Renewable Energy 83 (2015) 256–269

Contents lists available at ScienceDirect

Renewable Energy

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

Performance review of a novel combined thermoelectric power generation and water desalination system

Abhijit Date*, Luke Gauci, Raymond Chan, Ashwin Date

RMIT University, School of Aerospace, Mechanical and Manufacturing Engineering, Bundoora East Campus, Melbourne, Australia

ARTICLE INFO

Article history:
Received 23 November 2014
Accepted 8 April 2015
Available online

Keywords:
Thermoelectric generator
Phase change
Desalination
Heat pipes
Low grade heat
Passive cooling

ABSTRACT

A novel combined thermoelectric power generation and water desalination system is described with a system schematic. The proposed system utilises low grade thermal energy to heat thermoelectric generators for power generation and water desalination. A theoretical analysis presents the governing equations to estimate the systems performance characteristics combined with experimental validation. Experimental set-up consists of an electric heat source, thermoelectric modules, heat pipes, a heat sink and an evaporator vessel. Four heat pipes are embedded in a heat spreader block to passively cool the bottom side of the thermoelectric cells. The condenser of these four heat pipes is immersed in a pool of saline water stored in an evaporation vessel which is maintained at sub-atmospheric pressure. The liquid to vapour phase change cooling method achieve low saturation temperature and offers a high heat transfer coefficient for the cooling of the thermoelectric generators. At the same time this method utilises the low temperature heat extracted from the cold side of the thermoelectric generator for water desalination. It was observed that at low saturation temperatures greater heat flux could be supplied to the thermoelectric generators with less heat losses to the atmosphere.

1. Introduction and background

Electrical energy and fresh water are of vital importance socially and economically. With increasing population the earth's resources including fossil fuels and fresh water are becoming scarce. The world population is growing approximately at a rate of 1.2% and is expected to increase to around 8.9 billion by 2050 [26]. The critical water level to satisfy basic human needs is estimated to be 1000 m^3/capita annually [14].With only 3% of the earth's water constituting as fresh water, it is projected that by 2050 about 1.7 billion people in 39 countries will fall below this level [18]. In addition as hydrocarbons are currently the conventional means of producing electrical energy, fuel shortages are an inevitable concern unless radical changes occur in either the demand or supply of hydrocarbons [1]. In terms of oil consumption, it is estimated that about 200 million tons of oil per year is required to produce 22 million m^3 per day of desalinated water [15]. As a result the link between new ways to develop electrical energy and fresh water cannot be overlooked.

Numerous low-density populations around the world lack a combination of reliable access to electrical energy and fresh water. In these regions independent renewable energy and desalination technologies provide a moderate solution to this problem. Conventional desalination technologies include multi-stage flash (MSF), multi-effect distillation (MED), reverse osmosis (RO), electrodialysis (ED) and vapour compression (VC) processes. These desalination processes are highly energy intensive [11]. Depending on the economic situation, resource availability, and social sustainability support in a region, renewable energy sources are increasingly being studied to drive desalination. The current way forward is to power desalination plants with renewable energy technologies including photovoltaic cells (PV) or wind turbines alone, or in hybrid with an electrical grid [23].

The significance of finding new methods to meet the world's energy crisis and fresh water demand are highlighted in the studies undertaken by those in the field of global sustainability. Research into energy and fresh water suitability can be seen in the literature reviews by Refs. [9] and [19]. Also research has been done on distributed smart grids, like in Ref. [21] discussed a control framework for optimal operation of distributed energy/water system [21]. Although the recent advancements in electrical

* Corresponding author.
E-mail address: abhijit.date@rmit.edu.au (A. Date).

