Applied Energy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Performance analysis of solar cogeneration system with different integration strategies for potable water and domestic hot water production

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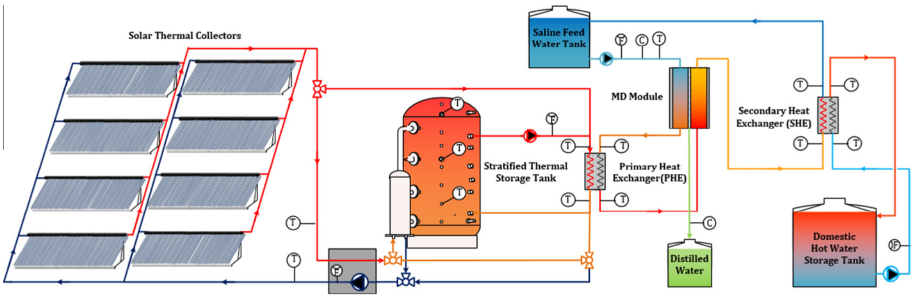
HIGHLIGHTS

- Solar driven cogeneration system integrating membrane distillation technology is developed.
- System utilizes solar thermal energy for the operations without auxiliary heaters.
- Three different system integrations are experimentally investigated in UAE.
- Economical benefits of solar cogeneration system is also reported.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 28 May 2015
Received in revised form 3 February 2016
Accepted 4 February 2016
Available online xxxx

Keywords:
Solar energy
Cogeneration
Evacuated tube collector
Membrane distillation
System integration
Thermal storage

ABSTRACT

A novel solar thermal cogeneration system featuring the provision of potable water with membrane distillation in combination with domestic hot water supply has been developed and experimentally analyzed. The system integrates evacuated tube collectors, thermal storage, membrane distillation unit, and heat exchangers with the overall goals of maximizing the two outputs while minimizing costs for the given design conditions. Experiments were conducted during one month's operation at AURAK's facility in UAE, with average peak global irradiation levels of 650 W/m^2. System performance was determined for three integration strategies, all utilizing brackish water (typical conductivity of 20,000 $\mu s/cm$) as a feedstock: Thermal store integration (TSI), which resembles a conventional indirect solar domestic hot water system; Direct solar integration (DSI) connecting collectors directly to the membrane distillation unit without thermal storage; and Direct solar with thermal store integration (DSTSI), a combination of these two approaches. The DSTSI strategy offered the best performance given its operational flexibility. Here the maximum distillate productivity was 43 L/day for a total gross solar collector area of 96 m^2. In terms of simultaneous hot water production, 277 kWh/day was achieved with this configuration. An economic analysis shows that the DSTSI strategy has a payback period of 3.9 years with net cumulative savings of $325,000 during the 20 year system lifetime.

1. Introduction

According to the World Health Organization (WHO) around 20% of world's population lacks sufficient access to drinking water. Even though over 70% of earth surface is covered with water, only

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http://dx.doi.org/10.1016/j.apenergy.2016.02.033
0306-2619/

Please cite this article in press as: Uday Kumar NT et al. Performance analysis of solar cogeneration system with different integration strategies for potable water and domestic hot water production. Appl Energy (2016), http://dx.doi.org/10.1016/j.apenergy.2016.02.033

Nomenclature

A	area (m^2)
C	cost ($)
c_p	specific heat capacity (J/kg K)
F_r	heat removal factor
h	enthalpy (J/kg)
I_r	irradiance (W/m^2)
L	liters
$\dot{m}$	mass flow rate (kg/s)
M	mass (kg)
Q	heat energy (kJ)
r	conversion factor (–)
T	temperature (K)
tp	time (s)
U	overall heat transfer coefficient (W/m^2 K)
V	volume (m^3)

Subscripts

amb	ambient
avg	average
B	benefits
C	cold
ch	chilled
col	collector
dis	distillate
DHW	domestic hot water
evp	evaporation
f	fuel
FW	fresh water
HST	hot storage tank
hyd	hydraulics
Ins	installation
in	inlet
MD	membrane distillation
H	hot
out	outlet
PHE	plate heat exchanger
sc	solar collector loop
T	thermal
w	water

