TECHNOECONOMICAL ANALYSIS OF
A RESIDENTIAL PHOTOVOLTAIC
VAPOUR COMPRESSION AIR CONDITIONING SYSTEM

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To whom care for

the environment

the next generation

peace and equality

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ABSTRACT

Photovoltaic (PV) is becoming a significant solar applications. Air conditioning is one of the basic needs for residential indoor comfort in tropical areas. A vapour compression air conditioning (VCAC) unit powered by PV is evaluated in this thesis by simulations. For energy-saving purpose, the VCAC unit is working with R134a, and variable compressor speed and condenser air mass flow rate are assumed. A typical residential house located in Senai is modeled and simplified cooling load temperature differential (CLTD) is used to find the peak load and determine the cooling capacities. Based on the peak load demands, psychrometric study is performed and VCAC model is developed to calculate the power supply needed. Then a crude stand-alone PV (SAPV) system size is predicted. To estimate the SAPV VCAC system performance, long-term average and detailed approaches are employed. The former adapted the simplified design method proposed by Hove (2000). It is found that without backup utility, 42.336 m^2 of PV array area and 441.14 Ah of battery capacity are required to achieve annual solar fraction of 0.9, using PV mean efficiency of 0.13. In the latter approach, transfer function method (TFM) and VCAC simulations are performed to compute the hourly cooling loads. A detailed modeling of SAPV system based on generality usage is developed and system performance for seven days during the highest cooling demands is studied. The simulations results are discussed and parametric analysis are shown. The SAPV VCAC system is found to be not cost-effective due to efficiency constraint of PV technology and high PV capital costs. Electricity cost of minimum RM1/kW will make PV applications favourable. The simulation methodology requires empirical data to verify. Recommendations are made for improved computations. However, this study believes PV still has potential beneficial effects for large-scale residential energy applications.

ABSTRAK

Fotovoltaik (PV) merupakan aplikasi suria yang semakin penting. Penyaman udara adalah suatu keperluan asas untuk keselesaan dalam rumah di kawasan tropika. Seunit penyaman udara mampatan wap (VCAC) yang dibekal kuasa oleh PV telah dinilai dengan simulasi. Demi tujuan menjimat tenaga, unit VCAC beroperasi dengan R134a, halaju pemampat dan kadar aliran jisim udara memeluwap dianggap sebagai pembolehubah. Sebuah rumah kediaman di Senai dimodel dan CLTD mudah diguna untuk mencari beban puncak dan menentukan muatan pendinginan. Berdasarkan keperluan beban puncak tersebut, psikrometrik dikaji dan model VCAC dibina untuk menghitung bekalan kuasa yang diperlukan. Seterusnya, saiz sistem SAPV kasar diramalkan. Untuk menjangka prestasi sistem SAPV VCAC itu, pendekatan secara purata jangka panjang dan perincian telah digunakan. Pendekatan secara purata jangka panjang disesuaikan daripada kaedah rekabentuk mudah yang diutarakan oleh Hove (2000). Tanpa utiliti backup, annual solar fraction sebanyak 0.9 dapat dicapai dengan menggunakan PV mean efficiency sebanyak 0.13, PV array seluas 42.336 m^2 dan kemuatan bateri sebanyak 441.14 Ah. Bagi pendekatan secara perincian, TFM dan simulasi VCAC dilakukan untuk mendapatkan beban pendinginan setiap jam. Satu permodelan sistem SAPV secara perincian berasaskan kegunaan umum dibina dan prestasi sistem dikaji selama tujuh hari semasa permintaan pendinginan adalah tertinggi. Keputusan simulasi telah dibincangkan dan analisis parameter telah ditunjukkan. Sistem SAPV VCAC didapati tidak berkesan dari segi kos kerana had kecekapan teknologi PV dan kos PV yang tinggi. Kos elektrik sekurang-kurangnya RM1/kW akan menjadikan aplikasi PV ini lebih digemari. Metodologi simulasi memerlukan pengesahan data empirikal. Cadangan telah dibuat untuk memperbaiki komputasi. Malah, kajian ini yakin bahawa PV mempunyai potensi membawa kesan bermanfaat terhadap aplikasi tenaga kediaman berskala besar.

