Research on LNG Vehicle Refrigeration Using Waste Cold Energy

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Abstract. In order to protect environment, traditional fuel car will be replaced by new energy car. LNG is one of the new energy that be used widely now. On the other hand, vehicle refrigerator is being used diffusely. Traditional vehicle refrigerator need automobile engine to provide extra electric energy to support its work. Indirectly, it will consume more fuel. According to the circumstance that car works, we study basic theory and experiment about recover the cold energy that LNG release during the gasification process to cooling the refrigerator. And provide theoretical direction to invent LNG zero energy vehicle refrigerator.

1. Introduction
In this paper, we put forward the basic principle of recovering and utilizing the cold energy of LNG gasification by studying the LNG automobile fuel system. The cold energy released by LNG gasification is recycled to the cooling system of the car refrigerator to realize free cooling. And we have developed a specific vehicle-mounted refrigerator. Through experimental testing, the results of its operation are consistent with the theory.

2. Basic Principle of Recovering Gasification Cooling Energy for Vehicle Refrigerator

2.1. Renovated LNG Fuel Flow
The use process of LNG is shown in Figure 1.

Figure 1. Principle Diagram of Recovery Gasification Cooling Energy Used in Vehicle Refrigerator

LNG is stored in storage tanks. When it is used, LNG at -162°C flows out of the open outlet valve and through the check valve into the heat exchanger in the cold storage tank. After absorbing heat in the heat exchanger, it enters the automotive cooling water tank for secondary heat transfer, and gasifies into...
gas at 5-10°C. Then it enters the low-pressure gas storage tank. The pressure of natural gas is controlled by a pressure stabilizing valve to meet the needs of the engine, and the gas is supplied to the engine.

2.2. Working Principle of Heat Exchanger and Cold Storage Box of LNG Vehicle Refrigerator

In the cold energy recovery system, the cold storage tank is filled with cold storage medium. The heat exchanger is completely immersed in the cold storage medium, and the LNG entering the heat exchanger absorbs heat from the cold storage medium, gasifies from the liquid to the low temperature gaseous state, and releases cold energy to the cold storage medium. The cold storage box contacts closely with the inner liner of the refrigerator and continuously supplies cooling to the refrigerator through the wall of the inner liner of the refrigerator. The storage medium in the cold storage tank needs to store the cold energy to ensure that the refrigerator can still work properly for a period of time after the car stops. Due to the limitation of refrigerator volume and required temperature, the refrigerant storage tank needs to choose the refrigerant and its usage which meets the working conditions of the refrigerator.

3. Theoretical research

Vehicles equipped with on-board refrigerators are mostly household or commercial vehicles, and self-driving or long-distance travel with high frequency of using on-board refrigerators. This paper takes self-driving travel of household cars as an example to design on-board refrigerators.

3.1. Effective Volume and Structure Form of Refrigerator

Investigation data of vehicle refrigerators [1] show that: Most consumers do not need precise temperature control and internal separation. They hope that the refrigerator material is dirty-resistant, the operation mode is simple, the shape is suitable for the car environment, and the capacity range is 10-20 L. According to the results of investigation, the effective volume of the refrigerator is 15 L, the back is set as inclined plane, the inclination angle is 65 degrees, which coincides with the inclination of the interior of the automobile tailbox, and the size of the refrigerator inner liner (length * width * height) is 300 mm * 250 mm * 200 mm.

3.2. Daily LNG Consumption of Self-driving Tour Vehicles

The data show that the volume of gaseous natural gas after gasification of 1 m³ LNG is about 650 m³ [2]. According to statistics, 1 m³ CNG can support the car to drive 11-14 km (take an average of 12.5 km), the average distance traveled by self-driving tour is 300 km, and the average driving speed of the car is 75 km/h. So the volume of LNG required for LNG car to drive for 4 hours every day is:

\[ V_{LNG} = \frac{300}{12.5 \times 650} = 0.037 m^3 \]

3.3. Daily consumption of LNG release gasification cold energy calculation

Under standard conditions, the mass of 1 m³ LNG is 426 kg, and the cooling capacity of 1 kg LNG gasification is about 840 kJ [3], so the car's daily consumption of LNG releases the gasification cold energy is:

\[ Q = 0.037 \times 426 \times 840 = 1.324 \times 10^4 kJ \]

3.4. Refrigerator unit time consumption calculation

The storage function of the LNG vehicle refrigerator is the same as that of the ordinary vehicle refrigerator. At present, the average power consumption of the ordinary 15 L vehicle refrigerator is about 1.0 kW·h for 24 hours, and the energy efficiency ratio is about 2.6 [4]. The refrigerator needs to work for 1 hour. Then the cold energy that the refrigerator needs to work for an hour is:
3.5. Cold storage tank cooling calculation
According to the use of the car refrigerator and the results of the poll, the refrigerator can be normally cooled within 4 hours after the car stops driving. Then the required cooling capacity for the 4-hour refrigerator is: 4×390 = 1560 kJ.

According to the literature, the cold storage tank cooling efficiency, the cooling efficiency and the cold retention rate are 80%, and the cold storage tank capacity is:

\[ Q_c = \frac{1560 \times 80\% \times 80\%}{80\%} = 3046.875 kJ \]

3.6. Selection and usage calculation of cold storage materials
Refrigeration temperature required for on-board refrigerators is relatively low (0-5°C). Considering its small volume, phase change materials with large cold storage coefficient should be selected. According to this requirement, pure water is selected as the cold storage material in this paper. The phase transition temperature of pure water is 0°C, and the latent heat of phase change is 335 kJ/kg [5]. The amount of water required in the cold storage tank is:

\[ \frac{3046.875}{335} = 9.095 kg \]

3.7. Heat exchanger selection and heat exchange area design

3.7.1. Heat exchanger selection. Considering the use of LNG car refrigerator heat exchanger, the plate-fin tube heat exchanger should be selected, the schematic diagram is shown in Figure 2. The heat exchanger is made of ACR single-row copper tube with aluminum inner diameter of 8 mm. The aluminum string fins are connected by a fixed plate, and the heat exchange tube is LNG. The water flows between the outer fins and is cooled to solidify into ice.

