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ANALYSIS OF ENTROPY GENERATION IN A PULSATING HEAT PIPE

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ABSTRACT

The entropy generation is based on the second law of thermodynamics. In the present study, the entropy generation in a U-shaped Pulsating Heat Pipe (PHP) is numerically investigated. The following five parameters, which are vapor mass, liquid temperature, latent heat, sensible heat, and friction, determine the entropy generation. The results show that the entropy generation is significantly affected by the initial temperature in the PHP. Particularly, the variation of the vapor mass is a primary factor of the entropy generation. On the other hand, the amplitude of the entropy generation is barely related with the pressure loss at the bend in the PHP. However, the frequency of the entropy generation with the pressure loss is faster than that without the pressure loss at the bend.

KEY WORDS: Entropy generation, Pulsating heat pipe, Second law of thermodynamics, Numerical analysis, Initial temperature, Pressure loss

1. INTRODUCTION

Research and development of heat pipe have been intensified in the last two decades because it offers unmatched capacity for electronics cooling. Akachi (1994) developed the PHP (Pulsating Heat Pipe) that the working fluid was partially filled and oscillates due to liquid-vapor phase changes. The PHP could run with the small pressure difference because the working fluid does not need to flow through the wick structure. Also, the PHP could reduce costs because the wick structure was not required. Therefore, most researchers have utilized the PHP in which the working fluid moves back and forth between the evaporator and the condenser for the heat transfer (Zhang et al., 2004, Khandekar and Groll, 2001, Khandekar and Groll, 2003, Khandekar et al., 2003).

The effects of the various parameters on the PHP, which include the diameter, the number of turn, the working fluid and the inclination angle, were studied by many researchers (Khandekar et al., 2003, Charoensawan et al., 2003, Tong et al., 2001). The PHPs with the working fluids such as water, methanol, ethanol and R-123 were tested by inclining the degrees 0 to 90. Consequently, the appropriate charge ratios (water: 30%, methanol: 60%, ethanol: 20% and R-123: 35%) were required for each working fluid in order to keep the maximum heat transfer of the PHPs.

On the other hand, the entropy is generated by the thermodynamic cycle when the working fluid moves in the PHP. The entropy generation is also caused by the friction loss and the heat transfer of the working fluid (Khalkhali et al., 1999). Furthermore, the entropy generation is directly related with the irreversible process, and the quantity of the entropy generation is determined by the entropy and the lost work during the process. Al-Zaharnah (2003) conducted the research on the effect of the wall temperature and the Reynolds number on the entropy distribution in the pipe system. Moreover, Al-Zaharnah *et al.* (2004) studied the effect of the fluid viscosity on the entropy generation for each different wall temperature. It was presented that the rate of the entropy generation is increased by the high temperature of the pipe wall. Sahin *et al*. (2003) studied the effect of the developing laminar viscous fluid flow on the entropy generation in the circular pipe. They showed that the entropy generation increases near the wall and decreases gradually toward the axial direction.

In this paper, the entropy generation will be numerically analyzed with considering two vapor plugs, a liquid slug, evaporation and condensation in the PHP. The effects of initial temperature and the pressure loss in the bend on the entropy generation in the PHP will also be studied.

2. PHYSICAL MODEL

The U-shaped PHP is shown in Fig. 1(a), and the two vapor plugs are located in both ends (Zhang and Faghri, 2002). The evaporator and the condenser are divided by the center dotted line. In other words, the evaporator is located in the above dotted line and the condenser is placed in the below dotted line. The U-shaped PHP can be converted to the linear pipe with the liquid slug located in the center of the pipe as shown in Fig. 1 (b).

