Applied Thermal Engineering 65 (2014) 384–393

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

# Dynamic performance of self-operated three-way valve used in a hybrid air conditioner

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## HIGHLIGHTS

- A self-operated three-way valve is proposed for hybrid air conditioners.
- The thermodynamic model and kinetic model of the self-operated three-way valve are developed.
- The validity of models is verified by experiments.
- Effects of four main design parameters on the operating performance of the valve are researched.

## ARTICLE INFO

*Article history:*
Received 19 June 2013
Accepted 19 January 2014
Available online 25 January 2014

*Keywords:*
Year-round cooling
Self-operated three-way valve
Vapor compression cycle
Thermosyphon cycle
Simulation

## ABSTRACT

A hybrid air conditioner combining a thermosyphon cycle with a vapor compression refrigeration cycle has a large energy saving potential compared with a common air conditioner for spaces requiring year-round cooling. The performance of the switch between the vapor compression mode and the thermosyphon mode largely impacts the safety and reliability of hybrid air conditioners. Therefore, a self-operated three-way valve is proposed. A thermodynamic model and a kinetic model are developed in this paper to evaluate the dynamic performance of the switch valve. The effects of the spring force constant, compressor discharging volume, fit clearance and piston length on the dynamic performance of the switch valve are analyzed. In conclusion, the proposed self-operated three-way valve can realize the switch operation accurately.



## 1. Introduction

The number of spaces with high heat generation, such as mobile base stations and internet data centers, is increasing quickly because of the rapidly development of information technology [1,2]. Large amounts of energy are consumed to cool these spaces year-round because of the large indoor heat generation [3,4]. Energy-saving devices, such as waterside economizers [5], airside economizers [6–8] and thermosyphon heat exchangers [9], are developed to reduce the energy consumption for cooling. Generally, these devices use the cooling energy in the outdoor low-temperature air to cool the indoor air freely when the outdoor temperature is lower than the indoor temperature. However, when the outdoor temperature is higher than the indoor temperature, the indoor heat cannot be transferred to the outdoor directly, and mechanical refrigeration is required. Therefore, two sets of facilities are needed, which increases not only the requirement for the installation space, cost and maintenance expenses but also the control complexity.

The hybrid air conditioner, which integrates the vapor compression cycle and thermosyphon cycle into one equipment, provides a solution [10–13]. The evaporator and condenser are shared, and the installation space, cost, maintenance expenses and complexity of the control strategy can be largely decreased. Theoretically, the vapor compression cycle is put to work when the outdoor temperature is higher than the indoor temperature. When the outdoor environment becomes cold enough, the thermosyphon is activated.

Hybrid air conditioners were first proposed by Lee [10,13] and Okazaki [11], in which the condenser and evaporator were shared by the thermosyphon cycle and vapor compression cycle. Therein, two solenoid valves [10,13] (shown in Fig. 1(a)) or a check valve and a solenoid valve [11](shown in Fig. 1(b)) were utilized in the gas pipe to switch the equipment between these two modes. However, the solenoid valve and check valve both have considerable flow resistance due to their inherent configurations. As Han reported [12], the pressure drop was 2.2–9.0 kPa through the solenoid valve

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http://dx.doi.org/10.1016/j.applthermaleng.2014.01.029

**Nomenclature**

| | |
|---|---|
| $A$ | sectional area of gas flow ($m^2$) |
| $A_p$ | sectional area of the piston ($m^2$) |
| $C_v$ | specific heat capacity (kJ/(kg K)) |
| $D$ | diameter (m) |
| $f$ | friction of the piston (N) |
| $h$ | specific enthalpy (kJ) |
| $k$ | force constant of the spring (N/m) |
| $L$ | length of the piston (m) |
| $m$ | mass (kg) |
| $\dot{m}$ | mass flow rate of compressor discharge (kg/s) |
| $M$ | mass of the piston (kg) |
| $P$ | pressure (Pa) |
| $P_d$ | gas pressure in the cavity over piston (Pa) |
| $P_m$ | pressure of the refrigerant gas in the valve piston shoulder (Pa) |
| $R_1$ | gas flow resistance between the piston upper surface and the valve body inner wall ((Pa s)/kg) |
| $R_2$ | gas flow resistance between the piston side surface and the valve body inner wall ((Pa s)/kg) |
| $T$ | temperature(°C) |
| $u_d$ | thermodynamic energy of the refrigerant gas in the cavity over the piston (kJ/kg) |
| $\upsilon$ | speed of piston (m/s) |
| $V_d$ | volume of the cavity over piston ($m^3$) |
| $V_{0,d}$ | initial volume of the cavity over the piston ($m^3$) |
| $V_{0,e}$ | initial volume of the cavity under the piston ($m^3$) |
| $x$ | moving distance of the piston (m) |
| $x_0$ | pre-compression length of the spring (m) |
| $x_c$ | distance between the piston upper surface and Port C upper line (m) |

