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Research Paper

Dynamic analysis of a thermoelectric heating system for space heating in a continuous-occupancy office room

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HIGHLIGHTS

- Coupling a thermoelectric heating system (THS) to an office room is presented.
- Real hourly climatic conditions of Fez (Morocco) are considered.
- Office room is simulated using TRNSYS 17.
- A more accurate mathematical model is proposed to simulate the THS.
- Dynamic operation and optimization of the overall system is investigated.

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ABSTRACT

The present study focuses on the theoretical analysis of a thermoelectric heating system (THS) coupled with an office room situated in Fez (Morocco). The office room under study belongs to an autonomous agency and stands for 24 h a day, 7 days a week as a readiness service. A mathematical model of temperature dependent material properties is proposed for the analysis and simulations are carried out to optimize the system performance. The periods of the year examined are January 13–14 for the case of high heating demand, March 11–12 for the case of medium heating and October 26–27 for the case of low heating demand. The annual heating load of the office room is found to be 325.70 kW h/year. The maximum hourly heating demand of the year is predicted in January (390.57 W) and to meet this demand hot air must be supplied at a temperature of 37.8 °C. The analysis shows that the optimal number of thermoelectric modules required to achieve the maximum coefficient of performance of 2.0 is 12 modules. The studied THS can help in reducing up to 64% of energy use in the office room as compared to the conventional electric heater.

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1. Introduction

Presently, the world is facing great challenges concerning energy supply and environment protection. Global energy demand, continuously increasing, is the obvious cause of population growth, increased technological advances and improved lifestyle standards [1–3]. Since the 19th century, global CO_2 emissions have grown rapidly (1.4% annually) to reach over 31.6 gigatonnes in 2012. The main contributor to these emissions is the energy sector [4]. According to recent projections, the global energy use could double by 2050 compared with 2009 and the total GHG emissions may rise even more [5]. The situation gets more complicated since a great part (more than 80%) of energy requirements is ensured by the combustion of fossil fuels [6]. Addressing these challenges will imply significant levels of emissions reductions from all sections of the economy. The building sector is responsible for an important proportion of energy consumption and carbon emissions worldwide [7]. Accordingly, an increasing number of governments have envisaged serious political actions to improve energy efficiency and mitigate dioxide carbon in buildings. These actions mainly focus on encouraging the development of new energy and cost efficient alternatives to meet energy needs in the building sector more sustainably. Heating, Ventilation, and Air-Conditioning (HVAC) systems are the most energy consumers in buildings. In fact, their contribution to the building's total energy consumption varies

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Nomenclature

Symbols

c_p	specific heat capacity (J/kg K)
I	electric current (A)
K	thermal conductance of the thermoelectric module legs (W/K)
l	leg length (m)
$\dot{m}$	mass flow rate (kg/s)
n	number of pairs of thermoelectric legs
N	number of modules
P	electrical power (W)
$\dot{Q}$	heat flux (W)
R	electrical resistance (Ω)
s	leg area (m^2)
T	temperature (K)
ΔT	temperature difference ($T_h - T_c$) (K)

Subscripts

b	balanced
c	cold side of the junction
cir	circulator
e	electrical
fr	fresh
h	hot side of the junction
m	average from inlet to the outlet of the hot and cold
mix	mixed
rej	rejected
rec	recycled
s	supplied

Greek symbols

α	Seebeck coefficient (V/K)
τ	Thomson coefficient (V/K)
λ	thermal conductivity (W/m K)
ρ	electrical resistivity (Ω m)

Abbreviations

COP	coefficient of performance
TEM	thermoelectric module
THS	thermoelectric heating system

between 16% and 50%, depending on climatic conditions and building size [8].

In Morocco, the fastest-growing energy consumer is the commercial sector with an average annual growth of 6.4% during 2004–2011 [9]. Cooling and heating demands in Moroccan modern offices are generally fulfilled by vapor-compression heat pumps in which the refrigerant undergoes phase changes with heat absorption and rejection processes. In the case of small size offices such in administrative buildings, electric heaters are often used.

Recently, many novel configurations of heat pumps have been introduced. Buker and Riffat [10] investigated numerically and experimentally a novel solar thermal roof collector coupled with a commercial heat pump unit. The reported results showed that the overall COP values of the system increase with the ambient air temperature and solar radiation and reach a maximum of 3.2 and an average of 2.98 over the course of testing for the space heating mode. It was also found that the payback period of the proposed system is about 3 years. Zhou et al. [11] proposed a solar driven direct-expansion heat pump system employing the novel PV/micro-channels-evaporator modules. The particularity of this system is the evaporator structure that was made of the parallel-laid micro-channels. The configuration permitted an increased refrigerant evaporation rate, and increased electrical and heat outputs. The average COP of the system reached 4.7. Wu et al. [12] studied the performance of a novel heating system based on a double stage air source absorption heat pump (ASAHP). In very cold regions, it was found that the system presented stable primary energy efficiency and provided a high heating capacity. Energy-saving rate of the coupled ASAHP was assessed to be above 20% in all the cities studied.

Thermoelectric heat pumps use the Peltier effect as a working principle. The Peltier effect announces that a temperature gradient between two junctions of semiconductor materials is observed when an electrical current is applied. In this case, thermoelectric devices involving multiple junctions in series are used to extract heat from one module side to the opposite one. The heat transfer fluid (or refrigerant) normally used in the classical heat pumps is replaced by a doped semiconductor material. Thermoelectric heat pumps can operate in heating and cooling modes. Switching between the two modes is simply ensured by changing the polarity of the applied DC voltage powering thermoelectric modules.

The reverse thermoelectric effect (i.e. electrical power generation when a thermal gradient across the two junctions exists) is called Seebeck effect. This subject was previously treated in several studies [13–17].

Solid state heat pumps using the thermoelectric effect have numerous advantages over their classical thermodynamic counterparts [18,19]:

(i) Possible operation without the use of potentially hazardous refrigerants and therefore do not cause environmental damages and ozone depletion.
(ii) A higher reliability since no moving parts are present.
(iii) The electrical compressor is avoided and instead thermoelectric devices with a longer lifetime, less maintenance, noiseless operation are utilized.

Several works have theoretically and experimentally focused on the development of thermoelectric heat pumps for heating and cooling applications. The literature review below has been carried out to report the main findings.

Kaushik et al. [20] performed an energy and exergy analysis of a thermoelectric heat pump based on four thermodynamic models considering the internal and external irreversibilities. They found that the exergy efficiency of the thermoelectric heat pump increases with larger differences between hot and cold sides temperatures. The feasibility and performance analysis of a novel thermoelectric radiant air-conditioning system and its comparison with the conventional air-conditioning system has been investigated by Shen et al. [21]. The reported results showed that the thermoelectric system can reach comparable results in terms of cooling and heating capacities if the figure-of-merit is close to 1. The figure-of-merit is a parameter that is generally used to gauge the performance of a thermoelectric material. A higher figure-of-merit implies better performance. Siviter et al. [22] proposed the integration of thermoelectric heat pumps in order to enhance the efficiency of a Rankine cycle electrical power plant. The authors indicated that the suggested system had the potential of reducing the burned fuel by 1.5% and increasing the overall cycle efficiency by about 0.15%.

For building purposes, Khire et al. [23] conducted a multi-objective optimization based design strategy of a thermoelectric

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