Journal of Southeast University (English Edition) Vol. 26, No. 2, pp. 316 – 319 June 2010 ISSN 1003—7985

Comparison of two schemes for district cooling system utilizing cold energy of liquefied natural gas

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Abstract: Two schemes (scheme Ⅰ and scheme Ⅱ) for designing a district cooling system (DCS) utilizing cold energy of liquefied natural gas (LNG) are presented. In scheme Ⅰ, LNG cold energy is used to produce ice, and then ice is transported to the central cooling plant of the DCS. In scheme Ⅱ, return water from the DCS is directly chilled by LNG cold energy, and the chilled water is then sent back to the central plant. The heat transportation loss is the main negative impact in the DCS and is emphatically analyzed when evaluating the efficiency of each scheme. The results show that the DCS utilizing LNG cold energy is feasible and valuable. The cooling supply distance of scheme Ⅱ is limited within 13 km while scheme Ⅰ has no distance limit. When the distance is between 6 and 13 km, scheme Ⅱ is more practical and effective. Contrarily, scheme Ⅰ has a better economic performance when the distance is shorter than 6 km or longer than 13 km.

Key words: district cooling system; liquefied natural gas (LNG); cold energy utilization; system efficiency

The global trade in liquefied natural gas (LNG) has been increasing rapidly during recent years. At receiving terminals, LNG is vaporized for final transmission to consumers. Because of the huge temperature difference between LNG (about −162 ℃) and the atmosphere, about 840 kJ/kg of cold energy can be released during the regasification process of LNG. The utilization of LNG cold energy is of vital importance for energy saving. A lot of work has been done in this area, such as a reduction in the CO_2 emission[1], refrigeration and air-conditioning, air liquefaction and separation, cryogenic power generation[2–3], and so on.

A district cooling system (DCS) is a massive and effective cooling supply system. In this system, coolant, usually the chilled water, is produced in a remote central chiller plant, and then delivered to separate buildings and facilities through a closed-loop piping network. Finally, it is distributed to air-conditioning equipment to exchange the heat with the indoor air, which can meet the demands of human comfort. The overall system efficiency of the DCS is higher than that of the individual chiller plants installed in a single building. The concentration effect and the high grade of operation are the most prominent advantages of the DCS. In spite of these advantages, there are not as many successful experiences of the DCS as expected. The utilization of natural cold energy is the key to the successful implementation of the DCS. The cold energy released from LNG can provide a nearly cost-free solution to this problem. This paper presents two schemes for the DCS utilizing the cold energy of LNG.

1 Feasibility Study

1.1 Daily cooling load and natural gas load estimation

In this study, all the buildings are regarded as in an integrated DCS; the differences among the categories of the buildings are not taken into account[4]. A typical DCS is established, and the operation is stimulated on July 15th. Fig. 1 shows the hourly variations of the cooling load factor during a day. The cooling load at 14:00 is assumed as the full load, so the cooling load factor at 14:00 is set to be 1. It can be seen that the cooling load of the DCS varies significantly during a day and the peak period is between 8:00 and 23:00[5].

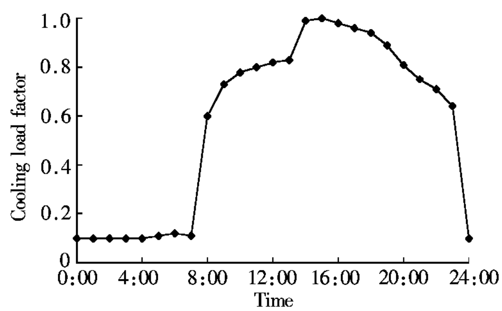

Fig. 1 Hourly variations of the cooling-load factor during a day

To investigate the difference between hourly variations of the cooling load and those of the natural gas load during a day, a Chinese inland city is modeled, where only domestic and commercial need of natural gas is considered because most industrial natural gas transmission systems are separated from others. Fig. 2 shows the hourly changes of the natural gas load factor of this model and the factor at 18:00 is set to be 1. In this figure, the natural gas load reaches its peak values 3 times, and most of the load is concentrated in two different time periods: 6:00 to 12:00 and 16:00 to 20:00[6].

