Gravity-Invariant Condition of Water Sublimator Characteristic Parameter Design: Analysis and Experiment

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Water sublimator is a kind of thermal control device, which takes advantage of the high latent heat of water and can reject spacecraft waste heat by evaporating/sublimating water to vacuum environment. Thus, sublimator could be exclusively be used for spacecraft which couldn't reject heat effectively through radiation. Sublimators have been successfully used in the spacecraft thermal management systems and the portable life support system (PLSS) of space suit. For the sublimator which will be used in micro-gravity or 1/6g environments, it's very important to evaluating their work performance's measurability and ground test results' creditability, through analysis of the gravity effect on their work performance. Detailed work mechanisms of liquid-gas/liquid-solid-gas phase change processes in sublimator porous structures were depicted, gravity effects on the fluidic flow in the work process of sublimator were analyzed, and restrain conditions for sublimator gravity-invariant characteristic parameter design were obtained. Analysis results indicate that the sublimator characteristic parameter which agrees with $\mathrm{Gr}/\mathrm{Re}^2 < 0.1$ has a very large value space. While Bond number and Rayleigh number provides more strict restriction of the gravity-invariant characteristic parameter. The gravity-invariant characteristic parameter of 1g environment meets the 1/6g gravity-invariant lunar conditions. For a sublimator with gravity-invariant parameter, its work performance in 1/6g or micro-gravity environment can be evaluated in earth's 1g environment. The reasonability of sublimator gravity-invariant parameter presented in this context is validated by the ground experimental results.

Nomenclature

A_c	=	flow section area in feed water gap
Bo	=	Bond number
d	=	characteristic parameter of the fluid system, sublimator characteristic parameter
d_p	=	average pore diameter of porous material
d_{mF}	=	characteristic parameter of the fluid system obtained by Fr condition
d_{mB}	=	characteristic parameter of the fluid system obtained by Bo condition
d_{mR}	=	characteristic parameter of the fluid system obtained by Ra condition
Fr	=	Froude number
Gr	=	Grashof number
g	=	gravitational acceleration
g_m	=	lunar gravitational acceleration
k	=	thermal diffusivity
K	=	permeability
L	=	length

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$\dot{m}_g$ = feed water mass flow rate
u = flow velocity
Ra = Rayleigh number
Re = Reynolds number
α = thermal expansion coefficient
σ = surface tension
ν = kinematic viscosity
ε = porosity
ΔT = Temperature difference

I. Introduction

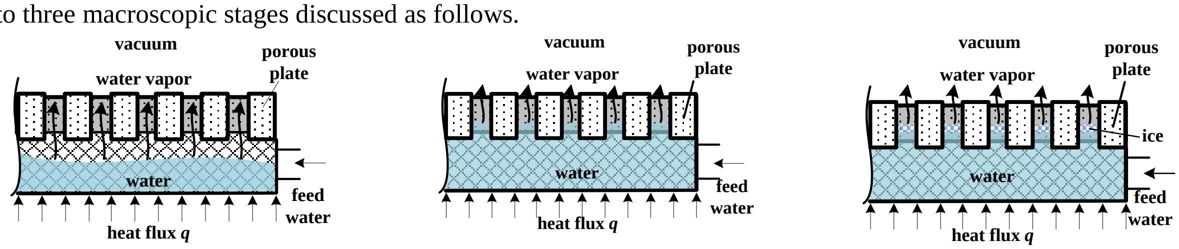
Water sublimator is a kind of thermal control device, which takes advantage of the high latent heat of water and can reject spacecraft waste heat by evaporating/sublimating water to vacuum environment [1-5]. Because of the advantages of small volume, high efficiency and reliability [1-5], sublimator has been successfully used in the spacecraft thermal management system and the portable life support system (PLSS) of space suit [1-5].

