Energy Conversion and Management 161 (2018) 225–233

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Performance improvement of a preheating supercritical CO_2 (S-CO_2) cycle based system for engine waste heat recovery

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ARTICLE INFO

Keywords:
Preheating S-CO_2 cycle
Engine waste heat recovery
Regeneration branch
Performance improvement

ABSTRACT

Due to the compact structure in addition to the system safety level and environmental friendly characteristics, supercritical CO_2 (S-CO_2) cycle has emerged as a promising method to be used in engine waste heat recovery. This paper explores the potential of using a preheating S-CO_2 cycle based system to recover the waste heat of a diesel engine. An original preheating system is presented, in which the high temperature engine exhaust gas is firstly utilized in the evaporator and then it is further cooled through preheating process together with the low temperature jacket cooling water. Though the entire heat load from these two heat sources could be entirely recovered, the high preheating temperature suppresses the heat transfer in the regenerator. An improved preheating S-CO_2 cycle based system with a regeneration branch is then presented. S-CO_2 flow from the compressor is divided into two parts, one of which is still preheated by the jacket cooling water and the cooled engine exhaust gas in series while the other is heated in a low temperature regenerator. The two flows converge and then continues to be heated in the high temperature regenerator and in the evaporator. The simulation results reveal that the improved system could achieve a deeper utilization of the regeneration heat load hence improve the system performance. The maximum net power output of the improved system reaches 68.4 kW, which is 7.4% higher than that of the original system, 63.7 kW. Adopting the improved preheating S-CO_2 cycle based system for waste heat recovery, the engine power output (996 kW) can be increased by 6.9%.

1. Introduction

Diesel engine is a primary choice for power source that is widely used in transportation vehicles, industrial and agricultural machines and small power units. With the development of human society, energy consumption by diesel engines is increasing rapidly. However, more than half of the total fuel combustion energy is wasted via exhaust gas and cooling system in a typical engine [1,2]. In recent years, interests in engine waste heat recovery have been recreated to alleviate the energy shortage and emission issues.

Although Organic Rankine Cycle (ORC) has been proven to be an effective method for engine waste heat recovery [3–7], the high temperature engine exhaust gas might cause the decomposition of organic working fluids [8–10]. Hydrocarbons with high critical temperature are then selected as candidates [11–14], but the flammable and explosive properties would also restrict the application due to safety considerations.

Recently supercritical CO_2 (S-CO_2) cycle has emerged as an alternative for high efficiency power generation. It is recognized that nuclear [15,16], fossil fuel [17,18], waste heat [19,20] and renewable energy such as solar thermal [21–23], geothermal [24,25] and fuel cell [26,27] are the potential application areas of S-CO_2 cycle. Choosing CO_2 as the working fluid in power cycles, which is readily available, non-flammable, environmental friendly and has no temperature limitation of decomposition, the aforementioned safety limits in ORC systems can be avoided. The technical feasibility of using CO_2-based system for engine waste heat recovery has been verified and guaranteed as it has already been used in vehicle air conditioning devices [28,29]. Moreover, heat transfer between the heat source and the supercritical CO_2 working fluid can be conducted directly. A better temperature match can be attained to reduce exergy loss in the heat exchangers and achieve higher cycle performance. Due to high density of the S-CO_2 working fluid, system would be compact with considerably small turbomachineries and heat exchangers, which would occupy only little space and could satisfy the miniaturization demand of engine waste heat recovery. Therefore, S-CO_2 cycle based system offers an attractive option if an efficient layout can be designed and established. Researches of using S-CO_2 cycle for engine waste heat recovery have drawn

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https://doi.org/10.1016/j.enconman.2018.02.009
Received 13 October 2017; Received in revised form 25 January 2018; Accepted 3 February 2018
Available online 08 February 2018
0196-8904/

Nomenclature

W	power, kW
$\dot{m}$	mass flow rate, kg/s
h	specific enthalpy, kJ/kg
Q	heat load, kW
T	temperature, °C
P	pressure, kPa
c_p	specific heat capacity, kJ/kg·K
ξ	heat exchange efficiency

Subscripts

$S{-}CO_2$	supercritical carbon dioxide
comp	compressor
preh	preheater
rege	regenerator
evap	evaporator
T	turbine
pre-c	pre-cooler
jw	jacket cooling water
gas	engine exhaust gas
in	inlet
out	outlet
net	net power output

