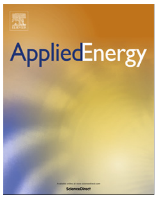
Applied Energy 180 (2016) 276–286

Contents lists available at ScienceDirect

Applied Energy

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



Night sky cooling for concentrating solar power plants

Ana Dyreson [*], Franklin Miller

Department of Mechanical Engineering, Solar Energy Lab, University of Wisconsin – Madison, 1500 Engineering Drive, Madison, WI 53706, United States

HIGHLIGHTS

- Night cooling with cold storage is proposed for power plants in the desert (CSP).
- The system uses uncovered, non-selective, black radiators to cool water at night.
- The cooling surface area is equal to aperture area of parabolic trough field.
- The annual cooling from radiators closely matches the CSP plant requirements.
- Uncertainties in radiator performance are sky temperature, convection coefficient.

ARTICLE INFO

Article history:
Received 9 May 2016
Received in revised form 14 July 2016
Accepted 28 July 2016

Keywords:
Concentrating solar
Radiation
Heat rejection
Air-cooling
Night sky
Water

ABSTRACT

Concentrating solar power (CSP) plants are currently designed with either cooling towers or air-cooled condensers. These two alternatives have a trade off: cooling tower evaporative cooling systems use water, which is a scarce resource in the desert environments where CSP is implemented, but air-cooling results in decreased power plant performance. In this paper, a radiation-enhanced cooling system for thermal power plants is analyzed with a detailed heat transfer model and shown to be feasible for CSP. The proposed system consumes no water and has the potential to out-perform air-cooling. Heat transfer occurs by convection and radiation to the cold night temperatures of desert environments. The radiators are uncovered black panels with tubes of cooling fluid circulated to a cold storage system. The radiators' performance is modeled using a two-dimensional finite difference model and the complete power plant system is modeled on an hourly basis using a standard power plant with thermal energy storage. If the night sky cooling system is the same size as the solar collector field, annual simulation shows that the system can provide over 90% of the required cooling. In addition, performance is improved compared to traditional air-cooling because the parasitic load for circulating water in the radiator system is about 1% of gross energy production while the parasitic load for an air-cooled power plant is about 4%. The night sky cooling system is a potential solution to the water issues that face CSP power plants and other power plants located in desert environments.

1. Introduction

There is a great need for more efficient low-water cooling sources for thermoelectric power plants, especially for concentrating solar power (CSP). This paper provides a comprehensive analysis using a detailed hourly simulation to show that the proposed radiation-enhanced nighttime cooling system is feasible. The system takes advantage of the low nighttime temperatures and clear skies in the regions where CSP is typically deployed. This type of black (non-selective), uncovered system of flat panels has been considered for building cooling applications in the past but has not been studied for the potential to provide power plant cooling (see Section 1.3).

1.1. The energy-water issue

CSP lives at the crossroads of the energy-water nexus; as water usage requires energy (for treatment, pumping, etc.) so energy usage requires water (for fossil fuel mining and refining, thermal power plant cooling, etc.) The water consumption of electricity produced in the US is estimated at 1.9 L (0.5 gallon) per kW h [1]. As water constraints become tighter, especially in the western U.S., the energy-water issue becomes more important. Moreover, the water issues for CSP are magnified because the solar resource is best in deserts where water is especially scarce.

---

* Corresponding author.
E-mail addresses: adyreson@wisc.edu (A. Dyreson), fkmiller@wisc.edu (F. Miller).

