

Comparison of Heat Pipes

Under Normal and Low Gravity Conditions

The heat pipe is a device with very high thermal conductance. It can transport large quantities of heat with small temperature differences between its hot and cold ends. It is normally used to transport heat from one location to another location or smooth the temperature distribution on a solid surface. The heat pipe is widely used in aerospace applications, military devices, temperature control systems and, now, personal computers.

Moreover, the heat pipe is a self-driven, two-phase heat transfer device. A schematic view of a heat pipe is shown in Figure 1. At the hot section (evaporator), the liquid evaporates and turns to vapor. The vapor flows to the cold section (condenser) and liquefies there. The liquid is driven back from the cold section to the hot section by capillary force induced by a wick structure.

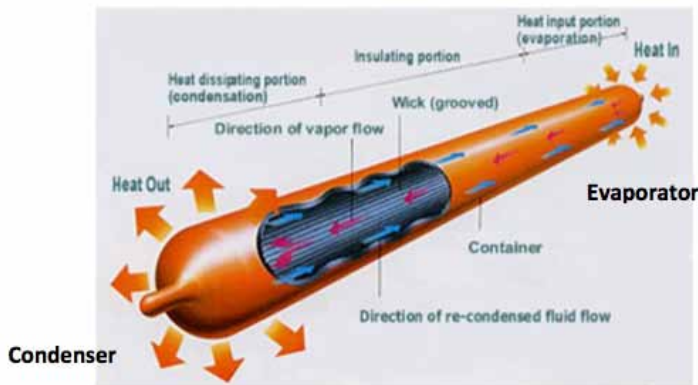


Figure 1. Typical Heat Pipe [1]

The heat transfer ability of a heat pipe is determined by its diameter, fluid type, wick structure and orientation. In order for the heat pipe to operate, the capillary pumping power must be greater than the total pressure drop in the pipe. The total pressure drop is made up of three components [2]:

- 1) The pressure drop ΔP_v required to drive the vapor to flow from the evaporator to the condenser.
- 2) The pressure drop ΔP_i needed to pump the liquid back to the evaporator from the condenser.
- 3) The pressure due to the gravitational head ΔP_g , which can be zero, positive or negative, depending on the relative location of the evaporator and the condenser. For the fluid inside the heat pipe to circulate, the following equation must be satisfied:

$$\Delta P_{capillary} \geq \Delta P_v + \Delta P_i + \Delta P_g$$

If this condition is not met, the wick on the evaporator will dry out and the heat pipe will overheat. On the ground application, the gravitational pressure head ΔP_g is determined by relative positions of the evaporator and the condenser. If the angle between a straight heat pipe and a horizontal one is θ (θ is positive when the evaporator is lower than the condenser), the gravitational pressure head ΔP_g can be calculated as follows:

$$\Delta P_g = -\rho g l \sin \theta$$

where ρ is liquid density and l is heat pipe length. In such cases, it is recommended that the heat pipes work on a vertical orientation with the condenser on top. C. K. Loh et al. [3] experimentally studied the effects of wick structure and orientation on heat pipe performance. They found that it is important to select the proper wick structure for heat pipes based on real application. If the heat pipe works on conditions with a favorable gravitational force and few bends, the groove wick heat pipe is a good choice, due to its superior thermal performance. If the heat pipe has complex geometry and works at a small or negative tilting angle, the sintered powder metal is the optimum wick structure for heat pipe.

In aerospace applications such as satellites, the heat pipes are working under microgravity conditions. The design of heat pipes for operation in such circumstance requires an understanding of their operating characteristics in low-gravity conditions. The thermal behavior of the two-phase thermal systems cannot be properly observed on Earth because gravity tends to dominate over other fluid mechanic phenomena. Actually, the gravitational force can mask some effects, so that when it is decreased or even removed to space applications, other forces can assume control of the fluid mechanics.

To investigate the effects of gravity, R. Savino et al. [4] experimentally compared the performances of different heat pipes under normal gravity and low gravity conditions. Some of the tested heat pipes have composite wick and others are wickless, some are filled with pure water and others are filled with water/alcohol binary mixtures. Their reduced gravity experiments have been carried out during the 45th ESA parabolic flight campaign onboard an Airbus A-300. Figure 2 shows their experimental hardware, including the experimental chamber (on the right, Figure 2b) and the experimental rack (Figure 2a) with the cooling unit, the data logger, the monitors for the visualization of the CCD and the thermographic images, the power supply and a vacuum pump.

a



b



Figure 2. (a) Experimental Rack Onboard Airbus A300. (b) Vacuum Chamber with Heat Pipes. [4]

Figure 3 shows the experimental setup for the heat pipes. The detailed test setup is described by R. Savino et al. [3] as follows. Each experiment has been carried out in parallel using four heat pipes with a 25 cm total length. The heat pipes have different diameters (4 and 8mm). The structure of the heat pipes with 8mm diameter is wickless. The 4mm heat pipes have a composite wick. The heat pipes are filled with pure water and with the same amount of water solutions of long chain alcohols. The liquid volume in the wickless heat pipes (8mm diameter) is 20% of the inner volume. For the heat pipes with composite wick (4mm diameter) different filling ratios, 10% and 20%, are used.

