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Alternative heat rejection methods for power plants

Robert A. Leffler [a,b], Craig R. Bradshaw [a,b], Eckhard A. Groll [a,b], Suresh V. Garimella [b,*]

[a] Herrick Laboratories, School of Mechanical Engineering, Purdue University, 140 S. Martin Jischke Drive West Lafayette, IN 47907-2031, USA
[b] Cooling Technologies Research Center, an NSF IUCRC, Purdue University, 585 Purdue Mall, West Lafayette, IN 47907-2088, USA

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ABSTRACT

Process waste heat in large power generation plants is commonly rejected to lakes or rivers, or through the use of cooling towers. Although these waste heat rejection methods are effective, they may not be feasible in every application due to cost considerations or geographic location. Moreover, it is desirable to put some of the waste heat to good use, both from the standpoint of improved plant efficiency as well as reduced environmental impact. An analysis of alternative methods of power plant waste heat rejection is presented here as applied to a coal-fired power generation facility in the Midwestern United States. Five approaches for rejecting or recovering the waste heat are considered: cooling canals, open-water algae bioreactors, wintertime greenhouse heating, spray ponds, and modified solar updraft towers. Each of the five technologies can be sized for the needs and operating conditions of a given power plant. The quantitative analysis tools developed in this work are validated by benchmarking against published results. Three of the alternative methods generate secondary benefits: the algae bioreactor, greenhouse heating, and the modified solar updraft tower produce biodiesel, extended periods for horticulture, and electric power, respectively. The land area required to reject 1.16 GW of heat (the condenser heat rejection from a 500 MW plant operating at 30% thermal efficiency) using each of the alternative technologies is compared. The sensitivity of the sizing of the different technologies to changes in the environmental and geometric parameters is quantified. Finally, the net water use for each technology is estimated and compared against a typical cooling tower solution for the same 500 MW plant.

1. Introduction

Basic thermodynamic considerations result in the production of a large amount of waste heat in power plants. For each megawatt of electricity generated, approximately two megawatts is discharged in the form of waste heat. The most common methods of handling the waste heat in large power plants involve rejection to lakes and streams, or the use of cooling towers. These methods are well established, offer reliable operation, and provide a working fluid return temperature that is close to that of the environment. However, heat rejection into lakes and streams may result in an undesirable increase in water temperature that could alter the bio-equilibrium and have a significant impact on living organisms in these water bodies. On the other hand, heat rejection using cooling towers can be costly and consumes large amounts of water. Furthermore, both of these heat rejection options do not provide a means for recovering any of the rejected heat for useful purposes. It is important to explore and assess other options for heat rejection that may prove to be viable alternatives. The present work explores five such heat rejection options for large power plants, including a detailed analysis and comparison study. These methods include cooling canal systems, algae bioreactors, wintertime heating of greenhouses, spray ponds, and modified solar updraft towers.

A shallow-water canal system can be used to cool the condenser discharge water with atmospheric air before re-entry to the condenser or discharge to a lake. As in a cooling pond, heat is rejected from the canal through a combination of convection and radiation heat transfer as well as evaporation of canal water. Cooling canals can be used to reject a portion of the required heat, or as the sole source of heat rejection from the power plant. A cooling canal system near Turkey Point, Florida, was evaluated by Frediani [1], who showed that 4.7 GW of heat could be rejected from the system consisting of 32 outflowing canals and seven return canals. Each canal is 8380 m long and 90 m wide, for a total cooling canal area of 17.7×10^6 m^2.

An open-water algae bioreactor pond transfers heat from condenser discharge water to a shallow pond with a layer of algae growing on the surface. The algae bioreactor pond is designed to operate without the aquatic life typical of cooling reservoirs, and may be operated at elevated temperatures. Species of thermophilic algae are grown in the bioreactor pond, with the algal biomass collected at specified intervals and processed into a biofuel or other

* Corresponding author.
E-mail address: sureshg@purdue.edu (S.V. Garimella).

