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Experimental study of a heat pump system with flash-tank coupled with scroll compressor

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Abstract

A heat pump system with a flash-tank coupled with a scroll compressor is compared with a system with a sub-cooler. The heat pump performance was measured experimentally. The heating capacity of the prototype decreased as the evaporation temperature decreased, but the decrease was much slower than that of a conventional air-source heat pump. The power input varied slightly with the evaporation temperature. The heat pump system with a flash-tank is more efficient than the system with a sub-cooler at low ambient temperatures, so it will be very useful as a small capacity air-source heat pump.

Keywords: Heat pump; Economizer; Scroll compressor; Flash-tank

1. Introduction

With economic development and improved living standards, people now want more comfortable environments which stimulate the development of new types of heat pump. Air-source heat pump (ASHP), which absorbs heat from the surrounding atmosphere, is more convenient than other heat pump systems. So they are widely used for residential heating [1]. However, in the past, ASHP applications have been limited to temperate zones, such as the Yangtze River basin and southern China. At present, the lower limit for the ambient design temperature in Chinese air conditioning handbooks is $-3\,^{\circ}C$ [2]. Therefore, conventional air-source heat pumps cannot operate efficiently and steadily during the winter in cold regions such as the Yellow River basin and northern China without improvements since their heating capacity decreases sharply and the compressor discharge temperature increases as the ambient temperature decreases.

Many efforts have been made to increase the operating temperature range of ASHPs in recent years. For example, proposed systems have used two stages with two compressors, vapor injection with an economizer, vapor injection with an economizer and a suction gas super-heater, and a separate heat pump loop for sub-cooling the condensate. The criteria for an improved system are (1) the heat pump system should have simple, easily manufactured components; (2) the system should work reliably at lower ambient temperatures with sufficient heating capacity for the application; (3) the system should have higher coefficients of performance at higher ambient temperatures. A heat pump system with a flash-tank coupled with a scroll compressor is an economic and efficient system according to these criteria [3,4].

Heat pump systems with economizers can use sub-coolers or flash-tanks. The heat pump system with a sub-cooler coupled with a scroll compressor has already been studied in detail (Ma et al., 2001, 2002, 2004; Chai et al., 2002, [5–7]) with a prototype developed for heating in cold regions. Tests show that the prototype can work smoothly and produce sufficient heat to satisfy heating requirements at ambient temperatures as low as $-15\,^{\circ}C$ [5]. Since heat pump systems with sub-coolers have one compressor and one-stage throttling, it is difficult to make sure that the vapor into the supplementary compressor inlets is at saturation. However, heat pump systems with flash-tanks have one compressor and two-stage throttling, so the components are simpler than in a system with a sub-cooler and the vapor into the supplementary compressor inlets is always very close to saturation. This paper analyzes a heat pump system with a flash-tank coupled with a scroll compressor with experimental tests of a prototype. The heat pump system with a flash-tank is shown to be more efficient than the system with a sub-cooler at low ambient temperatures.

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2. Heat pump system with economizer

2.1. System with flash-tank

The flow chart of the heat pump system with a flash-tank is shown in Fig. 1a. The system uses a scroll compressor with supplementary inlets. The high temperature, high pressure superheated refrigerant is discharged from the scroll compressor at state 3 and flows through the condenser where the refrigerant transfers heat to the cooling medium until it becomes a sub-cooled liquid at state 4. The heated cooling medium can then be used for heating or some other purpose. The liquid refrigerant from the condenser flows through expansion valve A, in which the refrigerant pressure is dropped to a pressure (state 4′) between the compressor suction and discharge pressures (also called the intermediate pressure or economizer pressure). The refrigerant then flows into the flash-tank, an economizer, in which the refrigerant mixture from expansion valve A separates with the vapor on the top and the liquid on the bottom. Part of the vapor on the top is sucked into the compressor through the supplementary inlets (state 6), which the sub-cooled liquid on the bottom (state 5) flows through expansion valve B so that the refrigerant pressure is reduced to the evaporation pressure (state 5′). The refrigerant mixture flows into the evaporator where the refrigerant absorbs heat from the surrounding atmosphere to become low pressure vapor. The vapor from the evaporator is sucked into the compressor through its suction port (state 1) and compressed to the intermediate pressure (state 2). When the supplementary inlet is open, the vapor at state 2 mixes with the vapor from the supplementary inlets (state 6) until the compression chamber is cut off with the inlets (state 2′) and then compressed continually to the condensation pressure (state 3). The vapor from the compressor flows into the condenser to complete the cycle.

