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Study on Solar-Assisted Cascade Refrigeration System

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Abstract

Energy-conservation and environmental protection are keys to sustainable development of domestic economy. The solar-assisted cascade refrigeration system is developed. The system consists of electricity-driven vapor compression refrigeration system and solar-driven vapor absorption refrigeration system. The vapor compression refrigeration system is connected in series with vapor absorption refrigeration system. Refrigerant and solution reservoirs are designed to store potential to keep the system operating continuously without sunlight. The results indicate that the system obtains pretty higher COP as compared with the conventional vapor compression refrigeration system. COP of the new-type vapor compression refrigeration system increases as sunlight becomes intense.

Keywords- solar energy; refrigeration; power consumption; cascade; energy storage

1. Introduction

Solar-driven vapor compression refrigeration has advantages in energy conservation and environmental protection, however, conventional solar-driven vapor compression refrigeration has many disadvantages, such as low efficiency, intermittent operation, too large unit size and too high capital cost [1-3]. As compared with the solar-driven vapor compression refrigeration, the electricity-powered vapor compression refrigeration features higher energy consumption and lower initial investment, it is unfavorable to energy conservation since it consumes high-grade electrical energy. Besides, the popularity and application of electricity-powered vapor compression refrigeration have been one of the main reasons of summer and winter electricity demand peak in China in recent years. In particular, 60% of the total electricity capacity is generated by coal. Not only does it exacerbate the depletion of fossil fuel, but also it can produce dangerous gases such as carbon dioxide, nitrogen oxides and sulfur oxides, which cause the greenhouse effect and deteriorate the global environment [4]. In order to solve the above problems in the

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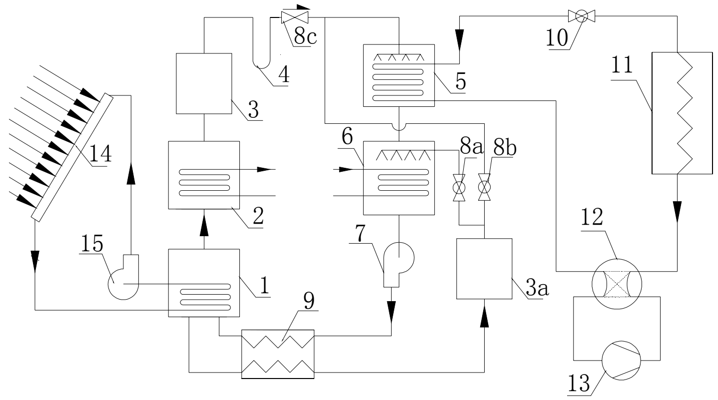
conventional electricity-powered vapor compression refrigeration system and solar-driven one, a solar-assisted cascade refrigeration system is analysed.

2. Features of the proposed system

Figure 1 shows schematically the proposed cascade refrigeration system which includes the solar-driven vapor absorption refrigeration unit and electricity-powered vapor compression refrigeration unit. Lithium bromide aqueous solution is used as absorption working pairs in the vapor absorption refrigeration unit, while HFC134a is used as refrigerant in the vapor compression refrigeration unit.

In the cooling mode, the vapor compression refrigeration unit is cascaded with the vapor absorption refrigeration unit. Low grade solar energy is used as heat source to drive the vapor absorption refrigeration unit and low temperature refrigerant water is obtained to cool the condenser in the vapor compression refrigeration unit. As refrigerant water which is used as cooling medium is at low temperature, condensing temperature decreases for the vapor compression refrigeration unit. Therefore, lower condensing temperature increases COP of the cascade refrigeration system. Refrigerant and solution reservoirs are designed to store potential to keep the system operating continuously without sunlight.



