ENVIRONMENTAL TESTS OF VAPOR COMPRESSION HEAT PUMP FOR SPACE APPLICATIONS

by

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Heat pumps are needed to provide a suitable temperature for both people and equipment in spacecraft. This paper reports on work designed to see if vapor compression heat pumps, in particular, can be expected to function normally in space. A vapor compression heat pump was built and tested under conditions of high temperature (70 °C), low temperature (0 °C), and near-vacuum (10^{-4} Pa). It was found that the coefficient of performance of this heat pump was 2.99 at both high and low temperatures, and was 2.1 under near vacuum conditions. The results suggest that vapor compression heat pumps are suitable for use in space.

Key word*: vapor compression heat pump, simulated space environment, environmental tests, coefficient of performance, spacecraft thermal load*

Introduction

As space technology advances, higher levels of power are required, increasing spacecraft thermal loads. Thermal (or heat) load can be handled by a thermal management system (in effect, an air conditioner) that collects waste heat and radiates it into space, maintaining a thermal environment that is needed to support life and normal system operation [1-5]. One promising technology for active thermal management in spacecraft is the vapor compression heat pump [6]. To be acceptable, it has to function in various regimes: on the ground, during launch, in orbit, and during re-entry (or landing on another body). Various simulation tests (referred to as space environment tests) must be carried out on Earth before launch [7]. The failure caused by space environment was about 46% of the total faults according to the statistics on the failure of communications satellite launched [8]. This was fundamentally different from the test of normal laboratory equipment, because ground instruments were usually operating in a more benign environment which could be repaired during its service life. Therefore, space environment test was most important for studying space environment and reliability. It was essential to ground-test the entire spacecraft or its subsystem, components, parts and materials for simulating space environment [9, 10]. The reliability of spacecraft needed to be verified, so did the reliability of

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vapor compression heat pump carry with. Relevant data, failure analysis and environmental test have been obtained by related companies in USA. The results showed that pre-launch testing not only reduced environmental satellite failures, but also provided numerous important means to ensure long service life of satellite [11, 12]. Environmental tests, such as temperature, pressure, vibration and electrostatic experiments, were essential for structure and material, as well as for checking environmental adaptability. Data published in this regard were little for confidentiality reasons. Goodman *et al.* [13] summarized the scope, objectives and value for various levels of thermal tests commonly performed on space-bound instrumentation, using gamma-ray large area space telescope as an example. Space reliability assessment was mostly stored for the ground or launch stage [14, 15]. Huang *et al.* [16] studied the influence of temperature on artillery's performance based on the impact of environmental factors on weapon. Liu *et al.* [17] reviewed the space agency research status regarding accelerated life testing. Wu and Liu [18] studied the feasibility of accelerated life testing of spatial moving parts liquid lubricated, and described some experiences of overseas trials. Zheng *et al.* [19] analyzed the equipment and steps needed to assess space reliability and service life based on ground tests. So far there had been a lot of research works for simulating accelerated life tests on the ground [20]. In addition, mechanical properties of some space materials and devices have been investigated in a simulated space environment [21]. Zhang *et al.* [22] investigated mechanical behavior of C/SiC composites under simulated space environments, including vacuum, cold and thermal cycling. Specimens were put into vacuum, cold and thermal cycling to verify whether there were significant changes in the flexural properties or the inter-laminar shear strengths, as well as in the associated fracture mode of C/SiC composites. Seo *et al.* [23] propose that component failure was strongly dependent on the temperature where the device operates. The failure occurring in an LM117 regulator, which was used as a microcircuit of the transponder unit during a space thermal environment test, was analyzed and discussed. Xu and Zhang [24] analyzed and studied the applicability of video image, infrared and ultraviolet/infrared flame detectors for high and large spaces, atrium in particular, and a test was designed for simulating actual working conditions and typical interference from ambient light.

To date, space environment tests of vapor compression heat pumps have been quite limited. Chen, *et al.* [25] carried out tests to study the gravity independence of compressor performance, and also investigated the performance of compressor and heat pump systems under microgravity. Ma *et al.* [26] used vibration tests to evaluate the anti-vibration capability of vapor compression heat pumps during transportation and use, finding that such heat pumps can operate normally after the vibration test with a COP that can reach 3.09. This paper reports extensions of that work to include high and low temperature tests and vacuum tests.

