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Liquid air fueled open-closed cycle Stirling engine and its exergy analysis

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ABSTRACT

An unconventional Stirling engine is proposed and its theoretical analysis is performed. The engine belongs to a "cryogenic heat engine" that is fueled by cryogenic medium. Conventional "cryogenic heat engine" employs liquid air as a pressure source, but disregards its heat-absorbing ability. Therefore, its efficiency can only be improved by increasing vapor pressure, accordingly increasing the demand on pressure resistance and sealing. In the proposed engine, a closed cycle structure of Stirling engine is added to combine with the open cycle structure of a conventional cryogenic heat engine to achieve high efficiency and simplicity by utilizing the heat-absorbing ability of liquid air. Besides, the theoretical analysis of the proposed engine is performed. The Schmidt theory is modified to model temperature variation in the cold space of the engine, and irreversible characteristic of regenerator is incorporated in the thermodynamic model. The modeling results show that under the same working pressure, the efficiency of the proposed engine is potentially higher than that of conventional ones and to achieve the same efficiency, the working pressure could be lower with the new mechanism. Composition of exergy loss in the proposed engine is analyzed.

1. Introduction

Recently zero emission vehicles have been explored extensively. They are generally categorized [1] into battery electric vehicles, hydrogen vehicles and air vehicles. The battery electric vehicles provide the highest efficiency. However, the heavy metal pollution, high initial cost, long charging time have proved the limitation of them [2]. The superiority of hydrogen is high energy density. Nevertheless, distribution and storage difficulties currently impede its wide application [3]. Air vehicles can achieve an energy density close to that of the battery ones. Furthermore, it provides lower operation cost and much less recharging time [4].

For the compressed air powered vehicles, the high energy density is achieved by increasing its storage pressure to several hundred atm. However, the compressed air powered engine is operated at several atm [5]. Generally, the pressure should be reduced from several hundred atm to several atm. The process results in over 50 percent of energy loss and ice blocking of exhaust port [6]. Liquefaction of air is an alternation to achieve high energy density without the necessity of high storage pressure, avoiding the energy loss caused by pressure reduction, and this study is concerned with engines fueled by liquid air [7].

The energy stored in liquid air can be divided into cryogenic energy and expansion energy. At atmospheric pressure, the temperature of liquid air is below $-196°$ C (liquid nitrogen $-196°$ C, liquid oxygen $-183°$ C). It can be employed as heat sink to cooperate with atmosphere (heat source) to convert heat into work. Due to the existence of the temperature difference, the energy converted into work is referred as cryogenic energy. On the other hand, when liquid air is vaporized, the pressure of air will increase, and the pressurized air can act as the pressure source of a piston or a rotary motor. This part of energy is referred as expansion energy.

In 1994, Knowlen [8] from University of Washington proposed to utilized liquid nitrogen as the working fluid to convert expansion energy to shaft work in an open Rankine cycle. Based on the theory above, later in 1998, Plummer [9] from University of North Texas manufactured a prototype of liquid air powered engine. The engine could only power a car for 24 km with up to 180 L of liquid nitrogen at 1.2 MPa. It produced 19 kJ of work per kilogram of nitrogen. Williams [10] develops a Frost-free cryogenic heat exchangers to enhance heat transfer. Knowlen [11] designs a quasi-isothermal expander to use the expansion energy sufficiently. Chen [12]

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Nomenclature

θ	temperature (K)
Φ	phase angle
κ	swept volume ratio, V_H/V_C
α	leading angle
p	pressure (Pa)
V	volume (m^3)
n	mass (kg)
t	time (s)
v	volume (m^3/kg)
w	work (kJ/kg), W (kJ)
q	heat (kJ/kg), Q (kJ)
e	energy (kJ/kg), E (kJ)
η	efficiency
h	enthalpy (kJ/kg)
Δh	enthalpy heat of vaporization (kJ/kg)
s	entropy
u	internal energy
C	molar heat capacity (kJ/kg K^{-1})
C_p	heat capacity at constant pressure (kJ/kg K^{-1})
C_v	heat capacity at constant volume (kJ/kg K^{-1})
T	period (s)
R	287 (J/kg K^{-1})
V_C	swept volume of displacer (m^3)
V_H	swept volume of power piston (m^3)
n_C	defined in Table 1
N	number of regenerator stage

