Renewable Energy 88 (2016) 95–101

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Design of direct solar PV driven air conditioner

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ARTICLE INFO

Article history:
Received 17 July 2015
Received in revised form
31 October 2015
Accepted 7 November 2015
Available online xxx

Keywords:
Solar cooling
Solar air conditioning
Solar PV cooling

ABSTRACT

Solar air conditioning system directly driven by stand-alone solar PV is studied. The air conditioning system will suffer from loss of power if the solar PV power generation is not high enough. It requires a proper system design to match the power consumption of air conditioning system with a proper PV size. Six solar air conditioners with different sizes of PV panel and air conditioners were built and tested outdoors to experimentally investigate the running probabilities of air conditioning at various solar irradiations. It is shown that the instantaneous operation probability (OPB) and the runtime fraction (R_F) of the air conditioner are mainly affected by the design parameter r_{pL} (ratio of maximum PV power to load power). The measured OPB is found to be greater than 0.98 at instantaneous solar irradiation $I_T > 600$ W m^{-2} if $r_{pL} > 1.71$. R_F approaches 1.0 (the air conditioner is run in 100% with solar power) at daily-total solar radiation higher than 13 MJ m^{-2} day^{-1}, if $r_{pL} > 3$.

1. Introduction

The cooling load and the energy consumption of air conditioning system in buildings or vehicles are in phase with solar radiation intensity. Solar cooling is thus promising. Many researchers developed solar cooling technology using absorption or adsorption chiller [2,5]; or ejector cooling [9,11] driven by solar thermal energy. Collector used to drive absorption, adsorption, or ejector chiller requires high energy conversion efficiency at high temperature. Usually, vacuum-tube or parabolic-trough collector is used. The cost of collector as well as heat-driven chiller is high and makes the solar cooling not economical.

Recently, many researches study solar cooling using vapor-compression cooler driven by solar PV system since solar PV system cost falls down very fast. Hartmann et al. [4] compared theoretically solar thermal and photovoltaic cooling for a small office building in Freiburg and Madrid and found that the grid-tied PV system has lower cost of primary energy savings. Similar result is obtained by Ref. [16]. Both [4] and [16] assumed that the PV system used in solar cooling is grid-tied type which does not have energy storage (battery). In these solar cooling systems, the power grid will supply electricity for cooling when solar energy is not available.

In off-grid applications, solar air conditioner needs to be powered by stand-alone PV system. The design of stand-alone solar cooling system is complicated in view of possible loss of power during low solar radiation periods. A typical example is solar refrigerator. The electricity is produced by photovoltaic panels to drive refrigerator based on vapor compression cycle through battery, charge controller [3,13,17,18] and inverter [14,15].

Axaopoulos and Theodoridis [1] designed a solar photovoltaic powered ice-maker which operates without the use of batteries and may be used in truly autonomous applications in remote areas. The refrigerator is made of four compressors. The operation of the compressors by the PV panels is ensured by the use of a controller, which provides startup, maximum power tracking and power management for the four compressors of the system.

Solar air conditioner is different from solar refrigerator in cooling capacity and load pattern. The refrigerator is always well-insulated and the cooling load may be increased only when it is suddenly or frequently opened. The effect of thermal mass plays a significant role in stabilizing the refrigerator temperature. In addition, the cooling power is usually small for refrigerator.

For air conditioner, the cooling load is usually large, in several kW, and may vary with solar radiation intensity and outside air temperature. Air filtration or people moving to or from the cooling space also affect the cooling load. Besides, solar radiation may fluctuate. All of these make the design of solar air cooling system

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http://dx.doi.org/10.1016/j.renene.2015.11.026
0960-1481/

much more complicated.

Huang et al. [12] developed a stand-alone solar air conditioner driven directly by solar PV. An air conditioner with 200 W ac power was driven directly by 430Wp solar PV module. No grid power is connected. In order to stabilize compressor operation and reduce battery cost, a small 24 V/12 Ah battery was used. An inverter is used to convert PV power into ac power to drive the air conditioner. The battery can supply power for less than 1 h during low solar radiation periods. Hence, the cooling system may suffer from loss of power. In the present study, six solar air conditioners are designed and tested. The field test results are analyzed to study the effect of design parameters on the system performance.