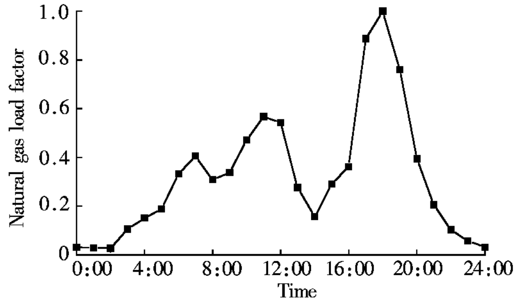

Fig. 2 Hourly variations of the natural gas load factor during a day

Received 2009-11-17.

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Citation: Wang Tao, Lin Wensheng, Gu Anzhong. Comparison of two schemes for district cooling system utilizing cold energy of liquefied natural gas[J]. Journal of Southeast University (English Edition), 2010, 26(2): 316 −319.

Figs. 1 and 2 exhibit the differences of the moment that the two loads reach the peak values and the differences of the load distribution characteristics. Aiming to match the cooling supply with the cooling load, at least one cooling storage medium or equipment is designed. Compared with the temperature-change cooling storage system, a phase-change cooling storage system can store much more cold energy.

1.2 Scheme design

Based on the rational match between the natural gas load and the cooling load, two schemes are designed for utilizing LNG cold energy. Here, ice is selected as the cooling storage medium.

In scheme Ⅰ, LNG is first regasified by a secondary refrigerant. Then the cold energy of the refrigerant is used to produce ice, which is stored or transported directly to the central cooling plant of the DCS. The water is chilled by ice in the central cooling plant and subsequently delivered to separate buildings and facilities.

In scheme Ⅱ, the processes are similar to scheme Ⅰ before ice is produced. The only distinction between them is the transport method of the cold energy from the LNG vaporizing station to the central cooling plant of the DCS. In scheme Ⅱ, the cold energy of the ice is used to chill the return water delivered from the central cooling plant to produce chilled water. After that, the chilled water is sent back to the central plant through cold water supply pipelines. Finally, it is distributed to separate buildings and facilities.

The processes of producing ice are similar in these two schemes. Two kinds of circuit plans are designed for ice-making: a phase-change flow process and a non-phase-change flow process. A pump is used as a power source in these processes.

1.3 Selection of secondary refrigerant

The selection of the secondary refrigerant has a major influence on the performance of the processes, and economical efficiency should be also taken into consideration. Tab. 1 shows the physical properties of some widely-used refrigerants.

Tab. 1 Physical properties of widely-used refrigerants ℃

Refrigerant	Boiling point	Freezing point
R23	−78.2	−100.7
R410A	−51.5	−155.0
R407C	−43.6	−115.0
R170	−88.6	−183.2
R290	−42.1	−187.7
R1150	−103.7	−169.5
R1270	−47.7	−185.0
R600	−42.2	−187.1

The principles of selecting secondary refrigerants are as follows:

1) The freezing point of the selected refrigerant should be lower than or, at least, not much higher than that of methane (−162 ℃). A too high freezing point can lead to "ice block" which results in abnormal operations of the system.

2) The cost of the refrigerant should be as low as reasonably possible.

3) If the refrigerant is used in the phase-change flow process, the boiling point corresponding to a maximum allowed pressure of the system should be close to 0 ℃ because ice-making equipment may not be applicable at a too low temperature.

For the reasons mentioned above, propane is selected as the secondary refrigerant.

1.4 Process simulation and flow process selection

In this simulation, an importing LNG receiving terminal in a city of southern China is regarded as the cold source. The maximum gas transmission volume is 8.2×10^5 m^3/h (under normal temperature and pressure conditions), while the minimum is 7.729×10^4 m^3/h (under normal temperature and pressure conditions). When the energy losses in processes, such as heat exchange and ice producing processes, are taken into account, cryogenic energy in half of the average gas transmission (190 t/h) can be absorbed by the secondary refrigerant in this simulation. When the cold energy loss is taken into account, 293.6 t ice is produced per hour. The HYSYS simulation program is used to study the processes of LNG gasification. Fig. 3 describes the cooling supply processes of the two schemes.

