Analysis of Test Methods for Durability and Performance of Heat-pipes for Solar Thermal Application

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Abstract

After introducing the configuration of a heat-pipe for solar thermal application, this paper analyses test methods for two main aspects which affect the durability of heat-pipes, i.e. high temperature resistance and freeze resistance, and also analyses test methods for three important parameters which indicate the performance of heat-pipes, i.e. starting temperature, temperature uniformity and heat transfer power. For each durability test and performance test of heat-pipes, their significance and necessity, as well as their test objective, test principle, test conditions, test apparatus, test procedure, test results, etc. are respectively introduced in this paper. These test methods have been newly developed as the International Standard ISO 22975-2: 2016, which will play an important role in enhancing product quality and reducing test cost of heat-pipes.

Keywords: Heat-pipe, test methods, durability test, performance test, International Standard

1. Introduction

Heat-pipe is a highly efficient heat transfer element and has been widely used for solar thermal application. For this reason, ISO/TC 180 has recently developed the International Standard ISO 22975-2: 2016 titled as Solar Energy – Collector components and materials, Part 2: Heat-pipe for solar thermal application – Durability and performance.

ISO 22975-2: 2016 specifies test methods for durability and performance of heat-pipes, and is applicable to all heat-pipes for use with evacuated tubes, including glass-metal sealed evacuated tubes and double-glass evacuated tubes, as well as for use with flat-plate collectors.

For each durability test and performance test of heat-pipes, their significance as well as test objective, test principle, test condition, test apparatus, test procedure, test results, etc. will be introduced in the paper.

2. Configuration of the heat-pipe

Heat-pipes operate only by utilizing latent heat of phase-change of the working fluid for heat transfer. Heat-pipes can be basically classified into two categories according to backflow manner of the working fluid. One is the heat-pipe with a capillary wick, and the other one is the heat-pipe without a capillary wick. For the former, backflow of the liquefied working fluid relies on the capillary action; whereas for the later, backflow of the liquefied working fluid relies on its gravity. Therefore, the later is also called as the gravity heat-pipe.

Since this international standard is only applicable to gravity heat-pipes, so the gravity heat-pipe essentially consists of evaporator, condenser, adiabatic section and working fluid, as shown in Fig. 1, and there is a highly evacuated space inside the heat-pipe. For the gravity heat-pipe, the liquefied working fluid returns from the condenser to the evaporator due to its own weight.

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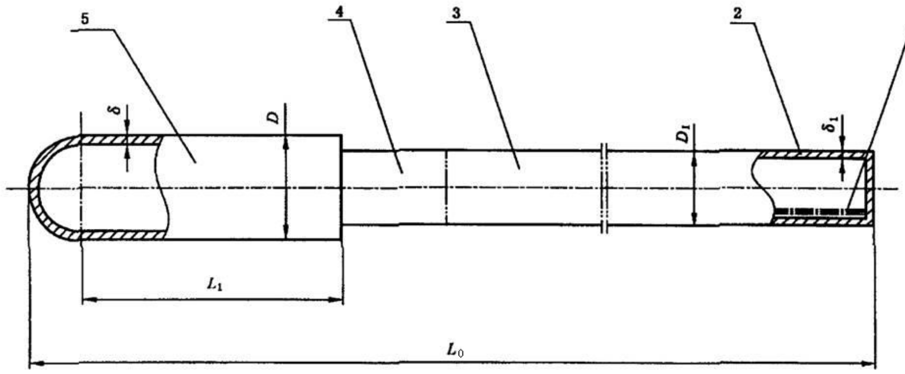


1) Working fluid
4) Adiabatic section
2) Shell (container)
5) Condenser
3) Evaporator

Fig. 1: Typical configuration of a heat-pipe for solar thermal application

3. Durability of heat-pipes

3.1. High temperature resistance test

As heat-pipes used for solar thermal application may probably undergo an exposure state under the sun to reach a quite high temperature, for example, in the range of 180 ℃ to 280 ℃ for different applications, so it is necessary to perform a high temperature resistance test.

This test is intended to assess the capability of the heat-pipe to withstand quite high temperature without failure.

