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Research Paper

Analysis of thermosyphon/heat pipe integration for feasibility of dry cooling for thermoelectric power generation

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HIGHLIGHTS

- Thermal resistance network analysis for two-phase thermosyphon heat exchangers.
- Feasibility of thermosyphon integrated direct condenser and indirect cooling tower.
- Parametric sensitivity study of dry-cooling for thermoelectric power generation.
- System comparison of flow dynamics, heat transfer, cost and resource utilization.

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ABSTRACT

Areas of minimal freshwater often struggle to provide the large amounts of water required for industrial processes, such as for the cooling of thermoelectric power plants. In an effort to decrease the water losses of a typical 500 MW_e thermoelectric plant, two concepts are investigated: (i) replacing the existing steam condenser with a direct-dry condenser, to provide the phase change and heat rejection of previous once-through and re-circulation cooling systems, and (ii) replacing the conventional wet cooling towers with completely dry indirect cooling of the recirculation water stream. For each concept, innovative hybridization of existing systems with closed two-phase thermosyphons allows for the necessary heat transfer of the power cycle. A modular top-down approach to system design allows for manufacturing and installation simplification, and system performance is considered in terms of thermal and cost analysis. The proposed direct steam condenser with heat rejection to ambient air yields an effectiveness, coefficient of performance, and cost per kW_{th} of 0.55, 376, and \$31/kW_{th}, while the dry indirect cooling tower performance specifications are 0.77, 206, and a cost per kW_{th} of \$54/kW_{th}, respectively. These values are near-to or exceed federally proposed standards for dry cooling of thermoelectric plants and outperform existing dry-cooling systems, proving the feasibility of each heat rejection design. Hybrid arrangements of the dry condenser and dry cooling towers are also presented and analyzed, which provide easier retrofit, along with lower costs and greater water savings if combined with existing conventional wet cooling components.

1. Introduction

Thermoelectric power generation represents one of the primary uses of freshwater in the United States. In 2010, water requirements for thermoelectric power accounted for approximately 45.0% (161,000 Mgal/day) of all water consumption in the United States, with 38.0% of the water being freshwater [25]. Limiting water usage in thermoelectric plants allows for vital repurposing of freshwater that is otherwise lost to power production needs.

The current water shortages of Southern California have reinforced the need for an improved water infrastructure. According to Maupin et al. [25], thermoelectric power requirements accounted for a water usage of 6600 Mgal/day (with 65.4 Mgal/day being freshwater) in California alone. The drought effects in 2014 resulted in greater need for groundwater recovery, which required significant pumping costs and a corresponding reduction in viable land for agriculture. Estimated damages totaled a combined \$2.2 billion, with job losses of approximately 17,000 [15]. Furthermore, the limitations and ecological consequences of power plants that use once-through cooling are well recognized [3,9], and such plants are currently being phased out in favor of those using

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Nomenclature

A	area [m^2]
A_c	free flow area of heat exchanger core [m^2]
A_{radial}	radial area of fin [m^2]
A_t	total heat transfer area [m^2]
c_p	specific heat [kJ/kg K]
d	diameter [m]
f	friction factor
g	gravitational acceleration [m/s^2]
h	heat transfer coefficient [W/m^2 K]
h_{lv}	heat of fusion/vaporization [kJ/kg]
k	thermal conductivity [W/m K]
L	length [m]
$\dot{m}$	mass flow rate [kg/s]
N	number (fins, thermosyphons)
Nu	Nusselt number
P	power (fan, pump) [W]
p	pressure [Pa]
Pr	Prandtl number
q	heat transfer rate [W]
q_{TS}	heat transfer of single thermosyphon [W]
q^*_{TS}	corrected heat transfer of single thermosyphon [W]
R	thermal resistance [K/W]
R_f	thermal resistance of fin array [K/W], $R = \frac{1}{A_t \eta_t h}$
Re_d	Reynolds number (diameter) $Re_d = \frac{\rho U d}{\mu}$
R_g	Universal gas constant [J/mol K]
S_D	spacing (diagonal) [m]
S_L	spacing (longitudinal) [m]
S_T	spacing (transverse) [m]
T	temperature [°C]
$T^*_{e,wall}$	corrected thermosyphon evaporator section wall temperature [°C]
t	thickness [m]
U	velocity [m/s]
$\dot{V}$	volumetric flow rate [kg/s]
W	width [m], work [J]
X	correction factor
x	quality

Greek letters

α	thermal accommodation factor
δ	film thickness [m]
ε	effectiveness
η	efficiency
η_{HX}	heat exchanger cooling efficiency
η_t	fin array efficiency
η_f	fin efficiency
μ	dynamic viscosity [N s/m^2]
ρ	density [kg/m^3]

Subscripts

a	air, adiabatic
atm	atmospheric
c	condenser
cell	cell
cold	cold (hot flow outlet, cold flow inlet)
cond	condensate
e	evaporator, electric
ex	external
f	fin
fan	fan
avg	average (temperature)
HX	heat exchanger
h	hydraulic (diameter)
hot	hot (hot flow inlet, cold flow outlet)
i	inlet, inner, component
in	internal
inter	interfacial
L	length
l	liquid
lim	limiting
lv	liquid–vapor
lm	log mean temperature difference
load	total heat rate required
max	maximum
o	outer, outlet
parasitic	parasitic power requirements
pump	pump
s	steam
TS	thermosyphon
t	total
th	thermal
transferred	heat transfer
unit	unit
v	vapor
W	width
wall	wall

Abbreviations

COP	coefficient of performance
DDTSC	direct dry thermosyphon condenser
HPDC	hybrid parallel direct condenser
HSCT	hybrid cooling tower
HPCT	hybrid parallel cooling tower
IDTCT	indirect dry thermosyphon cooling tower
TS	thermosyphon
TSHX	thermosyphon heat exchanger

recirculation-cooling methods. The water needs of California and other areas with a fragile balance between water supply and consumption motivate the need for innovative and enhanced water saving technologies.

Thermoelectric power generation operates on the principles of either the Rankine or Brayton cycle, which use expansion of gases at high temperature and pressure through a turbine for the production of electricity. However, where the Brayton cycle uses combustion gases and a gas turbine, the Rankine cycle uses the combustion of fuel to provide phase change for a working fluid (usually water). The water vapor passes through the steam turbine, and is condensed, which involves heat rejection to an external fluid (again, usually water). There are two primary areas where improved heat transfer methods may promote water savings of a conventional Rankine-thermoelectric power plant using recirculation cooling: (i) condensing the vapor after the steam turbine, and (ii) rejecting excess heat of the recirculated water flow.

Gravity-assisted thermosyphons and heat pipes are attractive devices for the effective cooling of thermoelectric power generation systems, and for integration in heat exchanger designs in general. Thermosyphons and heat pipes are passive devices that allow for exceptional heat transfer rates over large distances with little temperature gradient [5]. Conventional thermosyphons and heat pipes consist of a sealed container with a fixed quantity of fluid, which undergoes vaporization when heated in the evaporator section. The pressure driven vapor exits the evaporator section of the