Renewable Energy 74 (2015) 528–535

Contents lists available at ScienceDirect

Renewable Energy

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

Energy harvesting from atmospheric variations – Theory and test

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ARTICLE INFO

Article history:
Received 1 June 2014
Accepted 11 August 2014
Available online 16 September 2014

Keywords:
Energy harvesting
Mechatronics
Thermodynamics
Kinetics
Experimental testing

ABSTRACT

The last two decades have offered a dramatic rise in the use of digital technologies such as wireless sensor networks that require small isolated power supplies. Energy harvesting, a method to gather energy from ambient sources including sunlight, vibrations, heat, etc., has provided some success in powering these systems. One of the unexplored areas of energy harvesting is the use of atmospheric temperature variations to obtain usable energy. This paper investigates an innovative device to extract energy from atmospheric variations using ethyl chloride filled mechanical bellows. The apparatus consists of a bellows filled with ethyl chloride working against a spring in a closed and controlled environment. The bellows expand/contract depending upon the ambient temperature and the energy harvested is calculated as a function of the bellows' length. The experiments showed that 6 J of energy may be harvested for a 23 °C change in temperature. The numerical results closely correlated to the experimental data with a deviation of 1%. In regions with high diurnal temperature variation, such an apparatus may yield approximately 250 μW depending on the ambient temperature range.

1. Introduction

The field of electronics and wireless communication has witnessed many innovative trends over the decades. The size and power consumption of wireless devices have consistently reduced and the life span has seen regular growth. An ongoing challenge is to make power sources that match the life span and size of these devices, some of which need to be self-sufficient for their entire operating period as they may be located in remote or inaccessible regions. These constraints make the use of conventional power sources somewhat impractical. Traditionally, batteries, which are non-regenerative power sources, have been used to power such devices but they require frequent replacement and suffer from weight constraints. New generation micro-batteries increase the power density of the devices so that they can store enough energy to last complete life cycles. Other non-regenerative power sources such as micro-turbines and micro-heat engines, have also been used that may store chemical energy in the form of fuel which is slowly consumed over the system's lifetime. Even though the power densities of such devices have considerably improved, the energy available is always small and limited [1].

To overcome the disadvantage of having limited energy available, several regenerative power supplies have been developed. These power supplies “feed off” the environment capturing sufficient energy to operate the attached device. This method of utilizing ambient energy is called “energy scavenging” or “energy harvesting”. Table 1 shows a comparison of different sources of energy and the amount of power that can be harvested using current technology. Cook-Chennault et al. [1], Edgar [2], and Chalasani and Conrad [3] have discussed in detail the state of energy harvesting from different sources and their corresponding energy densities. Most energy harvesters can be classified into three categories based on the form of energy they capture.

Solar energy

Solar energy harvesters use photovoltaic cells to convert energy from ambient light to electric voltage. These are widely used for outdoor applications in places that receive ample sunlight all year round [4].

Vibrations and kinetic energy

These harvesters gather energy from mechanical vibrations and transduce it to an output voltage using a piezoelectric, electromagnetic or electrostatic converter. These harvesters are widely

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http://dx.doi.org/10.1016/j.renene.2014.08.033
0960-1481/

Nomenclature list

a	area of a single thermoelectric couple ($\mathrm{m^2}$)
A	area ($\mathrm{m^2}$), Riedel equation constant
B	Riedel equation constant
C	Riedel equation constant
c	specific heat (J/kg K), Damping constant (Ns/m)
D	diameter (m), Riedel equation constant
E	Riedel equation constant
e	Euler's number
F	force (N)
h	heat transfer coefficient ($\mathrm{W/m^2\ K}$)
I	current (A)
K	thermal conductivity (W/m K)
k	spring constant (N/m)
L	length of thermoelectric couple (m)
m	mass of the middle plate (kg)
N	number of couples per module
n	number of moles, number of terms
P	pressure inside bellows (bar)
PE	potential energy (J)
q	heat flux ($\mathrm{W/m^2}$)
$\dot{q}$	heat transfer rate (W)
R	resistance (Ω), Universal gas constant (J/K mol)
S	combined Seebeck coefficient (V/K)
T	temperature (K)
t	time (s)
V	volume ($\mathrm{m^3}$), voltage (V)
x	displacement of bellows (m)
Γ	proportionality constant (N/m K)
ΔT	temperature difference (°C)
Λ	compression of bellows & spring at 20 °C (m)
λ	length of the bellows (m)
ρ	density ($\mathrm{kg/m^3}$)

