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Theoretical study on the ideal open cycle of the liquid nitrogen engine*

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Abstract: This article described the characteristics of the liquid nitrogen engine's ideal open cycle. Using two interconnecting strokes to achieve the power output can mitigate the trade-off between high efficiency and the potential mechanical complexity of multiple-cylinder engines. The total specific energy of the binary media (methane-nitrogen) cycle system could be much higher than the unitary medium (liquid nitrogen) cycle system. By theoretical analysis, the reasonably acceptable driving range proved the feasibility of the liquid nitrogen engine used for supplying power for a lightweight car.

Key words: Liquid nitrogen engine, Ideal open cycle, Theoretical study
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INTRODUCTION

The cryogenic heat engine employs a cryogenic medium as a heat sink and the atmosphere as a heat source. The cryogenic mediums include liquid air and liquid nitrogen. In the cryogenic heat engine, the mechanical power is produced from the energy stored in cryogenic mediums, as distinct from internal combustion engine in which the mechanical power is produced from the chemical energy contained in the fuel. Further, there are three advantages of the cryogenic heat engine. Firstly, the cryogenic heat engine is definitely zero emission engine. The working mediums come from the atmosphere. Additionally, during the condensation process, the pollutants can be separated from the atmosphere. As a result, the atmosphere can be made cleaner(Plummer, et al.,1998). Secondly, the cryogenic heat engine configuration can be made simpler, more compact, more endurable, because the performance of the cryogenic heat engine, without combustion, is more direct, simpler, and more controllable. Thirdly, the car using cryogenic heat engine can realize the air-condition function in summer, without needing extra energy (Ordonez, 1996; Ordonez et al.,1997).

From former researches, we know the cryogenic heat engine can be classified into two types according to their work media, liquid air and liquid nitrogen engine. Additionally, they also can be classified into two types based on their configurations, reciprocating engine and turbine. The cryogenic heat engines can use air or nitrogen in conjunction with natural gas to realize the hybrid drive engine. In 1997, researchers at the University of Washington using the concept of a steam engine developed the cryogenic heat car using liquid nitrogen as the propellant for their LN2000 prototype car (Knowlen et al., 1994; Williams et al., 1997). To the authors' knowledge, there is no report on the research so far. This paper describes the theoretical cycle of the liquid nitrogen engine.

THEORETICAL ANALYSIS

Fig.1 shows that the liquid nitrogen goes

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through the heat exchanger to the reciprocating engine to provide mechanical energy (Ordonez, 1996). Fig. 2 shows the $p - v$ diagram of the open-cycle engine system (a). The processes that take place in the open cycle are isobaric expansion 1 − 2 and isothermal expansion 2 − 3.

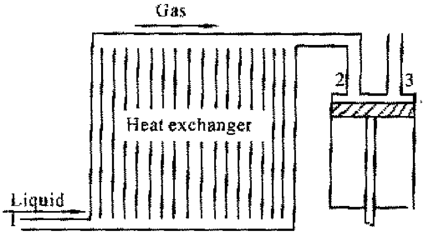

Fig. 1 Operation of an ideal open-cycle engine which runs on liquid nitrogen

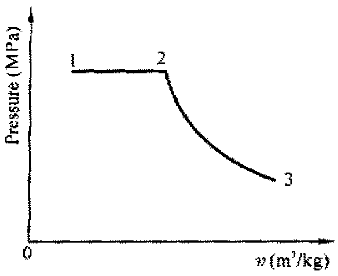

Fig. 2 $p - v$ diagram of the open-cycle engine system(a)

The specific energy (W_t) expended during the isothermal expansion process 2 − 3 is

$$W_t = RT_2 \ln\left(\frac{p_2}{p_3}\right). \qquad (1)$$

The specific energy taken by the engine from the atmosphere is

$$W_e = p_3(v_3 - v_2). \qquad (2)$$

So the specific energy (W_s) per unit mass of nitrogen for the model system is

$$W_s = W_t - W_e$$

$$= RT_2 \ln\left(\frac{p_2}{p_3}\right) - p_3(v_3 - v_2) \qquad (3)$$

In these formulas, p_3 is atmospheric pressure (0.1MPa), p_2 is the injection pressure, v_3 is the specific votume of the point 3, v_2 is the specific votume of the point 2, gas constant ($R = 297\text{J/(kg·K)}$). With Eq. (3), the total specific energy is affected by the thermodynamic state of point 2. In Fig. 3, the specific energy rises with the rise of the injection pressure (p_2). And the velocity of the rise of available energy slows down with the value of p_2. So if the process of raising the value of p_2 is realized in the heat exchanger, then, more specific energy can be available for the engine system. So rising the efficiency of the heat exchanger could provide more available energy. According to Eq. (3), the rise of the value of T_2 would increase the specific energy greatly, so the cryogenic heat engines using air or nitrogen in conjunction with natural gas to realize the hybrid drive engine can gain more specific energy.