http://dx.doi.org/10.1016/j.apenergy.2016.07.118
0306-2619/

Nomenclature

A_p	area of panel, m^2
dx	node width in lateral direction, m
dy	node with in flow direction, m
ϵ	emissivity of top of panel
ϵ_g	emissivity of ground
ϵ_p	emissivity of back of panel
f_{cloud}	cloud cover fraction
h_f	internal forced convection coefficient, W/m^2 K
h_{forced}	forced convection coefficient from top of panel, W/m^2 K
h_g	convection coefficient from back of panel, W/m^2 K
h_w	convection coefficient from top of panel, W/m^2 K
k	conductivity of radiator panel W/m K
k_{air}	conductivity of air, W/m K
L_c	characteristic length of panel, m
η_{gross}	gross efficiency of power plant
$Nu_{free,bottom}$	Nusselt number for free convection from the bottom of the panel
$Nu_{free,top}$	Nusselt number for free convection from the top of the panel
Q_{load}	heat rejection load from power plant, MW h
$Q_{thermal}$	thermal energy input to power plant, MW h
$\dot{q}_{cond,x}$	rate of conduction heat transfer from one node to another in the x-direction, W
$\dot{q}_{cond,y}$	rate of conduction heat transfer from one node to another in the y-direction, W
$\dot{q}_{conv,bot}$	rate of convection heat transfer from the top of the panel to surroundings, W
$\dot{q}_{conv,int}$	rate of internal convection heat transfer from the fluid in tube, W
$\dot{q}_{conv,top}$	rate of convection heat transfer from the top of the panel to surroundings, W
$\dot{q}_{conv,top}$	rate of convection heat transfer from the top of the panel to surroundings, W
$\dot{q}_{conv,tube}$	rate of convection heat transfer from the surface of the tube, W
$\dot{q}_{fluid}$	rate of change of internal energy of the fluid, W
$\dot{q}_{rad,bottom}$	rate of radiation heat transfer from the bottom of the panel to surroundings, W
$\dot{q}_{rad,top}$	rate of radiation heat transfer from the top of the panel to surroundings, W
$\dot{q}_{rad,tube}$	rate of radiation heat transfer from the surface of the tube, W
Ra	Rayleigh number
Re	Reynolds number
σ	Stephan-Boltzmann constant for radiation heat transfer, W/m^2 K^4
T_{db}	dry bulb temperature, K
$T_{dp,c}$	dew point temperature, °C
$T_{i,j}$	node temperature, K
T_s	sky temperature, K
t	hours after midnight, h
u	wind speed, m/s

CSP power plants have typically used evaporative cooling in cooling towers to cool a liquid stream which is circulated through a condenser to provide heat rejection from the power cycle. (Here this is also referred to as wet-cooling though other types of wet-cooling exist.) Most new plants such as Shams I (100 MW parabolic trough, United Arab Emirates) and Ivanpah (377 MW power tower, United States) employ air-cooled condensers to reduce water use. Water consumption was quantified for several CSP plant designs and locations by Turchi et al. [2] and the wet-cooled plants consumed 3.5 L per kW h compared to 0.3 L per kW h for dry-cooled (some water consumption still occurs due to mirror cleaning and other plant operations). Macknick et al. [3] reviews and consolidates data from many sources to estimate the water footprints of different electricity generation sources in the US. The median water consumption for wet-cooled parabolic trough CSP is 3.3 L per kW h and for dry cooled it is 0.3 L per kW h. About 3 L per kW h can then be attributed to wet-cooling. This 3 L per kW h can be confirmed from first principles using the enthalpy of vaporization of water and a power plant thermal efficiency of 0.33. Turchi et al. [2] point out that CSP plants tend to operate at a lower efficiency and with more start-up and shut-down periods than base load fossil fueled steam cycles, making their average efficiency lower and water consumption higher than would be expected for a typical steam cycle.

Though eliminating water usage for cooling, air-cooled condenser systems don't perform as well as wet-cooled systems. First, the parasitic load from the fans on an air-cooled condenser are much higher than the fan and pumping loads for a cooling tower system. Second, the condensing temperature of an air-cooled system is limited by the outdoor dry bulb temperature (for CSP this issue is magnified in the hot desert during the day). Wet-cooled systems, however, can approach the wet bulb temperature instead, allowing for lower condensing temperatures and therefore higher efficiency in the Rankine steam cycle. Thus, when choosing between air-cooled condensers and cooling towers, there is a trade off between performance and water usage. Currently most new plants are built with air-cooled condensers because the water use issue is paramount, but the plants suffer from the performance penalty as well as the increased capital cost of air-cooled condensers.

1.2. CSP power plant cooling

Because the energy-water issue for CSP power plants is critical, some have proposed alternative low-water cooling systems. Wagner and Kutscher [4] analyzed a hybrid cooling system composed of parallel evaporative and air-cooled systems for CSP and such a system is implemented at the Crescent Dunes power tower plant [5]. Muñoz et al. [6] proposed an air-cooled condenser that operates at night with cold storage at a CSP plant, taking advantage of low nighttime ambient temperatures. Goswami [7] analyzed using underground channels to pre-cool air for an air-cooled condenser at a CSP plant. Heller cycle indirect cooling with dry cooling towers has been proposed by USDOE [8]. Work is currently underway by Martin and Pavlish (in USDOE [9]) for a desiccant-based cooling system for CSP plants to reduce water usage compared to wet cooling. Of these proposals, the hybrid system is the most practical and has already been implemented. But it is not a complete solution because there is still some water consumption and since the systems operate in parallel, the condensing temperature of the cycle is limited by the air-cooled condenser.

1.3. Radiative cooling

Radiative cooling has been investigated in detail for building cooling and a few publications consider radiative cooling for power plants. A fundamental difference between these two categories is the temperature of the radiator surface. For comfort cooling a