For sublimator which uses water as the expendable, the environment pressure is required to be lower than the triple point of water (610Pa). Thus, sublimator could work in the processes of freezing, sublimation, and take advantage of the high latent heat of water. As a result of this, sublimator is always used in the spacecraft thermal control system. This means that the work of sublimator must be subject to micro-gravity, lunar 1/6*g* or other environments with different acceleration values. However, the performance tests, validation experiments of sublimator which are used in spacecraft thermal control system have to be developed in 1*g* ground environment. Thus, it’s very important to analyse the influences of gravity condition on the sublimator work performances, as well as to obtain the criteria to determine whether the effects of gravity is ignorable. These analyses will have great significances for evaluating sublimator work performance’s measurability and ground experiment results’ creditability.

The context described sublimator work mechanisms, analysed the influences of gravity on the heat and mass transfer of sublimator phase change work process. Criteria to preliminarily determine the gravity-invariant parameter of sublimator work in 1*g* and 1/6*g* environments was obtained, and was validated by the ground experiment results.

II. Work Mechanisms of Water Sublimator

A simplified structure of a single module water sublimator with constant heat flux boundary is shown in Figure.1 [6]. Sublimator shown in Figure.1 is mainly composed of porous plate and feed water gap, and the feed water gap is filled with porous material of the sublimator we studied in this context. Suppose the bottom wall of the feed water gap is heated with a constant heat flux *q*, the top of the feed water gap is covered by the porous plate. When sublimator works, water is sent to the feed water gap through feed water inlet under feed water pressure. To analyze the detailed work performance of sublimator, Yu-ying WANG [6] divided the transient startup process of sublimator into three macroscopic stages discussed as follows.



(a) (b) (c)

Figure 1. Water sublimator startup processes

(1). Water evaporates in feed water gap (Fig.1 (a)). If the sublimator is considered to startup, feed water is sent to the sublimator under a constant pressure, and water will evaporate in feed water gap. Water vapor produced by evaporation vents to the outer space through the porous plate.

(2). Water evaporates in the porous plate state (Fig.1 (b)). If the feed water gap is filled full of water before the evaporation surface freeze, feed water will enter to and evaporate in the porous plate under feed water pressure.

(3). Alternation of evaporation and sublimation in porous plate state (Fig.1 (c)). Evaporation in the porous plate will decrease the temperature of the water and porous plate. If the water temperature decreases to the triple point temperature before water moves into vacuum, water at the vacuum side of the porous plate will freeze and sublimation occurs. As a result of the sublimation and freeze or thaw, the thickness of ice in the porous plate finally becomes zero. Then water will move into porous plate again, and the process of evaporation, freezing and sublimation will repeat.

III. Dimensionless Numbers Relate to Gravity

In microgravity fluid mechanics, relations of gravity and fluid system are characterised by Bond number (*Bo*), Froude number (*Fr*) and Grashof number (*Gr*). Bond number represents the relations of buoyancy force and surface tension, Froude number represents the relations of inertia force and buoyancy force induced by gravity, Grashof number represents the relations between buoyancy force induced by the temperature difference and inertia force [7, 8]. The definition of *Bo*, *Fr* and *Gr* are described as Eq.(1), Eq.(2) and Eq.(3) separately.

$$Bo = \frac{\rho g d^2}{\sigma} \quad (1)$$

$$Fr = \frac{u}{\sqrt{gd}} \quad (2)$$

$$Gr = \frac{g\alpha\Delta T d^3}{\nu^2} \quad (3)$$

Where ρ is the fluid density (kg/m^3), g is gravitational acceleration (m/s^2), d is the characteristic parameter of the fluid system (m), u is the flow velocity (m/s), σ is the surface tension (N), α is thermal expansion coefficient (K^{-1}), ν is the kinematic viscosity (m^2s^{-1}). These dimensionless numbers represents the relative influences of different factors on the fluid system. For example, $Bo<1$ or the value of *Bo* number approximates 1 means surface tension plays more important role in the flow characteristic of a fluid system, while $Bo \gg 1$ means buoyancy force plays more important role in the fluid system. And on this condition, the system flow turns to buoyancy convection flow.

