorber bed and condenser heat exchanger, a receiver, an evaporator, and ice box.

Further more, the heat rejected by the adsorber beds and condensers during cooling process of refrigeration subsystem was recovered and used to heat water for the purpose of domestic consumption. In a continuous 24-hour cycle, 16.86 MJ/day of heat can be recovered for heating of water storage tanks. In the single-purpose intermittent solar adsorption system, this heat is wasted. The total energy input to the dual-purpose system during 24-hour operation was 61.2 MJ/day and the total energy output was 50 MJ/day. The latter was made up of 44.69 MJ/day for water heating and 5.3 MJ/day for ice making. The amount of ice that can be produced was 12 kg/day.

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Based on typical values for the efficiency (η) of evacuated tube collector of water heating system of 65%, the following Coefficients of Performance COP's were obtained: 44% for adsorption refrigeration cycle, 73% for dual-purpose solar water heater, 8.5% for dual-purpose solar adsorption refrigeration and 81.5% for dual-purpose of both solar water heater and refrigerator.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia Sebagai
memenuhi keperluan untuk ijazah Doktor Falsafah

REKABENTUK DAN SIMULASI SISTEM PENJERAPAN BERTERUSAN SOLAR DUA TUJUAN MENGGUNAKAN ARANG TERAKTIF MALAYSIA

Oleh

MOHAMMAD AHMED ALGHOUL

September 2005

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Peti sejuk penjerapan suria lazimnya direalisasikan dengan menggunakan karbon teraktif sebagai bahan penjerap dan methanol sebagai bahan jerapan. Kajian ini dijalankan untuk menguji sifat-sifat penjerapan berbagai jenis karbon teraktif di Malaysia ke atas methanol, dan dengan menyepadankan persamaan Dubinin kepada lengkung cirian karbon teraktif tersebut, nilai keliangan dapat ditentukan. Carta P-T-X (tekanan, suhu dan kepekatan) bagi setiap karbon teraktif dibina dari mana haba penjerapan dapat ditentukan. Perbandingan prestasi karbon teraktif dengan methanol sebagai bahan penyejuk dibincangkan dan kemungkinan menggunakan karbon teraktif dari Malaysia sebagai bahan penjerap untuk sistem peti sejuk penjerapan didapati baik.

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Bagi sistem penjerapan berkala suria, proses penyejukan berlaku pada waktu malam. Penggunaan dua alat-dasar (bed) penjerap yang bertindak tidak sefasa membantu mengekalkan kitaran penyejuk yang berterusan. Usaha telah dilakukan untuk mengkomersialkan sistem peti sejuk penjerapan suria satu gunaan tetapi tidak mendapat sambutan yang menggalakkan. Sistem penjerapan selanjar suria dua gunaan untuk tujuan penyejukan dan pemanasan di rumah adalah hasil kajian yang berterusan ke atas keperluan praktikal sistem peti sejuk penjerapan suria satu gunaan kepada industri dan pelanggan.

Satu reka bentuk bijak sistem penjerapan selanjar suria dua gunaan untuk tujuan penyejukan dan pemanasan di rumah dan prestasinya diperihalkan. Sistem ini terdiri dari tiub pengumpul vakum, tangki penyimpan air yang terdiri dari dua bahagian - tiap-tiap bahagian mengandungi alat-dasar penjerapan dan alat penukar haba kondenser, alat penerima, alat penyejat dan kebuk ais.

Setenjutnya, haba yang dibebaskan oleh alat-dasar penjerap dan kondenser semasa proses pendinginan subsistem penyejukan dapat dipulihkan dan diguna untuk memanaskan air untuk penggunaan domestik. Dalam kitaran selanjar 24 jam, sebanyak 16.86 MJ haba sehari boleh dipulihkan bagi memanaskan tangki penyimpan air. Dalam sistem penjerapan suria berkala satu gunaan haba ini terbazir sahaja. Jumlah tenaga yang diinputkan ke dalam sistem dua gunaan ketika beroperasi 24 jam adalah 61.2 MJ sehari dan jumlah tenaga yang dioutputkan adalah 50 MJ sehari. Daripada jumlah tenaga yang dioutputkan ini 44.69 MJ sehari digunakan untuk memanaskan air dan 5.3 MJ sehari untuk menghasilkan ais. Berat ais yang dihasilkan ialah 12 kg sehari. Berasaskan kepada nilai biasa

65% bagi kecekapan (η) tiub pengumbul vakum memanaskan air, Pekali Prestasi (*COP*) berikut diperolehi: 44% untuk kitaran penjerapan peti sejuk, 73% untuk pemanas air suria dua gunaan, 8.5% untuk peti sejuk penjerapan suria dua gunaan dan 81.5% untuk sistem dua gunaan pemanas air dan peti sejuk.