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A = area, m^2

A_L = effective leakage area, m^2

A_o^A = reference array area defined in equation (4.44), m^2

AC = alternating current

AD = array disconnection

ADP = array disconnection probability

AF = array failure

AFP = array failure probability

B = battery capacity, kWh

BF = battery failure

BFP = battery failure probability

BPF = by-pass factor

b_n = conduction transfer function coefficients

C_B = battery capacity, kAh

C_W = wind coefficient

C_S = stack coefficient

C_{B10} = battery capacity with discharge regime of 10 hours, kAh

Conv = convective portion of instantaneous heat gain

CLTD = cooling load temperature differential

COP = coefficient of performance

CTD = condenser temperature difference, °C

CTF = conduction transfer functions

c_p = specific heat at constant pressure, kJ/kg K

specific heat of air c_{p_a} = 1.006 kJ/kg K

c_n = conduction transfer function coefficients

d_n, = conduction transfer function coefficients

E = energy per day, kWh/day

ER = heat extraction rate, kW

E_t = equation of time, min

EE = excess energy

EEP = excess energy probability

ERSH = effective room sensible heat, kW

ERLH = effective room latent heat, kW

ESH = equivalent sun hours, h

F_c = fraction of the input energy lost back to the surroundings

F_s = solar fraction

F_d = dump fraction

F_{sa} = special allowance factor

F_{sh} = degrading factor due to the influence of superheated region

F_{ul} = lighting use factor

G = Irradiance, kW/m^2

g_n = SATF coefficients

H = Irradiation, MJ/h/m^2

H = enthalpy, kJ

h = specific enthalpy, kJ/kg

h_s = hour angle, °

specific enthalpy of evaporation of water at 0 °C h_{fg_0} = 2500.81 kJ/kg

h_w = specific enthalpy of condensation of water, kJ/kg

I = electric current, A

I_{cc} = circuit consumed current, A

I_o = dark saturation current, A

I_{ph} = photocurrent, A

I_{10}^{B} = battery discharge current of C_B at discharge regime, A

$I_{c\max}^{B}$ = maximum allowable charging current, A

$I_{d\max}^{B}$ = maximum allowable discharging current, A

IAB = increment annual benefits, RM

IAOC = increment annual operating costs, RM

ICC = increment capital costs, RM

J = parameter defined in equation (3.6)

K_θ = unit length conductance between the space air and surroundings, W/(m^2.K)

L =load per day, kWh/day

L_F = length of space exterior wall, m

LD = load disconnection

LDP = load disconnection probability

LHG = latent heat gain, W

$\dot{m}$ = mass flow rate, kg/s

N = number of day

N = number of PV components in the connections

N = number of people

N_p = compressor rotational speed, rpm

NPV = net present value, RM

n = polytropic index of compression

n = summation index

P = pressure, kPa

P_w = partial pressure of water vapour, kPa

PV = photovoltaic

PWAF = present worth annuity factor

$PWAF_E$= present worth annuity factor of main electricity costs

p_n = SATF coefficients

Q = heat transfer, kJ

Q = amount of exchanged charge during interval between previous time and current time of interest, kAh

$\dot{Q}$ = heat transfer rate, kW

q = component heat gain, kW

$\dot{q}$ = heat flux, W/m^2

gas constant of air R = 287 J/kg K

R_B = battery internal resistance, Ω

RH = relative humidity, %

RTF = room transfer functions

r = compressor clearance ratio

S = PV size combinations

SHG = sensible heat gain, W

SAPV = stand-alone photovoltaic

SATF = space air transfer functions

$SHGF_t$ = solar heat gain factor at time t, W/m^2

SC = shading coefficient

SOC = state-of-charge

SOC = standard operating conditions

SOCp = state-of-charge at previous measured time

STC = standard test conditions

s = specific entropy, kJ/kg K

T = temperature/dry bulb temperature, °C or temperature, K

T_{ADP} = room apparatus dew-point temperature, °C

T_{sol} = sol-air temperature, °C

T^* = wet bulb temperature, ºC

TFM = transfer function method

t_{PB} = pay-back period, year

t_{std} = standard time, h

t_{sol} = solar time, h

U = overall heat transfer coefficient, kW/m^2 K

U_L = thermal loss coefficient per unit area between array and ambient, W/m^2.°C

V = voltage, V

V = volume, m^3

V_p = piston displacement volume, m^3

V_{nom} = nominal system voltage, V

$\dot{V}$ = volume rate of flow, m^3/s

$\dot{V}_p$ = piston displacement rate, m^3/s

VC = vapour compression

VCAC = vapour compression air conditioning

v = specific volume, m^3/kg

v_n = room transfer function coefficients

v_w = wind speed, m/s

W = work, kW

$Watt_{app}$ = watts input from appliances (Section 4.3.3.1), W

w = humidity ratio, kg/kg d. a.

