Development of Titanium Heat Pipes for Use in Space

By

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Summary: This paper describes titanium heat pipe design, manufacture and tests. The heat pipes developed are a titanium-ammonia heat pipe with axial grooves (FCHP) and a titanium-ammonia-gas loaded variable heat pipe which has a heated reservoir (VCHP). Nitrogen was charged to the VCHP as non-condensible gas. In this heat pipe development program, the manufacturing processes were studied successfully and it was clarified that titanium is very desirable as heat pipe material for use in space.

1. INTRODUCTION

There have been many efforts to improve the heat rejection control system for spacecraft which accommodate the increased internal heat dissipation of electronic equipment.

In these efforts, gas-loaded variable conductance heat pipes have been applicalbe. Stainless steel has usually been selected as the envelope material, because of its low thermal conductivity and great strength. However, since stainless steel density is about 2.7 times that of aluminum, stainless steel usefulness is limited for space applications.

Therefore, titanium has been considered to be a useful material for space use heat pipes because of its lighter density and thermal properties. However, titanium has been abandaned for a long time as heat pipe material since it has been believed to be too hard and brittle for machining and fabricating during heat pipe production.

This paper covers the development of titanium-ammonia heat pipe (FCHP) and titanium-ammonia gas loaded variable heat pipe (VCHP) which has a heated reservoir and uses charged nitrogen as non-condensible gas. The paper also describes an outline of the manufacturing process and performance test results for both heat pipes.

2. VCHP AND TITANIUM

Figure 1 shows a sketch which expresses the principle of non-condensible gas control. The underlying principle of non-condensible gas control is the formation of a gas plug at the condenser end of the pipe, whic acts as a diffusion barrier to the flowing vapor. By varying the length of this gas plug, the active condenser area is varied. Hence, the system heat rejection properties are appropriately varied.

By introducing a fixed amount of gas into the pipe, the gas occupies a certain portion of the condenser section, depending on the operating temperature of the pipe's active region and environmental conditions.

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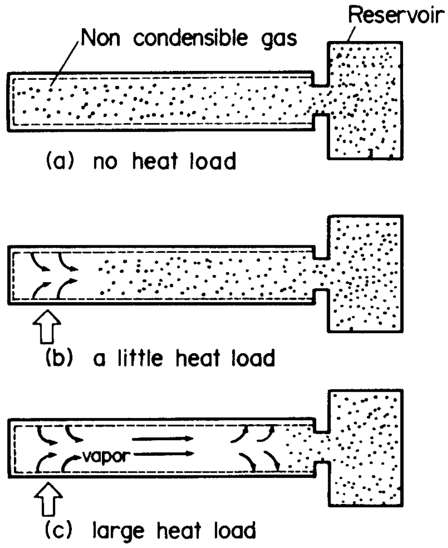


Fig. 1. Non-condensible gas control principle.

Table 1. Titanium (Ti), Stainless Steel (sus) and Aluminum (Al) Properties

	Temperature (K)	Termal conductivity (W/m.k)	Density (kg/m^3)	Tensile stregth (M Pa)
	280	20.7		455.1
Ti	418	19.0	4.4×10^3	310.2
	555	18.1		220.6
	280	15.1		641.2
SUS304	418	17.3	7.5×10^3	537.8
	555	19.1		448.2
	280	190.3		255.1
Al	418	190.3	2.8×10^3	137.9
	555	207.1		62.0

If operating temperature increases (heat load increases), the working fluid vapor pressure increases. This compresses the non-condensible gas into a smaller volume, thus, providing a greater active condenser area.

On the other hand, if the operating temperature falls (heat load decreases), the working fluid vapor pressure falls and fixed gas mass, expands to a greater volume, thus blocking a larger portion of the condenser. The net effect is to provide a passively controlled variable condenser area which increases or decreases with the heat pipe temperature. As a consequence, this reduces the temperature response for active zone to variations in the heat input rate or environment (sink) condition[(1)].

