Study on roof-mounted radiant cooling system for LNG-fueled refrigerated vehicles

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Abstract

A roof-mounted radiant cooling system incorporating a bypass structure, intended for use on liquid natural gas (LNG)-fueled refrigerated vehicles and offering stable dynamic regulation was designed. A model was established using the TRNSYS software package to simulate the operation of this system, and the effects of various factors on the refrigeration performance were analyzed. The quantitative relationship between the LNG flow rate and the ambient temperature was determined and a dynamic regulation strategy proposed. The results of this work show that, when the vehicle is operated at an economical speed, the cooling capacity provided by the system is greater than 1.2 kW, which meets the requirements for a refrigerated vehicle. The dynamic regulation approach developed in this study was found to allow use of the refrigerated vehicle under different climatic conditions and to improve the stability of the cooling system.

Keywords: TRNSYS, LNG cold energy utilization, refrigerated vehicle, radiation, cooling system

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1. INTRODUCTION

In recent years, there has been an increasing demand for cleaner energy sources [1]. Liquefied natural gas (LNG), which is the cleanest fossil fuel, has therefore received significant attention and has been widely used as an energy source in many different applications [2]. LNG is a cryogenic liquid [3] obtained through first purifying natural gas produced in the field (by removing heavy hydrocarbons, sulfides, carbon dioxide, water and other impurities) and then cooling the gas to $-162^\circ$C [4] at atmospheric pressure by means of cryogenic refrigeration. LNG is colorless, tasteless, non-toxic, non-corrosive [5] and its volume is reduced from that of the original gas by a factor of $\sim 600$ [6], which permits more efficient long-distance transportation. LNG is typically transitioned back to a gaseous state prior to use, which involves the exchange of $\sim 850.3$ to 914.5 kJ/kg of cold energy. Thus, a receiving station processing 3 million tons of LNG per year will exchange on the order of 80 MW of cold energy if the LNG is gasified continuously and evenly [7]. The utilization of this energy could potentially reduce some of the energy consumption and environmental pollution presently caused by mechanical refrigeration [8] and thus would have significant economic benefits and social value.

In recent years, the number of LNG vehicles in use has increased rapidly, and the application of LNG cold energy in ships, heavy trucks, buses and refrigerated vehicles has attracted much interest [9]. Gómez \textit{et al.} [10] proposed a new design for a boil-off gas liquefaction process that incorporates the recovery of cold energy from the LNG carrier. Through an energy and exergy analysis, a thermodynamic model was established that demonstrated improvements in the coefficient of performance (COP) and operating efficiency of 22.22\% and 19.35\%, respectively, based on this new concept. Wang \textit{et al.} [11, 12] designed an air conditioning system to recover the cold energy from an...
LNG-powered refrigerated heavy truck under the conditions associated with the actual use of this type of vehicle. Their results showed that the cooling capacity values during both uphill transport and at rest exceeded the minimum 3.5 kW cooling capacity requirement, and a certain amount of cold energy is stored. The use of a practical refrigeration regulation system as well as dynamic control of the air conditioning system under all road conditions allowed stable cab refrigeration in the vehicle. Deng et al. [13] studied automotive air conditioning systems based on heat pipes and LNG cold energy and found a refrigeration capacity of 4.2 kW under specific working conditions. Wei et al. [14] reported a low temperature air supply process and supercooling cycle based on LNG cold energy for use in air conditioning systems for buses. They concluded that the refrigeration capacity and COP of the system were increased by 2.7–3.3 kW and 6.8–8.6%, respectively, as a result of implementing a low temperature air supply, while these same two variables were increased by 3.4 kW and 18.2% during the supercooling cycle. Hongbo et al. [15] analyzed the feasibility and refrigeration performance of a self-refrigerated vehicle that recovered cold energy from LNG fuel and concluded that the refrigerated compartment could be kept below −20°C under certain operating conditions. The temperature field uniformity and temperature drop characteristics of the refrigerated compartment were also determined to be satisfactory. Zhang et al. [16] examined the utilization rate of LNG cold energy in refrigerated vehicles as well as the effect of adding a heat pipe cold recovery heat exchanger. Fadhel et al. [17] assessed a novel use for LNG cold energy utilization that liquefies air to be used in road vehicles, and it was pointed out that developing a new thermal approach to provide cold to both buildings and vehicles with near zero carbon emissions and avoiding the drawbacks of batteries was compelling. Han et al. [18] presented the energy analysis and multi-objective optimization of waste heat and cold energy recovery process in LNG-fueled vessels. The optimization results of different heat and cold sources as well as the design parameters had been discussed.

