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Design of Supercritical CO_2 Jointing Solar Thermal Refrigeration System with Utilization of Ship Waste Heat

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Abstract. In view of the current shipping industry is facing energy waste, environmental pollution and other issues, energy-saving and emission reduction are imminent. As combined the characteristics of high temperature waste heat produced by marine engine and other equipment on ship with solar thermal system, using supercritical CO_2 (s-CO_2) Brayton cycle to design a marine refrigeration cycle system. And analyzing the whole refrigeration system, verifying the feasibility of the system on board applications and it is able to meet the board requirements. Finally, an automatic control method is proposed to automate the entire waste heat refrigeration system in any environment.

Introduction

The world's energy crisis and climate change has become a major topic of common concern to the international community, energy conservation has become the common responsibility of the international community. At present, the extensive use of Freon in refrigeration system, such as R12, R22, etc., has been confirmed to destroy the ozone layer and produce greenhouse effect. With revive of the natural refrigerants research [1, 2], s-CO_2 began to emerge in industrial production. CO_2 is from earth, it has no harmful effect on environment even if it is discharged to the earth. Not only because of its environmental friendliness, but it is better in the supercritical thermal characteristics, which is widely used in heat pump system [3]. Solar energy is clean and widely distributed, it is an important renewable energy, but the solar radiation energy density is low, there is discontinuity that affected by the change of weather. Many scholars has made a series of research in the field of s-CO_2 [4, 5, 6], and part of marine machinery use CO_2 for the working fluid has been commercialized.

The waste heat resources are failed to use on the ship, resulting in a huge waste of energy. The survey shows that 95% of the world's civilian ship power is diesel, their thermal efficiency is about 50%, which exhaust heat loss is more than 25%, and the temperature is between 250°C and 350°C. There is only a small amount of exhaust heat being used for heavy oil heating and steam utilization, most of the exhaust heat is drained. The vast majority of military ships are powered by gas turbines, their dynamic efficiency of 40% or less, and the exhaust energy and temperature is greater, so the energy waste is more serious [7,8]. If the ship waste heat assists the solar heat pump and carbon dioxide refrigeration equipment to work, which can reuse the waste heat and solve the problem that the traditional solar energy device cannot be stable and continuous to work, then we achieve a system with efficient work, continuous heating and cooling.

At present, the research about solar energy and carbon dioxide heat pump is relatively small, where the reasonable combination of waste heat, solar thermal pump and carbon dioxide heat pump is far less, and lack of innovative design [9, 10]. A system is mainly designed which use the ship waste heat to assist conventional solar heat pump, and then to provide heat for the s-CO_2 refrigeration equipment, forming a ship waste heat, solar, s-CO_2 combined refrigeration system, which meets the requirement of cooling and heating when ship sails under different environments. Low emissions, zero pollution and energy-saving optimization in the ship's refrigeration can be achieved, it is of great significance for the future development of ship clean energy technology.

Analysis of Three Subsystems

Ship Waste Heat Recovery System

Figure 1 shows the process of the utilization of waste heat on some energy-saving ships, there are two main heat sources, waste heat and cooling water. The exhaust gas heat flow through the exhaust boiler and generate steam to drive the steam turbine to rotate, which is used to generate electricity. Another part of the exhaust gas is used to heat the auxiliary boiler, with cooling water, they flow to heating equipment to heat heavy oil, desalination and cooling. It can be seen that the waste heat generated by the ship has many applications.

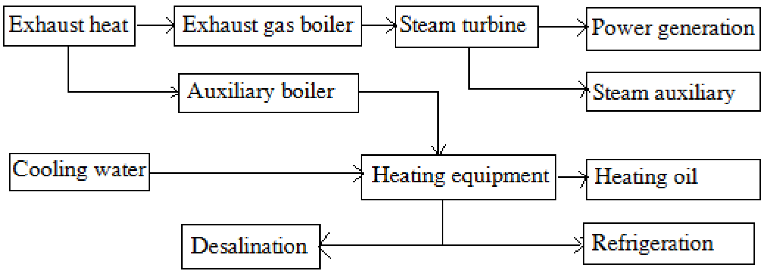

Fig. 1 Ship waste heat recovery process

Solar Assisted Heat Pump

The technology of combining solar heat with heat pump on the ship to provide energy for cabin has been developed since early 21st century, but it is not yet widely used [11]. In traditional solar energy system, to meet the demand of ship's heating and living hot water under the premise, it must use boiler, electric heaters and other auxiliary heat source to improve system stability.

Figure 2 is a marine solar heating system, when temperature of solar absorption is more than 90°C, it directly provides to the solar cooling machine, if the temperature is less than 60 °C, it provides to the coil heating tank, to heat hot water for life. Heat pump is used to assist the solar air conditioning system, to ensure the ship refrigerator work under any environment.