1- generator 2-condenser 3- refrigerant reservoir 3a-solution reservoir
4-U-type throttle valve 5-condensation evaporator 6-absorber 7-solution pump
9-solution heat exchanger 8-compressor 10-throttle valve 11-filter driver
12-four ways reversing valve 13-compressor 14-solar thermal collector

Fig.1 schematic diagram of the solar-assisted cascade refrigeration system

3. Thermodynamic mathematical models

In order to evaluate the cycle performance of the cascade refrigeration system, thermodynamic model of components which constitute the cascade refrigeration system is established. The cascade refrigeration system operates in the cooing mode or heating mode, but only thermodynamic performance of the system in cooling mode is evaluated in the paper. Accordingly, the thermodynamic model of the system in the cooling mode is presented. Based on the principles of conservation of mass and energy, the mathematical models of vapor absorption refrigeration system and vapor compression refrigeration system are presented.

3.1 vapor absorption refrigeration system (VARS)

According to conservation of mass, total mass balance equation and solution mass balance equation for the vapor absorption refrigeration system are shown as follows respectively:

$$\sum G_i - \sum G_o = 0 \tag{1}$$

$$\sum G_i X_i - \sum G_o X_o = 0 \tag{2}$$

According to conservation of energy, energy balance equation for each component of the vapor absorption refrigeration system is written as follows

$$Q + \sum G_i h_i - \sum G_o h_o = 0 \tag{3}$$

Where: G_i, G_o is mass flowrate of solution into and from the component, kg/s; X_i, X_o is concentration of solution into and from the component, %; Q is heat transferred in the generator, condenser and the condensation evaporator, kW; h_i, h_o is solution(or refrigerant water) inlet and outlet enthalpy to the component, kJ/kg.

Heat removed from the condenser:

$$Q_c = D(h_6 - h_7) \tag{4}$$

Cooling capacity of the evaporator:

$$Q_c = D(h_8 - h_9) \tag{5}$$

Energy balance for the absorber:

$$Q_a + Gh_1 = Dh_9 - (G - D)h_3 \tag{6}$$

Energy balance for the solution heat exchanger:

$$G(h_4 - h_3) = (G - D)(h_2 - h_5) \tag{7}$$

Energy balance for the generator:

$$Q_g + Gh_5 = Dh_6 + (G - D)h_4 \tag{8}$$

Energy balance equation for the vapor absorption refrigeration system:

$$Q_g + Q_e = Q_c + Q_a \tag{9}$$

The efficiency of solar radiation collector [5]:

$$\eta_{sc} = 0.80 - 3.5(T_i - T_a)/I \tag{10}$$

Where: η_{sc} is energy collection efficiency of the flat plate collector; I is the solar radiation intensity, W/m; T_i and T_a are the collector inlet and outdoor air temperature.

3.2 vapor compression refrigeration system (VCAS)

Cooling capacity in the evaporator:

$$Q_0 = G_r(h_{e,o} - h_{e,i}) \tag{11}$$

Power consumption of the compressor:

$$P_e = G_r(h_{com,o} - h_{com,i}) \tag{12}$$

Compression ratio:

$$\varepsilon = p_k / p_0 \tag{13}$$

Coefficient of performance (COP):

$$COP = \eta_m \eta_i Q_0 / P_e \tag{14}$$

where： $h_{e,o}, h_{e,i}$ is enthalpy of refrigerant into the evaporator and from the evaporator, kJ/kg; $h_{com,o}, h_{com,i}$ is compressor discharge and suction enthalpy, kJ/kg; G_r is mass flow rate of refrigerant R134a, kg/s; P_o, P_k is evaporation pressure and condensation pressure, Pa; η_m, η_i is mechanical efficiency and indicated efficiency.

4. Results and discussion

Based on meteorological parameter on July 2nd of some year in Zhengzhou area, China, codes using the Visual C++ are programmed to calculate the cycle performance of the cascade refrigeration system according to the thermodynamic mathematical models. In the standard working conditions, the parameters for VCRS are given as:

(1) Evaporating temperature =35.9℃; superheated temperature=5℃;

(2) Condensing temperature =25℃; subcooling temperature=5℃;

(3)The actual vapor compression process in the compressor is considered as a non-isentropic process. Indicated efficiency of the compressor is equal to 0.80, and the motor efficiency of the compressor is equal to 0.75.