The technologies to utilize the LNG cold energy have received significant attention over recent decades, various studies on the current LNG cold energy utilization systems has been given, including power generation, air separation, desalination, cryogenic carbon dioxide capture and LNG recovery. Recovering LNG cold energy on cold chain for food transportation, data center cooling and hydrate-based desalination is very promising, especially, developing a new thermal approach to provide cold to vehicles with near zero carbon emissions is compelling [19]. At present, the majority of research concerning systems for the utilization of cold energy in LNG-fueled refrigerated vehicle focuses on the design of the heat exchanger and the overall system structure, but does not address dynamic control strategies or radiative refrigeration. The present work paper proposes a radiant cooling system installed on the roof of an LNG-fueled refrigerated vehicle in conjunction with a bypass structure. The effects of various factors on the refrigeration performance and the dynamic regulation strategy for this cooling system under different climatic conditions are examined in this study.

2. DESCRIPTION OF THE COOLING SYSTEM

The model refrigerated vehicle considered in this research is assumed to transport strawberries in the Haikou of China and the size of refrigerated is considered as $x = 4000 \text{mm}$, $y = 1900 \text{mm}$, $z = 1900 \text{mm}$ with a total refrigeration cooling load of 1.06 kW. According to the feasibility analysis, the actual cooling energy recoverable from the LNG vaporization process is 1.59 kW, assuming 30% efficiency. Thus, the cooling energy that can be recovered during the LNG gasification process is higher than the total required refrigeration cooling load and so could possibly meet the refrigeration demand for this type of vehicle.

On this basis, we designed a radiant cooling system for the roof of an LNG-fueled refrigerated vehicle, incorporating a bypass structure [20]. As shown in Figure 1, the main components of this unit include an LNG cylinder, solenoid valve, three-way valve, sleeve-type heat exchanger, bypass tube, pump, radiative structure, heater, engine and controller.

In this system, the LNG initially flows out of the cylinder and passes through the solenoid and three-way valves. One exit path from the three-way valve enters the sleeve-type heat exchanger and exchanges heat with the low temperature phase-free coolant, while the other directly enters the heater through the bypass tube. The sleeve-type heat exchanger is equipped with a coolant tank that has an injection port in its upper part and an alarm at its base to indicate when the liquid level in the coolant tank is low. During normal operation of this system, coolant flow into the tank through the injection port. The lack of an alarm confirms that a minimum level of coolant is contained in the tank to ensure a sufficient supply of refrigerant throughout the whole unit and the absence of air in the lines. This also avoids the expansion of coolant during the heat transfer process. The LNG streams converge where the outlet of the sleeve-type heat exchanger meets the bypass tube. Following that point, the LNG acts as fuel for the engine after passing through the heater. Subsequent to heat exchange with the LNG, the coolant enters the radiative structure to provide cooling to the refrigerated compartment in the vehicle. The solenoid valve, three-way valve and pump are electrically connected to the controller.

Assuming that the air temperature in the vehicle is 5°C, if the temperature returned by the temperature sensor is greater than or equal to 0°C, the LNG exiting the cylinder enters the sleeve-type heat exchanger through the solenoid and three-way valves. This results in heat transfer with the cryogenic coolant without phase change. In contrast, if the temperature returned by the sensor is below 0°C, the LNG bypasses the heat exchanger. In this case, the LNG directly enters the bypass pipe through the three-way valve and is transitioned to a gas in the heater. After heating to the desired combustion temperature, this gas provides fuel for the engine.

This system employs a cryogenic phase-free coolant. Following heat exchange with the LNG, the temperature of the coolant is lowered, and it is sent to the interior of the refrigerated vehicle where it passes through the radiative panel. This provides the appropriate air temperature in the vehicle so as to satisfy the
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recreation requirements. The radiative structure consists of insulation material, a coolant pipeline and a radiant panel. The coolant pipeline is located between the insulation at the top and the radiant panel at the bottom, which is situated over the top of the carriage and also over one quarter of the upper parts of both sides of the vehicle.