The test needs indoor environment. The test shall be carried out using a set of test apparatus which consists of a heating chamber and a thermometric system, of which the test temperature shall be at 180 ℃ ± 5 ℃ or 230 ℃ ± 5 ℃ or 280 ℃ ± 5 ℃, depending on specific application and manufacturer's declaration.

In the test, place all sample heat-pipes with a tilt angle 90° ± 1° into the heating chamber; increase the temperature slowly (maximum 20 K/min) up to the selected test temperature; maintain the test temperature for 30 h; then let heat-pipes naturally cool down; after the heat-pipes have cooled to room temperature, visually inspect for damage such as leakage, breakage, distortion or deformation.

The heat-pipes will be qualified if there is no visual evidence of damage.

3.2. Freeze resistance test

As heat-pipes used for solar thermal application may undergo a freeze weather condition in winter season in many areas to reach a rather low temperature, such as below 0 ℃, so it is very important to perform a freeze resistance test.

This test is intended to assess the extent to which the heat-pipe which is claimed to be freeze resistant, can withstand freezing without failure.

The test needs indoor environment. The test shall be carried out using a set of test apparatus which consists of an appropriate freezing device and a thawing device. The freezing temperature shall be at −20 ℃ ± 1 ℃ and the thawing temperature shall be at 20 ℃ ± 1 ℃.

In the test, place all sample heat-pipes with a tilt angle 90° ± 1° into the freezing device for 60 min; remove the heat-pipes from the freezing device and insert them into the thawing device, keeping the evaporator in lower position; measure the temperature on the condenser surface; wait for 5 min after the temperature difference between the thawing device and the condenser surface is less than 9 K, which indicates that heat-pipes have started to operate again; repeat above-mentioned steps 20 times; then visually inspect for damage such as leakage, breakage, distortion or deformation.

The heat-pipes will be qualified if there is no visual evidence of damage.

4. Performance of heat-pipes

4.1. Starting temperature of heat-pipes

Heat-pipes used for solar thermal application always face such a problem, whether and when the heat-pipe can start operating. From the evaporation point of view, as there is a negative pressure inside the heat-pipe, the evaporation temperature of the liquefied working fluid should be lower than that at atmospheric temperature, so as to easily start operating of the heat-pipe, and undoubtedly the lower starting temperature the better for solar thermal application. Therefore, starting temperature is one of the important parameters of heat-pipes.

This test is intended to determine the minimum temperature required for a heat-pipe to start operating.

The test needs indoor environment. The test shall be carried out using a set of test apparatus which consists of a cold water bath at 10 ℃ ± 0.5 ℃ and a hot water bath at 25 ℃ ± 0.5 ℃ or 30 ℃ ± 0.5 ℃ or 40 ℃ ± 0.5 ℃, depending on specific application for different working temperature of the heat-pipe; however, 40 ℃ ± 0.5 ℃ shall be the maximum test temperature.

In the test, fit a surface temperature sensor to the condenser; immerse the lower end of the heat-pipe in the cold water bath with a tilt angle 90° ± 1°; wait for at least 3 min after stable conditions are reached; remove the heat-pipe from the cold water bath and immerse its lower end in the hot water bath; measure and record the temperature on the condenser surface every 10 s until at least 120 s after stable conditions are reached; record the condenser surface temperature together with the hot water bath temperature.

The measurement results shall be reported together with ambient temperature, cold water bath temperature, hot water bath temperature, insertion depth of the heat-pipe, distance of measuring point from top of the condenser and variation of the condenser surface temperature.

4.2. Temperature uniformity of heat-pipes

Under normal operating conditions, steam of the working fluid inside the heat-pipe is in a saturated state, and pressure of the saturated steam determines temperature of the saturated steam. As the pressure drop produced when saturated steam moves from the evaporator to the condenser is very small, so the temperature drop is also very small. That is why the heat-pipe possesses excellent isothermal. If there is an obvious temperature difference between the evaporator and the condenser, i.e. the heat-pipe loses the temperature uniformity; it means that non-condensable gas produced during the manufacturing stays in the condenser. Undoubtedly the smaller temperature differences the better for solar thermal application. Therefore, temperature uniformity is also one of the important parameters of heat-pipes.