There are several approaches to experiment the micro-gravity effects on fluid systems, such as drop-tower experiment, zero gravity plane experiment and experiments in space station [7, 8]. However, the lasting time of micro-gravity provided by drop-tower and zero gravity plane experiments are very short, efficient space is very limited for experiments in space station, thus, experiments take place in microgravity environment focus on the pool boiling, liquid-vapor two phase flow in tubes and so on [8]. Researches about forced flow, fluid flow in porous media and phase change in microgravity are so rare that microgravity effects and the efficiency of ground experiment results of sublimator could hardly be provided by present research results.

IV. Analysis of the Gravity Influences on Sublimator Work Processes

One of the most difficult items of the ground test of spacecraft fluid system is the simulation of micro-gravity. But the convection induced by gravity must inevitably influence the ground experiment results. Therefore, it is necessary to take actions at the beginning of designing the test module, to reduce the differences between the ground test and on-orbit use. At the first, we need to study the mechanism of gravity induced convection in fluid system.

A. Characteristic of the feed water flow in sublimator

Typical feed water mass flow rate in the startup processes of sublimator is shown in Figure 2. Figure 2 indicates that the feed water mass flow rate varies significantly in the first tens of seconds during the startup of sublimator. After feed water fills full of the feed water gap in about 30 seconds to 40 seconds [6], the feed water mass flow rate decreased significantly. This indicated that the sublimator gravity-invariant characteristic parameter should be determined based on comprehensive consideration about the mass flow rate variations in different processes during its startup.

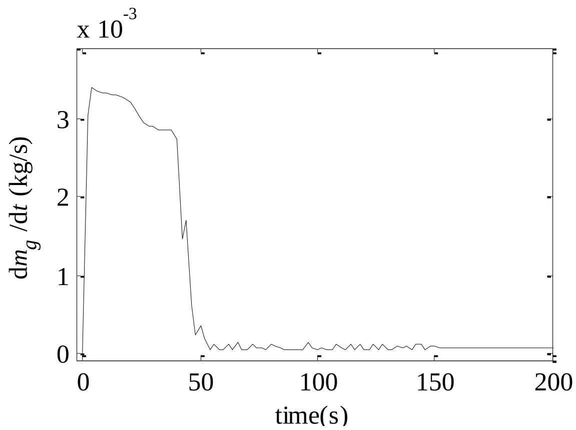


Figure 2. Feed water mass flow rate in the startup process of sublimator

B. Definition of sublimator characteristic parameter

The common factor related with the dimensionless numbers discussed in Eq.(1), Eq.(2) and Eq.(3) is the characteristic parameter of fluid system(*d*) and gravity (*g*). That is to say, in a special gravity condition, the characteristic parameter of fluid system(*d*) is pertinent with the Bond number (*Bo*), Froude number (*Fr*) and Grashof number (*Gr*). In other words, the characteristic parameter of fluid system(*d*) will influence the the relations of buoyancy force, surface tension and inertia force o of buoyancy force, surface tension and inertia force of a fluid system. So we considered to design the characteristic parameter number (*d*) of a fluid system to realize gravity invariant of a fluid system.

Specific to the fluid system of sublimator we discussed in this context, the dimensions of feed water gap and porous plate will influence the relations of buoyancy force, surface tension and inertia force. Because of the dimension of porous plate of sublimator is micron level, the capillary force induced by the surface tension will play leading role among the buoyancy force and Inertia force. Thus the dimension of feed water gap is the key parameter we should considered as the characteristic parameter of the gravity invariant design of sublimator. For the sublimator we discussed in this study, this characteristic parameter is considered as the pore size of porous material filled in the feed water gap.

C. Gravity influences of evaporation in feed water gap process

After water is sent to the feed water gap during the start-up of sublimator, evaporation with forced flow occurs in the feed water gap. The manifestation of liquid-vapor interface in the feed water gap will vary with the location of sublimator. Thus, the liquid-vapor phase change and fluid flow are very complicated.

