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Development and performance assessment of a parabolic trough solar collector-based integrated system for an ice-cream factory

Onder Kizilkan [a, *], Ahmet Kabul [a], Ibrahim Dincer [b]

[a] Süleyman Demirel University, Faculty of Technology, Department of Energy Systems Engineering, 32260 Isparta, Turkey
[b] Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, ON, L1H 7K4, Canada

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ABSTRACT

In this paper, a new solar-based renewable energy system integrated with PTSCs (parabolic trough solar collectors) is proposed, designed and analyzed for an ice-cream factory located in Isparta, Turkey. The present system includes a PTSC system to meet the heat energy demand for both heating the ice-cream mixture and cooling it down by means of an absorption refrigeration system. Comprehensive energy and exergy analyses of the system are carried out for determining the performance characteristics of the actual and the proposed processes. Instead of conventional energy resources, establishment of this kind of energy systems provides better operating conditions energetically, exergetically, economically, environmentally and hence sustainably. The results show that the energy consumption of the actual system is 85.81 kWh per day, while the energy consumption of the proposed system is calculated to be 1.235 kWh which leads to an energy saving of 98.56%.

1. Introduction

Both environmental pollution and energy crisis have brought serious problems to humankind to struggle with and provide solutions for better environment and sustainable development [1]. With the fast development of economy and community, the superfluous use of fossil fuels in the past decades has caused a lot of environmental and social problems. Therefore, great efforts have to be made each year to face with energy crisis, which cost a lot but with less return [2]. In this regard, an efficient use of the energy sources and a minimization of harmful emissions are considered very essential in energy production and consuming processes. Energy production and utilization options are controlled by the thermodynamic laws, and also application of exergy destruction and efficiency analysis to processes design can help identify and understand the high efficient energy production systems [3,4].

With recent technological advances in renewable energy, utilization of solar energy has become crucial in many systems and applications due to its environmental benefits through reduced use of fossil fuels, reducing problems associated with pollution and global warming, resulting in cleaner air and cleaner water. Renewable energy, such as solar and wind, do not generate waste or gases emissions. They participate in the fight against the greenhouse effect and releases CO_2 into the atmosphere [5]. Among those, solar energy has received considerable attention, as it is considered as inexhaustible and clear. The applications of solar energy to electricity generation and heat collection/refrigeration have become important due to increased attention that they have received [1,2]. In addition, solar energy presents economic benefits by reducing electricity cost [5].

A large number of industrial processes demand thermal energy in the temperature range of 100–240 °C which cannot be achieved by using flat plate-type collectors, but solar concentrators, dishes, trough, etc. can be employed to fulfill such requirements [6,7]. Solar parabolic trough collectors are efficiently employed for high temperature (300–400 °C) without any serious degradation in the efficiency [8]. Additionally, PTSC (parabolic trough solar collector) technology is considered the most established solar thermal technology for power production [9]. One of the major advantages of parabolic trough collector is the low-pressure drop associated with the working fluid when it passes through a straight absorber/receiver tube. The receiver is the most important component for solar radiation gathering and transferring to a specific application considered [8].

The main goal of this paper, which presents a unique case study, is to convert an existing conventional system to a solar energy-

* Corresponding author. Tel.: +90 246 2111428; fax: +90 246 2371283.
E-mail address: onderkizilkan@sdu.edu.tr (O. Kizilkan).

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Nomenclature

A	area (m^2)
c_p	specific heat (kJ/kgK)
D	diameter (m)
e	specific exergy (kJ/kg)
$\dot{E}x$	exergy (kW)
F_R	heat removal factor
F'	collector efficiency factor
h	specific enthalpy (kJ/kg)
k	thermal conductivity (kW/mK)
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number
$\dot{Q}$	heat energy rate (kW)
Re	Reynolds number
s	specific entropy (kJ/kgK)
S	absorbed solar radiation (kW/m^2)
$\dot{S}_{gen}$	entropy generation rate (kW/K)
T	temperature (°C or K)
U_L	overall heat loss coefficient (kW/m^2K)
U_0	overall heat transfer coefficient (kW/m^2K)
VRCS	vapor compression refrigeration system
VARS	vapor absorption refrigeration system
$\dot{W}$	work rate (kW)
X	concentration ratio of LiBr, %

