INTERNATIONAL JOURNAL OF REFRIGERATION 56 (2015) 126–139

Available online at www.sciencedirect.com
ScienceDirect
journal homepage: www.elsevier.com/locate/ijrefrig

Theoretical and experimental analyses of solar-thermoelectric liquid-chiller system

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ARTICLE INFO

Article history:
Received 16 October 2014
Received in revised form
20 December 2014
Accepted 10 January 2015
Available online 19 January 2015

Keywords:
Air-conditioning
Cooling down period
Coefficient of performance (COP)
Liquid chiller
Thermoelectric
Solar PV

ABSTRACT

A solar-thermoelectric liquid chiller (STLC) system is constructed and characterized using both theoretical and experimental analyses. A cold-plate (plate and tube type) heat exchanger, attached to the cold side of the STLC system, is utilized for removing the heat from the circulating water in the system. Analytical models include the thermoelectric Peltier effect, thermal convections in air and water, and conductions within the solid parts of the STLC system. Proposed analytical models are used to calculate different performance parameters (e.g., heat removal rate and coefficient of performance) of STLC system at different input electrical currents, temperature differences (between the bulk mean temperature of the liquid and the surrounding environmental temperature), and flow rates. Optimum values of the electrical current are calculated to achieve maximum heat removal rates for a wide range of temperature differences. It is observed that the heat removal rate by the STLC system increases with increasing bulk mean temperature of the water for considered ambient temperature conditions. However, small changes in the heat removal rate are observed when liquid flow rate changes inside the cold-plate heat exchanger. A prototype of the conditioned space is constructed to perform the experimental analysis. Experimental analysis includes the monitoring of the cooling down period of the water and conditioned space to achieve desired temperatures.

Analyses théorique et expérimentale d'un système de refroidisseur de liquide solaire-thermoélectrique

Mots clés : Conditionnement d'air ; Période de refroidissement ; Coefficient de performance (COP) ; Refroidisseur de liquide ; Thermoélectrique ; Solaire photovoltaique

1. Introduction

A chilled liquid has many engineering applications; for example, electronic cooling, air-conditioning, chemical process engineering, food refrigeration, medical science, and preservation of biological elements. The refrigeration processes, required to chill liquid, can broadly be classified into three types (Arora, 2008): (i) vapor compression refrigeration system, (ii) absorption refrigeration system, and (iii) special

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http://dx.doi.org/10.1016/j.ijrefrig.2015.01.003

Nomenclature

A_c	The apparent contact area (m^2)
$A_{fin,total}$	The total fin area of the heat sink (=number of fin × surface area of single fin) (m^2)
A_p	The wall surface area of the water channel inside the cold plate heat exchanger (m^2)
A_s	The surface area of the spreader (m^2)
A_{TE}	Cross-sectional area of a leg (*p*-type or *n*-type) of thermoelectric unit element (m^2)
AU	The total resistances ($W\ K^{-1}$)
A_{unfin}	The unfin area of the heat sink (=base area of heat sink − number of fin × base area of a single fin) (m^2)
COP	Coefficient of performance
C_p	Specific heat of the air ($kJ\ kg^{-1}\ K^{-1}$)
h	Convection heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
h_c	The thermal contact conductance ($W\ m^{-2}\ K^{-1}$)
h_w	The convection heat transfer coefficient inside the water tube ($W\ m^{-2}\ K^{-1}$)
i	Electrical current (A)
k	Thermal conductivity ($W\ m^{-1}\ K^{-1}$)
k_{fin}	Thermal conductivity of a single fin ($W\ m^{-1}\ K^{-1}$)
k_p	The thermal conductivity of the cold plate material ($W\ m^{-1}\ K^{-1}$)
k_s	The conductivity of the heat spreader ($W\ m^{-1}\ K^{-1}$)
L	Length of a single fin (m)
L_s	The thickness of the heat spreader (m)
L_{TE}	Length of thermoelectric unit element (m)
n	*n*-type material, the number of unit elements inside a thermoelectric module
$\dot{Q}$	Peltier heat (W)
$\dot{Q}_C$	The heat removal rate at the TEC cold side (W)
$\dot{Q}_{con}$	Heat removed by the condenser (W)
$\dot{Q}_{cpx}$	Heat removed by the cold plate heat exchanger (W)
$\dot{Q}_H$	The heat removal rate at the TEC hot side (W)
$\dot{Q}_L$	Heat removed by the air-conditioning module (W)
p	*p*-type material
$\dot{P}_{in}$	The power input (W)
R	Electrical resistance (Ω)
Re_L	The Reynolds number
S	The conduction shape factor for the solid metal part of the cold plate heat exchanger
T	The absolute temperature (°C)
TE	Thermoelectric
T_b	The bulk mean temperature (°C)
T_H	The ambient air temperature (°C)
T_1	Hot junction temperature (°C)
T_2	Cold junction temperature (°C)
T_0	The initial temperature inside the air-conditioned space (°C)
w	The width of a single fin inside the heat sink (m)
z	The thickness of a single fin inside the heat sink (m)