This test is intended to measure the temperature difference between the evaporator and the condenser when the heat-pipe operates under normal conditions.

The test needs indoor environment. The test shall be carried out using a thermostatic hot water bath at 90 ℃ ± 0.5 ℃.

In the test, fit a surface temperature sensor to the condenser at a point between 18 mm and 22 mm from top of the condenser; insert the heat-pipe into the thermostatic hot water bath to a depth of 3/5 - 2/3 of the total length of the heat-pipe at a tilt angle 90° ± 1°; measure and record the temperature on the condenser surface every 10 s until at least 60 s after stable conditions are reached; record the temperature difference between the hot water bath temperature and the stable condenser surface temperature.

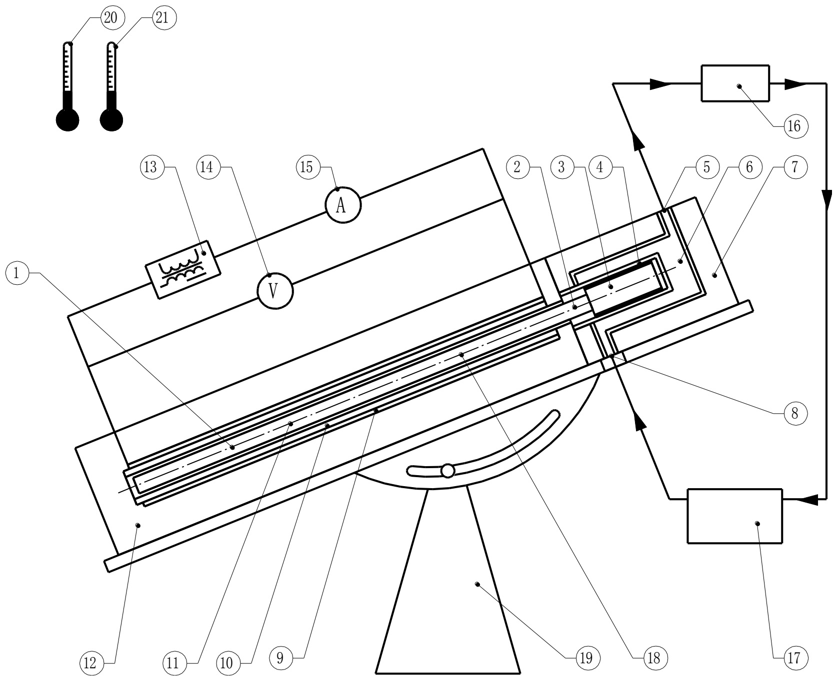
The measurement results shall be reported together with ambient temperature, test temperature in water bath, insertion depth of the heat-pipe, measuring point from top of the condenser, and condenser temperature variation.

4.3. Heat transfer power of heat-pipes

As a highly efficient heat transfer element for solar thermal application, it is concerned that how much power can be transferred. Therefore, heat transfer power is certainly one of the important parameters of heat-pipes.

As heat transfer power depends on operating temperatures and tilt angles of the heat-pipe, so this test is intended to determine the heat transfer power of the heat-pipe at different operating temperatures and different tilt angles.

The test needs indoor environment. The test apparatus includes tilt-angle adjustable mounting support, evaporator electric heating barrel, condenser cooling liquid jacket, thermostatic liquid bath, flow meter, etc. shown in Fig. 2.



1) heat-pipe evaporator
2) heat-pipe adiabatic section
3) heat-pipe condenser
4) heat transfer paste
5) temperature difference sensor
6) cooling liquid jacket
7) thermal insulation
8) inlet temperature sensor
9) electric heating barrel
10) heat-uniform tube
11) evaporator temperature sensor
12) thermal insulation
13) voltage regulator
14) volt meter
15) ampere meter
16) flow meter
17) thermostatic liquid bath
18) evaporator temperature sensor
19) tilt-angle adjustable support
20) thermometer
21) humidity meter

Fig. 2: Typical test apparatus for measuring the heat transfer power of a heat-pipe