However, with feed water fills full of the feed water gap, evaporation in feed water gap turns to alternation of evaporation and sublimation in porous plate process. This means that the evaporation in feed water gap is a transient process in the start-up of sublimator (Figure 2). And the influences of gravity acting on this process are also transient processes. As a result of the above reasons, analysis of the influences of gravity during the evaporation in feed water gap process is not included in this context.

D. Gravity influences of evaporation in the porous plate process

When sublimator works in evaporation in porous plate process, the feed water gap was filled full of water, and the feed water mass flow rate will reduce dramatically. Then the leading role of inertial force acting on the feed water flow becomes weakening, while the surface tension of the water in the porous plate becomes enhancing. In the ground experiment, if the feed water gap characteristic parameter is not well designed the free convection induced by gravity will influence the heat transfer in feed water gap significantly.

C.1 Analysis of the influences of inertia force and buoyancy force

In the ground 1*g* environment, the heat transfer in feed water gap is influenced by free convection induced by gravity and forced convection by feed water pressure. Generally, the criteria to judge whether the free convection or forced convection playing a leading role in the fluid system is the relations of buoyancy force and inertial force [9], which is written as Gr/Re^2 .

Generally, if $Gr/\mathrm{Re}^2 < 0.1$, the influence of natural convection on a fluid system could be neglected. According to the definition of Grashof number (*Gr*) and Reynolds number (Re), we can obtain Eq.(4).

$$\frac{Gr}{\mathrm{Re}^2} = \frac{g\alpha\Delta Td^3}{\nu^2}\frac{\nu^2}{u^2d^2} = \frac{g\alpha\Delta Td}{u^2} < 0.1 \tag{4}$$

According to the definition of Froud number (*Fr*), *Fr* refers to the relations of integral force and buoyancy force induced by gravity. Therefore, *Fr*>1 stands for the influences of inertia force is more obvious than the influences of buoyancy force. Otherwise, *Fr*<1 stands for the influences of buoyancy force is more obvious than the influences of internal force. Then we can obtain the gravity-invariant characteristic parameter (*d*) should meet the condition shown as Eq.(5).

$$\frac{u}{\sqrt{gd}} > 1 \tag{5}$$

Take both the condition shown in Eq.(4) and Eq.(5) into consideration, the gravity-invariant characteristic parameter (*d*) of sublimator should meet Eq.(6).

$$\begin{cases} d < \dfrac{0.1}{\alpha\Delta T}\cdot\dfrac{u^2}{g} \\ d < \dfrac{u^2}{g} \end{cases} \tag{6}$$

Eq.(6) indicates that the gravity-invariant characteristic parameter is proportional to the square of flow velocity (*u*). Thus, in the same environment, the fluid system with greater flow velocity (*u*) has larger gravity-invariant characteristic parameter.

When water evaporates in porous plate of sublimator, the average flow velocity in feed water gap can be defined as Eq.(7).

$$u \approx \frac{\dot{m}_g}{\rho A_c\varepsilon} = \frac{\dot{m}_g}{\rho(Ld)\varepsilon} \tag{7}$$

Where A_c is the flow section area in feed water gap, ε is the porosity of metal foam. ρ is the density of water, *L* and *d* is the length and height of flow section separately. And in engineering applications, feed water mass flow rate can be estimated from $\dot{m}_g = Q/h_e$, where *Q* is the heat load, h_e is the latent of evaporation.

C.2 Analysis of the influences of buoyancy force, surface tension and inertia force

Due to the small thermal expansion coefficient, the condition $\frac{0.1}{\alpha T} < 1$ shown in Eq.(6) will be satisfied when temperature differential (ΔT) between the evaporation surface and heating surface reaches several hundreds K. But this will not occur in the work process of sublimator during its working principle. This indicates that, the constraint condition determined by $Fr > 1$ is more strict than the condition determined by $Gr/\mathrm{Re}^2 < 0.1$. Thus the effective constraint condition shown in Eq.(6) turns to $d < \frac{u^2}{g}$, $u \approx \frac{\dot{m}_g}{\rho Ld\varepsilon}$, which can be reformed as Eq.(8).