Acronyms

WHR	waste heat recovery
S-CO_2	supercritical carbon dioxide
ORC	Organic Rankine Cycle
EPS	Echogen Power Systems
HT	high temperature
LT	low temperature
TIT	turbine inlet temperature

increasing attention in recent years. Experimental studies of a 250 kW supercritical CO_2 cycle system were conducted by Echogen Power Systems (EPS) Company to explore the possibility of using such kind of system to recover the waste heat from engine exhaust gas [30]. Anderson et al. [31] proposed an optimized S-CO_2 cycle based system for a two-stroke engine waste heat recovery, in which a novel expansion device was designed and included. Di Bella [32] carried out thermodynamic analysis of a supercritical CO_2 system for an MT-30 gas turbine engine waste heat recovery; the optimal operating parameters were obtained for the recovery system to give out the maximum power output. Hou et al. [33] presented a combined cycle system for marine engine waste heat recovery, which consisted of a supercritical CO_2 recompression cycle and a regenerative cycle; the results indicated that the S-CO_2 cycle based system could achieve a deep utilization of waste heat in addition to the merits of high compactness and low cost.

Among the previous researches, few focus on the layout innovation and thermal performance improvement of the S-CO_2 cycle recovery system. Based on some previous works of using ORC technology for engine waste heat recovery [12,34], the preheating system scheme with S-CO_2 as working fluid is selected. This paper studies and optimizes the preheating S-CO_2 cycle based system utilizing both heat loads from the low temperature jacket cooling water and the high temperature engine exhaust gas. In the original system, the jacket cooling water is used to preheat the S-CO_2 working fluid while the high temperature engine exhaust gas is firstly utilized in the evaporator. Since the outlet temperature of the cooled engine exhaust gas from the evaporator is still high and a considerable fraction of energy is untapped, it is further cooled in a high temperature (HT) preheater after the low temperature (LT) preheater with jacket cooling water. Entire utilization of the two waste heat sources could be achieved. However, the high preheating temperature as well as the high regenerator inlet temperature would suppress the heat utilization degree in the regenerator. An improved preheating S-CO_2 cycle based system with a regeneration branch is then presented. S-CO_2 flow from the compressor is divided into two parts, one of which is still preheated by the jacket cooling water and the cooled engine exhaust gas in series while the other is directly heated in a LT regenerator up to the same preheating temperature. The two flows then converge and continues to be heated in the HT regenerator and in the evaporator. Comparative analysis is conducted on the two systems and performance enhancement of the improved preheating S-CO_2 cycle based system is evaluated in detail.

2. Description of the diesel engine and the S-CO_2 cycle based system

2.1. The selected diesel engine

Based on the previous researches on ORC for engine waste heat recovery, the same inline six-cylinder turbocharged diesel engine [12,34,35,7] is selected in this paper, which is manufactured by Hudong Heavy Machinery, Co., Ltd. Waste heat recovery of both the jacket cooling water and the engine exhaust gas is still focused and studied. Table 1 lists the engine operating parameters under the design point. As for the low temperature jacket cooling water, the heat load reaches 199.9 kW, which is intended to be fully utilized in the LT preheater. As for the engine exhaust gas, the composition is listed in Table 2. The specific heat capacity is measured as 1.1 kJ/kg·K according to REFPROP 9.1 [36]. Temperature of the cooled engine exhaust gas from the heat recovery unit should be set above 100 °C to avoid acid corrosion [37]. Heat load would then be nearly 436.3 kW if the engine exhaust gas is cooled down to this acid dew point temperature. Total heat load of these two waste heat sources from the diesel engine reaches 636.2 kW. If this large amount of the waste heat is efficiently recovered, engine power output could be significantly increased without adding fuel consumption.

2.2. Preheating S-CO_2 cycle based system for engine waste heat recovery

The original preheating S-CO_2 cycle based system and the improved system are presented in this paper, schematic diagrams of which are shown in Fig. 1(a) and (b) respectively. In the original system, the S-CO_2 working fluid is firstly pressurized by the compressor and then preheated by the jacked cooling water in the LT preheater. Then in the HT preheater, the S-CO_2 fluid continues to be preheated by the cooled engine exhaust gas from the evaporator, within which the engine

Table 1
Main parameters of the diesel engine under the design point [12,34,35,7].

Property	Unit	Value
Power output	kW	996
Rotation speed	r/min	1500
Torque	N·m	6340
Initial temperature of the engine exhaust gas	°C	300
Mass flow rate of the engine exhaust gas	kg/h	7139
Inlet temperature of the jacket cooling water	°C	65
Outlet temperature of the jacket cooling water	°C	90
Mass flow rate of the jacket cooling water	kg/h	6876