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Thermodynamic analysis of diesel engine coupled with ORC and absorption refrigeration cycle

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ABSTRACT

In this paper, Rankine cycle and Ammonia absorption cycle are coupled with Diesel engine to recover the energy of exhaust gases. The novelty of this paper is the use of ammonia absorption refrigeration cycle bottoming Rankine cycle which coupled with diesel engine to produce more power. Bottoming system converts engine exhaust thermal energy to cooling and mechanical energy. Energy transfer process has been done by two shell and tube heat exchangers. Simulation processes have been done by programming mathematic models of cycles in EES Program. Based on results, recovered energy varies with diesel engine load. For the particular load case of current research, the use of two heat exchangers causes 0.5% decrement of engine mechanical power. However, the recovered energy is about 10% of engine mechanical power.

1. Introduction

Energy is divided into two types, renewable and non-renewable. Non-renewable energy consumption which mostly come from fossil is continuously increased. The growing usage of fossil fuels increases air pollution. So, the scientists are always looking for ways to increase non- renewable systems efficiency to reduce fossil fuel consumption Diesel engines are power generators which consume diesel fuel to produce mechanical energy. But, most of the energy that produced by diesel engine, are wasted to ambient through high-temperature combustion products. One way to use combustion products thermal energy, is to utilize Rankine cycle as the bottoming cycle with diesel engine [1]. Thermal energy of engine exhaust stream will transfer to Rankine cycle boiler by a heat exchanger. By transferring engine exhaust gases thermal energy to Rankine cycle boiler, Rankine cycle working fluid will vaporize and produce work by rotating turbine. Energy production of the investigated system which mentioned in paper [1–3,10] is less than 7 or 8 percent of total energy released in combustion chamber. In our system, energy recovery potential of system is about 10 percent of total energy released in combustion chamber. In this paper, temperature of exhaust gases at outlet of heat exchangers have been noticed to avoid formation of sulfuric acid [4]. Similar research has been done by Mohammadi [13] on coupling ammonia absorption cycle and Rankine cycle to Brayton cycle to build a CCHP system. In current research, CCHP system optimized by coupling ammonia absorption cycle to Rankine cycle with a heat exchanger to improve Rankine cycle input thermal energy.

Shu et al. [14], performed experimental investigation on thermal Oil Storage/Organic Rankine Cycle system for waste heat recovery from diesel engine. They have shown that higher evaporating pressure can improve the performance of OS/ORC. In addition, in another research [15] they compared R123 and R245fa as working fluids for waste heat recovery from heavy-duty diesel engine. According to their analysis, R123 shows its advantage for the waste heat recovery at heavy duty, while R245fa is more suitable at light-and-medium duty diesel engine. Other researches from different aspects have been conducted (in [16–18]) to investigate the effects of using Organic Rankine Cycle on diesel engine performance.

2. System description

Some solutions are proposed to recover wasted energy of diesel engine. One of them is the use of ORC cycle in diesel engine exhaust system. By coupling ORC cycle with diesel engine, one can recover wasted energy by converting it to electrical energy. Some studies have been done on coupled Rankine cycle and diesel engines by employing Rankine cycle as the bottoming cycle [1–3]. According to conducted researches [1,5], ORC cycle using R245fa as

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Nomenclature

ORC	organic Rankine cycle
$\dot{m}$	mass flow rate [kg/s]
$\dot{W}$	mechanical power [kW]
$\dot{Q}$	heat power [kW]
X	concentration
h	enthalpy [kJ/kg]
COP	coefficient of performance
BSFC	brake specific fuel consumption [g/kW h]
ICE	internal combustion engine
η	overall efficiency
P	pressure [bar]
T	temperature [K] & [°C]
s	entropy [kJ/kg°C]
CCHP	combined cooling, heating and power

Subscripts

i	inlet
e	outlet
E	engine exhaust system streamlines
A	ammonia absorption cycle streamlines
R	Rankine cycle streamlines

the working fluid has too many advantages compared to other working fluids. The important benefit of R245fa is that system efficiency increases because R245fa has less latent heat and less boiling point in comparison to water and other working fluids (Figs. 1 and 2).