Experimental system

Experimental arrangement

A vapor compression heat pump testing system contains three subsystems: refrigerant cycle, water system, and data acquisition. The refrigerant cycle – consisting of compressor, condenser, evaporator, and capillary – is the key subsystem. The principal pipe was connected with Ø6 mm Cu pipe. A miniature rotary compressor, shown in fig. 1, was chosen because of its small size, light weight, low power consumption, minimal vibration, and precise controllability. The compressor was hermetically sealed and operated with a rolling piston mechanism. The 24-V DC power and driving module were used to drive a brushless DC motor. Compressor speed was adjusted by a driving module. The R134a and POERL68H were selected as the refrigerant and lubricating oil, respectively.

Figure 1. The miniature rotary compressor

Figure 2. Plate heat exchanger

The radiant condenser ultimately discharges heat from the heat pump to the external space environment. When carrying out space test simulations on the ground, a vacuum environment should, in principle, to be created for the radiation condenser. Since this is impractical, a common water-cooled plate heat exchanger was used instead. This heat exchanger is suitable for a small refrigeration system. It is shown in fig. 2.

The heat sink was an evaporator containing a self-designed micro-channel heat exchanger, as shown in fig. 3. Its cold plate was comprised of a refrigerant flow path portion and an end-cap portion. Rectangular micro-channel arrays were used for the evaporator flow path with an equivalent diameter of 2.67 mm. The evaporator was directly attached to the back of the thermal load equipment. During the experiment, the heating film of the evaporator was heated by a power supply. The heat was transferred to the refrigerant in the flow channel through the wall surface, causing the refrigerant to evaporate. A diagram of the relationship between evaporator and heat source is showed in fig. 4. Aluminum alloy proved to be the best choice because of its light weight, high strength, and high thermal conductivity.

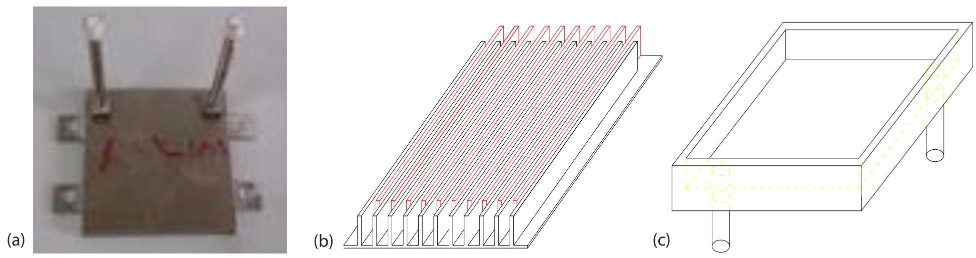
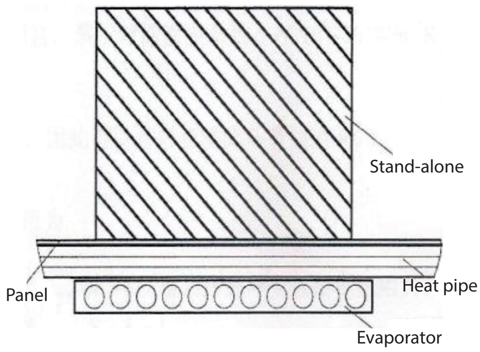


Figure 3. Heat sink (a), refrigerant flow path portion (b), and cap portion (c)

Figure 4. A diagram showing the relationship between evaporator and heat source



A capillary is suitable for heat pump systems with low mass-flow. Therefore, a capillary tube was selected as the throttle element. The diameter and length of the capillary were, respectively, 1.56 mm and 2 m. A schematic of the test set-up for the vapor compression heat pump tests is shown in fig. 5 and its photograph is shown in fig. 6.