![Figure 2. Heat exchanger schematic](image)

3.7.2. Heat Exchanger Design. The heat absorbed by heat exchangers is usually calculated by logarithmic mean temperature difference method [6]. The calculation formulas are as follows:

\[ Q = \int_{F}^{\Phi} K \Delta t dF + W_{LNG} \cdot c_p \cdot \rho \]

The total heat transfer coefficient can be calculated by the following formula:
In the middle: $Q$——The heat absorbed by LNG in the heat exchanger (W).

$K$——Total heat transfer coefficient of heat exchanger[W/(m$^2$·℃)].

$\Delta t$——Average temperature difference after LNG gasification into CNG(℃).

$W_{LNG}$——Mass flow of LNG (kg/s).

$c_p$——Constant pressure specific heat of LNG[kJ/(kg·℃)].

$\gamma$——Latent heat of vaporization of LNG (kJ/kg).

$F$——Total heat exchange area of the heat exchanger (m$^2$); $F = F_T + F_f$.

$F_T$——Heat Exchange Area of Heat Exchanger Tube (m$^2$).

$F_f$——Fin heat transfer area (m$^2$).

$$F_f = 2n_f \left[ H \times W - N_f \eta \pi \left( \frac{d_o^2}{2} \right)^2 \right]$$

$$F_T = N_f n_f \pi d_o (L - \delta_f n_f)$$

$F_T$——Heat Exchange Area of Heat Exchanger Tube (m$^2$).

$n_f$——Fin number.

$n_t$——Number of heat pipes per row.

$N_r$——The number of rows of heat exchange tubes, the value of this paper is 1;

$\tau$——Radius of heat exchange tube (m).

$\varphi$——Viscosity correction factor.

$d_0, h_0, R_{f,0}, d_i, h_i, R_{f,i}$ is Heat exchange tube inner diameter, Convective heat transfer coefficient of pipe fluid, Thermal resistance inside the pipe, Tube outer diameter, Convective heat transfer coefficient of external fluid, Thermal resistance inside the pipe, respectively; $H, W, L$ represent the length, width and height of the heat exchanger, respectively.

The structural dimensions of heat exchangers can be obtained by substituting the data from 3.1-3.6 into formula (1) - (4), as shown in Figure 2.

### 3.8 Volume calculation of cold storage tank

The volume required to store pure water is 9.095L. Considering the increase in volume after water condenses into ice: 9.095÷0.9=10.1L. Because the heat exchanger is completely immersed in the cold storage box, the volume of the heat exchanger is about 0.35L, the volume of air contained is 1.25L, so the required volume of the cold storage box is 11.7L. Its shape is right-angle trapezoidal and its size is 139mm * 220.8mm * 200mm (upper bottom * lower bottom * height). Its width is the same as that of the inner liner of the refrigerator, and it is 325mm.

The basic structure size of the refrigerator is shown in Figure 3.

![Figure 3. Refrigerator Structure Dimension and Profile](image-url)
4. Experiment
According to the basic principle of Figure 1 and considering the safety problem, this experiment is set up in a LNG refitting station, and a refitted car is used to simulate the operation condition. The car is equipped with a 70L LNG tank, two bottles of mineral water, two bottles of canned drinks and two apples in the refrigerator. The driving wheel is suspended at a fixed speed of 75 km/h. Because of the large cold energy and fast gasification speed of LNG gasification, the engine was only allowed to run continuously for 2 hours. The wall temperature of the refrigerator, the air temperature of the refrigerator, the temperature of the cooling water tank of the automobile and the temperature of the engine intake were tested respectively (see Table 1 below), and the external condition of the LNG gas supply pipeline was observed at the same time.

| Temperature location | Refrigerator inner wall | Air in refrigerator | Water temperature of cooling water tank | Engine intake |
|----------------------|--------------------------|---------------------|----------------------------------------|---------------|
| Temperature / °C     | -4.2                     | -0.7                | 43                                     | 12.3          |

LNG gas supply pipeline is no longer insulated after it comes out of heat exchanger. Observing its appearance, it is found that there is ice in a long section of pipeline after it comes out of heat exchanger. In addition, the cooling fan did not start because of the low water temperature of the cooling water tank. This shows that besides the use and storage of some cold energy in the refrigerator, more cold energy is released to the cooling water tank.

5. Conclusion
This paper studies the basic theory of recycling the cold energy released from LNG gasification into the refrigeration system of vehicle refrigerators, and verifies its feasibility through experiments, and draws the following conclusions:

1. LNG vehicle-mounted refrigerator can effectively store the cold, the storage tank has a large degree of supercooling, and the effect of energy saving is obvious.

2. In addition to refrigerators, most of LNG gasification cooling energy is used for cooling water tanks. If the space of the trunk is allowed, the refrigerator with larger capacity can be supported.

3. The cooling fan does not start and does not need power supply, thus reducing the fuel consumption of automobiles. Enlarging the cold storage capacity of the cold storage box can make the refrigerators on the car still provide normal cooling for a longer time after the car stops.

4. Enlarging the cold storage capacity of the cold storage box can make the refrigerators on the car still provide normal cooling for a longer time after the car stops.

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