2. Experimental setup

2.1. Experiment design

The power supply of air conditioning system is from a stand-alone solar PV system. It requires a steady power input to compressor for smooth operation under variable solar radiation. A small battery is thus used, called buffer battery. It acts as a buffer to stabilize the compressor operation. A capacitor is connected to the battery in order to suppress the surge power at compressor startup. A microprocessor-based controller with measurements of charge/discharge current, battery voltage, solar irradiation etc. [7] is used to control the battery charge/discharge and data recording. The schematic diagram is shown in Fig. 1.

The present system did not use MPPT (maximum-power-point tracking control) for maximum power tracking of PV module. Instead, the PV system design is based on nMPPO (near maximum-power-point operation) [6] which matches the performance of solar PV modules with the battery voltage. This avoids the energy loss of MPPT and reduces the cost as well as keeping high reliability.

The air conditioner is used to supply cooling load of a low-energy house (ZEH-2, Fig. 2) which is used as a meeting room for 12 persons. The inside space of the low-energy house is 7.4 m long, 3.8 m wide, 3 m high with floor area 28 m^2. Several passive designs are used in the construction of low-energy house to reduce heat penetration, including interior wall insulation using 10 mm thick vacuum-insulation panel laminated with 25 mm fiber material, outer-wall ventilated sun shades, and low-E window with plastic frame [8,10]. The overall U-value is 0.22 Wm^{-2} K^{-1}. The total cooling load of the house is estimated 2,200 W in summer.

2.2. Definition of design parameter and performance characteristics of solar air conditioner

The air conditioning system will suffer from loss of power if the solar PV power generation is not high enough at low solar radiation.

Fig. 2. Low-energy house (ZEH-2).

The instantaneous performance of solar air conditioner can be characterized by the operation probability (*OPB*) defined in eq. (1) [11]. *OPB* is defined as the ratio of total running time of the air conditioner to total occurrence time of solar irradiation at specific intensity $I_T \pm \triangle I_T$ where $\triangle I_T$ is the radiation increment chosen as 50 Wm^{-2}. *OPB* is used to characterize the running probability of air conditioner at given solar irradiation I_T.

$$OPB = \frac{\sum_j \Delta t_{on,j}}{\Delta t_{I_T}} \tag{1}$$

Another performance index called “runtime fraction” (R_F) defined as the ratio of the total running time t_{ON} of air conditioner to the total service time t_{total} (taken 8 h), eq. (2), can be used to characterize the daily performance [11].

$$R_F = \frac{t_{ON}}{t_{total}} \tag{2}$$

R_F is used to characterize the daily overall performance of solar air conditioner at daily-total solar irradiation H_T. Actually, $1 - R_F$ is the time fraction of power loss.

Two system design parameters, r_{pL} and t_{bp}, can be used to correlate the PV power generation, load power, and battery storage with OPB and R_F [11,12].

$$r_{pL} = \frac{W_{pv}}{W_L} \tag{3}$$

and

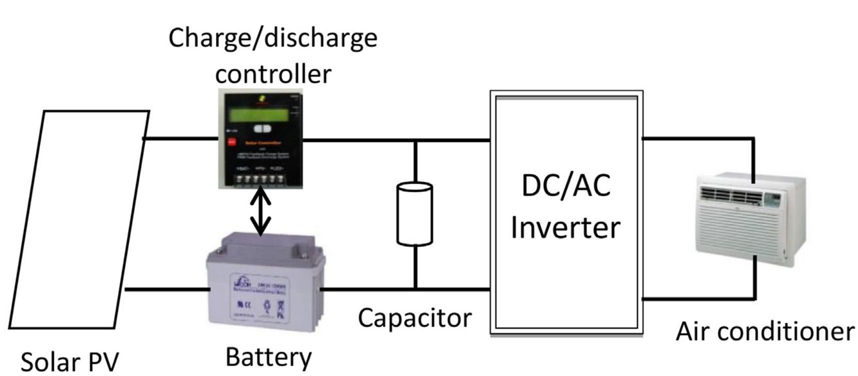

Fig. 1. Schematic diagram of solar air conditioning system.