Greek letters

ε	emittance
η_{ex}	exergy efficiency
σ	Stefan–Boltzmann constant, kW/m^2 K^4

Subscripts

0	reference state
a	unshaded collector aperture
c	cooling
comp	compressor
E	evaporator
g	glass cover
G	generator
h	heating
i	inside
in	inlet
o	outside
out	outlet
r	receiver
u	useful

based one by developing a new system for an actual ice-cream factory located in Isparta, Turkey, and assessing this thermodynamically through energy and exergy analyses and performance evaluations. Currently, the factory meets its energy demand from the local electricity grid for heating and cooling applications. Instead of this, a much cleaner renewable energy option is proposed and designed for the existing system. The proposed system involves a renewable-energy based combined system with PTSC (parabolic trough solar collectors) for meeting the heating demand of the processes. PTSC technology has been used in large power plants since the 1980s and shows a promising future. Therefore, this technology has been selected for this study [9]. In order to evaluate the proposed system performance, thermodynamic analyses of the heating and cooling processes are carried out. With these analyses, it is pointed out to encourage the use of solar energy in industrial applications and suggest modifications to the system design and operation to provide sustainable energy conversion.

2. Solar energy potential of Isparta

Solar energy is accepted as a key alternative energy source for the future. Therefore, solar energy is being seriously considered for satisfying significant part of the energy demand in Turkey, and the world [10]. Solar energy potential of Turkey is remarkably high and advantageous due to its geographical position in the northern hemisphere [11–17]. The annual average temperatures are between 18 and 20 °C in the south coast, falls down to 14–16 °C in the west coast and ranges between 4 and 18 °C in the central parts [18,19]. The city of Isparta is located in the North Mediterranean region of Turkey and its geographical position lies between 37°18′ and 38°30′N latitude and, therefore, most of the locations in Isparta receive plenty amount of solar energy. In terms of the climate conditions, winter is usually between the months of December and February. The summer season spans from May to September and it is usually hot. The average annual temperature is between 10.8 and 11.7 °C [20]. According to the latest measured data provided by the General Directorate of Renewable Energy (sub-organization of Ministry of Energy and Natural Resources of Turkey) Turkey has an average annual total global solar radiation of 1527.46 kWh/m^2-year and annual total sunshine duration of 2741.07 h/year. Based on same data, Isparta's annual total global solar radiation is of 1615.76 kWh/m^2-year and annual total sunshine duration is 2881.65 h/year which are higher than the Turkey's annual values (Fig. 1). Table 1 shows daily global solar radiation, daily sunshine duration and average solar radiation during sunshine hours for Turkey and Isparta, respectively [21].

3. System description

The ice-cream factory investigated in this study is located in Isparta and is considered one the most famous ice-cream manufacturers in Turkey. In the factory, an average 300 tons of ice-cream is produced annually. The main energy consuming sections of the ice-cream production are involving ice-cream mixture heating process and cooling process after mixture preparation. The current system includes a 60 kW electrically heated boiler for steam generation, ice-cream ingredient mixture tank for heating, and cooling and a refrigeration system (as shown in Fig. 2). The mixture heating process is considered as first stage and mixture cooling is considered as the second stage of ice-cream preparation. At first stage, water is heated by the electrical heaters to become saturated vapor at 158 °C. Steam generator is 800 lt in volume and working pressure is 600 kPa. Saturated vapor from steam generator then enters to the jacketed pan type heating tank and heats the ice-cream mixture up to 87 °C. After heating process, the mixture is pumped to cooling tank and from this point, the second stage starts. At the second stage, the ice-cream mixture is cooled down to 20 °C by means of chilled water which is at 8 °C. The chilled water is fed from refrigeration system of the factory.

The refrigeration system is working with R404a refrigerant and has got a refrigeration capacity of 40 kW. Heating the mixture and cooling it down involves the major energy consumption during the preparation period. The general characteristics of the current system are listed in Table 2 in brief.