Performance Analysis of a Dual-Cycle Waste Heat Recovery System Postprint

Authors: Song Jian, Xiaodong Ren, Gu Chunwei

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Abstract

This paper proposes a dual-cycle waste heat recovery system for a certain type of diesel engine, wherein the high-temperature cycle utilizes water as the working fluid to recover waste heat from the high-temperature exhaust gas of the diesel engine, while the low-temperature cycle employs an organic working fluid to sequentially recover waste heat from the low-temperature main engine cooling water and the heat load of the high-temperature cycle condenser; the high-temperature and low-temperature cycles are integrated via a shared heat exchanger. Through thermodynamic analysis, the influence of the high-temperature cycle condenser' s heat load on the low-temperature cycle is investigated. The results demonstrate that under different conditions, the pinch point temperature difference of the shared heat exchanger occurs at various locations, thereby resulting in different evaporation temperatures and other thermodynamic parameters for the low-temperature cycle. The dual-cycle system designed in this study achieves a maximum net power output of 115.2 kW, capable of enhancing the diesel engine' s power by 11.6%.

Full Text

Preamble

Performance Analysis of a Dual-Loop Waste Heat Recovery System

Song Jian, Ren Xiaodong, Gu Chunwei

(Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Thermal Engineering, Tsinghua University, Beijing 100084, China)

Abstract: This paper proposes a dual-loop waste heat recovery system for a diesel engine. The high-temperature (HT) loop uses water as the working fluid to recover waste heat from high-temperature exhaust gases, while the low-temperature (LT) loop uses an organic working fluid to sequentially recover waste heat from low-temperature engine cooling water and the heat load from the HT loop condenser. The two loops are integrated through a shared heat exchanger. Through thermodynamic analysis, the influence of the HT loop condenser heat load on the LT loop is investigated. The results demonstrate that under different conditions, the pinch point temperature difference of the shared heat exchanger occurs at different locations, leading to different evaporation temperatures and other thermodynamic parameters in the LT loop. The designed dual-loop system achieves a maximum net power output of 115.2 kW, representing an 11.6% improvement in engine power.

Keywords: waste heat recovery; dual-loop system; Organic Rankine Cycle; pinch point

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0 Introduction

Research on diesel engine waste heat recovery technology began in the 1980s, accelerating after the 1973 global oil crisis when rising fuel prices dramatically increased transportation costs. Numerous research institutes and major manufacturers worldwide initiated investigations into diesel engine waste heat recovery systems [1]. Scholars have proposed and studied various system configurations, including simple cycles [2][3], regenerative cycles [3][4], preheating cycles [5][6], and dual-loop systems. The dual-loop system is a recently developed concept in waste heat recovery that can simultaneously recover waste heat at different temperature levels. Such systems typically comprise a high-temperature loop and a low-temperature loop coupled through a shared heat exchanger, where the heat load from the HT loop condenser is utilized in the LT loop.

Shu et al. [7] from Tianjin University investigated the effect of evaporation temperature on dual-loop waste heat recovery systems, using water as the HT loop working fluid to recover high-temperature exhaust heat and various organic working fluids in the LT loop to recover cooling water heat load, HT loop condenser heat load, and low-temperature exhaust heat. Zhang et al. [8] from Beijing University of Technology employed R245fa in both loops to examine dual-loop system performance under full engine operating conditions. Choi [9] utilized water flashing in the HT loop and R1234yf in the LT loop to study the influence of HT loop condensation temperature on system performance. Panesar et al. [10] designed a dual-loop waste heat recovery system for truck engines, demonstrating power improvements of 5.8%-7.4%. In dual-loop systems, the LT loop typically recovers both low-temperature waste heat and the HT loop condenser heat load, meaning HT loop condensation parameters significantly affect LT loop performance. Investigating this relationship is crucial for understanding dual-loop system performance.

This study proposes a dual-loop waste heat recovery system for a specific diesel engine manufactured by Hudong Heavy Machinery. The HT loop uses water to recover high-temperature exhaust waste heat, while the LT loop employs organic working fluids to sequentially recover waste heat from engine cooling water and the HT loop condenser. The paper examines how the HT loop condenser heat load affects the LT loop. Calculation results reveal that under different HT loop condensation conditions, the LT loop pinch point occurs at different locations, resulting in varying evaporation temperatures and other thermodynamic parameters.

1.1 Diesel Engine Waste Heat

The waste heat source considered in this study is a diesel engine produced by Hudong Heavy Machinery. Under an ambient temperature of 25°C, the engine' s rated power output is 996 kW. The exhaust gas flow rate is 7139 kg/h with a temperature of 300°C after the turbocharger. The jacket cooling water has an inlet temperature of 65°C, outlet temperature of 90°C, and flow rate of 6876 kg/h, corresponding to a heat load of approximately 199.9 kW.