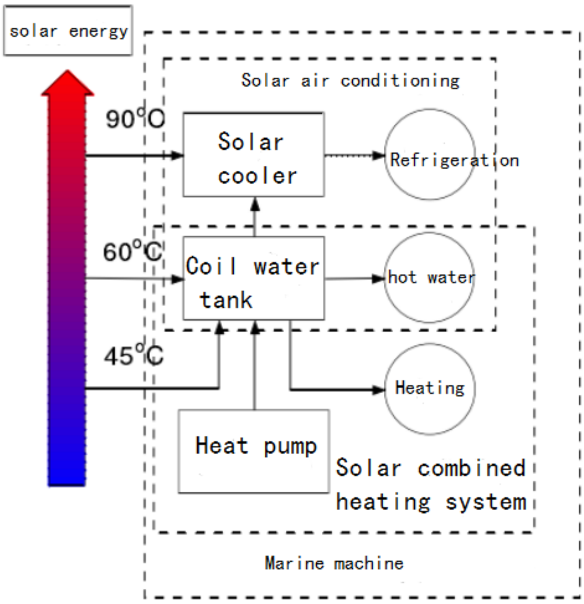

Fig. 2 Solar heat pump system

Supercritical CO_2 Refrigeration

CO_2 is a clean and non-corrosive gas, its critical temperature is about 31°C and critical pressure is 7.382MPa [12]. CO_2 reaches the supercritical state when the temperature and pressure are more than the critical value, it is characterized by dense, large density and they increases with the increasing of temperature and pressure, it has a partial nature of liquid. Figure 3 shows the P-T diagram of CO_2, in the pressure of T_p and temperature of T_c, there is a critical point, at this time CO_2 has been in a critical state. When the temperature and pressure continue to increase, CO_2 becomes supercritical fluid. This s-CO_2 is used as a medium for refrigeration systems, which can maximize the use of energy.

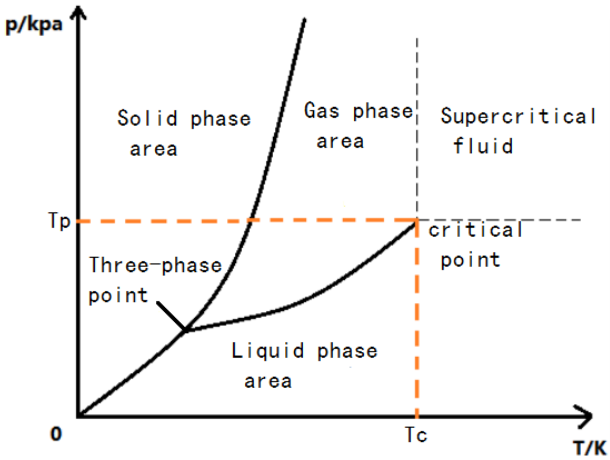

Fig. 3 Supercritical fluid P-T diagram

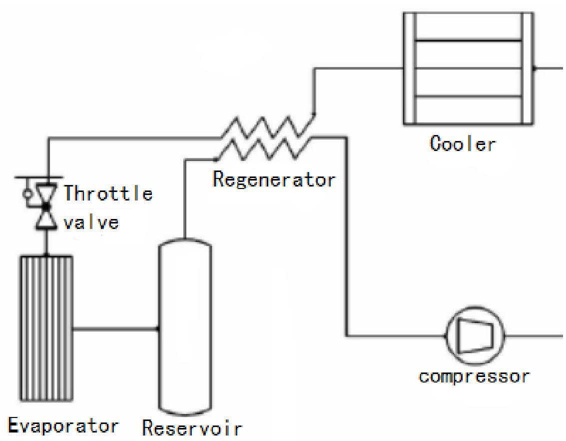

Fig. 4 S-CO_2 heat pump system

Figure 4 shows the s-CO_2 heat pump unit, its basic principles is that, the low temperature gaseous refrigerant CO_2 is compressed by the compressor, then it becomes into high temperature and high pressure state, and then it flows into the gas cooler to heat water, then CO_2 flows out from the gas cooler and flows through the throttle down to become into low temperature and low pressure state, then liquid CO_2 flows into the evaporator. In the evaporator, the low temperature liquid CO_2 absorbs the heat of the exhaust gas and cooling water of ship and continuously evaporates, it has become low temperature overheating dry gas at the outlet of evaporator, and then it flows back to the compressor suction port, so as the repeated cycle, to achieve the purpose of refrigeration.

Analysis of the System

Figure 5 shows the establishment of the s-CO_2 and solar thermal cooling system with utilization of the ship waste heat, as can be seen in the figure, the system is divided into three loops. The first loop is the solar collector loop, the collector collects solar energy, and then delivers to the heat storage loop through the heat exchanger, and the collected heat is stored in the tank. If the temperature of water in the storage tank is higher than the starting temperature of the absorber, then the hot water loop pump is automatically opened and transport the hot water. While, the sub cooled CO_2 of the second loop turns from the independent cooling mode into a mixed cooling mode, it delivers cold air to the terminal cabins through the chilled water pipeline. The third loop is the ship waste heat recovery system, the exhaust and cooling water generated by the diesel engine and other equipment is transported out through the heat transfer tube, one way is directed to the CO_2 machine, to work on the compressor and drive it work. The other is to the heat exchanger, to assist the solar heat pump work. In addition, the system also has the recycling cooling section, it can be used to pretreat the high humidity air before it enters into the cabin. The three loops are complement each other, they can optimize the use of energy.

