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Power cycles for waste heat recovery from medium to high temperature flue gas sources – from a view of thermodynamic optimization

Chengyu Li, Huaixin Wang *

Key Laboratory of Efficient Utilization of Low and Medium Grade Energy, MOE, School of Mechanical Engineering, Tianjin University, Tianjin 300072, China

HIGHLIGHTS

- Waste heat recovery from flue gas of a fairly wide temperature range.
- Cycle design to achieve a better thermal matching between fluid and heat source.
- Working fluid selection among organic compounds.
- Evaluation, optimization and comparison of various cycle layouts.

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ABSTRACT

Large quantities of waste heat generated during industrial production offer an opportunity for waste heat recovery (WHR). Several case studies are selected using flue gas as heat source, which are representative of a fairly wide range of source temperature (200–700 °C). The objective function of WHR refers to maximization of net power output. With a view to seeking an optimal combination of cycle configuration, fluid and cycle parameters under different heat source condition, the following researches have been performed. Different types of power cycles (e.g., Rankine cycle, transcritical cycle and combined cycle) as well as different cycle configurations (e.g., saturated or superheating, with or without regenerator) are evaluated. In order to compensate the defects of conventional cycles in some case studies, a novel improved transcritical CO_2 cycle and two combined cycle designs are presented. Working fluid selection among the organics is performed. After the parametric optimization, comparison and analysis are carried out among different cycles. Results indicate that the regenerative organic transcritical cycle produces the maximum power output at source temperatures up to about 500 °C, and different optimum working fluids are obtained under different heat source temperature. The improved transcritical CO_2 cycle shows satisfying performance in source temperature range of 500–600 °C. One combined cycle produces the largest work at source temperature above 600 °C. The traditional steam Rankine cycle shows bad performance at source temperature below 500 °C due to its bad thermal matching with sensible source. At source temperature of 700 °C, steam Rankine cycle shows satisfying performance, and produces a power output close to that of the combined cycle.

1. Introduction

During the industrial processes, such as steel, cement and ceramic industry, as much as 20–50% of the energy consumed is ultimately lost via waste heat contained in streams of hot exhaust gases and liquids, as well as through heat conduction, convection, and radiation from hot equipment surfaces and heated product streams [1]. In point of the temperature level, waste heat sources can be categorized into low-temperature (<230 °C), medium-temperature (230–650 °C), and high-temperature (>650 °C), and detailed distribution and utilization of the heat sources are summarized in [2]. Considering the temperature level and nature of the waste heat, a proper recovery method which includes generating electricity, preheating combustion air, and space heating, can improve energy efficiency by 10% to as much as 50% [1]. Unlike the use of fossil fuel, the waste heat is both free and zero emission, therefore, the waste heat recovery (WHR) raises more attention.

There are two principal ways to recover the waste heat, namely direct heat utilization and power generation. However, the end users are not always onsite or nearby the industrial zone, and it brings difficulty in long distance heating. For medium- and

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* Corresponding author.
E-mail address: wanghx@tju.edu.cn (H. Wang).

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Nomenclature

c_p	specific heat, kJ/(kg K)
h	specific enthalpy, kJ/kg
IHE	internal heat exchanger
$\dot{m}$	mass flow rate, kg/s
p	pressure, MPa
$\dot{Q}$	heat flow rate, kW
T	temperature, °C
$\dot{W}$	power produced or consumed, kW

Subscripts

avil	available
cond	condensing or condenser
crit	critical
eva	evaporating or evaporator
g	flue gas
h	high side
in	inlet
max	maximum
min	minimum
net	net
out	outlet
p	pump
reg	regenerative
s	isentropic
t	turbine
tot	total
w	cooling water
wf	working fluid

Greek symbols

η	component efficiency
η_I	thermal efficiency
Φ	heat recovery ratio

high-temperature heat sources which are high quality, power generation becomes the priority selection from the viewpoint of cascade utilization of energy and convenient transmission.