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Nomenclature

A	area (m^2)
A_{surf}	total air side heat transfer surface area of heat exchanger (m^2)
A_{ff}	minimum free flow area of the finned passages perpendicular to the flow direction in heat exchanger (m^2)
c_p	specific heat (kJ kg^{-1} K^{-1})
$\bar{D}$	average diameter (m)
D	diameter (m)
$\dot{E}''$	energy flux (kJ m^{-2} day^{-1})
f	friction factor in the heat exchanger (–)
g	gravitational constant (m s^{-2})
$\mathbf{G_{max}}$	maximum mass velocity (kg m^{-2} s^{-1})
G_{rad}	irradiation (Wm^{-2})
h	convective heat transfer coefficient (W m^{-2} K^{-1})
$\mathbf{h}$	enthalpy (kJ kg^{-1})
h_{fg}	heat of vaporization (kJ kg^{-1})
h_m	mass transfer coefficient (m s^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
L	length (m)
Le	Lewis number (–)
$\dot{m}$	mass flow rate (kg s^{-1})
Nu	Nusselt number (–)
NTU	Number of Transfer Units (–)
P	pressure (kPa)
Pr	Prandtl number (–)
$\dot{Q}$	heat transfer rate (W)
Re	Reynolds number (–)
T	temperature (°C)
t	time (s)
U	velocity (m s^{-1})
v	specific volume (m^3)
V	volume (m^3)
$\dot{V}$	volumetric flow rate (m^3 s^{-1})
$\dot{W}$	power (kW)
Z	height (m)
Greek	
α	absorptivity (–)
β	convective loss coefficient (W m^{-2} K^{-1})
Δ	change (–)
ε	emissivity (–)
ζ	algae production rate (kg m^{-2} day^{-1})
Θ	angle (°)
λ	caloric value of algae (J kg^{-1})
μ	dynamic viscosity (N s m^{-2})
ξ	mass percentage of algae oil (–)
ρ	density (kg m^{-3})
σ	Stefan–Boltzmann constant (W m^{-2} K^{-4})
$\boldsymbol{\sigma}$	ratio of the minimum free flow area of the finned passages perpendicular to the flow direction (A_{ff}) to the frontal flow area of the heat exchanger in heat exchanger (–)
ϕ	relative humidity (–)
Subscripts	
abs	absorbed
amb	ambient
avg	average
conv	convection
crit	critical
D	larger diameter
d	smaller diameter
em	emitted
evap	evaporation
f	final
fg	fluid to gas vaporization
fin	heat exchanger fin
hm	combined heat and mass transfer
hyd	hydraulic
i	initial
∞	free stream property
l	liquid
L	length
photo	photosynthesis
rad	radiation
refl	reflected
s	surface
sat	saturation

fuel source. Recent studies have shown that biofuels derived from algae have the potential to provide a renewable fuel with a lower life-cycle energy cost than petroleum fuels [2,3]. Ryan et al. [4] evaluated the surface heat loss from the Hazelwood cooling pond in Victoria, Australia, and from Lake Hefner in Oklahoma City, Oklahoma. A theoretical model was used to evaluate cooling due to wind-driven forced convection as well as natural convection, and served to demonstrate the use of cooling ponds for heat rejection as well as algal growth.

A greenhouse heated in the wintertime by the waste heat discharged from a power plant could produce agricultural products year-round in northern climates. Condenser discharge water pumped through pipes in the soil transfers heat to the greenhouse through conduction. Chinese et al. [5] designed a greenhouse heating system in Northeastern Italy heated by waste heat from a 2 MW plant fueled by scraps of wood from the chair-manufacturing industry. Manning and Mears [6] evaluated a greenhouse 11,000 m^2 in area in Washingtonville, Pennsylvania, heated by condenser discharge water from the PP and L Montour County Generating Station. In addition, Chou et al. [7] presented a simple analytical heat transfer model of a greenhouse space. These studies show that a greenhouse is a feasible method to exploit waste heat and can be modeled effectively.

A spray pond uses an array of water fountains issuing from the surface of a cooling pond. Heat is rejected from the spray droplets and the pond surface through evaporation of water and convection heat transfer. Previous works have modeled the heat transfer in such situations, and accounted for flow of the surrounding air. Analytical models have been developed by Chen and Trezek [8] and Porter and Chaturvedi [9], in which the thermal performance of the spray was expressed in terms of Number of Transfer Units (NTU). Spray ponds have been successfully used as the sole sources of heat rejection from nuclear power plants in a number of geographic locations around the United States [10].

A classic solar updraft tower consists of a large solar collector at the base of a tower and a gas turbine where the collector and tower meet. The solar updraft tower effectively captures solar energy through the greenhouse effect, and converts it into kinetic energy of atmospheric air through the suction of the tower which relies on a temperature differential along its length. Atmospheric air is drawn due to the suction of the tower into the solar collector at the base of the tower where it is heated before passing through the wind turbine and into the tower. Padki and Sherif [11] developed an analytical model for solar updraft towers. Their analytical model simplified the effects of various geometrical and operating parameters on tower performance. A similar model was recently