2.2. System with sub-cooler

The flow chart of the heat pump system with a sub-cooler is shown in Fig. 2a. This flow circuit differs from that of the flash-tank system. Here, the sub-cooled liquid refrigerant from the condenser is divided into two parts. One part (state 4) flows directly into the sub-cooler, while the other part flows through expansion valve A where the refrigerant pressure is reduced to the intermediate pressure (state 4′). The refrigerant from expansion valve A then flows into the sub-cooler where it absorbs heat from the other refrigerant stream at state 4. The refrigerant stream from expansion valve A is vaporized and sucked into the compressor through the supplementary pipe, while the other refrigerant stream is sub-cooled (state 5) and then flows through expansion valve A (state 5′) into the evaporator where the refrigerant is vaporized. The refrigerant mixing and compression processes in the compressor are the same as in the flash-tank system.

2.3. Systems comparison

The flash-tank heat pump system has a two-stage throttling process while the two refrigerant streams are separately throttled in the sub-cooler system. Therefore the flash-tank system is close to a two-stage system and has simpler components. In addition, the refrigerant entering the supplementary compressor inlets in the flash-tank system is less superheated than that in the sub-cooler system since the sub-cooler is a tube type heat exchanger and the heat exchange is reduced by the tube wall. Therefore, the heat pump flash-tank system gives better performance and reliability than the sub-cooler system, which is crucial to efficient, steady operation of an air-source heat pump with a low temperature heat source.

3. Analysis of the flash-tank cycle

3.1. Thermodynamic analysis

Assume that the mixing of the two refrigerant streams in the working chamber of the compressor is isasterical with the vapor then compressed adiabatically. The dimensionless flow rate through the supplementary pipe can be expressed as

$$a = \frac{q_{\mathrm{mb}}}{q_{\mathrm{m}k}} = \frac{q_{\mathrm{m}k} - q_{\mathrm{mo}}}{q_{\mathrm{m}k}} = \frac{v_2}{RkT_6}(p_6 - p_2) \tag{1}$$

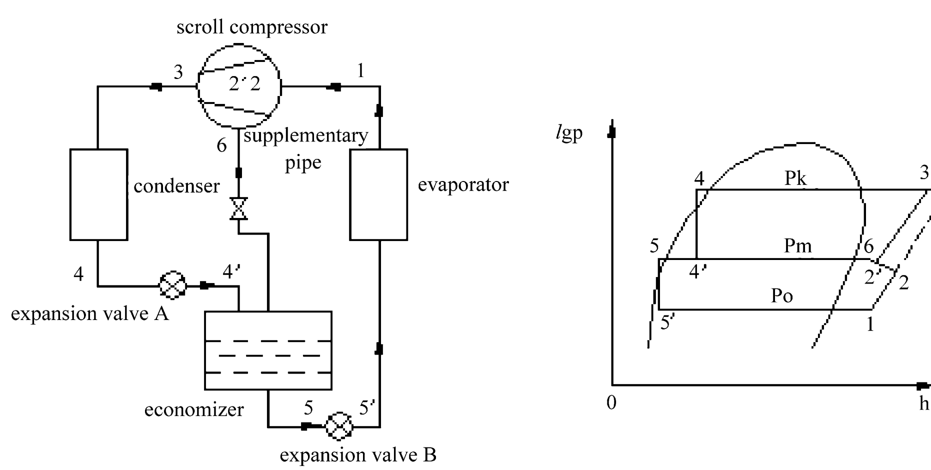

Fig. 1. Heat pump system with flash-tank. (a) Flow chart and (b) cycle on a p–h diagram.