Greek symbols

α	Seebeck coefficient ($V\ K^{-1}$)
η_{fin}	The fin efficiency
μ	Viscosity ($N\ s\ m^{-2}$)
$\dot{v}$	Volume flow rate ($m^3\ s^{-1}$)
ρ	Resistivity of a leg (p-type or n-type) of thermoelectric unit element
ρ	Density ($kg\ m^{-3}$)
π	The Peltier coefficient (V)

refrigeration systems (e.g., thermoelectric refrigeration). Convectional (e.g., vapor compression) refrigeration systems use harmful chemical like Chlorofluorocarbon (CFCs), which is considered to be one of the major causes for global warming. Therefore, researchers over the time, focus their attention to develop and improve new refrigeration and air-conditioning systems those utilize environmentally friendly refrigerants or alternate environmentally friendly and clean techniques (e.g., thermoelectric, thermoacoustic refrigeration systems). Special refrigeration systems utilize other special mechanisms to absorb and reject heat to complete the refrigeration cycle. For example, thermoelectric coolers utilize the Peltier effect (Rowe, 1995) to produce refrigeration or heat pumping effect. Thermoelectric coolers are solid state devices which replace circulation of typical refrigerant by electrical current flow (Le Pierres et al., 2008; Meng et al., 2009). Unfortunately, the coefficient of performance (COP) of thermoelectric refrigeration system (with other new technologies) remains lower than the conventional vapor compression system or absorption systems (Arora, 2008). However, several special refrigeration systems, including the thermoelectric system, exhibit potential of using low grade energy sources (e.g., solar, wind, sound, waste heat, etc.) as input which motivates many users to use such refrigeration systems in a remote location or in a location where electricity is in short supply. Solar energy can be utilized to operate a PV system to produce required electricity to run the cooling system (Le Pierres et al., 2008). Alternatively, solar energy can be utilized to produce power using thermoelectric power generation unit and then supply this power to a cooling unit (Meng et al., 2009). In this study, the required power input is produced by the solar PV system and stored in an array of batteries.

Reported results in the literature on solar thermoelectric liquid chilling are limited. Huang et al. (2010) conducted theoretical and experimental studies to identify the performance characteristics of thermoelectric water cooling system for electronic cooling applications. Authors concluded that thermoelectric cooler can enhance the performance of conventional water based cooling systems for a heat load below 57 W. Faraji et al. (2014) designed and developed a thermoelectric liquid chiller for general applications. Authors designed and constructed a 430 ml capacity thermoelectric chiller and measured the coefficient of performance and cooling down period for the constructed system. They compared their results with analytical solutions for different input voltages and currents to their system. Khonsue (2012) proposed a thermoelectric liquid cooling system for electronic application using micro-channel heat sink and investigated its performance using experimental