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Experimental comparison of dynamic responses of CO_2 transcritical power cycle systems used for engine waste heat recovery

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A B S T R A C T

CO_2 transcritical power cycle (CTPC) is attractive to engine waste heat recovery (WHR) due to its advantages of miniaturization and unique thermophysical properties of its working fluid. Since there is no, if any, literature considering dynamic characteristics of CTPC systems, in current work, a series of dynamic tests has been conducted on a kW-scale CTPC test bench for engine WHR. Effects of mass flow rate and pressure ratio on dynamic responses are mainly focused and compared among four CTPC systems, i.e. a basic CTPC (B-CTPC), a CTPC with a recuperator (R-CTPC), a CTPC with a preheater (P-CTPC) and a CTPC with both a recuperator and a preheater (PR-CTPC). Dynamic characteristics are quantified by time constant and settling time. Results show that the PR-CTPC system has the fastest dynamic responses among these four layouts and the P-CTPC system responds more quickly than the R-CTPC system thanks to the gas–liquid heat exchange. Moreover, for the same layout, larger initial CO_2 mass flow rate brings faster responses while initial system pressure ratio has little impacts on system dynamic responses. Also, dynamic characteristics of a basic CTPC system and a basic organic Rankine cycle (ORC) system are compared. The ORC system adopts R123 as its working fluid. Results indicate the basic CTPC system responds almost four times faster than the basic R123-ORC system.

1. Introduction

Energy crisis and environmental pollution have continuously stimulated the engine industry to improve engine efficiency and reduce engine emission. Waste heat recovery (WHR) technology has been regarded as a potential and viable method to boost engine towards a higher efficiency since almost two thirds of fuel energy are dissipated as waste heat. Also, WHR technology has been concluded as a longer-term opportunity for diesel engine to achieve its 55% brake thermal efficiency according to the results of the U.S. Super Truck I program sponsored by DOE [1]. Organic Rankine cycle (ORC) systems have appeared as particularly promising solutions in the context of WHR from engines for additional power generation. The reasons lie in their relatively high conversion efficiencies and low costs, as well as reduced impact on engine exhaust backpressure compared with other technologies such as turbo-compounding and thermoelectric generation.

Recently, CO_2 transcritical power cycle (CTPC) has been considered as a future pathway for engine WHR [2], which is based on ORC systems and only replaces organic working fluids with CO_2. This mainly owes to two aspects. From the aspect of working fluids, the employment of CO_2 brings many advantages. On one hand, given the natural characteristic, as one of the air composition, CO_2 is a safe and environment-friendly working fluid. It makes CO_2 more applicable than other organic working fluids (R123, R245fa, etc.) [3,4]. On the other hand, supercritical CO_2 (sCO_2) permits the use of compact heat exchangers and turbomachinery in CTPC systems, which means CTPC systems are likely to achieve minimization for engine WHR. Echogen Power Systems Company [5] demonstrated a 10 MW CO_2 turbine, of which the turbine impeller was only 0.24-m. Also, highly compact microchannel recuperator was proposed for sCO_2. Shu et al. [6] concluded the total heat transfer area and turbine size of CTPC were less than those of R123 ORC when compared under a comparable boundary conditions. From the aspect of system architecture, the operation of CTPC systems is safer than traditional subcritical cycles since there is no concern on droplet formation at the inlet of turbine. This feature makes CTPC systems fairly flexible when engine operating conditions vary transiently or even dramatically.

In recent years, research into ORC-WHR technology for engines has accelerated and resulted in significant progress. All these research methods on working-fluid selection or design, system architecture and component design, as well as benefit-cost evaluation systems [7–12] have been applied to CTPC system studies [6,13–15]. Generally, they considered the add-on system under steady state conditions. However, depending on the driving conditions, the heat source is variable and

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Nomenclature

P	pressure [kPa]
Pr_0	initial pressure ratio
t_s	settling time [s]
T	temperature [°C]

Greek letters

ω_{p0}	initial pump speed [rpm]
τ	time constant [s]

Subscripts

c	cooling process
crit	critical point
g	exhaust gas
gh	gas heater
hw	hot water
in	inlet
out	outlet
p	pump
preh	preheater
v	expansion valve
water	cooling water