Numerous power cycles have been proposed and well investigated for utilization of different types of heat sources. In general, with respect to the operation pressure, the power cycle can be divided into three categories, i.e., subcritical Rankine cycle (RC, always below critical pressure), transcritical cycle (TC, heat rejection below critical pressure, heat addition above critical pressure) and supercritical cycle (SC, always above critical pressure). Working fluids include both organic and inorganic compounds. The most frequently used systems for WHR are Rankine cycles using water or organic compounds as fluids. The organic Rankine cycle (ORC) has been widely investigated using geothermal, solar, biomass energy and industrial waste heat [3], and efforts have been made on cycle design, fluid selection, hardware components development and control strategy in the last decades. Various cycle configurations such as basic saturated cycle, superheating cycle, regenerative cycle and reheating cycle have been studied. A regenerative organic Rankine cycle was investigated by Zhang et al. [4] for the heat recovery from engine waste gas. A comparative study of the basic, internal recuperative and external recuperative ORC was carried out in [5]. Application of the internal heat recuperation in the basic cycle results in the output power increase of approximate 5%, addition of the external heat recuperation can rise the output power by approximate 2%. A new regenerative organic Rankine cycle with two-stage evaporator for power generation from geothermal sources was proposed in [6]. The results indicated that the new proposed cycle gave better thermodynamic and economic performance than the basic cycle. Two-stage evaporation strategy of ORC was investigated by Li et al. [7], as the geothermal water source was segmented in two temperature ranges. Parallel two-stage organic Rankine cycle and series two-stage organic Rankine cycle were proposed. It was concluded that the series two-stage ORC presents more excellent system performance. Working fluid selection is usually performed during the optimization procedure of the system configuration and design parameters. Lampe et al. [8] performed a simultaneous optimization of the working fluid and the process based on perturbed chain statistical associating fluid theory (PC-SAFT) equation of state. The hypothetical working fluid and process were first simultaneous optimized. Then the optimal hypothetical working fluid was mapped onto a database containing parameters of real working fluids. R227ea is the optimal real working fluid in the case study, and it matches well with the hypothetical working fluid. A multi-criteria approach for the selection of the cycle configuration, working fluid and operating parameters was presented in [9]. The performance of isobutane and R134a were comparatively assessed, and R134a produces a higher power output. The impact of ten organic working fluids on system internal and external exergy efficiencies were analyzed by Long et al. [10]. It was found that working fluids have little impact on internal exergy efficiency, but they play an important role in determining external exergy efficiency. Yang and Yeh [11] performed a thermodynamic and economic performances optimization for an ORC system among several working fluids. It was found that R1234ze is the optimal working fluid in the thermodynamic optimization and R245fa the optimal in the economic optimization. Organic working fluids are suitable for low temperature source, but they may suffer chemical decomposition under high temperature [12–14]. Therefore, most of the researches were performed using heat sources below about 300 °C. With respect to high temperature application, to avoid the decomposition, an upper cycle temperature limit is usually imposed [15–18], and an intermedium heat transfer loop using thermal oil is frequently introduced between fluid and high temperature sources [19]. Water is the most frequently used working medium for large scale steam RC in power plants under high-temperature operation, and it fails for economic and technical reasons in application of low temperature heat recovery [20]. A large amount of superheat is needed to improve the thermal efficiency and avoid the wet expansion. Due to large steam volumes at turbine exit and high enthalpy drop during expansion, a complex and expensive multi-stage turbine is required [2], moreover, turbine becomes less effective in small scale plant. As a result, water is more suitable for high temperature applications and larger centralized systems. Carbon dioxide, with excellent chemical and physical properties, becomes an attractive working fluid in power cycle. In view of its moderate critical pressure, carbon dioxide is usually operated in a transcritical or supercritical cycle. As a result, the variable heating temperature matches well with the temperature file of sensible heat sources. According to [21], the CO_2 transcritical cycle showed slightly higher power output than the ORC with R123 as working fluid. A comparison study of CO_2, ethane and R125 was performed in [22], using low-temperature industrial gas as heat source. The results indicated that R125 has the best thermal efficiency, ethane the highest specific net power output and CO_2 a lower heat exchange surface than the ethane, but analysis was not sufficient to determine the best fluid as well as the cycle design. With respect