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Thermal efficiency boundary analysis of an internal combustion Rankine cycle engine

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ABSTRACT

This paper discusses a novel oxy-fuel combustion method named ICRC (internal combustion Rankine cycle) used in reciprocating engines. Pure oxygen replaces air as oxidant for NOx emission avoidance and CO_2 recovery. Water is heated up through heat exchanger by exhaust gas, and then injected into the cylinder near top dead center to control the combustion temperature, meanwhile increases the mass of working fluid and therefore enhances the thermo efficiency of the cycle. An ideal engine thermodynamic model combined with a heat exchange model was developed to investigate the thermal efficiency upper boundary of this cycle. The results indicate that the added water increases the thermal efficiency significantly considering the heat exchange between water and exhaust gas, and thermal efficiency increase from 33% (without water injection) to 56% when engine speed is 2000 rpm and engine compression ratio is 9.2. Lower engine speed, intake pressure and higher compression ratio are propitious to higher thermal efficiency. The best thermal efficiency of the whole ICRC system can reach to 58% when engine compression ratio is 14. Thus this concept has the potential for high thermal efficiency and low emission.

1. Introduction

The combustion of fossil fuels for energy and transportation results in emission of greenhouse gases (main CO_2). To avoid the impact of the increasing greenhouse gases emission on climate, many new technologies have been developed. Oxy-fuel combustion integrated with carbon dioxide capture is one of the most effective technologies widely used in power generation industry [1]. High-purity oxygen instead of air is utilized during the combustion process. Therefore, the main components of exhaust gases are carbon dioxide and water vapor, and carbon dioxide is easily separated and captured [2]. Some parts of exhaust gas are usually recycled into the boiler in order to maintain a proper combustion temperature aiming to the acceptable limits of the boiler materials [3]. A large number of studies have investigated performance analysis and system optimization of oxy-fuel combustion [4–6].

Clean energy system merges oxy-fuel combustion and water injection [7,8]. In this system, a large amount of high pressure recycled water is injected into the gas generator during the oxy-fuel combustion to increase the mass of the working fluid, and therefore the thermal efficiency increases. The emissions only include water and carbon dioxide, which are easily separated and recovered. This type of oxy-fuel combustion power-plant cycles is called ICRCs (internal combustion Rankine cycles). The thermal efficiency of an ICRC can reach to 65% or more. The overall efficiency still can reach to 58% when the energy cost of separating oxygen from air is considered [9].

Addition of water into the combustion process in IC engines is not a novel concept [10]. Water injection at ambient temperature is mainly employed in IC engines, such as an internal coolant [11], and NOx emissions reduction [12,13], because water can reduce flame propagation and in-cylinder temperature. However, water injection contributes little to improving thermal efficiency (increased by a maximum of 4%) [13]. Water is generally utilized to inhibit combustion and decrease in-cylinder temperature in these applications, thus the mass of water is limited due to the significant negative effects of excess water during traditional air combustion process. Hence, thermal efficiency of the cycle benefits less from the evaporation of injected water.

Reciprocating engine versions of the ICRC was investigated for the potential application in automobiles [9]. The schematic figure of ICRC system is shown in Fig. 1. Oxygen mixed with EGR is inhaled

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Nomenclature

A	heat transfer area (m^2)
C	specific heat capacity (J/(kg K))
C_r	heat capacity ratio (–)
d_e	equivalent diameter of tubes (m)
d_i	internal diameter of tube (m)
d_o	outside diameter of tube (m)
D	shell diameter (m)
h	specific enthalpy (J/kg)
H	overall heat transfer coefficient (W/(m^2 K)
h_i	tube side heat transfer coefficient (W/(m^2 K)
h_o	shell side heat transfer coefficient(W/(m^2 K)
j_h	heat transfer factor (–)
L	tubes length (m)
L_b	baffle spacing (m)
LVH	lower heating value J/kg
m	mass (kg)
$\dot{m}$, q	mass flow rate (kg/s)
N	tubes number (–)
NTU	number of transfer units (–)
Pr	Prandtl number (–)
Pt	tubes center distance (m)
Q	heat (J)
Re	Reynolds Number (–)
T	temperature (K)
u	flow speed (m/s)
v	volume (m^3)
W	work (J)
η	efficiency (%)
ΔT_m	logarithmic mean temperature difference (K)
ρ	density (kg/m^3)
ε	exchanger effectiveness (–)

Abbreviations

BTDC	before top dead center
CR	compression ratio (–)
IC	internal combustion
ICRC	internal combustion Rankine cycle
I/F	intake charge/fuel
IMEP	indicated mean effective pressure
NOx	nitrogen oxides
ORC	organic Rankine cycle
TEG	thermoelectric generators

Subscripts

g	exhaust gas
i	indicated
in	inlet
inj	injection
min	minimum
max	maximum
out	outlet
w	water
1–6	state points in P–V diagram of an ICRC engine

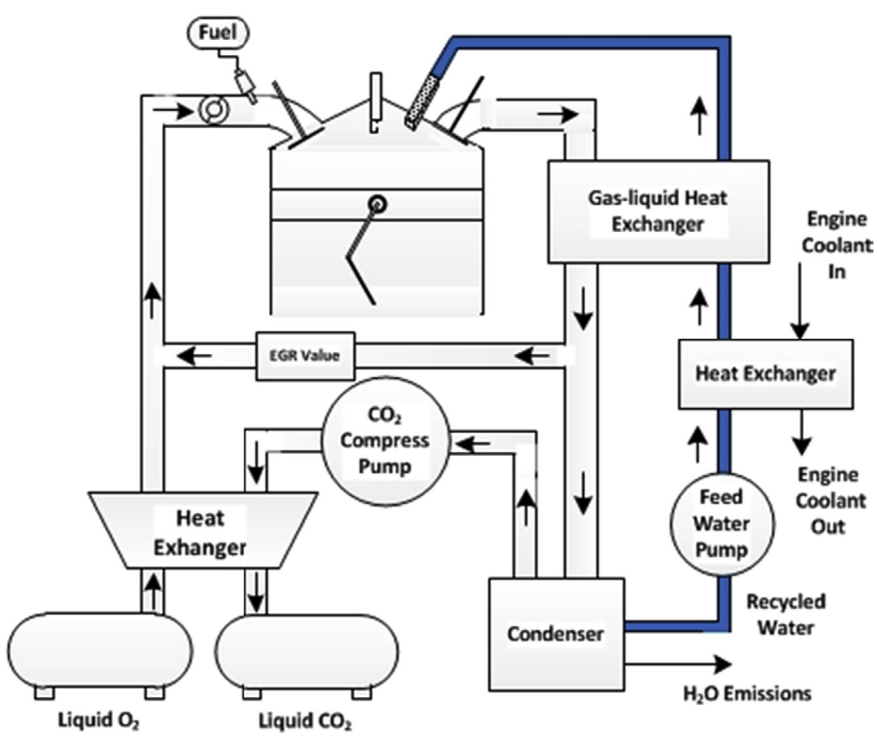

Fig. 1. Schematic of ICRC system.

into cylinder during intake stroke. Water recovered the thermal energy from the exhaust gas, and is directly injected into the cylinder during the combustion. Since combustion with higher oxygen concentration is more intense, more water can be added as working fluid to increase the work with less negative impact. The exhaust gas is the mixture of CO_2 and water vapor, which can be easily separated through condensation process at relatively low cost. In this way, high pure CO_2 can be captured and stored in a tank.