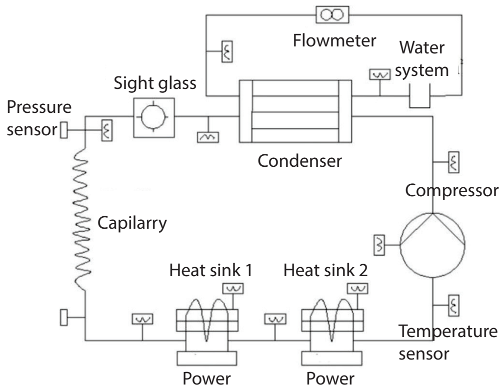


Figure 5. Schematic diagram of vapor compression heat pump test

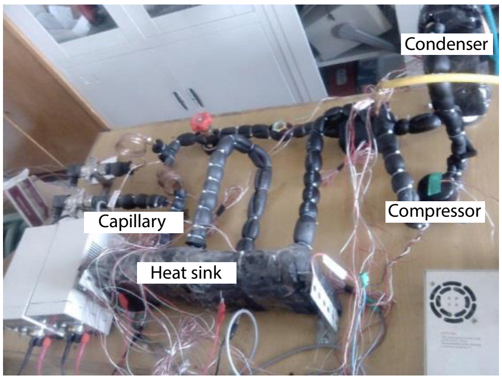


Figure 6. Photograph of the test set-up

The water system was composed mainly of a thermostatic water bath and a flow meter. The thermostatic water bath was used for adjusting the inlet temperature of the condenser. The flow rate of cooling water was measured by a small liquid turbine flowmeter covering the range from 0.04-0.25 m^3/h. A data acquisition system was used for recording data, including from temperature and pressure sensors, data loggers, DC power and computer. The Pt100 thermal resistances were used to measure the temperature to an accuracy of 0.1%. The high and low pressure sensors had ranges of 0-2.8 MPa and 0-2 MPa, respectively, and were accurate to within 0.25%. Constant heat was supplied to the heat sink by DC power. The exterior walls of critical components and systems were wrapped in black insulating cotton prevent external temperatures from affecting performance.

Data processing

Heat rejection, Q, on the condenser side is given:

$$Q = m_c c_p \left(t_1 - t_2\right) \tag{1}$$

where m_c is the mass-flow rate, c_p – the specific heat capacity, t_1 – the outlet water temperature, and t_2 – the inlet water temperature.

Compressor power is given:

$$W = UI \tag{2}$$

where U is the compressor voltage and I – the compressor current.

Thermal output heat, Q, from the refrigeration system is expressed:

$$Q = Q_c + W \tag{3}$$

where Q_c is the removed heat and W – the input electric energy.

The COP of the refrigeration system is then given:

$$COP = \frac{Q_c}{W} \tag{4}$$

Effect of high and low temperature on heat-pump performance

Experimental conditions

We adopted 0 °C and 70 °C as reference temperatures for assessing system performance. High and low temperature tests were performed in a temperature test chamber, as diagrammed in fig. 7. The dotted line encloses a temperature control box, within which the main refrigeration system is placed. Data acquisition and cooling water circulation are placed outside this temperature-control box, and some holes are provided for connecting the experimental parts inside and outside the box. The refrigerant charge was 150 g, and two heat sinks were supplied a total of 100 W of electric heating. The cooling water temperature was maintained at 30 °C. Compressor speed was set to 2500 rpm.

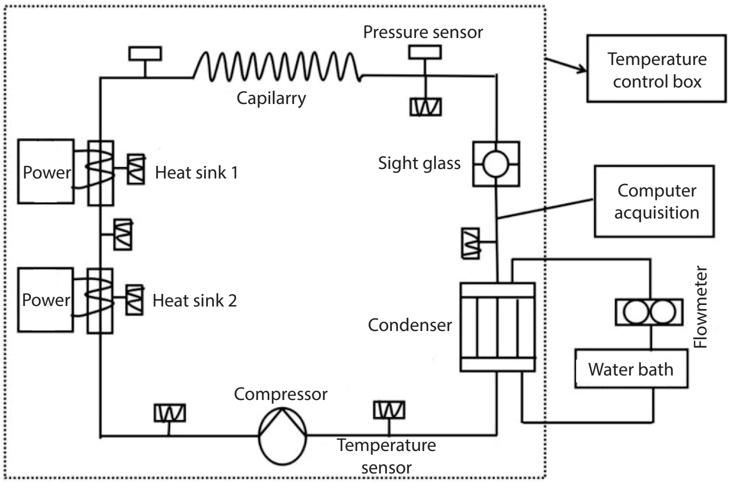


Figure 7. Schematic lay-out of vapor compression heat pump temperature tests

Experimental results

Figure 8 shows the temperatures of the heat sinks as a function of time in the low temperature test. After the heat sinks were heated to 45 °C, the compressor was turned on and the system started operating. The low temperature and low pressure liquid refrigerant, after throttling, flowed through the heat sinks to absorb and remove heat. Accordingly, the temperature of the heat sinks fell until being stabilized around 16 °C.