If there is no heat load or if it is very small, it is necessary to shut-off the heat flow conducting through the envelope from the evaporator to the condenser. Therefore, stainless steel has been usually used as the heat pipe evnelope material because of its low thermal conductivity. however, stainless steel has 2.7 times the density aluminum has. Therefore, titanium has been foreseen for use as the heat pipe because of its thermal properties and lower density. Table 1 presents the titanium (Ti), stainless steel (SUS) and aluminum (Al) properties. Ti density is 40% of that for SUS, while are thermal conductivities for both materials are comparable. Ti strength is slightly lower.

Except for the above mentioned factors, it is well known that pure titanium is outstanding among structural materials in regard to its resistance at ordinary temperature to strongly oxidizing acid, aqueous chloride solution, moist chloride gas, sodium hypochroride and sea water.

3. Design

Titanium was selected as the envelope material from such view points as thermal characteristics, strength, weight and compatibility with working fluid, as previously mentioned.

In selecting the type of wick, first priority was placed on achieving simple structure and high reliability. As a reasonable result, the axial groove was selected. The axial groove assured that the wick can provide a large radial heat transfer coefficient which is as important a parameter as the maximum heat transfer capability[(3)]. In this study on groove configuration, there is a restriction resulting from titanium hardness. The groove shape was initially designed so that the groove shape would be rectangular and that the groove depth would be more than 0.5 mm. However, it was found that the goal was difficult to achieve, so the final shape was decided upon through manufacturing by trial and error. Titanium has good compatibility with ammonia, selected as the working fluid, and its compatibility is validated by titanium-ammonia exchanger performance. Ammonia, which has larger Nf-value (figure of merit) and high vapor pressure in the operating temperature range, was selected as the working fluid. Therefore, it is convenient to study the maximum heat transfer rate and pinch-off performance for titainum heat pipes.

For the VCHP, reservoir volume was decided to be about 6 times the condenser volume with the standard selection from Reference (1), and pure nitrogen 99.99% was selected as non-condensible gas.

4. Manifacture

Figure 2 shows the manufacturing flow chart. The process mainly consists of, 1 envelope fabrication and cleaning, 2 welding fill tubes and endcaps, 3 designing and cleaning inside of envelopes and reservoir (VCHP). 4 charging the working fluid and non-condensible gas (VCHP). 5 enclosing pipes and 6 performance tests.

The pipes were produced by Toshiba's fabrication[(4)] process, shown in Fig. 3. First titanium plate was cold rolled and an appropriately grooved surface fabricaed. Then, the plate with the grooved surface was run out in a circular shape by roll forming and welding. Precision manufacturing was difficult, using ordinary fabrication processes, such as machining, extrusion and drawing. The process is especially suitable for fabricating the grooved surface on titanium and its alloys. The EB welding method is employed, and the TIG method is used in the pinch-off process. The cleaning process employed is a series of degreasing, acid and alkaline cleaning before welding the