*Greek symbols*

| | |
|---|---|
| $\rho$ | density of the refrigerant gas ($kg/m^3$) |
| $\delta_1$ | clearance between the piston upper surface and the valve body inner wall (m) |
| $\delta_2$ | clearance between the piston side surface and the valve body inner wall (m) |
| $\upsilon$ | dynamic viscosity of the refrigerant gas ($m^2/s$) |

*Subscripts*

| | |
|---|---|
| c | port connecting to condenser |
| d | port connecting to discharge |
| e | port connecting to evaporator |
| i | in |
| o | out |
| p | piston |
| 0 | initial |

and 0.5–2.4 kPa through the check valve when the refrigerant velocity was 2 m/s to 4 m/s. The pressure drop will largely degrade the performance of the thermosyphon cycle, which is driven by gravity and the circulation driving pressure is relatively small (approximately 20 kPa when the vertical distance is 2 m). At the same time, the solenoid valve in the compressor branch is installed at the suction tube of the compressor to avoid the failure possibility of the valve under a high discharge temperature when it is installed in the discharge line. However, under the thermosyphon mode, this design leads to another possibility that the gaseous refrigerant condenses and goes back to the compressor through the discharge pipe, which increases the risk of a liquid slug for the compressor during the next refrigeration compression cycle. Overall, the hybrid air conditioner provides a potential energy-saving solution for year-round cooling applications. Its performance largely depends on the switching device, and the existing solutions are unsatisfactory. A better switch device is required.

A self-operated three-way valve driven by the pressure difference between the inlet and outlet of the compressor is developed [14], which is expected to be more reliable due to no solenoid coil and more efficient due to the large flow area and quite small flow pressure drop. In this paper, a physical model is established to validate the concept. With this model, the dynamic characteristics of the self-operated three-way valve in different design parameters are analyzed to optimize the valve.

## 2. Self-operated three-way piston valve

A self-operated three-way piston valve for a hybrid air conditioner is proposed by Shi [14]. The valve utilizes the pressure difference between the compressor suction and discharge as the driving power to achieve efficient switching. An air conditioner with a self-operated three-way piston valve is shown in Fig. 2.

When the hybrid unit works in thermosyphon mode (Fig. 2(a)), the compressor is switched off. Because there is no pressure difference between Port D and Port E, the spring pushes the piston to the left side and closes Port D. The refrigerant evaporates in the evaporator, enters the self-operated three-way valve by Port E and exits the valve by Port C. After that, the gaseous refrigerant flows into the condenser and condenses, finally, flows back to the evaporator through the solenoid valve.

When the compressor starts, the pressure in Port D will increase quickly, and the pressure in Port E will remain almost constant. The increasing pressure difference will push the piston to the right side in a few seconds. As a result, the hybrid unit switches to the vapor compression mode (Fig. 2(b)). In the vapor compression mode, the gaseous refrigerant at the outlet of the evaporator is sucked in by the compressor and compressed to the discharging pressure. Then, the compressed refrigerant enters the self-operated three-way valve by Port D and exits the valve by Port C. The refrigerant condenses in the condenser and flows to the evaporator through the expansion valve. Finally, the refrigerant flows back to the suction port of the compressor and starts another cycle.

From the thermosyphon mode to the vapor compression mode (known as the startup process), the self-operated three-way piston valve is shifted by the pressure difference between the compressor suction and discharge. When the pressure difference is not sufficient to overcome the pre-compression force of the added spring and the static friction of the piston, the piston will fail to start. Even if the piston normally starts to move, the driving pressure difference will largely vary due to the variation of the refrigerant leakage from Port D to Port C and Port E when the piston moves from the left position to the right position. If the driving pressure difference decreases largely, the self-operated valve will possibly stay at an intermediate position and the switch process will not be finished, which will result in bypassing of the compressor discharge gas into