Figure 9 shows the evaporating pressure and condensing pressure as functions of time in the low temperature test. Condensing pressure is affected by cooling water temperature and by ambient temperature. However, since cotton insulation inhibited the effects of ambient temperature on the system, the condensing pressure was determined mainly by the cooling water temperature. The cooling water on the condenser side removed the heat of the system, and evaporating pressure and condensing pressure were reduced and stabilized at 0.44 MPa and 0.78 MPa, respectively. The stabilized evaporating temperature was 11.8 °C and the stabilized condensing temperature was 30.4 °C. Based on the inlet and outlet temperatures of the condenser and the net cooling water flow, heat rejection was calculated to be 129.4 W. Compressor power was 33.5 W. The COP in the low temperature environment was 2.99.

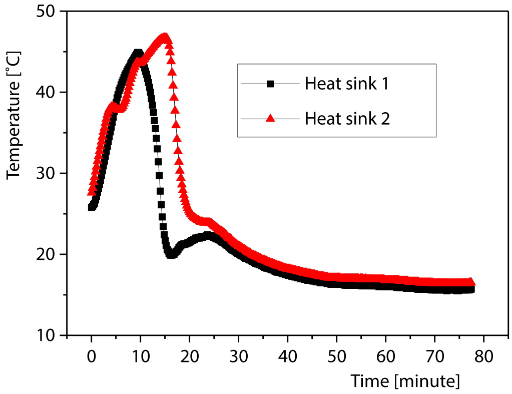


Figure 8. Temperatures of the heat sinks *vs.* time in the low temperature test

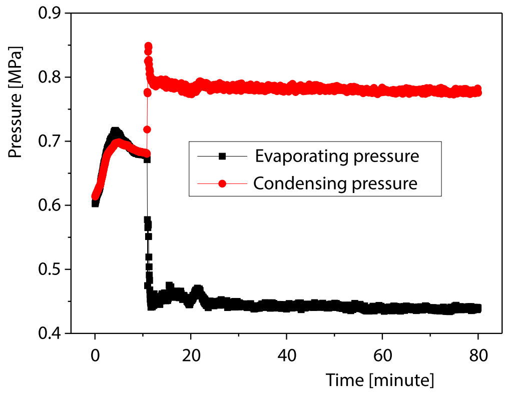


Figure 9. Evaporating pressure and condensing pressure in the low temperature test

The temperature set for the high temperature test was 70 °C. Just as with the low temperature test, when the heat-sink temperature rose to 45 °C, the compressor was started. Figure 10 shows temperatures *vs.* time for the heat sinks in the high temperature test. As the figure shows, the temperatures of the heat sinks stabilized at 16 °C.

Figure 11 shows the time dependence of the evaporating pressure and condensing pressure in the high temperature test. As shown in the figure, the evaporating and condensing pressures were stabilized at 0.45 MPa and 0.78 MPa, respectively. The corresponding evaporating temperature was 12.5 °C and condensing temperature, 30.4 °C. According to inlet and outlet temperature of cooling water and the collected cooling water flow, cooling capacity was calculated to be 127.3 W and compressor power was 33.5 W. Therefore, the COP in the high temperature environment was 2.99.