In current study, Combustion products thermal energy transfers to ORC cycle working fluid by a heat exchanger. Accordingly, R245fa flows into heat exchanger and absorbs thermal energy from diesel engine exhaust gases then exits the heat exchanger and expands in turbine to produce power. The most important point that we worked on it in this paper, is coupling ammonia absorption cycle to system to build a CCHP system. Ammonia absorption cycle is used to produce cooling energy from diesel engine exhaust gases [6,7]. Generated cooling energy could be used in intercooler or engine cooling system. If the diesel engine is used in a truck, the cooling energy could be used in truck air conditioning system or make a truck refrigeration unit. It will be a good extension for trucks carrying perishable items.

The block diagram of the entire system is shown in Fig. 3. To achieve higher efficiency of Rankine cycle, some of absorption cycle condenser energy is used to preheat ORC working fluid before entering main boiler (heat exchanger A). To achieve mentioned purpose, in the absorption cycle a heat exchanger is located before the condenser (heat exchanger E). The heat exchanger transfers ammonia gas thermal energy from absorption cycle to ORC working fluid. The exchanged heat will increase ORC efficiency and more electrical power will be generated by ORC turbine. Real conditions are taken into account for the performance of the heat exchangers.

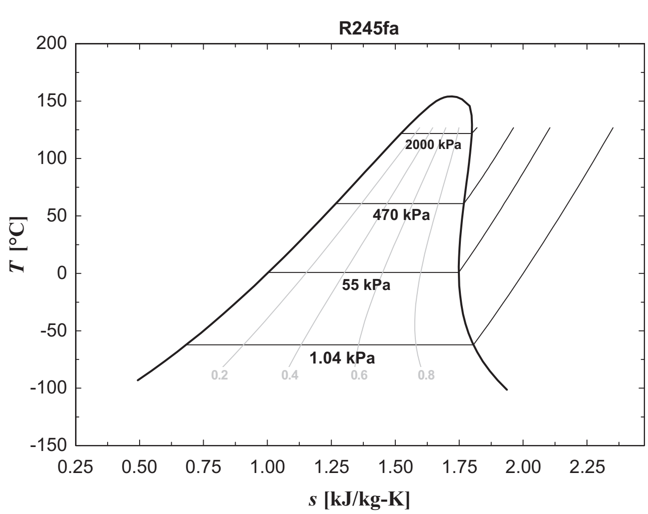

Fig. 1. T-S Diagram of R245fa Fluid.

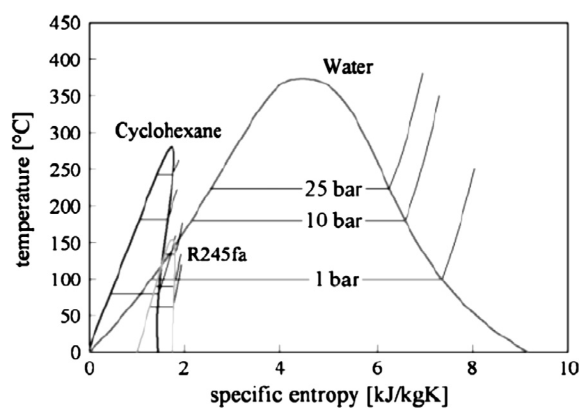

Fig. 2. Comparison of phase change properties between water and R245fa fluid in various temperatures.

2.1. Diesel engine

Based on some researches [2,3], the overall efficiency of internal combustion engines is in the range of 32–40 percent. Accordingly, about 60–68 percent of combustion energy are wasted through exhaust system, radiation and engine cooling system. Therefore, the first law thermodynamic equation for the diesel engine is as follow:

$$\dot{Q}_{Input} = \dot{Q}_{radiation} + \dot{Q}_{coolant} + \dot{Q}_{exhaust} + \dot{W} \tag{1}$$

In this paper, engine exhaust gases thermal energy is used to run ORC and absorption cycle.

3. Mathematical modeling

The whole system contains three cycles; Diesel engine, Ammonia absorption cycle and organic Rankine cycle. In order to thermodynamically analyze the system, the conservation equations of energy, mass, and concentration are used as following [7–13,19]:

– Mass equation:

$$\sum \dot{m}_i = \sum \dot{m}_e \tag{2}$$

– Energy equation:

$$\sum \dot{Q} + \sum \dot{W} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i \tag{3}$$

– Concentration equation:

$$\sum \dot{m}_i X_i = \sum \dot{m}_e X_e \tag{4}$$