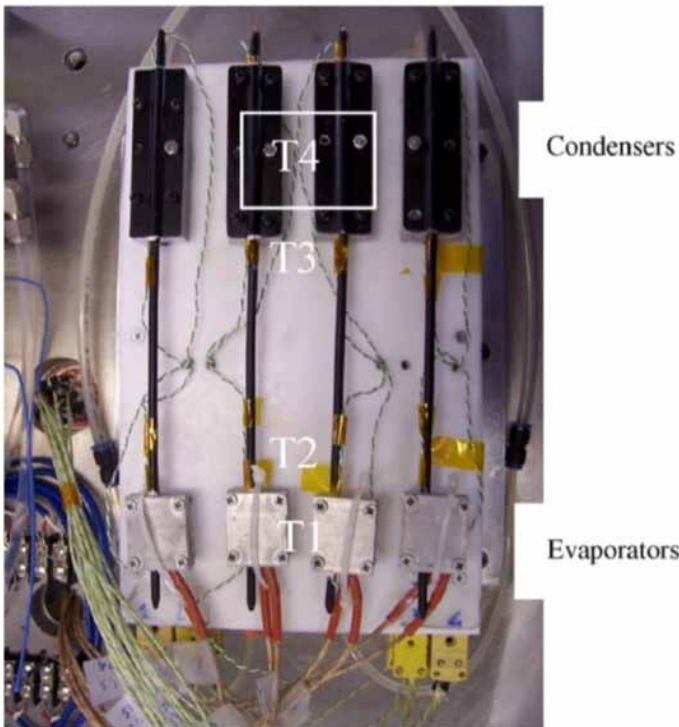


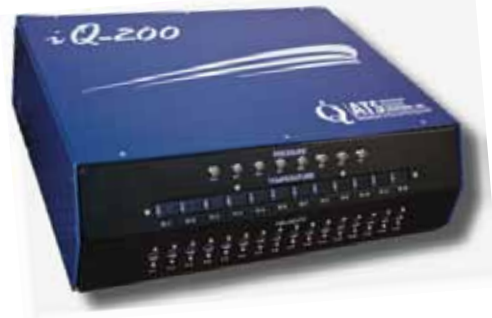
Figure 3. Heat Pipe Test Setup

At the evaporator side, the pipes are placed between aluminum blocks with cartridge heaters inside as heat source. The heat pipe condensers are aluminum blocks with tubes. Water circulates inside tubes to maintain a constant cooling temperature. The heat pipes are all black painted. An infrared thermocamera (FLIR SC3000) is used to measure their surface temperature.

In addition, four thin thermocouples (K-type) are placed on each heat pipe (see Figure 3). The thermocouple T1 is located in the center of the evaporator block. The thermocouple T2 is located close to the evaporator at the beginning of the adiabatic region. The thermocouples T3 and T4 are placed, respectively, at the beginning and in the middle of the condenser.

Figure 4 shows the laboratory results obtained for the copper heat pipes, including wickless heat pipes with $D=8\text{mm}$ and heat pipes with diameter $D=4\text{mm}$ and composite wick, filled with water or with the alcoholic aqueous solution.

iQ-200



iQ-200 is a new instrument from Advanced Thermal Solutions, Inc. that measures air flow, air temperature, surface temperature and differential pressure drop simultaneously. The instrument comes with 16 velocity channels, 12 thermocouples and 4 pressure transducers. All three functions are bundled in one instrument.

OVERALL DIMENSIONS
(D x W x H)
43 cm x 34 cm x 12.6 cm
(17" x 13.3" x 5")

NUMBER OF VELOCITY CHANNELS - 16

FLOW RANGE
0 to 50 m/s (0 to 10,000 ft/min)

NUMBER OF THERMOCOUPLES
12 (J, K, T, and E types)

NUMBER OF PRESSURE SENSORS
4 (Differential)

PRESSURE RANGE
0 to 0.15 psi

SOFTWARE
IQstage™

VOLTAGE INPUT
110V or 220V

WEIGHT
7.5 kg (15 lbs.)