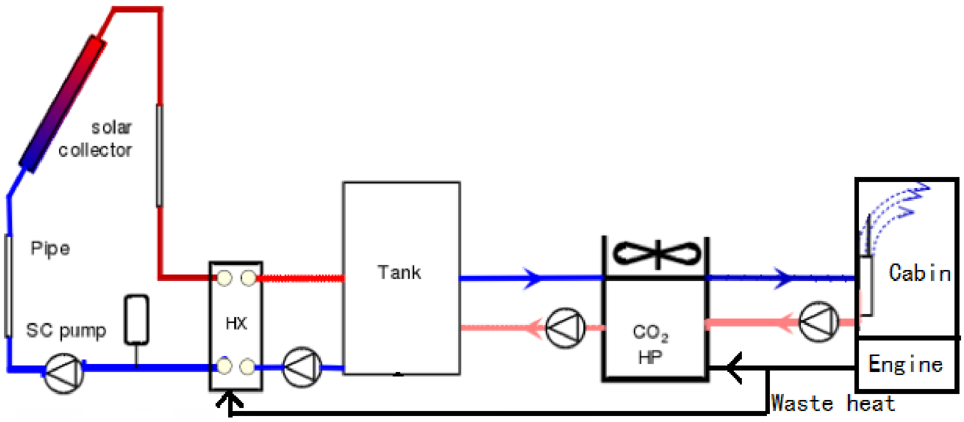

Fig. 5 S-CO_2 and solar thermal refrigeration system with ship waste heat

In above cycle, the compressor, gas cooler, solar sub cooling device, throttle, evaporator and storage tank are the main component, they are consisted a closed refrigeration circuit through the connection of pipes. Two major categories of equipment consist of the thermal cycling system, impeller machinery, such as compressor, turbine, and heat transfer equipment, such as heaters, coolers and so on. We usually establish thermodynamic model for different equipment to analyze the thermal cycle, and then solve the state parameters of each point through the connection between each other to form a closed loop.

Design of Control System

Figure 6 is the flow chart of the control system of s-CO_2 and solar thermal cooling system with ship waste heat utilization, firstly, the ship's cabin temperature is set, such as humidity and other environmental parameters, on the centralized controller, after the digital-to-analog conversion, the control signal delivers into the ship waste heat system, and it is processed by the controller to provide heat to the solar heat pump and CO_2 refrigeration machine, the heat source will be distributed according to the working condition of the CO_2 refrigerator and the solar heat pump.

When the sunshine is sufficient, the solar heat pump can produce a lot of heat, then the ship waste heat system does not provide heat to it and only to the CO_2 heating machine, so Q1 = 0, Q2 = Q, if the solar energy is superfluous, it will provide heat q to the CO_2 refrigerator, if the CO_2 refrigerator can operate normally by them, there is no extra energy required. When the sunlight is not enough, the ship waste heat system will provide heat Q1 to the solar heat pump, to ensure that the heat pump can work properly, at this time, the CO_2 refrigerator needs additional energy. The solar heat pump and CO_2 refrigerator provide heat to the cabin for energy of Q3 and Q4, then the cabin temperature changes. The indoor temperature sensors monitor the temperature and deliver the signal to the centralized controller, compared with the set initial temperature T, if the temperature deviation is greater than 1°C, the central controller controls the solar heat pump and the CO_2 refrigerator directly to change the working condition, to change the cabin temperature quickly, until the temperature deviation is less than 1°C. This design achieves automatic control of the system.

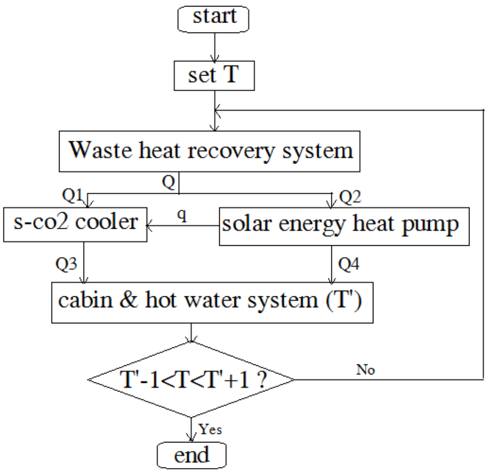

Fig. 6 Flow chart of the control program

Conclusion

A ship waste heat assisting s-CO_2 and solar thermal refrigeration system is mainly designed, the core of it is the solar heat pump and carbon dioxide engine. Through the analysis of the principle and heat calculation process of ship waste heat recovery system, the solar heat pump system and s-CO_2 refrigeration machine, respectively, the three subsystems are redesigned and they are combined properly, to verify the feasibility of the system on board refrigeration. Under the premise to ensure energy saving, a closed-loop automatic control method is designed and the control process of the system is drew, which takes account into the impact of outdoor weather conditions, living hot water load and heating load on the system performance, to achieve automatic adjustment of the cabin temperature. The designed s-CO_2 and solar thermal refrigeration system with ship waste heat utilization, which can be used for reference in the future development of high energy-efficient ships.

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