$$d < \left[\left(\frac{\dot{m}_g}{\rho L\varepsilon}\right)^2 \Big/ g\right]^{1/3} \tag{8}$$

Based on the above analysis, the effective constraint conditions to determine the gravity-invariant parameter turns to be determined by *Bo* and *Fr*. Where *Bo* and *Fr* stands for the relations between buoyancy force and surface tension, buoyancy force and inertia force respectively. That is,

$$\begin{cases} Bo \ll 1 \\ Fr \gg 1 \end{cases} \tag{9}$$

Then the gravity-invariant parameter (*d*) of sublimator should meet the condition shown as Eq.(10), in the processes of water evaporates in the feed water gap.

$$\begin{cases} d \ll \sqrt{\dfrac{\sigma}{(\rho_l - \rho_v)g}} \\ d \ll \left[\left(\dfrac{\dot{m}_g}{\rho L \varepsilon} \right)^2 \Big/ g \right]^{1/3} \end{cases} \tag{10}$$

E. Analysis of the gravity influences when sublimation occurs in the porous plate process

When ice forms in the porous plate, feed water stops flow in to the feed water gap, and the free liquid-vapor free interface vanished. If ignoring the convection induced by the phase change at the ice-water interface, the convection in feed water gap is a typical Rayleigh-Bénard convection in the earth environment. Temperature gradient parallel to the gravitational field will bring density difference, the density difference will bring buoyancy force opposite to the gravity gradient, and this buoyancy force is the reason for the onset of convection in the fluid system [7, 10]. When the influences of buoyancy force overcome the viscous force, convection cells forms in the fluid system [7, 10]. To study the convection driven by buoyancy force, Rayleigh number (*Ra*) is defined as Eq.(11) to represent the ratio between gravity and buoyancy force.

$$Ra = \frac{\alpha g \Delta T d^3}{\nu k} \tag{11}$$

Where, α is the thermal expansion coefficient (K^{-1}), ν is the kinematic viscosity (m^2s^{-1}), k is the thermal diffusivity (m^2s^{-1}), d is the height of fluid system (*m*), ΔT is the temperature difference (K). To study the flow and convection in the porous medium, modified Rayleigh number (*Ra*) was derived as Eq.(12) [16, 17].

$$Ra = \frac{K \alpha g \Delta T d}{\nu k} \tag{12}$$

Where, K is the permeability (m^2), but K of metal foam is difficult to obtain due to the variety forms of porous material. Thus, experimental methods are always used to test the permeability. Present researches [11-15] about the metal foam permeability indicated that permeability related with the pore diameter and has a general form as Eq.(13).

$$K = f(\varepsilon) d_p^2 \tag{13}$$

Where $f(\varepsilon)$ is the function of porosity (ε), d_p is the pore diameter of porous material. Some of the research results shows that, the critical Rayleigh number for the flow in porous materials is $4\pi^2$ [16, 17]. Substitute Eq.(13) into Eq.(12), we get Eq.(14).

$$Ra = \frac{f(\varepsilon) \alpha g \Delta T d_p^2 d}{\nu k} < 4\pi^2 \tag{14}$$

Suppose pore diameter $d_p < d$, then we obtain Eq.(15).

$$\frac{f(\varepsilon) \alpha g \Delta T d_p^2 d}{\nu k} \le \frac{f(\varepsilon) \alpha g \Delta T d^3}{\nu k} \tag{15}$$

That is,

If $\dfrac{f(\varepsilon) \alpha g \Delta T d^3}{\nu k} < 4\pi^2$, then $Ra = \dfrac{K \alpha g \Delta T d}{\nu k} < 4\pi^2$,

Then the gravity-invariant parameter can be obtained as Eq.(16).

$$d < \sqrt[3]{\frac{4\pi^2 \nu k}{f(\varepsilon) \alpha g \Delta T}} \tag{16}$$

From the above analysis, we can conclude that, in order to design a sublimator with gravity-invariant parameter to inhibit convection in ground experiment, the characteristic parameter of sublimator should meet both Eq.(10) and Eq.(16). On the other way, we can validate whether the design of sublimator meet the gravity-invariant condition by Eq.(10) and Eq.(16).