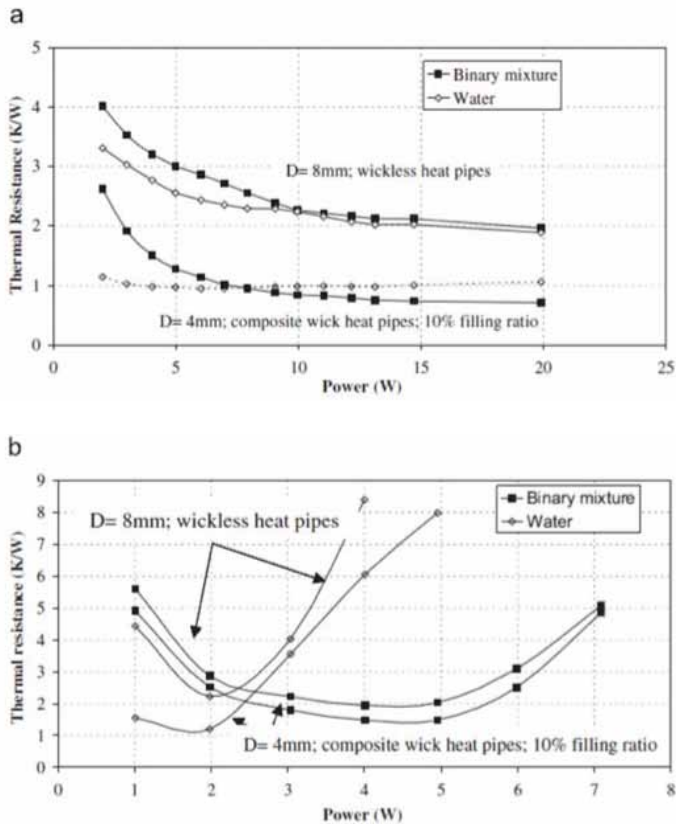


Figure 4. Thermal Resistance as a Function of Power for Wickless Heat Pipes and Heat Pipes of Composite Wick Filled with 10% Liquid Volume Ratio. (a) Vertical Configuration, (b) Horizontal Configuration.

In the vertical configuration, the thermal resistance of heat pipes decreases with an increase of power. For 8mm wickless heat pipes, the performance difference is small between water and an alcoholic, aqueous solution when $Q > 10\text{W}$. For 4mm wick heat pipes, heat pipes with an alcoholic aqueous solution have a smaller thermal resistance when $Q > 7.5\text{W}$. In the horizontal configuration, the heat pipe with water dried out easily when power was increased. On the other hand, heat pipes with alcoholic aqueous solution maintain performance with higher power input; but, then, they eventually dry out after 7 Watts.

Figure 5 shows typical temperature results obtained during the parabolic flight for the wickless heat pipes (8mm diameter). The duration of each reduced gravity phase is about 20 s, with more or less the same period of

hypergravity conditions immediately before and after the low gravity phase. The time between two consecutive parabolas is about 3 min. The power supplied at the evaporator block is maintained at 12W.

During testing, the temperatures are stable in normal gravity conditions at first. For the heat pipe filled with water, during the reduced gravity phases, the temperature in the hot region (evaporator) suddenly rises; on the contrary, the temperatures at the cold region (condenser) decrease abruptly. This behavior systematically occurs during each parabola and is more evident when increasing the power. During the phase of increased gravity, the hot region (evaporator) and the cold region (condenser) maintain a steady temperature.

The behavior of the heat pipe filled with the binary mixture is different. The temperature variation is smaller under gravity change. The thermocouples and the infrared images reveal periodical temperature fluctuations, but the heat pipe steadily operates during the low gravity and high gravity situations.

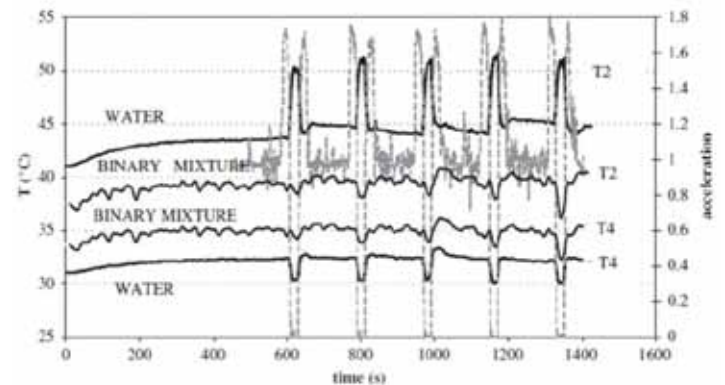


Figure 5. Time Histories of the Temperatures in the Wickless Heat Pipes Filled with Water and the Binary Mixture, $Q=12\text{W}$.