Legend: 1 = LNG cylinder, 2 = solenoid valve, 3 = three-way valve, 4 = temperature sensor, 5 = sleeve-type heat exchanger, 6 = bypass tube, 7 = coolant tank, 8 = alarm, 9 = injection port, 10 = pump, 11 = radiation structure, 12 = heater, 13 = engine, 14 = controller.

3. SIMULATION MODEL

Using the TRNSYS software package, a model simulating the proposed radiant cooling system on the roof of an LNG-fueled refrigerated vehicle during the months of April to September was constructed. Figure 2 showed the flow chart for the model used to simulate a radiant cooling system on the roof of an LNG-fueled refrigerated vehicle. This software offered to users to specify the components that constitute the system and to realize the connection between these models. Each component (type) was characterized by a number of PARAMETERS, INPUT parameters and OUTPUT parameters. The connection between models was performed through a flow chart and a given output parameter of a type could be used as input parameter to any number of other types. Compared to other simulations codes of thermal behavior such as, CODYRUN and EnergyPlus, TRNSYS software was identified as the most suitable energy simulation program in case of assessing novel cooling systems or non-typical configurations of the cooling systems [21]. This model included multi-zone building, parallel flow, differential controller, pump, TMY2 and equation components. The cooling capacity of LNG-fueled refrigeration and heat exchange in the sleeve-type heat exchangers were given in type5a of TRNSYS software package. The outdoor temperature could be obtained by using type5-2 component, which would read the data from external weather data. The use of TRNSYS as a tool to simulate radiant cooling systems had been widely researched and documented with numerous studies in a variety of locations. The software had also been validated by comparison to experimental radiant cooling system that was constructed at a laboratory room in Bang Kun Tien Campus, King Mongkut's University of Technology Thonburi. TRNSYS was used to simulate the operations of the radiant cooling system using the whole year tropical climate data. The study results demonstrated that the cooling panels, temperatures of interior surface and chilled water supply and the operation of the radiant cooling system using TRNSYS was demonstrated with an acceptable level of accuracy [22].

According to the operational characteristics of an LNG-fueled refrigerated vehicle and the design requirements of the cooling system, the operational parameters of each component of the system were set as follows. The multi-zone building was used to model the radiant structure and because this unit was affixed to the roof of the vehicle, a metal radiant panel was added to roof through the wall type manager in TRNBuild. This was done by selecting chilled ceiling to modify the specific heat of the fluid, following which the temperature and flow rate of the fluid flowing into the radiant panel were defined.

Parallel flow was used primarily to simulate the heat exchange between the coolant and the LNG. During these simulations, the inlet temperatures and flow rates at the source and load side were defined. The inlet temperature for the LNG was set to $-120^\circ\text{C}$ while the LNG flow rate was dependent on the speed and load of the refrigerated vehicle. The inlet temperature of the coolant was set to 5$^\circ\text{C}$ and the coolant flow rate varied with the LNG flow rate, within the range of 50–90 kg/h.
The differential controller was employed primarily to control the air temperature in the vehicle. The differential controller was an on/off differential controller, which generates a control function whose value can be 1 or 0. By setting the minimum input temperature and the upper and lower limits of temperature difference control, the purpose of refrigeration was achieved. When transporting fresh strawberries, the optimum refrigeration temperature is in the range of $-1$–$2^\circ{\text{C}}$, and so the differential controller parameters were set so as to maintain the air temperature between $0.5$ and $1.5^\circ{\text{C}}$. During the calculations, the air temperature in the insulated compartment was taken as the upper input temperature, $T_h$, while the lower input temperature, $T_l$, was set to $0^\circ{\text{C}}$. When $T_h - T_l > 1.5^\circ{\text{C}}$, the output signal is 1 and the cooling system starts up, while in the case that $T_h - T_l < 0.5^\circ{\text{C}}$, the output signal is 0 and the cooling system shuts down.