V. Influences of Gravity Conditions on the sublimator Characteristic Parameter

A. Analysis of the influences of lunar gravity

Sublimator is an important heat rejection device for the spacecraft, especially in lunar exploration. Thus, sublimator must have high reliability in the 1/6 *g* lunar environment. However, it's difficult to simulate the 1/6 *g* or micro-gravity environment in 1 *g* earth environment. Thus, we try to design a sublimator with gravity-invariant parameter, and could be tested in earth environment.

We can derive from Eq.(10) and Eq.(16) that if the characteristic parameter (*d*) of sublimator meet the gravity-invariant condition of 1 *g* environment, then *d* must meet Eq.(17) and Eq.(18).

$$\begin{cases} d \ll \sqrt{\dfrac{\sigma}{\rho g_m}} \\ d \ll \dfrac{u^2}{g_m} \end{cases} \tag{17}$$

$$d < \sqrt[3]{\frac{4\pi^2 \nu k}{f(\varepsilon)\alpha g \Delta T}} \tag{18}$$

Where $g_m = 1/6\, g$. Eq.(17) and Eq.(18) indicate that if the characteristic parameter (*d*) of sublimator meet the gravity-invariant condition of 1 *g* environment must meet the gravity-invariant condition of 1/6 *g* environment.

We can obtain Eq.(19) from $Fr \gg 1$,

$$\frac{u}{\sqrt{gd}} = \frac{u}{\sqrt{g_m 6d}} = \frac{\frac{1}{\sqrt{6}}u}{\sqrt{g_m d}} = \frac{u_m}{\sqrt{g_m d}} \gg 1 \tag{19}$$

Where $u_m = \dfrac{u}{\sqrt{6}}, u > \dfrac{\dot{m}_v}{\rho A_c \varepsilon}$. Eq.(19) indicates that on condition *d* is remained unchanged, if the feed water velocity is reduced to the $1/\sqrt{6}$ times of *u*, *d* is still meet the gravity-invariant condition of 1/6 g environment.

We also can obtain Eq.(20) from $Fr \gg 1$,

$$\frac{u}{\sqrt{gd}} = \frac{u}{\sqrt{g_m 6d}} = \frac{u}{\sqrt{g_m d_{mF}}} \gg 1 \tag{20}$$

And we can obtain Eq.(21) from $Bo \ll 1$,

$$\frac{\rho g d^2}{\sigma} = \frac{\frac{1}{6}\times 6\rho g d^2}{\sigma} = \frac{\rho g_m (\sqrt{6}d)^2}{\sigma} = \frac{\rho g_m (d_{mB})^2}{\sigma} \ll 1 \tag{21}$$

While we can get Eq.(22) from $Ra < 4\pi^2$,

$$\begin{aligned} \frac{K\alpha g \Delta T d}{\nu k} &= \frac{f(\varepsilon)\alpha g_m \Delta T (6 d_p^2 d)}{\nu k} \le \frac{f(\varepsilon)\alpha g_m \Delta T (6 d^3)}{\nu k} \\ &= \frac{f(\varepsilon)\alpha g_m \Delta T (\sqrt[3]{6}d)^3}{\nu k} = \frac{f(\varepsilon)\alpha g_m \Delta T (d_{mR})^3}{\nu k} < 4\pi^2 \end{aligned} \tag{22}$$

Where $d_{mF} = 6d$, $d_{mB} = \sqrt{6}d$, $d_{mR} = \sqrt[3]{6}d$. Eq.(20), Eq.(21) and Eq.(22) indicate that, the gravity-invariant parameter of 1/6 g environment can be extended the 6 times, $\sqrt{6}$ times and $\sqrt[3]{6}$ times of the gravity-invariant parameter in 1 *g* environment respectively, according to different judgment criterions. That is to say the gravity-invariant parameter of sublimator in 1/6 *g* environment could extend at least $\sqrt[3]{6}$ times of the gravity-invariant parameter in 1 g environment.