Tab. 2 Parameters of phase-change and non-phase-change flow processes in Fig. 3

Parameter	Point 1		Point 2		Point 3	
	Phase-change	Non-phase-change	Phase-change	Non-phase-change	Phase-change	Non-phase-change
Phase	Vapor	Liquid	Liquid	Liquid	Liquid	Liquid
Temperature/℃	−10.0	−10.0	−100.0	−100.0	−99.9	−99.9
Pressure/kPa	345	1 100	245	1 000	445	1 200

Tab. 2 shows the main parameters of the phase-change and non-phase-change flow processes. The mass flow of LNG is set to be 190 t/h. The main difference in the simulation results of these two processes is the volume flow of the secondary refrigerant. The standard ideal liquid flow rate of the secondary refrigerant in the phase-change flow process is 64.6 kg/s while that in the non-phase-change flow process is 197.8 kg/s. Therefore, the diameter of the pipe in the non-phase-change process is 1.75 times that in the phase-change process. The volume flow rate of the gaseous secondary refrigerant in the phase-change process is 89 times as much as that of the liquid. So the diameter of the pipes and the size of the heat exchange need to be increased. Besides, the non-phase-change flow process is more stable. For the reasons mentioned above, the non-phase-change flow process is selected.

1.5 Economic verification and comparison

In this study, the two schemes are similar except for the long distance transportation mode of the coolant. So the

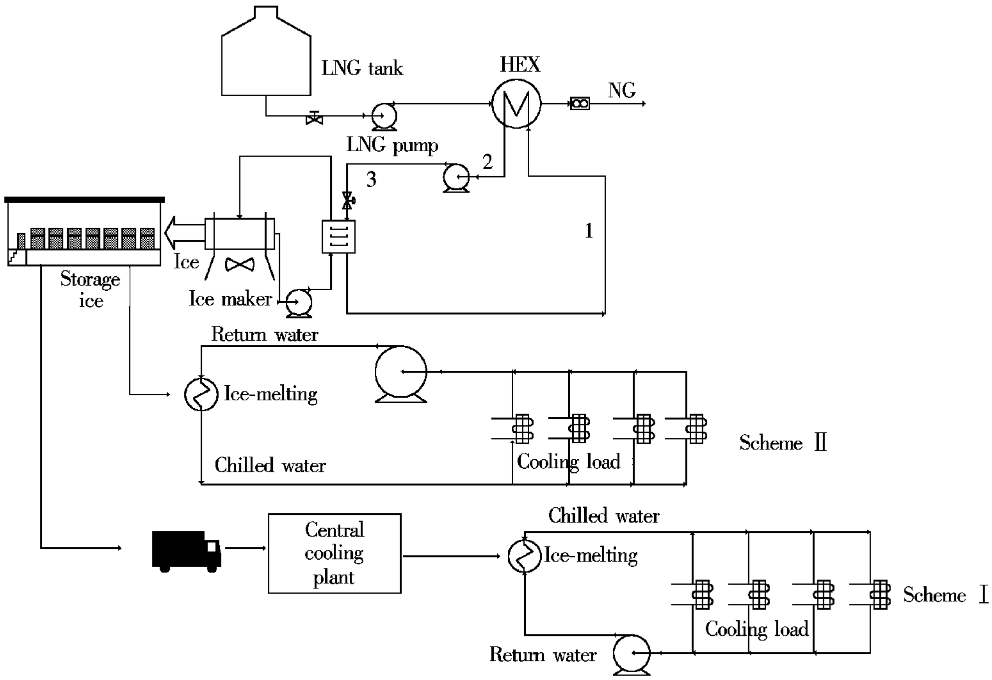

Fig. 3 Flow diagram of two schemes

comparisons are focused on the initial investment cost and the operation cost of the coolant transportation processes. It is assumed that there is no loss of refrigerating capacity in scheme Ⅰ. The loss of the refrigerating capacity in scheme Ⅱ is dependent on the distance between the LNG vaporizing station and the central cooling plant of the DCS. Thus, the refrigerating capacity of scheme Ⅰ is a little greater than that of scheme Ⅱ. In order to better understand the advantages and disadvantages of these two schemes, a comparative study is carried out with different distances. The cooling area that each scheme can supply is calculated on the basis of the refrigerating capacity and the cooling demands of the DCS. The cooling load is estimated as 150 W/m^2. The annual cost per unit area (ACPUA) is used to evaluate these two schemes. It is assumed that the system operates 4 months a year and runs 15 h a day, which means that the annual operation time of this system is estimated as 1 800 h.

2 Results and Discussion

The main cold energy loss in scheme Ⅱ is the heat exchange between the pipelines and the surroundings. The estimated cold energy loss in the chilled water pipeline is 0.03 ℃ per 100 m while that in the backwater pipeline is 0.01 ℃ per 100 m. Therefore, the distance between the vaporizing station and the DCS is limited by the cooling loss in the pipelines. The chilled water obtained by the separate buildings should be below 7 ℃. As a result, the temperature of the chilled water arriving at the central cooling plant is required to be no higher than 5 ℃. To ensure this, when the temperature of the chilled water from the gasification station is set to be 1 ℃, the maximum cooling supply distance in scheme Ⅰ is 13 km. That is, the comparison is made in the distance range from 1 to 13 km.

