Energy Conversion and Management 84 (2014) 244–252

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Thermoelectric topping cycles for power plants to eliminate cooling water consumption

Kazuaki Yazawa [a,*], Menglong Hao [b], Bin Wu [c], Armin K. Silaen [c], Chenn Qian Zhou [c], Timothy S. Fisher [a,b], Ali Shakouri [a]

[a] Birck Nanotechnology Center, Purdue University, West Lafayette, Indiana 47907-2057, United States
[b] School of Mechanical Engineering, Purdue University, United States
[c] Center for Innovation through Visualization and Simulation, Purdue University Calumet, United States

ARTICLE INFO

Article history:
Received 15 January 2014
Accepted 9 April 2014
Available online 4 May 2014

Keywords:
Thermoelectric
Topping cycle
Rankine cycle
Power generator
Boiler
Steam temperature

ABSTRACT

This work shows that thermoelectric (TE) topping generators can add 4–6% to the overall system efficiency for advanced supercritical steam turbines (Rankine cycle) that nominally generate power with 40–42% efficiency. The analysis then considers how this incremental topping energy can replace cooling water flow with air-cooled condensers (ACC) while maintaining current power output and plant efficiency levels with commensurate economic benefit ($/kW h). The simulated TE modules are located inside a coal-fired boiler wall constructed of wet steam tubes. The topping TE generator employs non-toxic and readily available materials with a realistic figure-of-merit range (ZT = 0.5–1.0). Detailed heat transfer and thermal analyses are included for this high-temperature TE application (e.g., 800 K for the cold side reservoir). With the tube surface enhanced by fins, the TE elements are designed to perform optimally through a distributed configuration along the wall-embedded steam tubes that are more than 20 m high. The distribution of the gas temperature in the furnace along the wall height is predicted by thermo-fluid dynamic analysis. This foundational design and analysis study produces overall realistic efficiency predictions in accordance with temperature–entropy analysis for superheated Rankine cycles. Lastly, the approach also allows for the addition of waste heat recovery from the flue gas. The analysis shows that the power output from the topping TE generator is significantly larger, compared to that from the waste heat recovery, due to the larger available temperature difference.

1. Introduction

Improved energy efficiency of power production is still important for most common coal-fired power plants, which provide 50.4% of electricity supply in the U.S. [1] while the penetration of renewable energy sources remains hindered by capital cost, intermittency, and seasonal swings [2,3]. Some large solar concentrated power plants using Rankine cycles operate primarily in desert areas [4]. Energy efficiency is not only important for economic reasons, but it is also critical for conserving natural resources [5]. We investigate the performance and economic impact of adding thermoelectric (TE) topping generators to provide additional power output from current-technology coal-fired boiler furnaces within an advanced supercritical steam turbine (Rankine cycle).

Fig. 1 shows results from a prior analysis for a combined cycle [6], which indicates an optimum steam temperature for maximizing total output power. This additional power output can cover the deficit in power output by higher temperature condensation utilizing an air-cooled condenser [7]. There is another way to enhance the total power output by utilizing a waste heat recovery cycle either by thermoelectric or other energy conversion principle. The waste heat recovery can coexist with the topping cycle without mutual interference. Waste heat recovery TE generators for automotive exhaust applications [8,9] require some exotic materials, about figures-of-merit (ZT) of 1.5–2, to realize performance improvements of practical utility. In contrast, topping TE generators for higher temperature range could consist of non-exotic and readily available materials with thermoelectric with ZT of unity or less, due to the larger available temperature difference. Furthermore, the energy not converted by TE generators is used for the steam turbine. However, the associated high temperatures (e.g., >800 K for the cold side) have, so far, precluded commercialization of TE topping cycles. Here we investigate thermoelectric materials and a thermal design based on the dimensions and conditions of a real boiler existing in a power plant.

---

* Corresponding author.
E-mail address: kyazawa@purdue.edu (K. Yazawa).

http://dx.doi.org/10.1016/j.enconman.2014.04.031
0196-8904/© 2014 Elsevier Ltd. All rights reserved.