B. Analysis of the gravity influences on the sublimator characteristic parameter- example and experiment

B.1 Analysis of the relations between sublimator characteristic parameter and the criterion number

In this context, we study the sublimator with basic structure shown as Figure 1, the characteristic temperature is about 293.15K, the steady-state temperature difference between the hot and cold side of sublimator feed water gap is about 20K, the porosity of metal foam filled in the feed water gap is 95%, L=0.15m.

Then the criterion numbers variation with the sublimator parameter in different gravity conditions (figure 3 to figure 5) could be calculated according to Eq.(10) and Eq.(16). Figure 3 to figure 5 indicates that the sublimator gravity-invariant parameter determined by Fr number, Bo number and Ra number separately will lead to great differences.

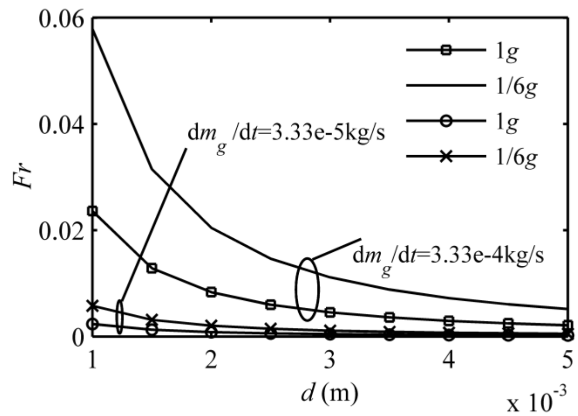


Figure 3. Froude number variation with characteristic parameter of feed water gap

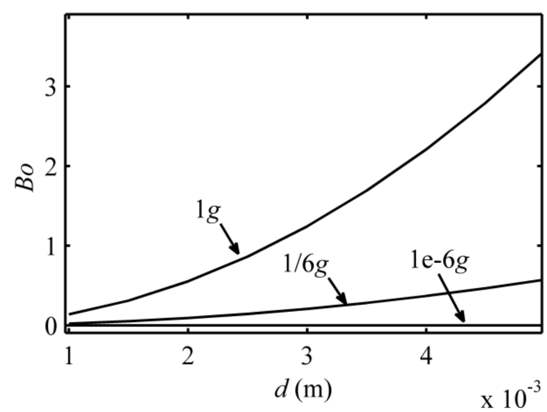


Figure 4. Bond number variation with characteristic parameter of feed water gap

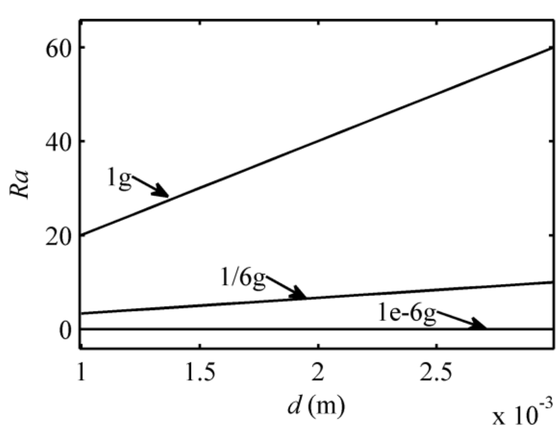


Figure 5. Rayleigh number variation with characteristic parameter of feed water gap

Figure.3 shows that, due to the small feed water mass flow rate of sublimator work in the evaporation in porous plate process, even if the value of the sublimator characteristic parameter is very small, the value of *Fr* is still satisfied $Fr \ll 1$. This indicates that, during the evaporation in porous plate process, the inertial force acting on the water decreased largely because of the decreasing of the feed water mass flow rate. Thus, *Bo* number is more suitable for determining the sublimator gravity-invariant parameter.

Results displayed in figure.4 and figure.5 indicates that if the characteristic parameter (*d*) of sublimator meets the gravity-invariant condition of 1 *g* environment must meet the gravity-invariant condition of 1/6 *g* environment.