Subscripts

a	atmosphere
c	cold space/cryogenic
h	hot space
g	gas state
l	liquid state
ph	phase change
0	initial condition
L	loss
H	enthalpy
U	internal energy
Q	heat
r, R	regenerator
ep	expansion
exh	exhaust

Superscripts

*	dimensionless variable
l	liquid state

analyzed characteristics of the open cycle engine. Theoretically, the energy of liquid nitrogen is 760 kJ/kg [9]. The low energy efficiency (2.5%) probably resulted from the very insufficient use of the cryogenic energy. The experiment shows that due to the poor efficiency, liquid air fueled vehicles have to face the limitation of driving range, which will seriously restrict its wild application.

Therefore, more research was done on the exploration of compound thermodynamic cycles to use the cryogenic energy to improve the efficiency. Knowlen [13] used liquid nitrogen to liquefy high-boiling point mediums (CH_4, C_2H_6), and introduced a multi-stage Rankine cycle to the basic single-stage open Rankine cycle. Thermal analysis showed that the net work of the cycle could reach 400 kJ/kg. Ordonez [4] employed closed Brayton cycle to convert the cryogenic energy to mechanic work. Knowlen also proposed another two compound thermodynamic cycles based on liquid nitrogen fueled engines and hybrid-drive internal combustion engines. Theoretical analysis shows that combining liquid air as the heat sink with the thermodynamic cycle of an internal combustion engine can increase the driving range of liquid air fueled engine. Liu and Guo [14] proposed a novel cryogenic cycle by using a binary mixture as working fluids and combined with a vapor absorption process for cryogenic energy recovery. Lee [15] designed a multi-component Rankine cycle with three heaters and a two-stage turbine to use liquefied gas cryogenic energy. Although the compound Rankine cycle provides a solution to convert expansion energy into work, if a single-stage closed Rankine cycle is used, a large amount of exergy loss will be inevitably caused by the big temperature difference during the heat transferring process. To avoid this situation, to design a multi-stage one is a solution. However, that will greatly increase the system's complexity. More compressors and expanders should be added to accomplish the compound cycle.

A simple open-closed cycle Stirling engine is proposed by this study to use one set of compressor and expander to accomplish the compound cycle. Stirling cycle is utilized as the closed cycle. To avoid large exergy loss, a design of multi-stage regenerator is used to take place of a multi-stage system. This effectively averts the complexity of a multi-stage Rankine system. Generally, in the practical use of Stirling engines, the complexity and high cost of heaters that are made of stainless steel or ceramic to support high temperature restrict the wide application of Stirling engines [16]. Fortunately, the liquid air engine is operated in low temperature, and thus Stirling engine could be feasible for the liquid air application. To accomplish the open cycle, modifications should be made on conventional Stirling engines. A liquid air reservoir is integrated with the cold space of Stirling engine. The vaporized air is used as working medium of the open cycle, and is mixed with the air which participates the previous closed cycle. The mixture flows together to the same expander and then expands. Therefore, additional expanders used to form the compound cycle can be avoided.

Besides of the open-closed cycle structure, the challenge of this work also lies in the low temperature difference (LTD). For conventional Stirling engines, the temperature of their heat sources is not lower than 700° C [17] and the atmosphere (20° C) is taken as their heat sinks. Thus, the temperature difference is not smaller than 680° C. However, the maximum difference of the liquid air engine is 216° C. If a Stirling engine runs in such a low temperature difference (LTD) [18], it is characterized as: the heat transfer surface of the displacer cylinder should be enlarged to absorb or to release more heat than that of normal Stirling engine by Rizzo [19]. The low temperature difference condition will result in increasing weight and size of Stirling engines and stricter demand on heat transfer rate.

The proposed Stirling engine can be applied practically. Firstly, the theoretic thermal efficiency is not lower than that of a conventional Stirling engine. The thermal efficiency of the proposed Stirling engine is (293.15−77.36)/293.15 and that of a conventional one is 680/(680 + 293.15). Secondly, to avoid increasing size, a new heat transferring subsystem is designed for the proposed engine. The proposed Stirling engine takes built-in liquid air as power source. The working gas exchanges heat with liquid air directly, avoiding wall-structure and new structure made of porous copper is also added to increase heat exchange area.

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