Numerical computations are iterated by bisection method. Tab 1 shows the results of thermodynamic performance of the cascade refrigeration system obtained for the normal working conditions.

Tab.1 Results of thermodynamic performance designed for the standard working conditions

Parameter	Value	Parameter	Value
Generating temp (℃)	70.00	Mass flowrate of refrigerant R134a (kg/s)	0.28
Evaporating temp for VARS (℃)	20.00	Mass flowrate of refrigerant water (kg/s)	0.023
Condensation temp for VARS (℃)	41.00	Heat load at the condensation evaporator (kW)	55.14
Unit mass power input to the compressor (kJ/kg)	18.13	COP of VCRS for the new cascade refrigeration	5.83

Fig 2 shows the relationships of solar radiation intensity and generation temperature with the time of day. It is seen that solar radiation intensity began to increase and then decreased from 9:00 to 16:00, when it reached a maximum value of 900 W/m2 at about 13:00. Generation temperature depends on hot water outlet temperature to the solar radiation collector, so it also began to increase and then decreased from 9:00 to 16:00 with the variation of the solar radiation intensity, and it reached a maximum value of 70.8℃ at about 13:00.

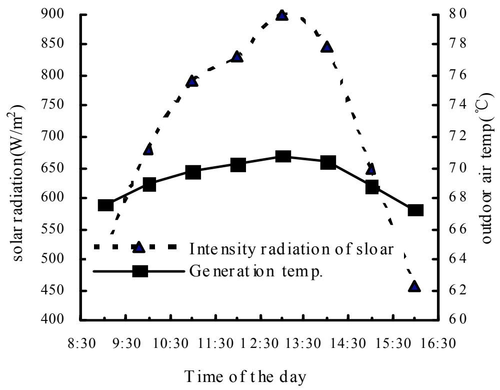


Fig. 2 Solar radiation intensity and generation temperature vs. time

Fig 3 shows the relationships of outdoor air temperature and cooling water temperature with the time of day. Solar radiation intensity has a significant influence on outdoor air temperature. It is noted that outdoor air temperature began to increase and then decreased from 9:00 to 16:00 with the variation of solar radiation intensity, and it reached a maximum value of 32.8℃ at about 15:00. Heat of condensation and absorption for VARS is rejected to the atmosphere through the cooling tower, so cooling water temperature is dependent on both heat removed through cooling tower and outdoor air temperature. When cooling water flowrate is kept constant, cooling water outlet temperature to the cooling tower is 32℃ at 9:00, while it reaches a maximum value of 32.9℃ at 12:00. It indicated that, at that time, higher cooling capacity needs to be provided by the cascade refrigeration system, and more heat of condensation and absorption for VARS is removed owing to lower solar radiation intensity and lower refrigeration efficiency, so cooling water temperature rises to the maximum at 12:00.