w_n = room transfer function coefficients

w^* = humidity ratio based on wet-bulb temperature, °C

Greek symbols

β = module temperature coefficient of maximum power efficiency, V/°C

Δt = time step, *s*

δ = declination, °

δ = time interval, h

ε = heat exchanger effectiveness

η = efficiency

η_v = volumetric efficiency

λ = latitude, °

$\mu_{V_{ov}}$ = temperature coefficient of V_{oc}, V/°C

ρ = density, kg/m^3

ρ_g = ground reflectivity

τ = time constant, h

$\tau\alpha$ = array trasmissitivity-absorbance product

$\frac{\alpha}{h_o}$ = surface colour factor

$\delta \frac{R\varepsilon}{h_o}$ = long-wave radiation factor, °C

Superscripts

A = array

B = battery

C = solar cell

I = inverter

L = load

M = module

Subscripts

a = air

amb = ambient

c = condenser air/condenser/condensing

con = conventional air conditioning system

D = design

d =day

e = evaporating air/evaporator/evaporating

f = refrigerant

i = inlet

in = indoor

ini = initial

inf = infiltration

isen = isentropic

h = hour

l = latent

lim = limit

m = mixture of room return air and outdoor air

mp = maximum power point

max = maximum

mech = mechanical, include motor

min = minimum

out = outdoor

o = outlet

oc = open circuit

P = parallel in connection

p = compressor/compression

pc = power conditioning equipment

pv = photovoltaic

r = room

r = reference

s = sensible

S =series in connection

sol = sol-air temperature

sh = superheat
sc = subcool
sup = supply
sys =system
t = time
T = tilt
var = variable speed air conditioning system
ven = ventilation
w = condensation
y = year
1’ = saturated gas state point, at evaporating temperature
1 = compressor inlet state point
2 = compressor discharge state point
2’ = saturated gas state point, at condensing temperature
3 = condenser outlet state point
3’ = saturated liquid state point, in the condenser
4 = evaporator inlet state point

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CHAPTER 1

INTRODUCTION

1.1 Air Conditioning and Solar Energy

Generally, high solar irradiation requires cooling for food preservation or human comfort. Therefore, the application of solar energy instead of popular electricity or gas for cooling purposes appears logical for countries with a high solar energy supply (Erhard *et al.*, 1997). In Malaysia, air conditioning is a popular facility. The necessity of air conditioning for thermal comfort in hot areas and the abundance of sunshine have always intrigued the mind of researchers on how to combine the two for people's benefit.

For Grossman (2002), the greatest demand for cooling occurs when the solar radiation is most intense, thus making its use for cooling all the more attractive. Alizadeh (2000) agreed with similar point, stating that cooling load and availability of solar radiation are approximately in phase.

Today, the attractive idea of solar air conditioning has been put into numerous ways of practices.

1.2 Main Types of Solar Energy Application in Air Conditioning,

Two types of large commercial solar-driven cooling systems have been developed: (1) generating electricity from solar radiation to operate a mechanical chiller, and (2) converting sunlight to heat which in turn drives an absorption chiller (Gordon *et al*., 2000).

A mechanical chiller involves a vapour compression refrigerator, with a solar-powered prime mover. This may be done through converting solar energy into electricity via means of photovoltaic devices, and then using the electricity in an electric motor to drive the vapour compressor, or by Rankine heat engine.

Absorption systems are similar to vapour compression air conditioning systems but differ in the pressurization stages. An absorbent on the low-pressure side absorbs an evaporating refrigerant. The most usual combinations of fluids include lithium bromide-water ($LiBr$-H_2O) and ammonia-water (NH_3-H_2O) systems where water vapour and ammonia are the refrigerants respectively. The pressurization is achieved by dissolving the refrigerant in the absorbent in the absorber section. Subsequently, the solution is pumped to a high pressure with an ordinary liquid pump. The addition of heat in the generator is used to separate the low-boiling refrigerant from the solution. In this way the refrigerant vapour is compressed without the need of large amounts of mechanical energy that a vapour compression air conditioning system demands (Florides *et al.*, 2002).

The most widely used solar air conditioning system operates on absorption cycle for the time being. One reason is, absorption air conditioning is the only air conditioning system compatible with the upper collection temperature limits imposed by currently available flat-plate collectors (Kreider *et al*., 1982).

1.3 Other Attempts of Cooling Methods

The weaknesses of solar absorption cooling have lead to numerous efforts of exploring other cooling cycle possibilities (Refer Chapter 2).