Figure 6 compares the IR images taken in normal gravity and in low gravity for a power $Q=12\text{W}$. For heat pipes using water, the temperature in the evaporation region appreciably increases and the temperature of the condenser decreases under low gravity conditions. In contrast to this, the temperature distribution of the heat pipe filled with the binary mixture is almost the same in normal gravity and in reduced gravity and its temperature distribution is more uniform.

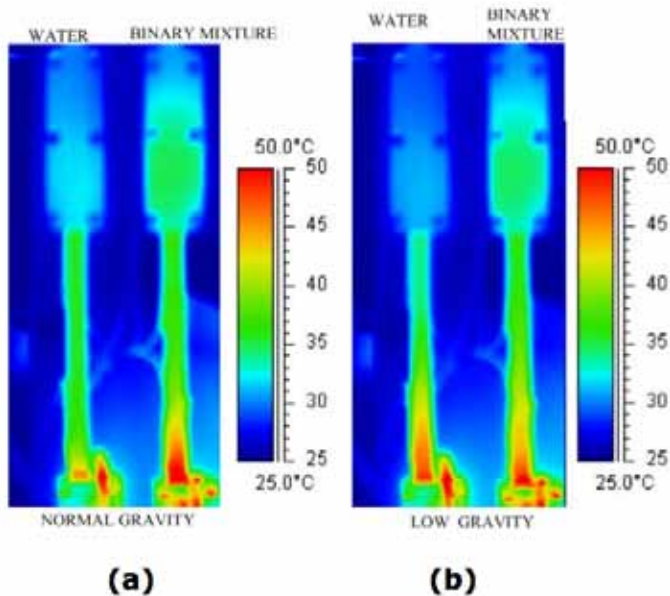


Figure 6. Infrared Images of the Wickless Heat Pipes Filled with Water and Binary Mixture in (a) Normal Gravity and (b) Low Gravity, $Q=12W$.

All the IR images have been analyzed by R. Savino et al. [3] and the temperature increase between the evaporator and the condenser occurring during the parabolas has been analyzed at the different powers. The results are summarized in Figure 7. It is found that for the water heat pipe, the temperature increase is proportional to the applied power. For the heat pipe filled with the binary mixture, it still operates well in low gravity.

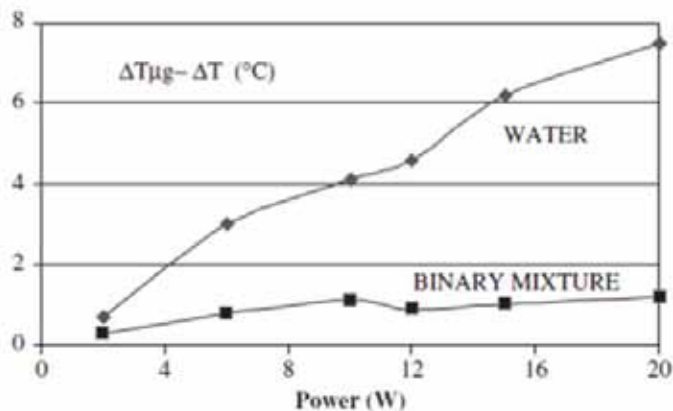


Figure 7. Temperature Difference Increase During the Reduced Gravity Phase for Wickless Heat Pipes

The study of R. Savino et al. shows that the heat pipe's performance decreases under low gravity conditions. But, the performance variations are different for heat pipes with different working fluids. For heat pipes using water, gravity plays a big role and their thermal resistance increases rapidly at low gravity conditions. The test of R. Savino et al. also shows that the heat pipes using an alcoholic aqueous solution can maintain their performance under low gravity conditions. Their thermal resistance only increases slightly under low gravity conditions. With an increase of heat dissipation in electronic conditions, it is feasible to design high performance heat pipes for aerospace applications whose thermal performance is less dependent on gravity. However, there is more work needed to be done to investigate how heat pipes with different wick structures and working fluids behave under low gravity or even non gravity conditions, before we can claim to have a clear understanding of boiling and condensation inside heat pipes under such conditions.

References:

1. <http://www.lightstreamphotonics.com/technology.htm>
2. David, R. and Peter, K., **Heat Pipes: Theory: Design and Application**, Butterworth-Heinemann, USA, Fifth Edition 2006.
3. Loh, C.K., Harris, E., and Chou, D.J., **Comparative Study of Heat Pipes Performances in Different Orientations**, Semiconductor Thermal Measurement and Management Symposium, 2005, Page 191-195.
4. Savino, R., Abe, Y., and Fortezza, R., **Comparative Study of Heat Pipes with Different Working Fluids under Normal Gravity and Microgravity Conditions**, Acta Astronautica (2008).