http://dx.doi.org/10.1016/j.renene.2015.04.024
0960-1481/

Nomenclature

A	active outer surface area of heat pipe condenser or evaporator (m^2)
C_p	specific heat (J/kg K)
C_{sf}	experimental constant that depends on surface fluid combination
g	gravitational acceleration (m/s^2)
h_{fg}	enthalpy of vaporization (J/kg)
J	current density (A/m^2)
k	thermal conductivity (W/m °C)
D	diameter of heat pipes (m)
m	mass of saline water (kg)
$\dot{m}$	rate of fresh water (kg/s)
n	quantity indicated where
N	experimental boiling constant that depends on the fluid
NU	overall Nusselt number
Pr	Prandtl number of liquid
$\dot{Q}$	rate of thermal energy (W)
r	radius (m)
R	thermal resistance (°C/W)
S	Seebeck coefficient (V/K)
t	time (s)
T	temperature (°C)
x	distance (m)
α	Seebeck coefficient
β	volume expansion co-efficient (1/K)
υ	viscosity (Pa s)
σ	surface tension of liquid vapour interface (N/m)
ρ	density (kg/m^3)

Subscripts

1	represents first set of heat pipe
2	represents or second set of heat pipe
amb	represents local/surrounding atmosphere
avg	average
c	condenser of heat pipe
cold	cold side of thermo-electric generator
cond	condensation process
conv	resistance due to convection
e	evaporator of heat pipe
emf	electric motive force
evp	evaporation process
f	final
fw	fresh water
hot	hot side of thermoelectric generator
hp	heat pipe
hp	represents heat pipe set
hs	heat spreader plate
i	initial
l	liquid
lat	latent
loss	loss of energy or
max	maximum value
other	other sources
out	output
sen	sensible
sup	wall super heat
TEG	thermoelectric generator
v	vessel
vap	vapour
w	water

energy and fresh water production technologies, new innovative ways to produce clean energy and fresh water are still pressing areas of study. This can be noted with increasing government attention and funding for research and development in these fields. For example the European Commission has agreed on ambitious targets to reduce CO_2 emissions by more than 80% by 2050 in comparison to 1990 levels and to increase renewable energy use and energy efficiency by 20% by 2020 [2]. While the growth rate of desalination plant capacity is currently growing at a rate of 55% per year [11].

A relatively new method to generate electric power is through the uses of Thermoelectric Generators (TEG). TEGs are able to directly convert the temperature difference to an electric voltage (and vice versa) by the thermoelectric effect. At the atomic scale an applied temperature gradient causes charge carriers in the material to diffuse from the hot side to the cold side of the module generating a current [32]. In 1961 the first real application of TEGs was used by the National Aeronautic and Space administration in spacecraft's [10]. Since then thermoelectric technology has been used to harness waste heat for industrial processes, power generation and heating applications [22,31] including boilers [6,30], cookers [5,20], pipelines [28], exhaust emissions [27], and remote communication towers [8] to generate electricity. TEGs are advantageous as they have no moving parts and require little to no maintenance [13,22]. Conversely, their major drawn back is due to their inherently low output efficiency. This paper presents a newly devised application to incorporate TEGs with desalination. Work in the field of combining power generation and desalination over the last 50 years has only included conceptual patents and papers listed below;

- ➢ Combined solar evaporator and turbine generation systems [12].
- ➢ Steam evaporator and turbine generation systems [17].
- ➢ Combined solar energy distillation with photovoltaic cells [25].
- ➢ Solar water pond for fresh water collections and power generation [24].
- ➢ Closed cycle turbine using waste heat to generate potable water and electricity [3].
- ➢ Combined desalination and power generation [7,29].

This paper attempts to design and build a small scale experimental prototype for a combined thermoelectric power generation and desalination to validate its performance against an analytical model. Obtaining feasible solutions for a new innovative system which combines power generation and desalination is a new field with a large scope for further analysis and experimentation. This study provides an innovative attempt to further the progressive development of global sustainable power generation and desalination knowledge maturity.

2. Proposal of combined thermo-electric power generation and desalination

Combined thermo-electric power generation and desalination system is referred to as C-TED in this paper. Fig. 1 shows a schematic and thermal resistance network of a C-TED system. For the system to generate constant DC voltage and fresh water, a constant heat flux from any heat source is supplied to the hot side of the TEG. The heat source used can include, but not limited to, solar energy or industrial waste heat.