All the refrigeration processes can be classified into open and close cycle. Experience has shown that closed-cycle systems most suitable for solar cooling, is based on absorption cycles (Grossman, 2002). Absorption and adsorption process are referred as sorption process as a whole. In these sorption processes, they can still be divided into whether the cycle is continuous or intermittent.

Adsorption cooling is another class of sorption air conditioners besides absorption cooling that utilizes an adsorbent for adsorbing moisture from the air then allow air to evaporative cooling. Besides, when simple absorption and adsorption refrigerators operate discontinuously rather than in a cycle, this is called intermittent operation. An intermittent solar powered system operates on diurnal cycle with one-generation cycle per day (Bansal *et al.*, 1997). During this operation, the thermodynamic processes are far from reversible, and are dependent upon the properties of the refrigerant-absorbent combination used and the proportion of refrigerant present at the commencement of generation. Most work to date on these cycles has been directed at food preservation rather than comfort cooling. These cycles may be of interest in air conditioning because they offer potential solutions to the energy storage problem (Duffie *et al.*, 1980).

In the solid sorption systems, silica gel is taken for utilized commercial chiller. In contrast, complex compounds of ammonia are used more often whereas zeolites and hydrides play a minor role in the R&D field (Lamp *et al.*, 1998).

Another air conditioning system has been given focus is the open-cycle desiccant cooling system. It uses a desiccant dehumidifier to convert latent cooling load into sensible load and then meet this load using evaporative coolers (Sheridan *et al*., 1985). Its advantage is using low-grade heat such as solar energy can do the regeneration of desiccant. Open cycle regenerates the weak absorbent solution by losing refrigerant to the atmosphere. Cooling takes place by evaporating refrigerant from an external source in the evaporator (Collier, 1979). The system usually can operate in one of two modes: ventilation and recirculation (Kreider *et al*., 1982).

1.4 Environmental Considerations

Solar energy is certainly more environmental friendly compared to current main conventional energy sources. Most conventional cooling systems are either directly or indirectly driven by gas and fuel or dam-generated electricity. It is our main environmental concerns today that lead us to replace them with renewable energies. In a tropical country such as Malaysia, the rich solar energy throughout the year is ready for us to fully utilize.

From the energy supply perspective, air conditioners can be classified into thermally and electrically driven coolers. Most researches have focused on the former method since the providing work from solar heat seems convenient. The main problem arise here is storage. In the mean time, electrically driven coolers are relatively lack of attentions.

One of the becoming popular ways to produce electricity from sun is photovoltaic (PV) technology.

For air conditioning applications, an ideal PV system is producing energy, which exceeds the load demand when sunlight is intense. The excess energy shall be stored to maintain the storage component such as battery in a fully charged state. When solar radiation is less or during the nights, the battery can be discharged to provide energy to the load.

Europe, Japan, United States and Australia have installed large-scale residential PV roof subsidised programs (Green, 2004). Our society should have preparations regarding popularise renewable energy applications at residential level. As shall be illustrated in Chapter 2, PV energy has a great potential in terms of performance and costs in the future. Therefore, researchers have to work on exploring the future benefit of PV applications such as air conditioning.

Besides the power supply of air conditioning requires attentions, the refrigerants used in the conventional vapour compression air conditioning (VCAC) units have been identified to cause environmental destructions. R134a is one of the ecological refrigerants for its replacement.

1.5 Problem Statement

Study the potential of applying photovoltaic power, to generate the highly efficient commercial VCAC system for residential application in Malaysia. This is one of the efforts to overcome the low-efficiency and high-costs problems encountered by current solar cooling methods, particularly those operate in absorption cycle. The ultimate goal is to enhance energy saving as well as environmental friendly engineering design.

1.6 Research Objectives

The research objectives are:

- To develop a program to simulate a photovoltaic vapour compression air conditioning system working with R134a
- To study the system performance and suggest the optimum system sizing

1.7 Scopes

The scopes of the study are:

- The air conditioning system is designed for typical residential purpose
- Only vapour compression cooling cycle is investigated
- Consider environmental factor, R134a is used as the cooling refrigerant
- As an attempt for energy saving purpose, variable compressor speed and condenser air flow rate is permitted in this study
- Analysis is done based on Malaysian climatic conditions
- Stand-alone photovoltaic (SAPV) powers the major load portion of the air conditioning unit, i.e. the compressor energy demand only
- Silicon is the solar cell material type to allow applications of some modelling assumptions.
- Modelling of PV system is based on typical SAPV system configurations, and generality of component model is allowed
- Long-term economic study is performed on the PV system

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