In scheme Ⅰ, a low-temperature logistic company is employed to transport ice, and the transport cost is 1 yuan/(t·km). 293.6 t ice is transported every hour. The operation cost can be calculated when the cooling supply distance is known.

The operation cost of scheme Ⅱ consists of the power consumption of the pumps, the maintenance cost and the depreciation expense of the pumps and pipeline. The power consumption of the pumps can be calculated by

$$P = \frac{RLQ}{\eta} \tag{1}$$

where R is the friction pressure loss; L is the length of the pipeline; Q is the volume flow of water; η is the pump efficiency. Here, R is estimated at 60 Pa/m, and η is 0.65. The electricity price is set to 0.6 yuan/(kW·h).

The inside diameter of the pipeline is estimated at about 0.6 m and the velocity of the water flow is set to be 2 m/s. So the cost of the pipeline can be estimated as 1 800 yuan/m and the pumps cost 4 million yuan[7]. The sum of the maintenance cost and the depreciation cost is estimated as 10% of the initial investment. The results of the ACPUA are shown in Fig. 4.

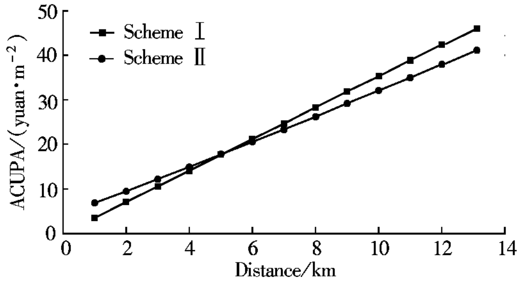

Fig. 4 ACPUA of scheme Ⅰ and scheme Ⅱ

As shown in Fig. 4, the values of the ACPUA of scheme Ⅰ and scheme Ⅱ vary linearly with the cooling supply distance. When the cooling supply distance is no more than 5 km, the ACPUA of scheme Ⅰ is less than that of scheme Ⅱ. Although scheme Ⅱ has a better performance when the distance is between 6 and 13 km, its cooling supply distance is limited to 13 km as a result of the cooling energy loss in the transposition. Unlike scheme Ⅱ, scheme Ⅰ can still be applied when the cooling supply distance is longer than 13 km. The ACPUA of scheme Ⅰ is estimated at about 176.7 yuan/m^2 when the cooling supply distance is 50 km. The cooling price of an ordinary DCS is estimated at about 0.8 yuan/(kW·h)[8], and its ACPUA is about 216 yuan/m^2. Thus, scheme Ⅰ is still technically feasible and economically reasonable at a cooling supply distance of 50 km.

3 Conclusion

In this study, the DCS utilizing cryogenic energy in LNG shows a promising prospect, where two processes and two cold energy transporting schemes are designed for this utilization. Relative merits of different flow processes and schemes are analyzed, and then the process without phase change of the refrigerant is chosen. The comparison of two schemes of transporting ice or chilled water is made. The results show that the change of the cooling supply distance between the vaporizing station and the DCS has a significant impact on the performance of the schemes. Sending chilled water with a pipe is more practical when the cooling supply distance is between 6 and 13 km, while transporting ice with vehicles may be applied to a much longer distance. In conclusion, the schemes utilizing cold energy of LNG for the DCS are technically feasible and economically reasonable.

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利用液化天然气冷能进行区域供冷的2种方案比较

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摘要:针对利用液化天然气冷能作为冷源的区域供冷系统,设计了2种方案.方案1使用冰作为蓄冷介质,先用液化天然气的冷能制冰,然后将冰运送至区域供冷系统的中心冷站.方案2则直接利用液化天然气冷能冷却回水,并通过管道运输冷冻水至需冷终端.冷能运输过程中的冷量损失是影响系统效率的主要因素,在评估2种方案的效率时对其进行了重点分析.分析结果显示,利用液化天然气冷能进行区域供冷在经济上是现实可行的.方案2的供冷距离限于13 km以内,方案1则没有供冷距离的限制.当供冷距离在6~13 km之间时,方案2的效率更高;当供冷距离小于6 km或大于13 km时,采用方案1在经济上更为合理.

关键词:区域供冷系统;液化天然气;冷能利用;系统效率

中图分类号:TB69