From the above analysis, we can obtain that the determination of sublimator gravity-invariant parameter is mainly influenced by *Bo* number and *Ra* number. The sublimator gravity-invariant parameter *d*<2mm can both meet the condition $Bo \ll 1$, according to the temperature and mass flow rate conditions of the example discussed in this study.

B.2 Analysis of the experiment results of sublimator ground test

During the ground experiment of spacecraft fluid system, the system is usually located with hot side up while cold side down to reduce the convection induced by the buoyancy force. To validate the sublimator gravity-invariant parameter obtained in this paper, we tested a sublimator(Figure. 6) model with 2 mm characteristic parameter of feed water gap in vacuum chamber. The sublimator is tested with two locations, one is set heating side at the bottom and the other is set heating side at the top. The temperatures are measured by calibrated copper constantan thermocouples, the measurement error is within ±0.5℃. Sublimator steady-state heating surface temperature of the heating side in the two locations with five different heat loads is displayed in Table.1.

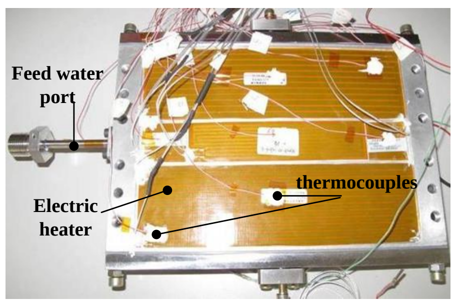


Figure 6. The test module of sublimator

Table 1 Results of sublimator ground experiment

heat load *q* (W/cm^2)		0.4	0.6	0.8	1.0	1.2
Heating surface temperature (℃)	bottom heating	11.2	19.6	25.91	33.3	37.5
	top heating	12.6	19.7	25.92	32.9	36.3

Table.1 indicates that, when the heat load of sublimator increases from 0.4W/cm^2 to 1.2W/cm^2 in two different locations, the largest temperature difference of sublimator heating surface is 1.4℃. Considering the measurement error, the experiment results show that influence of the location on sublimator could be neglected.

In the ground experiment, the vapor-liquid distribution in the feed water gap during the evaporation in feed water gap processes will be inevitably influenced by the location of sublimator. However, evaporation in feed water gap is a transient process in the start-up of sublimator, thus the differences of the vapor-liquid distribution in the feed water gap during the evaporation in feed water gap process has little influence on the heat and mass transfer in the evaporation and sublimation in porous plate process.

Based on the above analysises and experiment results, the gravity induced free convection influences on the heat and mass transfer in the evaporation and sublimation process in sublimator porous plate could be neglected. The experiment results validated the value range of gravity-invariant parameter deduced in this study.

VI. Conclusion

This context analyzed the characteristic of fluid flow and influences of gravity on the fluid flow during the different work processes of sublimator. Constraint conditions included *Bo* number, *Fr* number and *Ra* number were obtained to get the gravity-invariant parameter of sublimator.

Analysis shows that, (1). on condition characteristic parameter d is remained unchanged, if the feed water velocity is reduced to the $1/\sqrt{6}$ times of that on the ground experiment, d is still meet the gravity-invariant condition of 1/6 g environment, and the gravity-invariant parameter of sublimator in 1/6 g environment could extend at least $\sqrt[3]{6}$ times of the gravity-invariant parameter in 1 g environment. (2). During the steady-state working process, the feed water mass flow rate is very small, thus the inertia force acting on the fluid is so small that the criteria is not suitable to judge whether convection is not neglected in the fluid system. Therefore, the criteria to determine the gravity-invariant parameter of sublimator becomes $Bo \ll 1$ and $Ra < 4\pi^2$. (3).The gravity-invariant parameter of sublimator at the given conditions obtained in this paper is less than 2mm, and validated by the experiment results. The results obtained in this paper could be used to guide the design of sublimator, and also can be used to judge the efficiency of the sublimator ground experiment, which will be used in the 1/6 g or micro-gravity environment.

Acknowledgments

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