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Experiments on the effect of engine speed, load, equivalence ratio, spark timing and coolant temperature on the energy balance of a turbocharged hydrogen engine

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ABSTRACT

Internal combustion engines are used to translate the chemical energy of fuel to the brake power and over two-third of energy is wasted in the form of exergy and anergy in this process. An experimental energy balance analysis can make the engine energy flow clear and help to recycle the exergy of exhaust gas to increase brake thermal efficiency. In this paper, the effect of five different parameters on the energy distribution was investigated using heat balance test data from a 2.3 L turbocharged hydrogen engine. The results show that when proportion of exhaust gas energy ranges from 24.1% to 36.4% with various engine speeds, brake thermal efficiency can increase 3.69% at 2000 rpm and 7.67% at 4000 rpm with various load, which means that high engine speed and load are beneficial to increase exergy of total system. Both Engine speed and brake thermal efficiency increase with equivalence ratio ranging from 0.4 to 0.9, while proportion of energy of cooling system decreases, which means that both power and economic ascend with increasing equivalence ratio and anergy of total system decreases at low engine speed and load. Furthermore, proportion of exhaust gas energy can increase by 3% at 75% load and 2.5% at 50% load with spark timing closing to TDC and NOx emission is decreasing. Finally, the variation of the coolant temperature has an almost negligible effect in terms of brake thermal efficiency but it can decrease anergy of total system.

1. Introduction

Internal combustion engines are part of the powertrains for automobiles, ships and gen-set application at present. With increasingly stringent emission regulations and the fossil energy depletion, increasing brake thermal efficiency (BTE) and reducing emission are getting urgent for internal combustion engines. Exhaust gas and cooling process account for a great deal of wasted thermal energy and this wasted energy includes a lot of exergy can be recycled to increase BTE. Heat balance analysis is an efficient way to know the energy flow and then put forward a highly potential method to reduce fuel consumptions of the engines [1]. Due to the benefit of energy saving, many researchers have done much work in conventional engine [2–5]. For example, Payri et al. studied the effect of the engine speed, load, coolant temperature, inlet temperature and start of injection (SOI) on each energy distribution in an engine map of a direct injection Diesel engine [3]. Their results showed that the variation of the coolant temperature has an almost negligible effect in terms of BTE whilst cooling the air yields in an improvement about 1% and advancing the SOI about 1.5%. Martín et al. studied the effect of three parameters (low/high reactivity fuel ratio, injection timing and exhaust gas recirculation (EGR) rate) on reducing engine emissions and fuel consumption in a single-cylinder engine operating with dual-fuel [4]. Their results showed that increasing the low reactivity fuel can increase the BTE about by 1% and injection timing swept can increase by up to 4% but EGR has a limited effect.

As another way to solve the fossil fuel depletion, alternative fuel for automotive engines has been more stimulated in recent years. Heat balance analysis can not only improve the BTE for conventional engines, but also the alternative fuel engine [6–9]. For example, Yusri et al. carried out the energy balance experiment for the 2-butanol–gasoline percentage volume ratios of 5:95 (GBu5), 10:90 (GBu10) and 15:85 (GBu15) of gasoline to butanol [6]. Their results mainly exhibited an improvement in effective power, cooling energy and exhaust energy by average differences of 3.3%, 0.8% and 2.3% for GBu15 compared with G100. Das et al. have used the exergy analysis to study three compositions of biogas: BG93, BG84 and BG75 (containing 93%, 84% and 75% of CH_4 by volume respectively) on a small CI engine in dual fuel mode [7]. Their results showed that biogas dual fuel could replace 80–90% of diesel fuel at lower engine loads. Under higher loads, total

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Nomenclature

PFI	port fuel injection
BTE	brake thermal efficiency
SOI	top dead center start of injection
BTDC	before top dead center
EGR	exhaust gas recirculation
WOT	wide open throttle
PMEP	pumping mean effective pressure
λ	equivalence ratio
ST	spark timing
$\dot{Q}_{H_2}$	chemical energy of fuel, kJ/kg
$\dot{M}$	mass flow, kg/h
q_{LHV,H_2}	heat value of hydrogen, MJ/kg
$\dot{M}_a$	air mass flow, kg/h
h^{sens}	specific enthalpy, kJ/kg/K
$\dot{M}_{cooling}$	mass flow of the coolant, m^3/h
$\dot{M}_{oil}$	mass flow of the oil, m^3/h
$\dot{Q}_{cooling}$	energy taken away by the coolant, kW
$\dot{Q}_{oil,b}$	energy taken away by the oil, kW
$\dot{Q}_{exh}$	energy taken away by exhaust gas, kW
ω_{NO}	mass fraction of NO in the exhaust pipe
$\dot{Q}_{inter.cooler}$	energy taken away by intercooler, kW
N	effective work, kW
c_p	specific heat capacity, kJ/kg/K
T	temperature, K
T_{tq}	torque
$\dot{Q}_{mis}$	uncounted heat loss, kW
n	engine speed, rpm
p	pressure
MBT	minimum best timing
HICE	hydrogen internal combustion engine