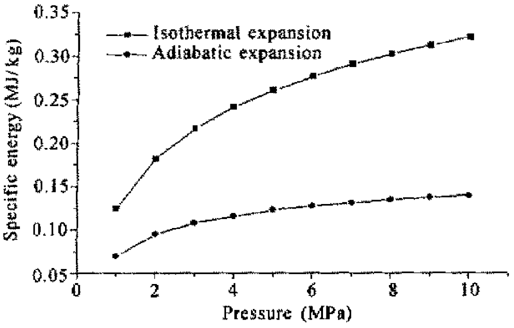

Fig. 3 Relation between injection pressure (p_2) and specific energy

If the second expansion process 2 − 3 with no heat flow into the nitrogen, the expansion is adiabatic and the specific energy of the expansion is

$$W_t = \frac{k}{k-1} RT_2 \left[1 - \left(\frac{p_2}{p_3}\right)^{\frac{1-k}{k}}\right] \qquad (4)$$

Thus

$$W_s = \frac{k}{k-1} RT_2 \left[1 - \left(\frac{p_2}{p_3}\right)^{\frac{1-k}{k}}\right] - p_3(v_3 - v_2) \qquad (5)$$

Here for a diatomic gas, $k = 1.4$ (Ceng et al., 1997). According to the result of calculation, this is a great reduction compared with using an isothermal expansion process for the second expansion.

In fact, there are two difficulties in realizing the ideal open cycle. Firstly, the realization of the isotonic expansion process that is involved in the control of pressure and the high efficiency heat exchanger. The second is the realization of the isothermal expansion in the expander. This process is instantaneous, and the decalescence is uneven in the process. During the forepart of the expansion process the highest rate of work output is realized, thus the greatest demand for heat input to approach isothermal performance (Knowlen et al., 1997). So high efficiency of the heat exchanger and high operation efficiency of the expander are the keys for the satisfactory performance cryogenic heat cars. Table 1 lists the liquid nitrogen engine operating parameters, and Fig. 2 is the engine operation cycle. According to Eq. (3), the specific energy is 0.242MJ/kg.

Table 1 Operating parameters for the open-cycle engine system (a)

Parameter	State point		
	1	2	3
p(MPa)	4	4	0.1
T(K)	127	300	300
v(m^3/kg)	0.0022	0.0222	0.89

As discussed above, the high efficiency heat exchanger and the realization of isothermal expansion in the cylinder are keys for the satisfactory performance of the liquid nitrogen engine. Fig. 4 gives an optimization of the engine cycle. In this open cycle system, two cylinders are connected to each other to overcome the two difficulties. In the new system, two heat exchangers are used to realize the isotonic expansion processes $1-4$ and $5-6$ (Mitty et al., 1999). This alteration of the cycle would mitigate the need for high efficiency for each heat exchanger. In two cylinders, the isothermal expansion processes $4-5$ and $6-3$ are realized. The realization of the isothermal expansion in one cylinder is difficult, because the rise of efficiency in one cylinder means the reduction of the bore-to-stroke ratio (d/s) (Knowlen et al., 1997). Long strokes would result in low RPM and low power output, and mechanical complexity of the engines. After the configuration of the engine is defined, the value of the injection pressure can be calculated. So the careful design trade-off between high efficiency and the potential mechanical complexity of multiple-cylinder engines required to generate sufficient power for automotive propulsion is key for the satisfactory performance of cryogenic heat engines. Therefore, the two cylinders that are connected to generate power can resolve the problem of trade-off, and contribute to the realization of quasi-isothermal expansion during the total cylinder expansion process.

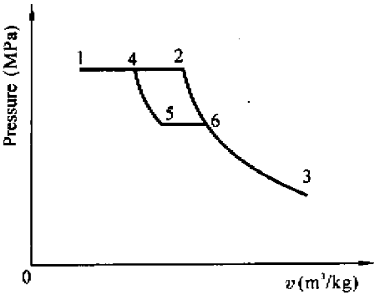

Fig. 4 $p-v$ diagram of the open-cycle engine system (b)

The operating parameters for the open-cycle engine system (b) are listed in Table 2. Eq. (3) was used to obtain the total specific energy as 0.194MJ/kg. So the new open cycle in Fig. (4) is more reasonable for mitigating the trade-off, without too much reduction of the total specific energy.