Subscripts

ar	air inside the bellows
n	n-type semiconductor
p	p-type semiconductor
rs	restoring force
sb	bellows' spring
se	external spring
t	total
0	free length of the bellows, atmosphere
1	cold side of thermoelectric
2	hot side of thermoelectric
3	outer heat sink
4	inner heat sink
5	air enclosed in the acrylic tube
6	metal frame
7	bellows
8	acrylic tube
9	ethyl chloride

used at locations that have a source of mechanical excitation such as a vibrating machine or vibration-inducing airflow [1].

Thermal energy

Thermal energy harvesters are generally classified in two categories. The first type utilizes Peltier effect to generate a voltage output from a temperature gradient, whereas the second type utilizes thermodynamic expansion or phase change for generating useful energy from a heat source. The energy harvester being discussed in this paper falls under the second category [2].

The focus of this research was to explore thermal energy harvesting through thermodynamic expansion of a substance in a closed system, using temperature changes in the atmosphere. If a substance is hermetically sealed in a bellows or a piston cylinder arrangement, the temperature change could be used to obtain useful work from the expansion. The expansion is most prominent when the substance changes phase. Therefore, ethyl chloride, with its normal boiling point of 287 K was ideal for such an application as the average diurnal temperature variation would be sufficient to vaporize and condense it.

The principle of utilizing atmospheric temperature and pressure variations was first used by Cornelis Drebbel in the early 17th century and later more extensively by Jean-Léon Reutter when he designed the Atmos clock [5,6]. The Atmos clock was the first device to use ethyl chloride as the working substance to power the escapement and discretize the passage of time [7,8]. These clocks are highly efficient devices with a 1 °C change in temperature sufficient for two days of operation [2,9].

The experiment discussed in this paper, illustrated in Fig. 1, uses a hermetically sealed brass bellows to contain ethyl chloride. As the ethyl chloride was heated/cooled by the temperature change, the

Table 1
Approximate power that may be harvested from different sources [1–3,10–12].

Energy source		Characteristics	Harvested power
Solar	Outdoor	Uncontrollable, predictable	$15(\mathrm{mW/cm^2})$
	Indoor	Uncontrollable, predictable	$100(\mu\mathrm{W/cm^2})$
Vibration	Piezoelectric method	Uncontrollable, unpredictable	$500(\mu\mathrm{W/cm^2})$
	Electromagnetic method	Uncontrollable, unpredictable	$4(\mu\mathrm{W/cm^2})$
	Electrostatic method	Uncontrollable, unpredictable	$3.8(\mu\mathrm{W/cm^2})$
Thermoelectric	5 °C gradient	Uncontrollable, predictable	$100(\mu\mathrm{W/cm^2})$
	30 °C gradient	Uncontrollable, predictable	$3.5(\mathrm{mW/cm^2})$
Airflow	Outdoor (Speed $\approx 8(\mathrm{m/s})$)	Uncontrollable, predictable	$3.5(\mathrm{mW/cm^2})$
	Indoor (Speed $\leq 1(\mathrm{m/s})$)	Controllable	$3.5(\mu\mathrm{W/cm^2})$
Ambient radio frequency	Transmitter nearby ($\approx$30 cm)	Controllable	$3.5(\mathrm{mW/cm^2})$
	Transmitter faraway	Uncontrollable, unpredictable	$<1(\mu\mathrm{W/cm^2})$
Electromagnetic wave	Electric field $= 1(\mathrm{V/m})$	Uncontrollable, unpredictable	$0.26(\mu\mathrm{W/cm^2})$
Acoustic	Noise $= 100(\mathrm{dB})$	Uncontrollable, unpredictable	$960(\mathrm{mW/cm^2})$
Atmospheric variation	Temperature change $\Delta T = 23$ °C	Uncontrollable, predictable	$6(\mathrm{J})$, $15(\mu\mathrm{W/cm^2})$[a]

[a] For areas with high diurnal temperature variation.