In accordance with the energy conservation law, the heat transfer power of the heat-pipe shall be calculated according to Equation (1).

$$\dot{Q} = \dot{Q}_1 - \dot{Q}_2 \qquad \text{(eq. 1)}$$

where

$\dot{Q}$	=	heat transfer power of heat-pipe, W
$\dot{Q}_1$	=	thermal power transferred to cooling liquid from heat-pipe, W
$\dot{Q}_2$	=	thermal power transferred to cooling liquid from environment or apparatus, W; normally $\dot{Q}_2$ is negligible if the cooling liquid jacket is well insulated

The thermal power received by cooling liquid shall be calculated according to Equation (2).

$$\dot{Q}_1 = \dot{m} C_p (\vartheta_2 - \vartheta_1) \qquad \text{(eq. 2)}$$

where

$\dot{m}$	=	mass flow rate of cooling liquid, kg/s
C_p	=	specific heat capacity of cooling liquid, J/(kg • K)
ϑ_2	=	inlet temperature of cooling liquid, °C
ϑ_1	=	outlet temperature of cooling liquid, °C

In the test, the evaporator of the heat-pipe is inserted into the sleeve of the electric heating barrel; a copper tube shall be placed between the evaporator and the electric heating elements to ensure uniform heating power distribution; the outer surface of the electric heating barrel shall be thermally insulated; meanwhile, the condenser of the heat-pipe is inserted into the sleeve of the cooling liquid jacket and surrounded with heat transfer paste which has not been used previously; the outer surface of the cooling liquid jacket shall be thermally insulated.

After measuring all necessary parameters, such as mass flow rate $\dot{m}$, inlet temperature ϑ_2 and outlet temperature ϑ_1 of the cooling liquid, then determine the heat transfer power $\dot{Q}_1$ at different operating temperatures and different tilt angles, according to Equation (2).

The test operating temperatures shall be respectively at 60 ℃ ± 0.5 ℃, 90 ℃ ± 1 ℃ and 120 ℃ ± 2 ℃ (when the heat-pipe is claimed to be able to operate at above 100 ℃).

The tilt angle of the heat-pipe shall be from the lowest recommended angle to 90°, i.e. respectively the lowest recommended angle, 20° ± 1°, 30° ± 1°, 45° ± 1°, 60° ± 1°, 75° ± 1°, 90° ± 1°.

In this test, the maximum heat transfer power $\dot{Q}_{max}$ also could be determined. This test shall be conducted directly after carrying out the test of heat transfer power at the test operating temperature 120 ℃ ± 2 ℃ and test tilt angle 90° ± 1°.

For determining the maximum heat transfer power $\dot{Q}_{max}$, the procedure shall be as follows:

Slowly increase the power input to the evaporator electric heating barrel, i.e. at a rate of less than 5 W/min; observe the test operating temperature of the heat pipe; once there is an obvious sudden temperature increase, or the temperature shows obvious oscillation and instability, it means that the heat-pipe has reached its heat transfer limit; then quickly reduce the power input to the evaporator electric heating barrel to a point just before the heat transfer limit; when steady state conditions have been achieved, begin to record the values of mass flow rate $\dot{m}$ of the cooling liquid, and inlet/outlet temperature difference ($\vartheta_2 - \vartheta_1$) of the cooling liquid, at intervals of 30 s for a period of 10 min; finally calculate the maximum heat transfer power $\dot{Q}_{max}$ of the heat-pipe according to Equations (2), using the averages of the recorded values for mass flow rate and inlet/outlet temperature difference of the cooling liquid.

5. Conclusion

Heat-pipe is one of the important components in solar thermal application. Through a lot of experiments and accumulated practical experience, this paper analyses two main aspects which affect the durability of heat-pipes, including high temperature resistance and freeze resistance,

In addition, this paper also analyses three important parameters which indicate the performance of heat-pipes, including starting temperature, temperature uniformity and heat transfer power.

Based on these achievements, under the joint efforts of WG 3 members, ISO/TC 180 has recently developed International Standard ISO 22975-2: 2016. The newly developed International Standard will play an important role in enhancing product quality and reducing test cost of heat-pipes.

6. References

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