



Performance evaluation of a low-grade power generation system with CO₂ transcritical power cycles

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HIGHLIGHTS

- Experiment in a power generation system with CO₂ transcritical power cycles (T-CO₂).
- Preliminary test results from the T-CO₂ power generation system.
- Model development and validation of the tested T-CO₂ power generation system.
- Some important operating parameters on system performance are identified.
- The research outcomes can be used to instruct the system control and operation.

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ABSTRACT

Globally, there are vast amounts of low-grade heat sources from industrial waste and renewables that can be converted into electricity through advanced thermodynamic power cycles and appropriate working fluids. In terms of the working fluid's environmental impact, temperature match of cycle heat processes and system compactness, CO₂ transcritical power cycles (T-CO₂) were deemed more applicable for low-grade heat to power conversion. However, the system thermal efficiency of a T-CO₂ requires further improvement. Subsequently, a test rig of the small-scale power generation system with T-CO₂ power cycles was developed with essential connected components. These include a plate thermal coil CO₂ supercritical heater, a CO₂ transcritical turbine, a plate recuperator, an air-cooled finned-tube CO₂ condenser and a CO₂ liquid pump. Various preliminary test results from the system measurements are demonstrated in this paper. Meanwhile, the system model has been developed and applied to predict system performance at different operating conditions. The simulation results can therefore instruct further design and optimisation of system and components.

1. Introduction

The extensive consumption of fossil fuels worldwide in power generation has been increasingly contributing towards global warming, air pollution and the imminent energy crisis. One of the challenges of the 21st century is to tackle the risks arising from excessive CO₂ emissions by replacing fossil fuels with recovered waste heat and renewable energy. Waste heat sources can be divided into three main categories according to their temperature ranges: high temperature (> 650 °C), medium temperature (230–650 °C) and low temperature (< 230 °C) [1]. However, statistics have shown that more than 50% of industrial waste heat and renewables are within the low-grade range [2]. These include heat from manufacturing and process industries,

solar energy, geothermal energy, and from internal combustion engine exhausts and coolants used in commercial, institutional or automotive applications. Therefore, low-grade waste heat recovery for power generation is a significant and highly recommended strategy to tackle global warming, utilising advanced thermodynamic power cycles and appropriate working fluids [3,4].

Organic Rankine Cycles (ORC) are a known feasible option for the application of low-grade heat sources in terms of operating parameters, system sizes, thermal and exergy efficiencies. The ORC functions similarly to a Clausius-Rankine steam power plant, but instead uses an organic working fluid such as R245fa, which is able to condense at a lower pressure (compared to evaporator pressure) and evaporate at a higher pressure (compared to condenser pressure). However, one

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Nomenclature			
A	heat transfer area (m^2)	α	heat transfer coefficient ($\text{W}/\text{m}^2 \text{K}$)
C	product of mass flow rate and specific heat (W/K)	β	chevron angle
CP	constant pressure specific heat of air ($\text{J}/\text{kg K}$)	δ	plate thickness (mm)
k	thermal conductivity ($\text{W}/\text{m K}$)	ρ	density (kg/m^3)
L	vertical length of heat exchanger (m)	μ	kinematic viscosity (mm^2/s)
$\dot{m}$	mass flow rate (kg/s)	Subscripts	
N	number of plate	<i>air</i>	air
P	pressure (pa)	<i>aircd</i>	condenser air inlet
Q_T	heat capacity (W)	<i>ci</i>	cold fluid inlet
T, t	temperature ($^\circ\text{C}$)	<i>co</i>	cold fluid outlet
ΔT	temperature difference (K)	<i>exp</i>	expander
U	heat transfer coefficient ($\text{W}/\text{m}^2 \text{K}$)	<i>expin</i>	expander inlet
UA	overall heat conductance (W/K)	<i>hi</i>	hot fluid inlet
W	power generation (W)	<i>ho</i>	hot fluid outlet
Greek symbols		<i>max</i>	maximum
ε	heat transfer effectiveness (–)	<i>min</i>	minimum
ϕ	length ratio	<i>oil</i>	thermal oil
		<i>p</i>	plate
		<i>sc</i>	subcooling

important limitation of the ORC is its constant evaporation temperature, which increases irreversibly during the heat addition process when using sensible heat sources such as waste heat [5]. In addition, a hydrofluorocarbon (HFC) working fluid is conventionally applied in an ORC, which has zero Ozone Depletion Potential (ODP) but a relatively high Global Warming Potential (GWP). This will affect the future application of ORCs in low-grade waste heat recovery.