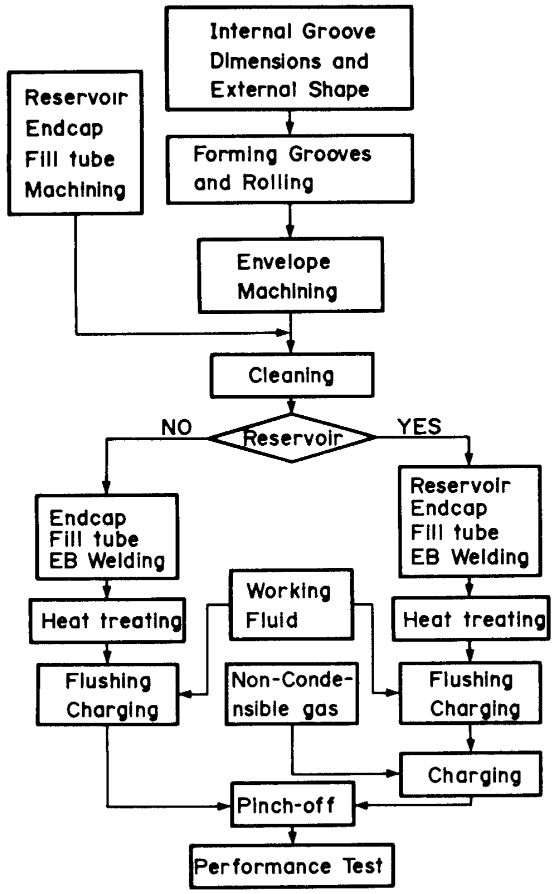


Fig. 2. Manufacturing flow chart.

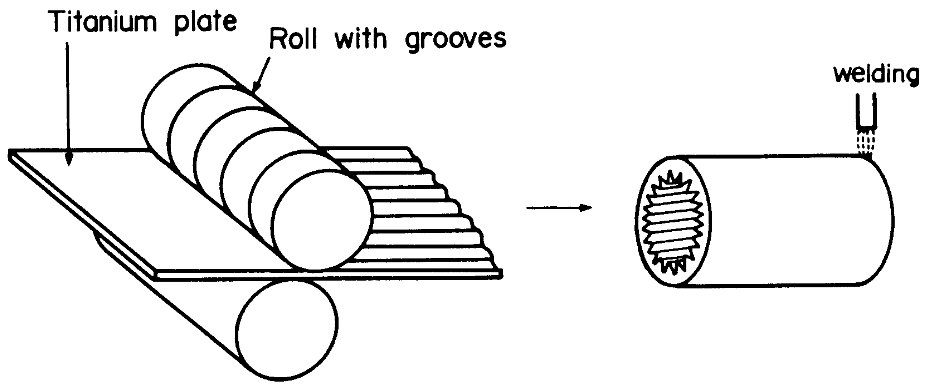


Fig. 3. Pipe fabrication process.

envelope, flushing with the working fluid and vacuum backing before and after the flushing, keeping heat pipes attached to the charging equipment. For the working fluid, purity ammonia 99.999% was procured. For the non-condensible gas, 99.99% purity nitrogen was charged.

The working fluid charging amount has a great influence on the heat transport characteristics. It has been decided to be almost the same volume as the grooves in a pipe for the fixed conductance heat pipe (FCHP). On the other hand, for VCHP, a little larger amount working fluid was used, considering a small amount of vapor in the reservoir.

The VCHP was charged initially with 3.0 gram non-condensible gas. However, the amount of gas was adjusted by a valve during the operating tests so that gas front would be located at a reasonable position. The fill tube pinching-off process is as important a process as welding, since it greatly efforts heat pipe reliability.

Pipe cross section photos are shown in Figs. 4 and 5. Figure 4 shows the groove shape and shows that there is no grooves in a small portion of the upper side of the pipe, because of the welding part. Figure 5 shows the grooves along the pipe axis.

A photo of the pipe condition after pinching-off and welding is shown in Fig. 6. It has been clarified that titanium has very good characteristics for pinching-off and that titanium is weldable with good ductility. These are very satisfactory results.

Specifications of the two produced types heat pipes are shown in Table 2, including the dimensions of the groove shapes and the reservoir size. The FCHP weighed 135 grams including the ammonia and is very light.

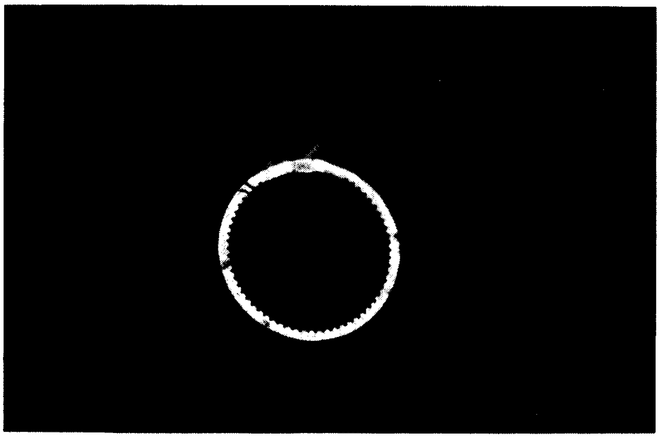


Fig. 5. Grooves along the pipe axis.