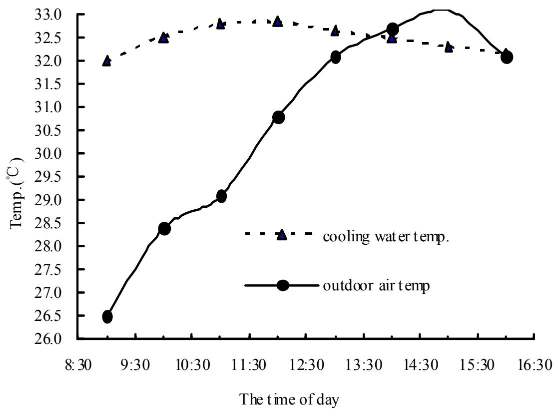


Fig.3 Outdoor air temp. and cooling water temp. vs. the time of day

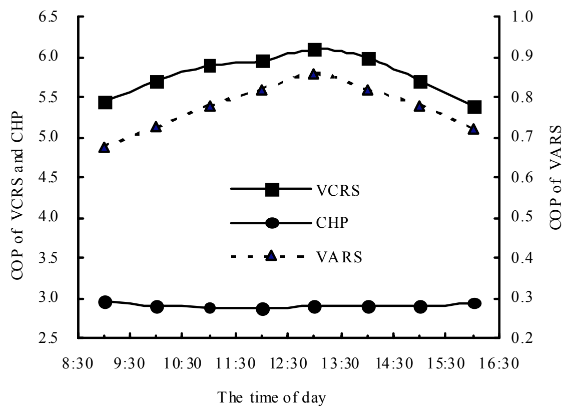


Fig.4 COP vs. the time of day

Fig 4 shows the relationships of COP of VARS, VCRS and conventional vapor compression refrigeration system (CVCRS) with the time of day. The cascade refrigeration system is made up of

VARS and VCRS. Refrigeration efficiency of VARS depends on generation temperature, condensing temperature and evaporating temperature for VARS, while that of VCRS is largely dependent on condensing temperature and evaporating temperature for the VCRS. As for VARS, COP increases and heat removal decreases with solar radiation intensity rise, so that variation trend of COP is largely in accord with that of solar radiation intensity. COP is up to the maximum at 13:00. It follows that generation temperature or solar radiation intensity has a considerable influence on COP of VARS, when cooling water flowrate and evaporating temperature is constant. As for VCRS, condensing temperature hinges on evaporating temperature for VARS, so the variation trend of COP for VCRS is in line with that of solar radiation intensity. COP of VCRS reaches the maximum at 13:00, just like VARS. As for conventional vapor compression refrigeration system(CVCS), condensing temperature has an important influence on refrigeration efficiency, when evaporating temperature is constant. Consequently, COP of CVCS is dependent on cooling water temperature or outdoor air temperature. It is observed that COP of CVCS begins to decrease and then increases, because outdoor air temperature increases at first and then decreased from 9:00 to 16:00 with the variation of solar radiation intensity. For the cascade refrigeration system, VCRS is cascaded with VACS, so condensing temperature for VCRS depends on evaporating temperature for VACS. However, condensing temperature for CVCS is dependent on cooling water temperature. Consequently, condensing temperature for VCRS is 15℃ lower than that for CVCS, and COP for VCRS is twice higher than that for CVCS. For instance, COP of VCRS is 6.1 at 13:00, while that of CVCS is only 2.1. Power consumption of the compressor for CVCS is twice higher than that for VCRS.

Solar radiation intensity has an important effect on refrigeration efficiency of the cascade refrigeration system. The greatest advantage of the cascade refrigeration system is that refrigeration efficiency of the cascade refrigeration system increases with the solar radiation intensity rise. When solar radiation intensity is the maximum, cooling load in air-conditioning rooms is up to the maximum as well. The greater solar radiation intensity, the higher refrigeration efficiency of the cascade refrigeration system. It follows that variation trend of refrigeration efficiency is in line with that of cooling load in air-conditioning rooms, which helps to meet the demand of air conditioning rooms for cooling capacity. As compared with the cascade refrigeration system, the refrigeration efficiency of the conventional vapor compression refrigeration system (CVCS) is too low to provide the cooling capacity for the air conditioning rooms, when solar radiation intensity is the greatest. Obviously, the cascade refrigeration system contributes to solve the problems that cooling capacity of CVCS decreases with solar intensity or outdoor air temperature rise.

5. Conclusions

The solar-assisted cascade refrigeration system includes the solar-driven vapor absorption refrigeration unit and electricity-powered vapor compression refrigeration unit. Refrigerant water and solution reservoirs are used as energy storage units to store solar energy, in order to keep the system operating continuously without sunlight. COP of the cascade refrigeration system is up to 6.1 with the solar intensity of 700W/m2, outdoor air temperature of 35℃ and chilled water supply temperature of 7℃. Power consumption of the cascade refrigeration system is 50% lower than that of the conventional vapor compression refrigeration (CVCS) in the cooling mode. The COP of the new vapor compression refrigeration system (VCRS) increases as sunlight becomes intense. COP of the cascade refrigeration system is up to the maximum when COP of the conventional vapor compression refrigeration system is minimal.

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