Various equations were used to calculate the cooling capacity of the system. In this design, in which the cooling agent flows through the roof of the carriage after undergoing a thermal energy transfer with the LNG, there are two types of cooling. One is the cooling capacity of the system ($Q$) resulting from the refrigerant entering the roof of the vehicle, while the other is the radiative cooling capacity of the roof ($q_r$) that results from both radiation and convection from the roof itself [23].

The value of $Q$ can be calculated as:

$$Q = c_p \times m \times (T_2 - T_1).$$

The total cooling capacity per unit area of the cold radiant panel was calculated as the sum of radiative cooling capacity and convection cooling capacity:

$$q = q_r + q_c,$$

where $q$ was the sum of the radiative cooling capacity per unit area, $q_r$, and the convective cooling capacity per unit area, $q_c$. The American society of heating, refrigerating and air-conditioning engineers (ASHRAE) calculation method was used to calculate radiate cooling capacity per unit area and the convective cooling capacity per unit area. These two variables are defined as [22]:

$$q_r = 5 \times 10^{-8} \times \left[ \left( \frac{St + 273}{100} \right)^4 - \left( \frac{t + 273}{100} \right)^4 \right]$$

$$q_c = 2.13 \times (t_a - t)^{1.31}.$$  

4. RESULTS AND DISCUSSION

4.1. Factors affecting the cooling capacity

4.1.1. Relationship between LNG flow and cooling capacity

Figure 3 depicts the relationship between the LNG flow rate and the cooling capacity of the system at a coolant flow rate of 70 kg/h in Haikou area on April 9. It is evident that increasing the flow rate significantly raises the cooling capacity of the radiant cooling system on the roof of the LNG-fueled refrigerated vehicle. In addition, at all flow rates, the total cooling capacity is maintained above 1.2 kW, which satisfies the cooling demand of 1.06 kW. As the flow rate is increased from 5.5 to 9.9 kg/h (due to an increase in vehicle speed or load), the cooling capacity is raised in an approximately linear manner, from 1.24 to 2.46 kW. Overall, the cooling capacity of the system increases by 0.28 kW with each 1 kg/h increase in the LNG flow rate.

4.1.2. Relationship between the coolant flow rate and the radiant panel inlet/outlet temperatures and cooling capacity

Figure 4 summarizes the relationships between the coolant flow rate and the inlet and outlet temperatures of the radiant panel as well as the cooling capacity of the system, all at an LNG flow rate.
rate of 8.8 kg/h. As the coolant flow rate increases, the inlet temperature of the radiant panel also increases, while the outlet temperature decreases and the cooling capacity of the system increases slightly. Specifically, upon raising the coolant flow rate from 50 to 90 kg/h, the inlet temperature increases from −29.22 to −25.35°C, the outlet temperature decreases from −12.43 to −15.47°C and the cooling capacity of the system improves from 1.97 to 2.09 kW. An increase in the coolant flow rate of 1 kg/h raises the inlet temperature of the radiant panel by 0.097°C and decreases the outlet temperature by 0.076°C while increasing the cooling capacity of the system by 0.003 kW. Increasing the coolant flow rate also reduces the temperature difference between the panel inlet and outlet, although the cooling capacity of the rooftop cooling system still exhibits an upward trend.

4.1.3. Relationship between ambient temperature and cooling capacity
Figure 5 depicts the relationship between the external ambient temperature and the cooling capacity of the system based on the recorded temperatures between 7:00 and 20:00 in this region of China on April 9. The data in this figure were obtained using an LNG flow rate of 8.8 kg/h and coolant flow rate of 70 kg/h. The ambient temperature is seen to first rise and then decrease, with a maximum temperature of 35.3°C at 1500. As the external temperature varies, the cooling capacity of the unit initially increases, followed by a slight decrease, another increase and finally a continuous decrease, producing two peaks. The first peak appears at 12:00 and an ambient temperature of 34°C can be explained by the maximum solar radiation at this point in time. The second peak is located at 15:00 at an ambient temperature of 35.3°C, representing the highest temperature during the time period assessed. These data demonstrate that, under these conditions, the cooling capacity of the system can meet the minimum requirements to maintain the air temperature of the unit at ∼0°C.