1.2 Dual-Loop System

The dual-loop waste heat recovery system designed and analyzed in this paper consists of a high-temperature loop and a low-temperature loop. The HT loop uses water as the working fluid to recover exhaust waste heat, while the LT loop uses R123, R236fa, and R245fa as working fluids to sequentially recover waste heat from engine cooling water and the HT loop condenser. The two loops are integrated through a shared heat exchanger, where the HT loop condenser simultaneously serves as the LT loop evaporator. A schematic diagram of the dual-loop system is shown in [Figure 1: see original paper], and the corresponding T-s diagram is presented in [Figure 2: see original paper]. Thermodynamic calculations and analyses are performed using fluid property data and calculation routines from REFPROP 9.1 through secondary program development [6][11].

2 Thermodynamic Analysis of the High-Temperature Loop

The HT loop recovers waste heat from high-temperature exhaust gases. According to literature [12], the exhaust gas final temperature is set above 378.15 K to effectively avoid acid corrosion. The HT loop uses water as the working fluid with a condensation temperature of 375 K. Different dryness fraction conditions (0.2-1.0) are examined to determine appropriate evaporation temperatures, with thermodynamic calculation results shown in [Figure 3: see original paper].

The results indicate that at a given evaporation temperature, higher dryness fractions lead to higher exhaust final temperatures. While the total heat absorption of the HT loop decreases as the exhaust final temperature increases, the heat required per unit mass of water vapor increases with dryness fraction, causing the water vapor mass flow rate to decrease significantly as shown in [FIGURE:3(b). At each evaporation temperature, the HT loop net power decreases with increasing dryness fraction, demonstrating that the reduction in mass flow rate dominates the performance. Additionally, the HT loop condenser heat load decreases with increasing dryness fraction due to the substantial reduction in total heat absorption.

Under low dryness fraction conditions, the HT loop operates as a wet expansion process. This configuration yields better HT loop performance while maintaining a relatively high condenser heat load, which can subsequently be utilized by the LT loop. Therefore, a dryness fraction of 0.2 is selected for the HT loop. The corresponding thermodynamic calculation results are presented in [Figure 4: see original paper].

3 Thermodynamic Analysis of the Low-Temperature Loop

The HT loop condensation temperature of 375 K is higher than the jacket cooling water inlet temperature, meaning the LT loop pinch point may occur at three different locations: the second heat exchanger, the outlet of the first heat exchanger, or within the first heat exchanger, as illustrated in [Figure 5: see original paper]. The pinch point location primarily depends on the HT loop condenser heat load.

The LT loop thermodynamic calculation results are shown in [Figure 6: see original paper]. For R123 and R245fa, the evaporation temperature decreases as the condenser heat load decreases. R236fa exhibits a different trend: at high condenser heat loads, its evaporation temperature remains constant at 369 K, which is exactly the difference between the HT loop condensation temperature (375 K) and the pinch point temperature difference (6 K). As the condenser heat load decreases, the R236fa evaporation temperature begins to drop rapidly, then declines more gradually at low heat loads.

This analysis reveals that as the condenser heat load decreases, the LT loop pinch point location shifts from the second heat exchanger (corresponding to the HT loop condenser heat load) toward the first heat exchanger (corresponding to the jacket cooling water heat load). The working fluid mass flow rate decreases with reducing condenser heat load, and the LT loop net power also decreases accordingly. Notably, the net power trend for R236fa clearly exhibits three distinct stages, mirroring its evaporation temperature behavior.

While the HT loop net power increases with higher exhaust final temperatures, the LT loop net power decreases. The overall system net power variation is shown in [Figure 7: see original paper]. The maximum dual-loop system net power of 115.1 kW is achieved at an HT loop evaporation temperature of 480 K with R236fa as the working fluid, representing an 11.6% improvement in diesel engine power.

4 Conclusions

This paper designs a dual-loop waste heat recovery system for a diesel engine manufactured by Hudong Heavy Machinery. The HT loop uses water as the working fluid with a wet expansion process to recover exhaust waste heat, while the LT loop employs organic working fluids to sequentially recover waste heat from engine cooling water and the HT loop condenser. The HT loop condenser heat load significantly affects the LT loop by determining the pinch point location. The proposed dual-loop waste heat recovery system achieves a maximum net power output of 115.1 kW at an HT loop dryness fraction of 0.2 and evaporation temperature of 480 K with R236fa as the LT loop working fluid, corresponding to an 11.6% improvement in diesel engine power.

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Note: Figure translations are in progress. See original paper for figures.