On the other hand, as a natural working fluid, CO_2 has been widely applied in refrigeration [6] and heat pump [7] systems owing to its zero ODP, negligible GWP and superb thermophysical properties, despite its high critical pressure and low critical temperature. The high operating pressures of a CO_2 energy system require special designs for system components and controls, while the low critical temperature will turn a CO_2 low-grade power generation system into a transcritical Rankine cycle (T-CO_2) or even a supercritical CO_2 Brayton cycle. Of these CO_2 power cycles, the T-CO_2 is most effective at harvesting low-grade heat sources when a low temperature heat sink is accessible [8,9]. The supercritical heat-addition process of a T-CO_2 can produce high-efficiency temperature matching between the sensible heat source and the working fluid, leading to no pinch limitations. In addition, the superb thermophysical properties of CO_2 can create a more compact T-CO_2 system than those of ORCs. These include a higher density, latent heat, specific heat, thermal conductivity, volumetric cooling capacity, and lower viscosity. Therefore, the T-CO_2 has considerable potential for low-grade power generation. Nevertheless, the performance of such a system requires thorough investigation in order to understand operational mechanisms for optimising system efficiency.

Due to the high critical pressures of CO_2 , the pressure of heating processes in CO_2 transcritical power cycles would also be high (typically above 90 bar), such that conventional heat exchangers, gas turbines or expanders and power cycles cannot be directly applied. Consequently, up to now, investigations on low temperature heat source energy conversion systems with CO_2 transcritical power cycles have been limited to small-scale laboratory work and theoretical analyses. A solar-powered test rig with a CO_2 transcritical power cycle was set up to examine system performance at designated operating states [10]. As this test rig used a throttling valve to simulate expansion device, power generation could not be measured directly. A highly promising solution to the CO_2 turbine market problem is to use a CO_2 scroll expander for the test rig or practical installation. The expander works as the corresponding compressor in reverse, which is a positive displacement machine. CO_2 scroll expanders and compressors have already

been implemented in refrigeration and air conditioning [11]; however, its application in transcritical power cycles needs to be explored as it plays an important role in the power system. A steady-state thermodynamic model for the above solar- CO_2 power system showed that the power and heat outputs and efficiencies varied remarkably in different seasons of the year, due to the periodical change of solar radiation [12]. Therefore, a transient mathematical model would be more suitable in simulating the real performance of the solar system. In the application of waste heat with a maximum heat source temperature of 150°C , the performance of a CO_2 transcritical power cycle with optimised supercritical pressure was compared thermodynamically to a R123 ORC subcritical cycle [13]. The total system efficiency of the CO_2 transcritical cycle was proven to be higher than that of a R123 subcritical cycle due to better matching of the CO_2 flow temperature variation to its heat source temperature glide. In addition, the CO_2 power system is more compact and the cycle also shows no pinch limitation in the heat exchanger. This result is encouraging since the R123 subcritical cycle was formerly recognised to harbour a higher system performance [14]. Significantly, this research demonstrates the importance of the design and selection of the high side supercritical CO_2 gas heater and optimal supercritical pressure control in order to determine overall system efficiency [15]. However, comprehensive experimental and theoretical analyses for a low-grade T-CO_2 system are necessary to gain full understanding of system operations and achieve optimal designs and controls. So far, to the authors' acknowledges, very few experimental investigations have been carried comprehensively on low-grade power generation with T-CO_2 systems in which actual power generations were measured. On the other hand, some theoretical analyses including energy and exergy were conducted on the T-CO_2 systems but mostly were limited to thermodynamics bases [16–19]. Nevertheless, to fully understand and model the system performance and controls, the detailed system component models need to be involved. These issues will be addressed in the paper in terms of comprehensive experimental investigation and detailed model development.

In this paper, a test rig of a low temperature power generation system with the T-CO_2 power cycle is described and measurements demonstrated for the effect of CO_2 mass flow rates and heat source flow rates on system performance. In the meantime, a mathematic model of the tested system was developed and validated with measurements from current and previous research projects. The model predicts the effect of heat sink and source parameters and CO_2 pressures at the turbine inlet on system performance, which aids in the understanding of

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