irreversibility of the engine was increased from 59.56% for diesel operation to 61.44%, 64.18% and 64.64% for the BG93, BG84 and BG75 biogas compositions respectively. Furthermore, combustion irreversibility was found to be decreasing with higher CO_2 concentrations in biogas. BG93 showed comparable results to that of diesel operation with 26.9% and 27.4% second-law efficiencies respectively. Li et al. studied the energy distributions of biogas using heat balance test [8]. They summarized proportion of BTE in 28.45%, exhaust gas in 40.34%, cooling system in 26.86% and heat radiation and convection from the engine only accounted for 2.99%. Gharehghani et al. investigated the thermal balance and performance of a turbocharged gas spark ignition engine at full and half loads and at different cooling fluid temperatures [9]. Results indicated that increasing the engine load and coolant temperature would lead to the increase of the percentage of transferred energy to the exhaust gas and the decrease of the percentage of coolant energy. Other alternative fuels such as alcohols [10], biodiesels [11] were also investigated using the heat balance test. By summarizing these achievements it can be found that the property of fuel property is the main reason accounting for the differences among different alternative fuel engines.

Due to the properties of hydrogen such as the faster combustion velocity, shorter quenching distance and higher RON than the other fuels [12], the energy distribution of hydrogen engine is different from the traditional and other alternative engines. With exergy analysis method, Subramanian et al. have studied the maximum available work and irreversibility (mixing, combustion, unburned, and friction) of a dual-fuel diesel engine (hydrogen-diesel) [13]. They found that the maximum available work of the diesel engine at rated load increased from 29% with conventional base mode (without H_2) to 31.7% with dual-fuel mode (18% H_2 energy share) whereas total irreversibility of the engine decreased drastically from 41.2% to 39.3%. Yüksel et al. carried out the energy balance experiment in a gasoline engine using three different hydrogen mass flows as supplement [14]. Their results showed that addition hydrogen could decrease the energy of cooling water and unaccounted heat loss and increase the BTE by rate of 5%. Ozcan et al. studied the energy balance of a nature gas engine using hydrogen as supplement with a zero dimensional, two-zone computational model [15]. They found that increasing hydrogen content and lean burn have considerably affected the exergy transfers, irreversibility and second law efficiency. With the increasing hydrogen content, the irreversibility produced during combustion decreased, and the second-law efficiency sharply increased at near the lean limit. These results showed that the hydrogen as supplement can change the energy distributions for other fuel engine. Furthermore, Navale et al. carried out the energy balance experiment in the speed range of 1100 rpm to1800 rpm [16]. Results have shown that maximum brake power was reduced by 19.06% and peak BTE is increased by 3.16% in the case of hydrogen operation than the gasoline engine. Das et al. [17] introduced a 2.5 L turbocharged-intercooled hydrogen engine that can obtain a power of 66.7 kW at 3200 rpm. Results showed that BTE were above 30% at all engine speed ranges and a maximum BTE of 38% was obtained at 2000 rpm. Ford Groups studied the energy distribution in a 4.0 L six-cylinder port-injected hydrogen-fueled engine operating by natural aspiration and turbocharging [18]. They found that a BTE of 35.5% can be achieved at 1500 rpm. When increasing equivalence ratio (the ratio of the actual air-fuel ratio to the theoretical air-fuel ratio, λ), the BTE ranged from 32.8% to 34.8% and the exhaust fraction generally increased and residual decreased. These energy balance analysis results were important achievements for hydrogen engine. However, these results didn't consider different parameters (such as engine speed, load, equivalence ratio, spark timing (ST) and coolant temperature) from global heat balance and put forward reliable strategies to solve the contradiction among power, economic and emission. Thus, this paper has studied the energy balance based on different parameters and presented some controlling strategies at different working conditions using test data of a 2.3L turbocharged hydrogen engine.

2. Material and method

2.1. Theoretical method

Heat balance test can be used to explore the effects of different parameters, such as engine speed, load, equivalence ratio, spark timing, and coolant temperature, on the characteristics of different energy distributions for a turbocharged hydrogen internal combustion engine (HICE). Before performing the tests, theoretical method must be used to analyze the energy distribution. Fig. 1 shows the energy flows

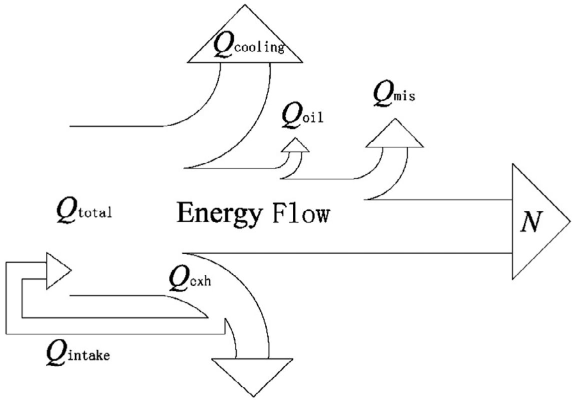

Fig. 1. Sketch of the energy flows considered.