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LIST OF ABBREVIATIONS

A_0	Constant of equation [3.15]
A_1	Constant of equation [3.15]
AC	Activated Carbon
A_{con}	Heat transfer area of the condenser (m^2)
A_{evp}	Heat transfer area of the evaporator (m^2)
A_{coll}	Area of collector (m^2)
$C_{V\ ice}$	Specific volume of ice at 0^{0}C (m^3/kg)
C_{steel}	Specific heat of galvanized steel (kJ/kgK)
C_{ac}	Average specific heat of activated carbon (kJ/kgK)
C_a	Specific heat of adsorber tube (kJ/kgK)
C_w	Specific heat of water (kJ/kgK)
C_{copper}	Specific heat of copper (kJ/kgK)
$C_{l,meth}$	Average specific heat of liquid methanol (kJ/kgK)
$COP_{cycle-ice}$	Coefficient of performance of the refrigeration cycle
$COP_{dual.system-ice}$	Coefficient of performance of ice production in the dual system
$COP_{dual.system-domestic.hot.weater}$	Coefficient of performance of water heating production in the dual system
$COP_{dual-system}$	Coefficient of performance of the dual system
D	Constant of equation [3.6]
$H_{global-horizontal}$	Global solar radiation on horizontal surface (MJ/day)
h	Average enthalpy of heat of adsorption of the first adsorber bed (kJ/kg)
h'	Average enthalpy of heat of adsorption of the second adsorber bed (kJ/kg)
H_{ads}	Heat of adsorption (kJ)
$I.D_{ads-tube}$	Inside diameter of adsorber copper tube (m)
$I.D_{con,evp,perforated-tube}$	Inside diameter of condenser, evaporator, and perforated copper tubes (m)

$I.S.A_{ads-tube}$	Inside surface area of one meter length of adsorber copper tube (m^2 /m)
$I.S.A_{con,evp,perforated-tube}$	Inside surface area of one meter length of condenser, evaporator, and perforated copper tube (m^2 /m)
K_{ice}	Conductivity of ice layer (W/m.K)
$l_{ads-tube}$	Length of adsorber tube (m)
L_{meth}	Latent heat of methanol (kJ/kg)
L_{ice}	Latent heat of ice (kJ/kg)
$l_{con-tubes}$	The total length of condenser tube (m)
$l_{evptubes}$	Total length of evaporator tube (m)
M	Molecular weight of the methanol (kg/mol)
m	Number of adsorber tubes
M_{ice}	Mass of domestic ice during 24 hours (kg)
M_{meth}	Mass of desorbed methanol (kg)
M_{a}	Mass of adsorber tubes (kg)
M_{ac}	Mass of activated carbon (kg)
M'_{ac}	Mass of activated carbon in the second adsorber (kg)
$M_{hw} = M_{hot-water}$	Mass of hot water (kg)
M_{con}	Mass of condenser (kg)
M_{evp}	Mass of evaporator (kg)
M_{rec}	Mass of receiver (kg)
n	Constant of equation [3.6]
$O.D_{ads-tube}$	Outside diameter of adsorber copper tube (m)
$OSA_{ads-tube}$	Outside surface area of one meter length of adsorber copper tube (m^2 /m)
$O.D_{con,evp,perforated-tube}$	Outside diameter of one meter length of condenser, evaporator, and perforated copper tube (m)
$OSA_{con,evp,perforated-tube}$	Outside surface area of one meter length of condenser, evaporator, and perforated copper tube (m^2 /m)
P_{con}	Pressure of methanol at condenser temperature (bar)
P_{evp}	Pressure of methanol at evaporator temperature (bar)
$Q_{heat-ads}$	Heating energy of the first adsorber bed (kJ)
$Q'_{heat-ads}$	Heat energy of the second adsorber bed (kJ)

$Q_{cool-ads}$	Cooling energy of the first adsorber bed (kJ)
$Q'_{cool-ads}$	Cooling energy of the second adsorber bed (kJ)
$Q_{hot.water}$	Energy of solar water heating (kJ)
$Q_{solar.heat}$	Useful heat produced by solar energy (kJ)
$Q_{hot.water-heat.recovery}$	Total energy of hot water produced from heat recovery (kJ)
$Q_{domestic.hot.water-total}$	The total energy output of domestic hot water during 24 hours (kJ)
Q_{con}	The rejected heat energy during condensation process (kJ)
Q_{evp}	The gained heat energy during evaporation process.
Q_{cc}	Sensible cool energy of metallic (evaporator, receiver, water tray) from $T_0 \to T_{ice}$ (kJ)
$Q_{Netcooling}$	Net cooling energy for producing ice(kJ)
R	Gas constant (kJ/kgmoleK)
T_0	City water temperature (°C)
T_{evp}	Evaporator temperature for ice making (°C)
T_{a1}	Initial temperature of adsorption process in the first adsorber bed (°C)
T'_{a1}	Initial temperature of adsorption process in the second adsorber bed (°C)
T_{a2}	Minimum temperature of adsorption process (°C)
T_{con}	Minimum temperature of condensation process (°C)
$T_{hw} = T_{hot-water}$	Hot water temperature as heat source for heating process of the second adsorber bed (°C)
$T_{g2} = T_{g2-2nd-adsorber.bed}$	Maximum temperature of the first adsorber bed during desorption process (°C)
$T'_{g2} = T_{g2-1st-adsorber.bed}$	Maximum temperature of the second adsorber bed during desorption process (°C)
T_{ice}	Ice temperature (°C)
$Time_{heat.process}$	Time of heating process (hr)
$Time_{cooling.process}$	Time of cooling process (hr)
$Time_{isoster(a2-g1)}$	Time of sensible heating process of the adsorber bed from $T_{a2} \to T_{g1}$ (hr)
$Time_{desorption}$	Time of desorption process (hr)
$Time_{isoster(g2-a1)}$	Time of sensible cooling process of the adsorber bed (hr)
$Time_{adsorption}$	Time of adsorption process of the adsorber bed (hr)

