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Analysis of recoverable exhaust energy from a light-duty gasoline engine

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ABSTRACT

While EER (Exhaust Energy Recovery) has been widely pursued for improving the total efficiency and reducing CO_2 emissions of internal combustion engines, the improvement on engine efficiency has been investigated with experimental work and numerical simulation based on a steam Rankine cycle EER system. The test was conducted on a light-duty gasoline engine connected with a multi-coil helical heat exchanger. Combining those experimental and modelling results, it demonstrates that the flow rate of working fluid plays a very important and complex role for controlling the steam outlet pressure and overheat degree. For achieving required overheat and steam pressure, the flow rate must be carefully regulated if the engine working condition changes. The flow rate has also significant influence on the heat exchanger efficiency. To achieving better heat transfer efficiency, the flow rate should be maintained as high as possible. From the simulation, it is found the EER system based on the light-duty test engine could increase the engine fuel conversion efficiency up to 14%, though under general vehicle operating conditions it was just between 3% and 8%. From the test, it is found the installation of heat exchanger can increase the exhaust back pressure slightly, the total fuel saving of the engine could be up to 34% under some operating condition.

1. Introduction

In recognition of the need to further reduce vehicle exhaust emissions and the greenhouse gas CO_2 as the oil price has kept roaring up, there has been an increasing interest in the development of cleaner and more efficient energy saving vehicle powertrain. It is thought future sustainable vehicle powertrain developments beyond the next decade are likely to be focused on four topics: emission legislation and control, new fuels, improved combustion and a range of advanced concepts for energy saving [1]. Among various advanced concepts, EER (Exhaust Energy Recovery) for Internal Combustion (IC) engines has been proved to not just bring measurable advantages for improving fuel consumption but also increase engine power output (power density) or downsizing, further reducing CO_2 and other harmful exhaust emissions correspondingly [2]. It was predicted by Vazaquez et al. that if 6% of the heat contained in the exhaust gases were converted to electric power, 10% reduction of fuel consumption can be achieved [3].

Early researches on EER have investigated the basic concepts, problems and expected improvements for such a system. An example could be found from the research conducted by Chammas and Clodic [4], who presented the advantages offered by a Rankine Cycle (RC) system designed for hybrid vehicles. Up to 18% fuel economy improvement could be achieved when water was used to recover the exhaust heat. Compared to the conventional exhaust waste heat recovery by turbocharger which has normally 15% fuel saving and significant power increase, Rankine cycle can have over 20% of fuel saving and similar power increase [5]. Although RC EER system has higher manufacture cost, it does not increase the exhaust back pressure obviously and it can be installed after turbocharger to regenerate further exhaust energy which turbocharger can't absorb.

Some recent reports have showed how further investigation of the technology and architectures are possible [6]. For instance, Teng et al. carried out a series of experiments [7–9] on heavy-duty diesel engines to explore the potential of EER, with hybrid energy systems combined the exhaust system with the charge air cooler and EGR cooler(s). Their results show that up to 20% increase in the engine power and 25% improvement in fuel savings over the ESC 13-mode test could be achieved by the EER system. Ringler et al. [10] selected two basic EER configurations (one just with exhaust gas only and another with exhaust gas plus coolant) from numerous illustrated Rankine cycle layouts for a detailed evaluation of heat recovery based on a four-cylinder IC engine. Their experimental works

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demonstrated that waste heat recovery can produce an additional power output of about 10% at typical highway cruising speeds. Weerasinghe et al. [5] identified the substantial potential of EER for IC engines via two most promising and technically viable technologies: turbo-compounding and exhaust heat secondary fluid power cycles. Their results revealed that the two EER technologies would contribute more power output in the order of 4.1%–7.8% and fuel savings by 2%–22%. Various researches have underlined the interest in light to heavy-duty vehicle applications and suggest that fuel economy improvements of over 20% can be expected from EER.

In this paper, the study which has been focused on the exhaust energy from a light-duty gasoline engine with the objective of exploring the available recoverable energy in exhaust gas is presented. While the exhaust temperature and gas flow rate vary with engine operating conditions, the available exhaust energy for a steam Rankine cycle EER system and its characteristic under different engine operating conditions would be understood. Then the optimal operating areas for utilizing the exhaust energy could be identified.

2. Parameter definition and model description

The EER system which will be used in the present research is based on Rankine cycle and physically it comprises four main components: an evaporator/heat exchanger, an expander, a condenser and a pump, as shown in Fig. 1.

With the evaporator/heat changer, the working fluid is superheated by absorbing thermal energy provided from the exhaust gas. Flowing out from the evaporator as high temperature steam, the working fluid is driving the expander to produce useful work. Then the waste steam from the expander will be cooled down through the condenser to return to liquid phase. In the next step, the working fluid is pumped to maintain the circulation.