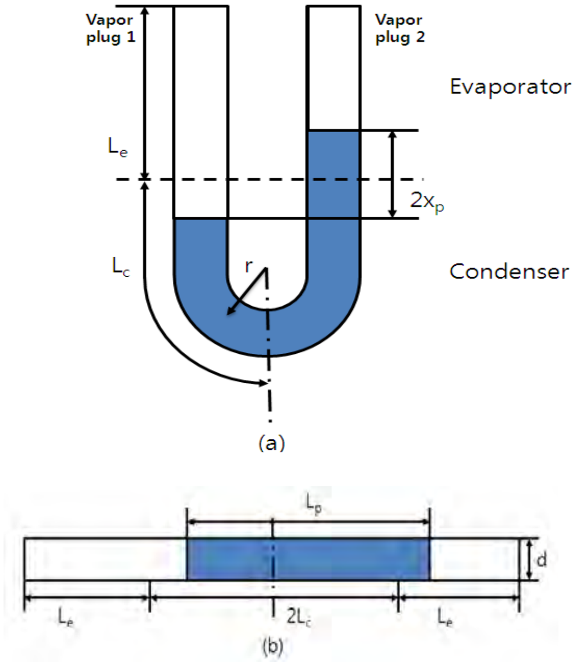


Figure 1. Configuration of pulsating heat pipe

The physical model for oscillatory flow and heat transfer can be found in Shao and Zhang (2011). The masses, temperatures and pressures of the two vapor plugs and displacement of the liquid slug can be obtained through a numerical procedure.

2.1 Entropy generation of vapor plugs

The sensible heat transfer in and out of the liquid slug can be obtained by integrating the heat transfer over the length of the liquid slug:

$$Q_{in,s,l} = \begin{cases} \int_{L_p - x_p}^{L_p} \pi d h (T_e - T_l) dx_l, & x_p > 0 \\ \int_0^{|x_p|} \pi d h (T_e - T_l) dx_l, & x_p < 0 \end{cases} \tag{1}$$

$$Q_{out,s,l} = \begin{cases} \int_0^{-x_p} \pi d h (T_l - T_c) dx_l, & x_p > 0 \\ \int_{|x_p|}^{L_p} \pi d h (T_l - T_c) dx_l, & x_p < 0 \end{cases} \tag{2}$$

where the sensible heat transfer coefficient can be obtained from $h = Nuk_l / d$.

The entropy is generated during evaporation and condensation process. The rate entropy generation due to phase change can be calculated by:

$$\frac{dS_v}{dt} = \sum \dot{m}_{in} s_v - \sum \dot{m}_{out} s_v \tag{3}$$

The entropy generation in the vapor plug 1 is

$$\frac{d(m_{v1} s_{v1})}{dt} = s_{v1} \frac{dm_{v1}}{dt} \tag{4}$$

since the change of specific entropy with respect to time is zero, i.e., $ds_{v1} / dt = 0$.

Thus, the entropy generation in the vapor plug 1 is:

$$\frac{dS_{v1}}{dt} = s_{v1} \frac{dm_{v1}}{dt} \tag{5}$$

Similarly, the entropy generation in the vapor plug 2 is

$$\frac{dS_{v2}}{dt} = s_{v2} \frac{dm_{v2}}{dt} \tag{6}$$

Therefore, the equations of the entropy generation in the vapor plug 1 and 2 can be rearranged as:

$$S_{v1} = m_{v1} s_{v1} \tag{7}$$

$$S_{v2} = m_{v2} s_{v2} \tag{8}$$

Also, these equations can be written as following because the specific entropy of the two vapor plugs is equal in the reference state.

$$S_{v1} = m_{v1} s_0 \tag{9}$$

$$S_{v2} = m_{v2} s_0 \tag{10}$$

Finally, the entropy generations in the two vapor plugs can be obtained by:

$$\Delta S_{v1} = (m_{v1} - m_{v1,0}) s_0 \tag{11}$$

$$\Delta S_{v2} = (m_{v2} - m_{v2,0}) s_0 \tag{12}$$

2.2 Entropy generation of liquid slug

Since the liquid phase is incompressible, the following entropy equation is valid:

$$\frac{ds}{dt} = \frac{c_p}{T} \frac{dT}{dt} \tag{13}$$

Integrating Eq. (13) yields

$$s_l = s_{l,0} + c_p \ln \frac{T_l}{T_0} \tag{14}$$

The entropy generation of the liquid slug can be obtained by integrating Eq. (14) over the length of the liquid slug:

$$S_l - S_{,l0} = \Delta S_l = \rho_l \frac{\pi}{4} d^2 c_p \int_0^{L_p} \ln \frac{T_l}{T_0} dx \tag{15}$$