Nomenclature

A	area (m^2)
d	thickness of thermoelectric leg (m)
D	diameter (m)
F	fill factor (fractional area coverage of thermoelectric element) (–)
m	load resistance ratio (ohm/ohm)
Q	heat (W)
s	entropy (J/kg K)
T	temperature (K)
W	electric power [W]
x	height along the boiler chamber (m)
Z	figure of merit of thermoelectric (1/K)

Greek symbols

η	efficiency (–)
ψ	thermal resistance (K/W)

Subscripts

F	flue gas cycle
g	steam temperature
in	input
s	source (flame) temperature
ST	steam turbine
T	topping cycle
TE	thermoelectric

Abbreviations

ACC	air cooled condenser
CTE	coefficient of thermal expansion
FGD	flue gas discharge
JPL	Jet Propulsion Laboratories
NASA	National Aeronautics and Space Administration
ODS	oxide dispersion strengthened
RTG	radioactive thermoelectric generator
T-s	temperature-entropy
TE	thermoelectric
TP	topping cycle
WHR	waste heat recovery

Fig. 2 illustrates the system schematic of a current state-of-the-art 520 MW class power plant unit, including the cooling portion enclosed in a dashed line. This subsystem is of particular importance in minimizing water resource usage. To enable a realistic and practical evaluation, we analyze the fluid-dynamic behavior of the gas in the furnace and solve the conjugate heat transport by thermo-fluid dynamic modeling. With surface area enhancement, the TE modules are designed between the wall of the boiler and the water tubes. The TE elements are optimized locally for the simulated gas temperature profile, which is graded along the wall height of over 20 m. These basic designs and analysis enable the prediction of a realistic overall efficiency in accordance with temperature-entropy (T-s) diagram analysis for a complete superheated Rankine cycle.

2. Boiler thermo-fluid analysis

Power plants burn fossil fuel and turn water into steam, which is then used to move turbines and generate electricity. Typically, water is circulated inside tubes around the wall of the furnace (boiler). In a subcritical boiler, the water/steam mixture leaving the tube risers is separated into water and steam. The water returns to an evaporator inlet, and the steam flows into a superheater. The superheater raises the steam temperature to avoid the formation of water droplets when the temperature drops due to expansion in the steam turbine. In a supercritical boiler, water enters the boiler above the critical pressure (22 MPa) and is heated to a temperature above the critical temperature (647 K). The water does not boil as it is heated, but rather decreases in density until it becomes vapor. The thermodynamic efficiency of a power plant using supercritical steam is typically higher (40–42%) than that of a similar subcritical plant (36–38%).

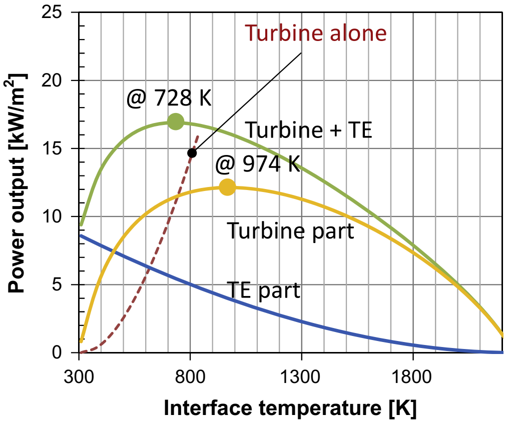

Fig. 1. Power output as a function of the interface temperature between a TE module (with ZT ~ 1) and the steam temperature in Rankine cycle (Ref. [4]). The green curve shows the system total power output while the red dashed curve shows the Rankine cycle (steam turbine) which is limited by the steam temperature.

Power plant modeling can incorporate issues ranging from flow optimization to simulation of different operating conditions using state-of-the-art, high-fidelity thermodynamic models in addition to new water conservation and water treatment technologies [5]. One such example is a 1943 MW coal-fired power plant that includes two subcritical boilers and two supercritical boilers (one of the latter is shown in Fig. 3). The facility uses pulverized coal in ten burners. The combustion products heat the burner walls, and the heat energy is transferred primarily by radiation. When the flue gas leaves the burners, the heat energy in the gas is transferred to the tubes located along the furnace wall by convection. The gas temperature reaches 1700 K, but the steam temperature leaving the boiler is only 640 K.

A numerical study has been performed to calculate the impact of thermoelectric modules on the walls of the boilers and to estimate the total output power [10]. Fig. 4 below shows the temperature distribution near the boiler wall obtained from a computational fluid dynamics model. The 5.1 million cell meshes were generated based on the 3D model for calculating flow regime and temperature distribution. The conjugate problem is solved with popular k-ε turbulent model. Based on the gas temperature distribution, four different locations with different gas temperatures (1680 K, 1500 K, 1300 K, and 1150 K) inside the boiler were used for the thermoelectric power generation analysis. At each location the thermoelectric leg thickness was optimized to obtain the maximum power output. The results show that the thermoelectric module at those four locations can increase the local work output per unit area by 7.1%, 7.0%, 5.6% and 4.4%, respectively. Increased thermal resistance by the TE generator requires the