For most internal combustion engines, there is approximately 20–40% of total fuel energy which is dissipated through exhaust gas, with the majority as sensible enthalpy due to high exhaust temperature and the minority as chemical enthalpy due to incomplete combustion. To evaluate energy amount in the exhaust gas, it is necessary to obtain the thermo-physical parameters of exhaust gases. Considering currently all diesel engines and most gasoline engines during dominant operating period are driven with lean combustion condition, an assumption of complete in-cylinder combustion would be used for the following analysis while the focus of this research work is on the thermal energy recovery of exhaust gas. Then small amounts of incomplete combustion products such as CO and unburnt hydrocarbon and other small emission components such as NOx could be ignored and the compositions of exhaust gases could be considered as the mixture of CO_2, H_2O, N_2 and O_2.

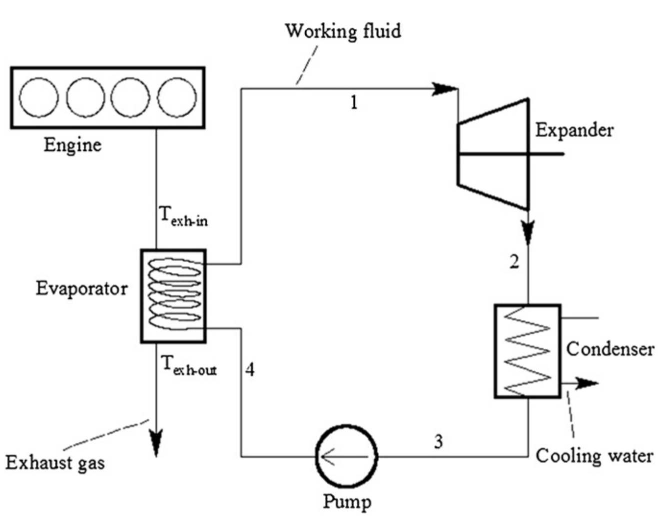

Fig. 1. Layout of the EER system.

Provided that the stoichiometric air-fuel ratio in the gasoline combustion is a_0, and the actual one is α, the molar fractions for N_2 and O_2 in the air mixture is k_{N_2} and k_{O_2}, respectively. While the atom numbers of carbon and hydrogen in the hydrocarbon fuel molecular are θ_C and θ_H, respectively, the molar fractions of compositions in the exhaust gases could be obtained by the following equations, respectively.

$$\begin{aligned}\varphi_{N_2} &= \frac{ak_{N_2}}{1+a+a_0k_{O_2}-\theta_H/2}\\ \varphi_{O_2} &= \frac{(a-a_0)k_{O_2}}{1+a+a_0k_{O2}-\theta_H/2}\\ \varphi_{CO_2} &= \frac{\theta_C}{1+a+a_0k_{O_2}-\theta_H/2}\\ \varphi_{H_2O} &= \frac{\theta_H/2}{1+a+a_0k_{O_2}-\theta_H/2}\end{aligned} \tag{1}$$

Considering the above four compositions are all ideal gases, their constant pressure heat capacity $C_{p,i}$ could be achieved by the empirical formula [11]:

$$C_{p,i} = \left(c_0+c_1T+c_2T^2+c_3T^3+c_4T^4\right)R \tag{2}$$

Given the exhaust gases ideal condition, the specific enthalpy could be calculated by:

$$h = \sum_i \omega_1 M_i h_i \times 10^{-3} \tag{3}$$

where, ω_i, M_i and h_i are the molar fraction, molar mass and specific enthalpy for each composition. And the latter could be expressed by:

$$h_i = h_0 + \int_{T_0}^{T} C_{p,i}\mathrm{d}T \tag{4}$$

Combined the equations (1)–(4), the specific enthalpy of exhaust gases can be achieved.

It should be noted the above formulae can only be selected for calculating the specific enthalpy of exhaust gases when all thermal recovery process did not involve steam condensation of exhaust gas and there is only the sensible heat of the exhaust gases which is absorbed by the thermal recovery system. When the steam condensing heat should be included if there is phase change of exhaust gas via the evaporator, the exhaust specific enthalpy was obtained from NIST-Refprop database.

Then, the exhaust heat q_{exh} and its fraction in the total fuel energy could be given by:

$$q_{exh} = (h_{exh}-h_{out})\dot{m}_{exh} \tag{5}$$

$$\chi_{exh} = \frac{q_{exh}}{h_f\dot{m}_f} \tag{6}$$

where, $\dot{m}_{exh}$ and $\dot{m}_f$ are the mass flow rate of exhaust gas and fuel, respectively, h_{exh} and h_f are the corresponding exhaust gas enthalpies, and the low heating value of fuel.

After possible sensible heat in the exhaust gas could be determined with above formulae, the EER Rankine cycle efficiency would