Table 2 Operating parameters for the open-cycle engine system (b)

Parameter	State point			
	4	5	6	3
p(MPa)	4	0.7	0.7	0.1
T(K)	200	200	300	300
v(m^3/kg)	0.0137	0.0835	0.1291	0.8900

For the liquid nitrogen engine described in this paper, the atmosphere takes cold stored from the cryogenic medium in the heat exchanger. Another cryogenic medium can be used to vaporize the liquid nitrogen and even bring nitrogen to comparatively high thermal state, and to realize the closed-cycle into which the mechanical energy also outputs. In the binary media system, the two cryogenic media must have relatively large differences in saturation temperature. For methane, under 1atm, its saturation temperature is about 110K. So methane and nitrogen could be used to realize the binary cryogenic media engine system. The total specific energy of the binary media cycle system could be much higher than the unitary medium cycle system. Theoretically, if isothermal expansion can be realized in cylinders, the specific energy of the binary media (methane-nitrogen) engine increases 68.2% over the specific energy of the unitary medium (liquid nitrogen) engine. Additionally, since the majority of the heat transfer occurs during the boiling and condensing processes, the heat exchanger system can be relatively compact (Knowlen et al., 1998).

As discussed above, the cryogenic media of the cryogenic engine include liquid nitrogen and liquid air. Although, the liquid air is cheaper than liquid nitrogen, the car using liquid air can result in oxygen rich environment, which means potential danger. Therefore, liquid nitrogen engine will be preferred in cryogenic heat engines.

FEASIBILITY ANALYSIS

The total power needed to drive an automobile is the sum of the power required to overcome fiction and the power required to increase speed:

$$p(a,v) = Fv = mv[a_f(v) + a]. \tag{6}$$

Here, a is the acceleration of the car and a_f is the speed-dependent force per unit mass needed to overcome friction. Assuming the car runs on stable speed $v = 12m/s$ and weights 1000 kg, so $a = 0$.

$$p(a,v) = mv[0.122 + 0.00393v + 0.000191v^2] \tag{7}$$

With Eq. (7) (Plummer et al., 1998), $p(a,12) = 2.36$kJ/s. Assuming 200 kg liquid nitrogen is used to drive the car, with the specific energy 0.242MJ/kg, its driving range is calculated to be 223 km. If the binary cryogenic media system is used, the specific energy can be 0.407MJ/kg, the driving range can be 375 km.

Assume that the coefficient of performance (COP) associated with extracting heat, Q_c, from a quantity of nitrogen gas to convert it to liquid nitrogen at atmospheric pressure is a fraction, η_{ref}, of the Carnot coefficient of performance. Thus,

$$COP = \frac{Q_c}{W_{\text{in}}} = \eta_{\text{ref}} COP_{\text{carnot}} = \eta_{\text{ref}} \frac{Q_c}{W_{\text{carnot}}}.$$

Here, W_{in} is the energy required by the cryogenic refrigerator for extracting heat, Q_c, while W_{carnot} is the minimum possible (Carnot) value for W_{in}. For the liquid nitrogen engine that operates using the atmosphere as a heat source ane a cold substance as a heat sink, the amount of heat that can be absorbed is limited, but the amount of heat available from the atmosphere is not limited. For the liquid nitrogen engine, the inverse coefficient of performance (ICOP) is a more appropriate performance parameter for characterizing the LN2 engine than the usual heat engine efficiency. Suppose that the inverse coefficient of performance associated with producing an amount of energy, W_{out}, using a quantity of liquid nitrogen is a fraction, η_{che}, of the Carnot *ICOP*. Then,

$$ICOP = \frac{W_{\text{out}}}{Q_c} = \eta_{\text{che}} \frac{W_{\text{carnot}}}{Q_c} = \eta_{\text{che}} ICOP_{\text{carnot}}$$

Thus, $W_{\text{out}} = \eta_{\text{che}} W_{\text{carnot}} = \eta_{\text{che}} \eta_{\text{ref}} W_{\text{in}}$.

Modern plants are capable of producing liquefied nitrogen at more than 40% of the Carnot value (Knowlen et al., 1997), and can exceed this even when they include the energy cost associated with the air separation process. With an LN2 engine that operates at 25% of the Carnot ICOP, the total efficiency is 10%. But if the economy is considered, the efficiency is just one factor, because the fossil crisis requires us to research the alterative for the fossil energy. Through the analysis of the driving range, total efficiency, and the advantages of the cryogenic heat engine， the prospect the of the cryogenic heat car is promising in the future（Ewald，1990）.

CONCLUSIONS

1. Theoretical analysis of the cryogenic heat engine's ideal cycle and careful consideration of the difficulties in actual application， led the authors to prefer the alteration that uses two or more cylinders to connect to each other to provide energy.

2. The total specific energy of the binary media（methane-nitrogen）cycle system could be much higher than the unitary medium（liquid nitrogen）cycle system.

3. The authors' analysis of the driving range， total efficiency， advantages of the cryogenic heat engine， and the feasibility of the liquid nitrogen car led to their conclusion that LN2 cars have promising prospects.

4. The authors' comparison of different media for cryogenic heat engines showed that liquid nitrogen is the best choice.

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