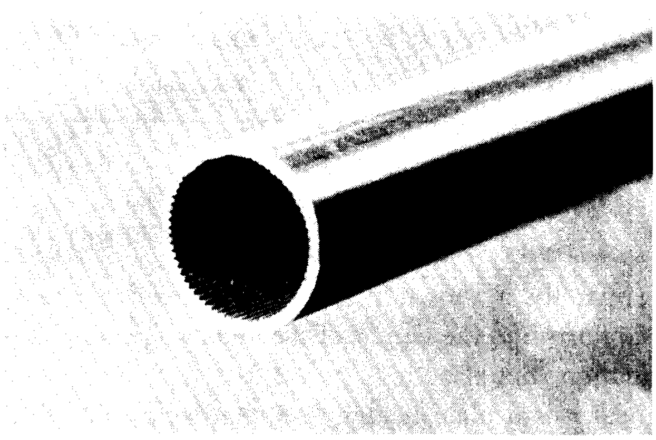


Fig. 4. Groove shape.

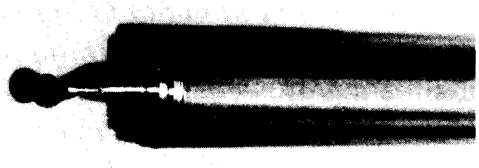
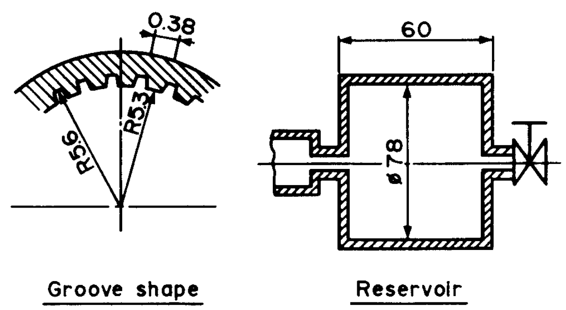


Fig. 6. pipe condition after prinching-off.

Table 2. Specification of the two produced Types of Heat Pipes

	FCHP	VCHP
Wick	Axial grooves	
Working Fluid	NH_3 5.0g	NH_3 8.5g
Non-Condensible Gas		N_2 1.8g
Envelope	Pure Titanium	
Outer Diameter	ϕ 12 mm	
Evaporator Length	0.4 m	
Condenser Length	0.4 m	
Heat Pipe Length	1.2 m	1.06 m
Reservoir Volume		$\phi 78 \times 56 (2.7 \times 10^{-4} m^3)$



5. Test Apparatus and Procedure

A sketch of the apparatus is shown in Fig. 7 While testing the VCHP, the pipe ends were mounted on supports and the height of the ends was adjusted by the dial gauge, so that heat pipe inclination should be less than 0.01.

The evaporator heater is a plate heater, 2.5 centimeters in width and 0.4 meters in length. The heater was attached to the evaporator by epoxy glue.

The outside of the heater was shielded with several wrappings of insulation to cut down on radiation losses. The condenser transferred heat to cold water through a jacket 40 mm in diameter and 0.4 meters in length. The cold water controlled by the cooling system was circulated through the jacket.

Figure 8 shows the VCHP with a jacket made from vinyl chroride.

The cooling system circulated water was temperature controlled by about ±2°C at an about 1 kg/min rate.

A small resistance heater was attached to the gas reservoir and controlled by about ±1°C by the thermostat. Temperature were measured by several copper-constantan thermocouples spot-welded to the pipe at positions shown in Figs. 9 and 11, which present heat pipe temperature distributions.