Greek notations

τ	transmittance
α	absorbance
η	efficiency (%)

1% is available for human needs as most of the available water content is either saline or trapped in ice caps [1]. Lack of fresh water resources with allowable salinity levels for human consumption (<500 mg/L) is one of the biggest issues in the Middle East and North Africa (MENA), and concerns continue to grow [2]. In order to provide required fresh water in the MENA region and elsewhere, various technologies have been developed in the past few decades for desalination of seawater and brackish water [3]. At present, the most widely used desalination technology is reverse osmosis (RO) followed by multi-stage flash (MSF) and multi effect distillation (MED) processes [4]. Although most of these desalination methods are energy intensive and rely on fossil fuels, little progress has been made in developing solar driven technologies. Since the MENA region receives abundant solar energy (average solar irradiation of 600 W/m^2 [5]), developing solar driven desalination processes would be beneficial for future generations providing both energy efficient and environmentally friendly freshwater solutions.

Membrane distillation (MD) is a promising desalination technology in this context. MD is a combination of thermal and membrane separation processes, lending itself for operation with solar thermal energy. In the MD process, vapor molecules are transported through a hydrophobic micro-porous membrane; heat and mass transfer is driven by the vapor pressure difference arising from an imposed thermal gradient applied across the membrane [6]. The process has four different configurations: direct contact membrane distillation (DCMD), sweeping gas membrane distillation (SGMD), vacuum membrane distillation (VMD) and air gap membrane distillation (AGMD). In this research work, AGMD configuration is considered as it has lower parasitic conductive losses due to the presence of an air gap [7].

Solar powered MD has received significant attention in recent years. The simplest system configuration involves direct solar integration. For example, Banat et al. [8] designed and manufactured a compact solar driven, spiral-wound AGMD system with internal heat recovery to operate autonomously in arid and remote locations. The system had a fresh water production capacity of 120 L/day. The AGMD module was directly integrated with solar collectors without external heat exchanger to achieve higher performance by reducing heat losses. However this integration has a disadvantage in that the solar collector should withstand seawater and requires high solar irradiation during operational hours due to absence of thermal storage. A more flexible approach involves the use of thermal energy storage, as exemplified by Chafidz et al. [9], who developed an integrated solar driven multi effect VMD system with integrated 600 L thermal store. This system was designed for operation in remote areas of Saudi Arabia with a production capacity of 100 L/day. The thermal store was shown to provide stability in operation, although drawbacks like heat losses, operational time lag, and reduction in supply temperature were observed.

Beyond direct and thermal store configurations, MD can be combined with one or more heat-driven components to provide services in addition to desalination or water purification. Some relevant studies are listed below:

- Abdelhady et al. [10] dynamically modeled a large scale solar cogeneration system for production of electricity and heat to meet the demands of textile and paper industries in Egypt. In the study, parabolic trough collector area of 200,000 m^2 was installed to produce 6 MW of electricity and 21.5 MW of thermal power with 17.6% and 68% efficiencies respectively. Lifetime levelized cost of electricity (LCOE) was estimated as 1.25 $/kWh, whereas the investment cost was calculated as $38.7 million.
- Twomey et al. [11] evaluated the dynamic performance of small scale solar cogeneration for production of electricity and hot water (CHP) for weather conditions of Brisbane, Australia. In this study, an Organic Rankine Cycle (ORC) with scroll expander was utilized for electricity production, powered by an evacuated tube collector field of 50 m^2 area. During a typical day, 1710 kWh of thermal energy and approximately 2.5 m^3 of hot water were produced with peak power of 0.67 kW.
- Calise et al. [12] analyzed the performance of a novel solar cogeneration system for production of electricity and low temperature heat energy. Evacuated flat plate collectors were utilized to drive the 6 kW_e ORC solar plant. The system has an estimated payback period of 8–10 years for the MENA region.

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