The friction by the liquid slug is related to area, velocity and shear stress. The entropy generation due to the friction on the liquid slug can be gained by:

$$S_f - S_{f,0} = \Delta S_f = \tau_l \pi d v_p \int_0^{L_p} \frac{1}{T_l} dx \tag{16}$$

2.3 Entropy generation of latent heat and sensible heat in heating and cooling sections

When the working fluid is pulsating, the system is affected by the latent heat and the sensible heat. The entropy generations of the latent heat for the evaporation and the condensation are as follows:

$$\Delta S_{e,lat} = -\frac{Q_{e,lat}}{T_e} \text{ and } \Delta S_{c,lat} = \frac{Q_{c,lat}}{T_c} \tag{17}$$

The entropy generations of the sensible heat transfer are obtained by using the sensible heat from:

$$\Delta S_{e,sen} = \frac{Q_{e,sen}}{T_e} \text{ and } \Delta S_{c,sen} = \frac{Q_{c,sen}}{T_c} \tag{18}$$

As a result, the total entropy generation in the U-shaped PHP can be obtained by adding all the terms of the entropy generation.

$$\dot{S}_{tot,gen} = \Delta S_{v1} + \Delta S_{v2} + \Delta S_l + (\Delta S_{e,lat} + \Delta S_{e,sen}) + (\Delta S_{c,lat} + \Delta S_{c,sen}) + \Delta S_f \tag{19}$$

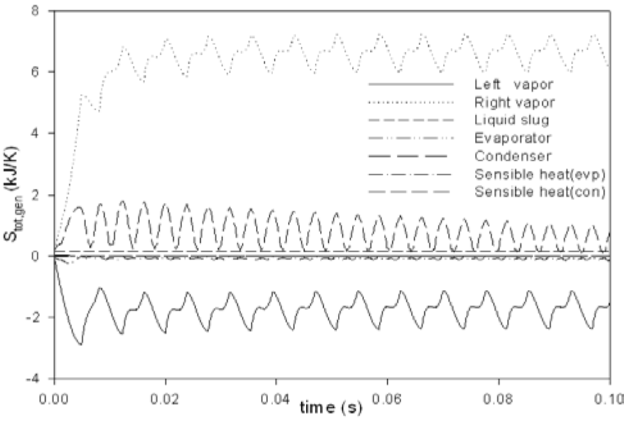
3. NUMERICAL APPLICATION

The iteration method and the implicit finite difference method are used to solve the physical model of the vapor plugs and the liquid slug numerically. Also, the equation of the heat conduction is solved by TDMA (Tridiagonal Matrix Algorithm) in order to get the temperature distribution of the liquid slug. The numerical procedures are similar to those of Shao and Zhang (2011).