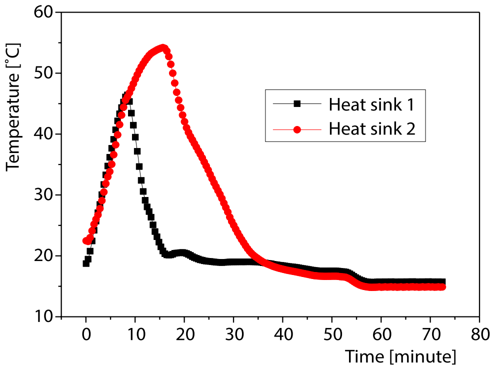


Figure 10. Temperatures *vs.* time in the high temperature test

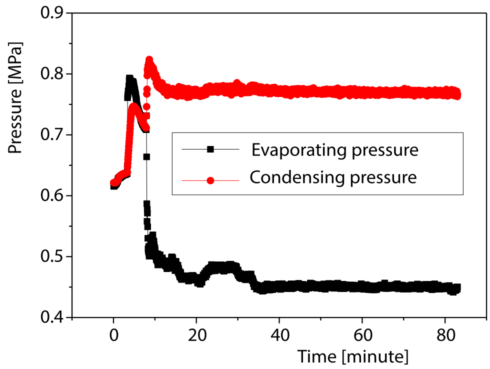


Figure 11. Evaporating pressure and condensing pressure in the high temperature test

High and low temperature test conditions and results are summarized in tab 1. These results indicate that vapor compression heat pumps can operate normally at the selected low temperature (0 °C) and high temperature (70 °C).

Table 1. Conditions and results of high and low temperature experiments

Condition	Refrigerant charge [g]	Compressor speed [rpm]	Compressor power [W]	Cooling water temperature [°C]	Cooling capacity [W]	COP
Low temperature 0 °C	150	2500	33.5	25	100	2.99
High temperature 70 °C	150	2500	33.5	25	100	2.99

Vacuum test

The second question be addressed is whether vapor compression heat pumps can operate properly in a vacuum environment, as they would need to do in space.

Experimental conditions

For experiments conducted on the ground, it is impractical to use a radiant condenser as would be used in space. For the vacuum tests, the vapor compression heat pump established in the previous section was modified, with the condenser placed in a sealed tank filled with water for heat transfer. Figures 12 and 13 show schematic lay-out and physical maps of vapor compression heat pump for vacuum testing, respectively. Figure 14 showed the vacuum test of vapor compression heat pump. The degree of vacuum was set to 10^{-4} Pa. The temperature in vacuum cabin was kept at 6 °C.

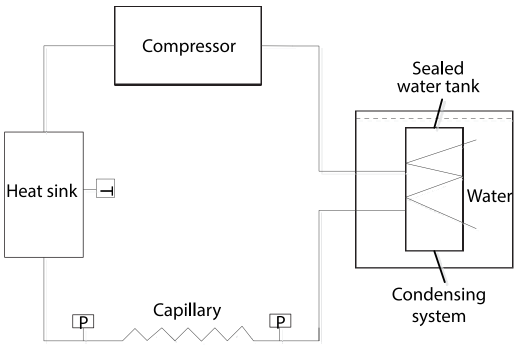


Figure 12. Schematic lay-out of vapor compression heat pump for vacuum tests

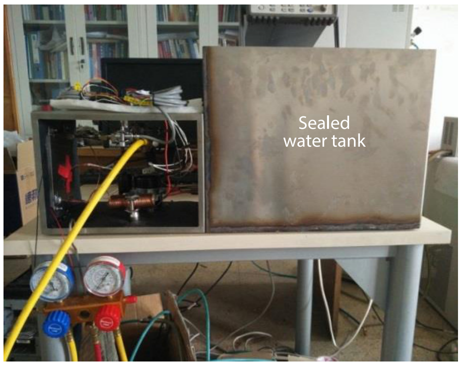


Figure 13. Photograph of the vapor compression heat pump for the vacuum test

Experimental results

The refrigerant charge was 150 g and the heat sink was supplied with 100 W of electric heating, just as in the temperature tests. When the heat sink temperature reached 35 °C, the compressor was started. Refrigerant gas-flowed through condensation and throttling process into the heat sink under the driving force of the compressor. As can be seen in fig. 15, the temperature of the heat sink decreased and eventually stabilized at 13 °C.