The power input to the heater was used as the power transported by the heat pipe. Because of the very small temperature rise in the cooling water, an accurate heat balance could not be made.

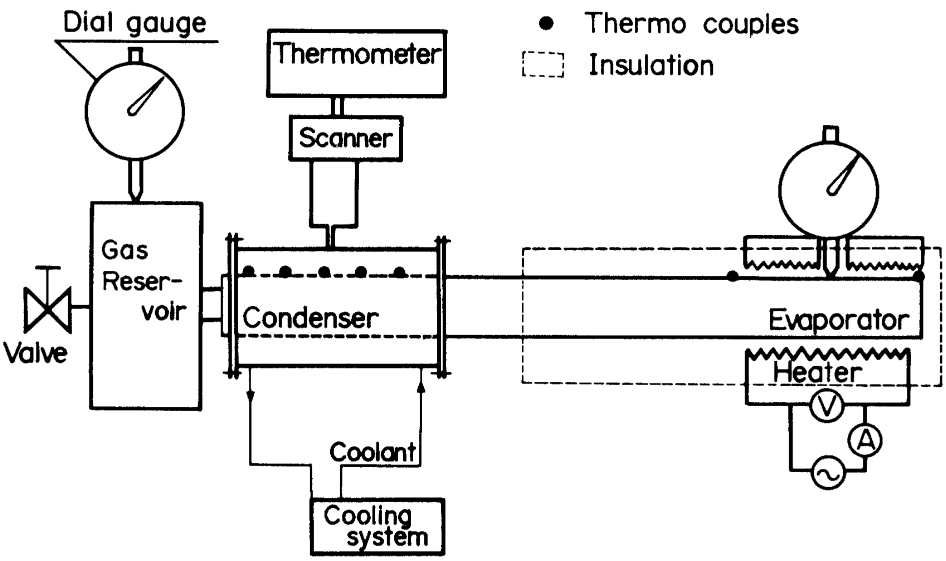


Fig. 7. Sketch of the Apparatus.

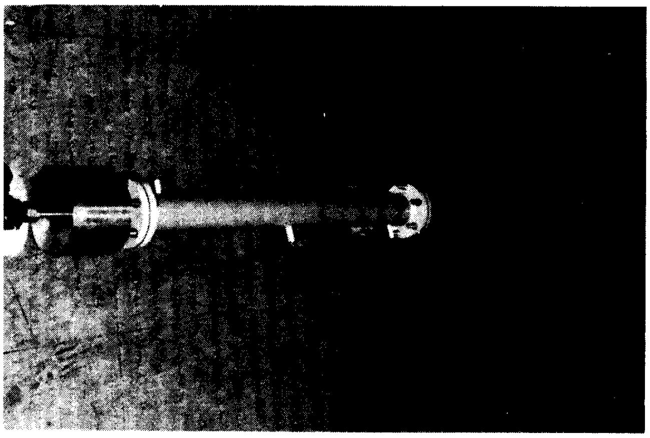


Fig. 8. VCHP and a jacket.

6. Results and Discussion

6.1 FCHP Performance Tests

First, the FCHP was tested, Figures 9 and 10 show an example of the axial temperature distribution and the heat pipe characteristic curve respectively, Figure 9 shows that the FCHP operates satisfactorily as a heat pipe. The heat pipe characteristic curve, that is, the heat load relation to the temperature difference between the evaporator and the condenser, shows maximum heat transfer rate Q_{max} and heat transfer coefficient of the condenser.

Maximum heat transfer rate Q_{max} is defined as the heat load at the dry out point in the heat pipe characteristic curve. Heat transfer coefficient, h_c, for the condenser is defined from the relation of the heat load in temperature difference between the adiabatic section and the heat sink.