4.2. Factors affecting the radiant cooling capacity
Figure 6 depicts the relationships between the radiant roof temperature, air temperature and radiant cooling capacity of the roof-mounted unit at an LNG flow rate of 8.8 kg/h and a coolant flow rate of 70 kg/h. These data show that decreasing the radiant roof temperature initially leads to a slight increase in the air temperature, following which the air temperature rapidly decreases to ∼0.5°C and remains at that value. In addition, the cooling capacity of the roof-mounted unit rises rapidly and then plateaus. The air temperature increases as a result of the higher radiation roof temperature as well as the reduced temperature difference between the radiation roof and the air. The cooling capacity decrease is attributed to the decreased rate of heat transfer from the radiant panel. In this data set, the radiation roof temperature decreases from 1.08 to −9.85°C, while the air temperature first rises from 1.54 to 1.56°C, then gradually decreases to 0.51°C and
4.3. The quantitative relationship between LNG flow and ambient temperature

Figure 7 plots the LNG flow as a function of the ambient temperature on April 9, at a coolant flow of 70 kg/h. According to the meteorological data, the temperature variation between 7:00 and 20:00 in this region of China is from 27°C to 34°C. Here, the red line represents a straight line fit to the data.

As the external temperature increases from 27 to 34°C, the LNG flow increases from 4.5 to 5.1 kg/h. Over this same temperature range, the cooling capacity of the system increases from 0.92 to 1.12 kW and thus would be able to satisfy the cooling demand for the vehicle. At ambient temperatures above 34°C, the maximum cooling capacity of the unit is 1.06 kW at an LNG flow rate of 5.1 kg/h, which is able to meet the cooling demand. The quantitative relationship between the LNG flow rate and the ambient temperature is:

\[ y = \frac{3.07 + 0.02x + 0.001x^2}{5.1} \quad (4) \]

This equation allows dynamic regulation of the LNG flow based on the external temperature. In the formula, y is LNG flow rate and x is ambient temperature. Between 27 and 34°C, the LNG exchanges heat with the coolant at a flow rate of \( y = 3.07 + 0.02x + 0.001x^2 \) to cool the refrigerated compartment, while LNG in excess of this amount enters the heater directly through the bypass pipe to provide fuel for the engine. In contrast, when the external temperature is in excess of 34°C, the LNG exchanges heat with the coolant at a set flow rate of 5.1 kg/h. This is because the heat insulation effect of the refrigerated truck, the increase of air temperature in the insulated compartment becomes relatively small as the external temperature is in excess of 34°C. Hence, the actual demand for cooling capacity has no significant increase in this condition, and the LNG exchanges heat will meet the demand as the coolant flow rate is given as 5.1 kg/h.

5. CONCLUSIONS

The performance of a roof-mounted radiant cooling system designed for LNG-fueled refrigerated vehicles was simulated and analyzed using the TRNSYS software package. The main results can be summarized as follows.

(1) The simulation data show that when the refrigerated vehicle is operated at an economical speed in the range of 60–80 km/h, which means that better fuel consumption performance can be obtained in this running speed for the LNG-fueled refrigerated vehicles. The LNG flow rate varies from 6.6 to 8.8 kg/h. Under these conditions, the cooling capacity of the refrigeration system is in the range of 1.56–2.17 kW and so can meet the cooling capacity requirements for a refrigerated vehicle transporting strawberries in the Haikou region.

(2) The cooling capacity of the system increases as the LNG flow rate, coolant flow rate and ambient temperature are increased. The radiative cooling capacity of the roof-mounted unit is determined by the radiation roof temperature and air temperature. Specifically, higher air temperatures and lower radiation roof temperatures increase the cooling capacity.

(3) An analysis of the relationship between cooling capacity and the LNG flow under different climatic conditions allowed a dynamic regulation strategy to be developed. At ambient
temperatures from 27 to 34°C, the LNG draws heat from the coolant at a flow rate of $y = 3.07 + 0.02x + 0.001x^2$ to ensure that the refrigerated compartment is held at the required temperature. The LNG flow in excess of this amount directly enters the heater via the bypass pipe to fuel the engine. Above 34°C, the LNG exchanges heat with the coolant at a set flow rate of 5.1 kg/h to cool the vehicle.

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