Abbreviations

CTPC	CO_2 transcritical power cycle
B-CTPC	basic CTPC
P-CTPC	CTPC with preheater
R-CTPC	CTPC with recuperator
PR-CTPC	CTPC with both preheater and recuperator
HE	heat exchanger
ORC	organic Rankine cycle
sCO_2	supercritical CO_2
WF	working fluid
WHR	waste heat recovery

highly transient. The add-on system is often forced to operate under these variations once it is integrated to the original engine. The performance is quite different from that under the design condition. Based on performance prediction, Shu et al. [16] found that the auxiliary net power produced by the CTPC system under engine mapping conditions varied greatly and there was even no extra power output when engine operated under low-speed and low-load conditions. Xie and Yang [17] demonstrated that the add-on system during driving cycle was inefficient whose efficiency (3.63%) was less than half of that at the rated condition (7.77%). Li et al. [18] analyzed system sensitivity of CTPC system with respect to the external inputs and concluded that system was more sensitive when system conditions became severe. Therefore, the transient behavior of heat sources in transport applications poses a great challenge for system integration [19]. When engine operating condition changes, it is necessary for CTPC systems to take measures to adapt to the variations. For CTPC systems, the actuators would be the pump, the expander, the expander bypass valve and the exhaust bypass valve if they were all equipped. In normal power producing mode, the main actuators are the pump and the expander. At least, mass flow rate, i.e. the pump rotational speed, needs to be adjusted for optimum performance of CTPC systems according to the Ref. [16] or for superheat control of ORC systems [20–22]. Feru et al. [23] manipulated the expander speed to maximize system pressure and output power.

Hence, the control of pump and expander is essential to enable viability and attain satisfactory performance over a broad range of operating conditions. Many investigations have come up with similar conclusions that the available two degrees of freedom that can be manipulated are the pump and expander speed in WHR systems [24,25]. In order to design the control strategy and controllers, the dynamic responses and characteristics of CTPC systems should be examined at first. Characteristics of dynamic responses, i.e. time constant or settling time, will be helpful for dynamic system simulation and then the controller design. This is especially true when there are few available actuators and sensors in the automotive industry. Espinosa et al. [26] dynamically simulated the impact of the pump speed and expander bypass opening on the evaporating pressure, turbine inlet temperature and superheating in an ORC by using GT-Power software. Step changes were chosen as inputs and only variation processes were given in results. Lee et al. [27] focused on the effect of mass flow rate of the cooling water on the system performance and only qualitative results were reported. Li et al. [28] presented several testing results of CTPC systems and mainly demonstrated a systematic process for experimental results analysis. Other research on dynamic responses is mainly related to working fluid scanning [29] and heat exchangers [30–32]. The dynamic responses of the whole systems have not been considered yet. The preliminary exploration work is insufficient to provide a comprehensive understanding of the dynamic characteristics of CTPC systems. Towards future application and commercialization, further theoretical and experimental research on CTPC dynamic performance is required for control algorithm and strategies design.

As for CTPC systems, the basic CTPC (B-CTPC) system consists of four main parts, namely: a gas heater, a turbine, a condenser and a pump. CO_2 is first pumped to a supercritical pressure and then heated in the gas heater. The heated sCO_2 expands in the turbine and then is condensed in the condenser. Generally, the vapor discharged from the turbine outlet is still of high temperature due to the small pressure ratio in the turbine. Therefore, an internal heat exchanger or a recuperator is usually introduced to the basic system to optimize the system performance, which forms an R-CTPC. The simulation of Chen et al. [33] indicated that under the same boundary conditions, system thermal efficiency of R-CTPC could achieve 0.19 and 0.31 if effectiveness of the recuperator was assumed to be 0.6 and 0.9 respectively, while system thermal efficiency of B-CTPC was 0.08. Shu et al. [13] compared four CTPC systems and results showed that R-CTPC was superior to B-CTPC in terms of thermal efficiency, exergy efficiency and net power output. Theoretical analysis by Li et al. [34] showed that a recuperator was preferable and desirable in CTPC systems because R-CTPC not only improved thermal efficiency and exergy efficiency, but also could operate at a higher expander inlet pressure, higher heat source temperature and lower heat sink temperature than B-CTPC. Therefore, a recuperator is essential for not only improving system performance significantly but also reducing heat load in the condenser.

In addition to a recuperator, a preheater is also significant for CTPC to better recover engine waste heat. For commercial diesel engines, apart from high-temperature heat sources such as exhaust gas (200–600 °C) and EGR (200–750 °C), low-temperature heat sources are also significant to be recovered, which mainly include coolant (80–100 °C) and charge air cooling (50–70 °C) [35]. These low-temperature heat sources occupy around one third of the fuel energy and are related to the engine radiators or fans. If the energy could be recovered, it can reduce the accessory power of engines. Hountalas et al. [36] proved that WHR from engine low-temperature heat sources could improve efficiency by 50% and also be beneficial for overall system packaging. CO_2 enables CTPC to possess an excellent ability in low-temperature heat sources recovery since the specific heat capacity of working fluids vary with temperature and that of CO_2 peaks at the