From the figures, values can be estimated roughly as follows,

$$Q_{\max}=22.7\ \mathrm{W} \tag{1}$$

$$h_c=2000\ \mathrm{W/m^2K} \tag{2}$$

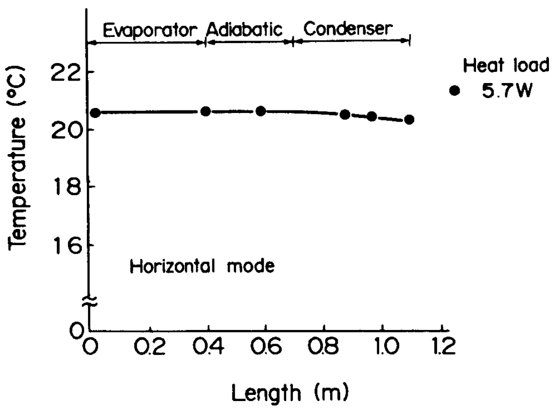


Fig. 9. Axial temperature distribution of the FCHP.

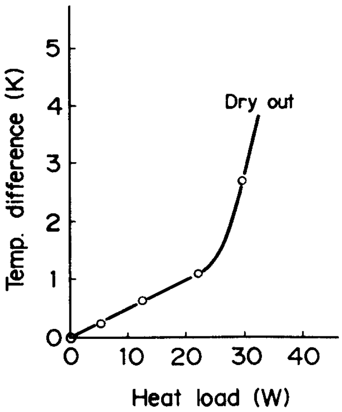


Fig. 10. FCHP characteristic curve.

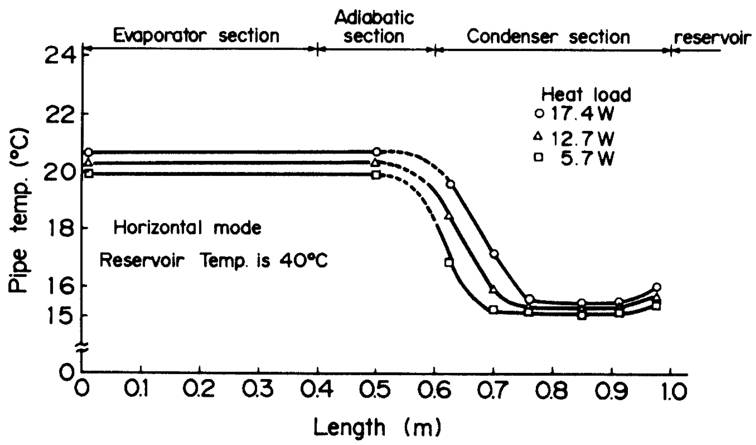


Fig. 11. VCHP temperature distributions.

h_c value is rather high, comparing the aluminum heat pipe h_c range of 3000 to 6000 W/m^2K, in spite of large thermal conductivity difference. This is because of the thin envelope thickness and as many as 50 grooves.

6.2 VCHP test

Figure 11 presents temperature distribution measured at three heat load levels. The reservoir was external to the heat pipe and its temperature T_R independently controlled. T_R must be higher than heat sink temperature T_S to prevent vapor from condensing in the reservoir, since the reservoir does not have a wick. T_R was fixed at 40°C. Therefore, the right side temperature of the condenser was effected as shown in Fig. 11. The VCHP dry out point was lowered to $Q_{max}=17.5$ W by comparing to Eq. (1), because of the gas invading. The evaporator temperature variation range was controlled at less than 1°C in the 5 W to 17.5 W heat load range. The VHCP control sensitivity was able to be estimated by assuming the front model of the gas and the vapor, and using Eq. (2).

Conductance length variation rate was about 1 cm/W.

7. Conclusion

Titanium heat pipes were produced and tested to study titanium performance in application as space use heat pipe material. The results show that there are no problems in welding and pinch-off for titanium and that the grooves made by the proposed method have the capability to carry 22.7 W heat load for the FCHP.

Reasonable VCHP test results were also obtained. This study has clarified that titanium is very desirable as heat pipe material for use in space.

References

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