$Time_{sensible.cooling-water}$	Time of sensible cooling of water from $T_0 \rightarrow T_{ice}$ (hr)
$Time_{for\min g-ice}$	Time of forming ice process (hr)
$Thick_{con,evp,perforated-tube}$	Wall thickness of condenser, evaporator, and perforated copper tube (m)
$Thick_{steel}$	Thickness of galvanized steel (m)
$Thick_{ads-tube}$	Wall thickness of adsorber copper tube (m)
U_{con}	Overall heat transfer coefficient of condenser (W/K.m^2)
$V_{ads-bed}$	Volume of adsorber bed (m^3)
V_{rec}	Volume of the receiver of methanol (m^3)
$V_{storage.\tan k-partition}$	The volume of the partition of water storage tank (m^3)
W_0	Maximum volume of the adsorption space (m^3/kg$_{ac}$)
$w_{ads-tube}$	Weight of one meter adsorber copper tube (kg/m)
$w_{con,evp,perforated-tube}$	Weight of one meter copper tube used for condenser, evaporator, and methanol mass transfer (kg/m)
$w_{rec-tube}$	Weight of one meter steel tube used for receiver (kg/m)
x	Thickness of ice layer (m)
X_{conc}	Maximum concentration of methanol during adsorption process (kg_{meth}/kg_{ac}).
X_{dil}	Minimum concentration of methanol at the end of heating process (kg_{meth}/kg_{ac}).
X'_{dil}	Minimum concentration of methanol in the second adsorber at the end of heating process (kg_{meth}/kg_{ac}).
η_{coll}	Efficiency of solar evacuated tube collector on average summer performance level
ρ_{ac}	Bulk density of activated carbon (kg/m^3)
ρ_{steel}	Density of galvanized steel (kg/m^3)
ρ_{ice}	Density of ice at 0°C (kg/m^3)
ρ_{evp}	Density of methanol at evaporator temperature (kg/m^3)
ρ_{con}	Density of methanol at condenser temperature (kg/m^3)

CHAPTER I

INTRODUCTION

Background

Solar power technology has gradually become more efficient and widespread. It has recently gained prominence in many areas as the full effects of burning fossil fuels for electricity are being realized. Global climate change, acid rain, and smog are among some of the key environmental problems that solar energy could solve besides the increasingly important problem of peak load in summer. It is also important to remember that as supplies of fossil fuels continue to be depleted, their price will increase. Solar technologies on the other hand will become less expensive as they evolve into more efficient forms.

In most developing countries there is a demand for extensive use of refrigeration. The prospect for an increased production of perishable foodstuff is very high in many areas, but lack of adequate storage and transport facilities severely limits the utilization of these potentials. In the health field, the role of refrigeration in the immunization of populations against infectious diseases, thanks to refrigerators for vaccine storage, can be highlighted and linked to increasing life expectancy. A striking example is the contribution of refrigeration to the eradication of poliomyelitis: in 2000, the number of cases of poliomyelitis occurring worldwide was less than 3500, which is a 99% decrease in comparison with the 350000 cases registered in 1988 as reported by IIR and UNEP (2000). Conventional refrigeration plants are dependent on a regular energy supply as well as on the availability of trained servicemen, demands that in many countries can be met only in the vicinity of urban areas. Since most of developing countries are located in the tropical or subtropical zones, solar-powered refrigeration systems present attractive alternative.

Solar cooling is needed most when the solar radiation is at its peak, thus making its use for this purpose all the more attractive. Among the various thermal applications of solar energy, cooling is one of the more complexes, both in concept and in construction. This is one of the reasons why its utilization at present is not as wide spread as space or water heating. Here it is not sufficient to collect the solar heat, store and distribute. The energy must be converted to cold effect through suitable device, capable of absorbing heat at a low temperature from conditioned space and rejected it into the environment.

The use of solar energy to drive cooling cycles has been considered for two different but related purposes. The first is to provide refrigeration for food preservation, vaccine storage, ice making...etc. The second is to provide comfort cooling.

The electric driven vapor compression refrigeration system is facing a real challenge as CFCs and HCFCs are not suitable for sustainable development. The commonly used substitutes for refrigerant, R134a is also facing the problem of green house effect. Natural refrigerants fluids such as water, ammonia, methanol, etc. will be welcome for the future refrigeration and air conditioning industries.