Figure 14. Vacuum test of vapor compression heat pump

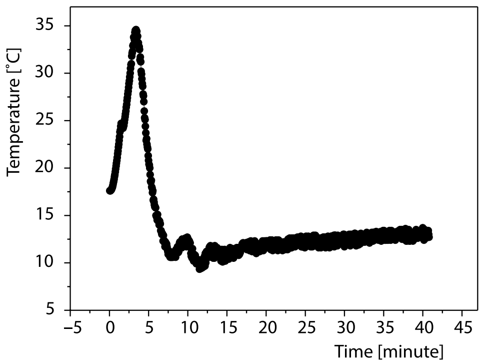


Figure 15. Temperature of heat sink *vs.* time in vacuum test

Figure 16 shows the evaporating pressure and condensing pressure in the vacuum test, during which the condenser and the water in the tank continuously exchanged heat. As a result, the water temperature in the tank increased and the heat transfer performance was reduced, resulting in an increase in condensing temperature. Even though the condensing temperature was increased, refrigerant liquid produced by condensation and throttling was sufficient to take away the heat of heat sink. Evaporating pressure was eventually stabilized at 0.4 MPa and condensing pressure at 0.85 MPa. The corresponding temperatures were, respectively, 10 °C and 33.5 °C.

Since the vapor compression heat pump was in a vacuum environment, nearly all the heat loading was transmitted to the water tank through the condenser. The water tank then discharged its heat to the vacuum chamber through radiation. Heat rejected at the condenser side was approximately equal to electrical heating plus compressor power. The vapor compression heat pump transferred heat to the water in the tank, which caused the water temperature to rise. The temperature of the water in the tank could be reduced only slowly by radiation of the tank. As shown in fig. 17, the temperature of the water in the tank decreased and then remained constant in the vacuum test. The vacuum test can therefore, be considered successful, since the heat sink temperature was reduced and met the design requirements. Specific parameters of the vacuum test are shown in tab 2.

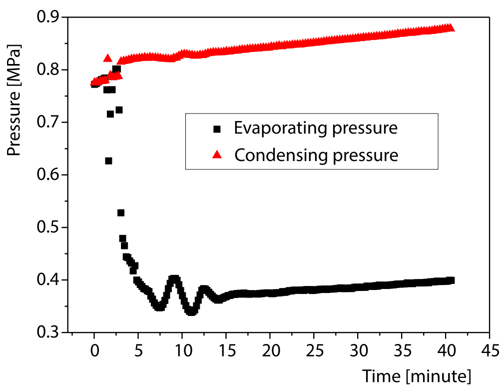


Figure 16. Evaporating and condensing pressures *vs.* time in the vacuum test

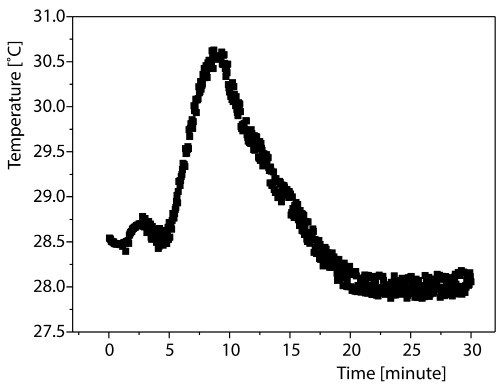


Figure 17. The temperature of water in the tank vs. time in the vacuum test

Table 2. The specific parameters of vacuum test

The degree of vacuum [Pa]	Refrigerant charge [g]	Compressor speed [rpm]	Compressor power [W]	Cooling capacity [W]	COP
10^{-4}	150	2500	48	100	2.1

Conclusions

Temperature and vacuum tests of a vapor compression heat pump were carried out to simulate space conditions. The vapor compression heat pump can operate normally at both low (0 °C) and high (70 °C) temperature. The COP of the tested vapor compression heat pump was 2.99 at both high and low temperatures in a normal environment but was reduced to 2.1 in a vacuum environment. The results indicate that vapor compression heat pumps can be expected to operate successfully in future space missions.

Acknowledgment

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Nomenclature

c_p – specific heat capacity, [Jkg^{-1}°C^{-1}]
I – compressor current, [A]
m_c – mass-flow rate, [kgs^{-1}]
Q_c – refrigeration capacity, [W]
t_1 – outlet water temperature, [°C]
t_2 – inlet water temperature, [°C]
U – compressor voltage, [V]
W – compressor power, [W]

Subscripts

c – refrigeration

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