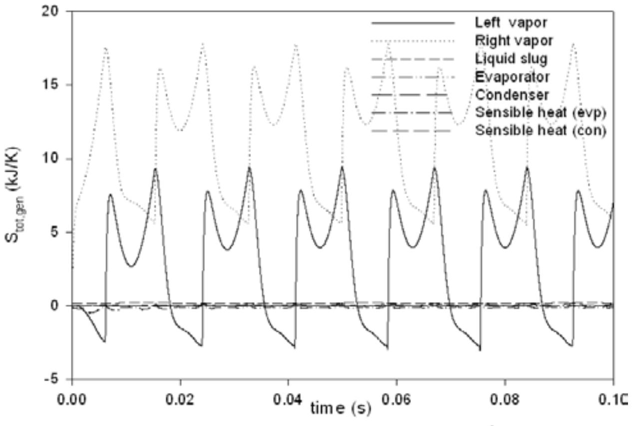
4. RESULTS AND DISCUSSION

The main parameters are used in the numerical calculation, which are obtained from Zhang and Faghri (2002). When the initial temperatures in the U-shaped PHP are 70^{o}C and 20^{o}C, respectively, the entropy generations with the initial temperature are shown in Fig. 2. Although the value of the entropy generation in the vapor plug 1 is supposed to be positive, the entropy generation has the negative value because the initial mass is larger than the new mass. The entropy generation in the vapor plug 1 with the initial temperature of 20^{o}C shows the relatively large amplitude and the constant pattern with time. Unlike the initial temperature of 20^{o}C, the entropy generation in the vapor plug 1 with the initial temperature of 70^{o}C presents the relatively small amplitude. Also, the amplitude and the frequency of the entropy generation in the vapor plug 2 with the initial temperature of 20^{o}C are relatively larger than those with the initial vapor temperature of 70^{o}C. The reason of this phenomenon is that the difference between the initial and the current masses at 20^{o}C is relatively larger than those at 70^{o}C. The entropy generation of the liquid slug is almost uniform without the difference of amplitude and not significantly affected by the initial temperature.

Figure 2 also represents the entropy generations in the evaporation and the condensation, and the entropy generations in the vapor plugs 1 and 2 increase sharply with the regular intervals at the initial temperature of 20^{o}C because of the noticeable difference in temperature. Unlike the evaporation process, the entropy generation at the initial temperature of 70^{o}C in cooling section is higher than that at the initial temperature of 20^{o}C because the difference between the cooling section's temperature and the initial temperature of 70^{o}C is larger than that with the initial temperature of 20^{o}C. However, the frequency at the initial temperature of 20^{o}C is longer than that at the initial vapor temperature of 70^{o}C.



(a) Total entropy generation at 70 ^{o}C



(b) Total entropy generation at 20^{o}C

Figure 2. Total entropy generation at different initial temperatures

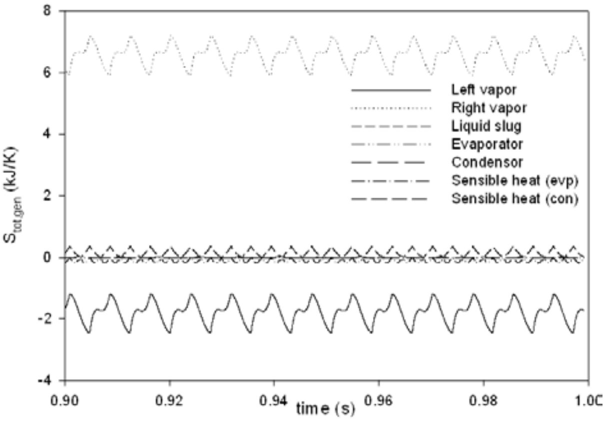
When the liquid slug is pulsated, the entropy generation is related with the sensible heat as well as the latent heat. As seen from Fig. 2, the graph at the initial temperature of 70^{o}C presents the entropy generation of the constant period and shape when the sensible heat transfers into the liquid slug. However, the change of the entropy generation at the initial temperature of 20^{o}C is gradually decreased with increasing time because the sensible heat is sensitive to the temperature difference. On the other hand, the entropy generation in the cooling section at the initial vapor temperature of 70^{o}C is larger than that at the initial temperature of 20^{o}C. The amplitude of the entropy generation at the initial temperature of 70^{o}C is gradually decreased because the difference of temperature is reduced with increasing time. However, there is a little change in the entropy generation at the initial temperature of 20^{o}C.

The entropy generations due to the friction of the liquid slug are considered at the initial temperatures of 70^{o}C and 20^{o}C. There is a little difference in the entropy generation because the velocity of the liquid slug is not nearly affected by the initial temperature. The values of the entropy generation due to the friction are very small. Therefore, it can be ignored.

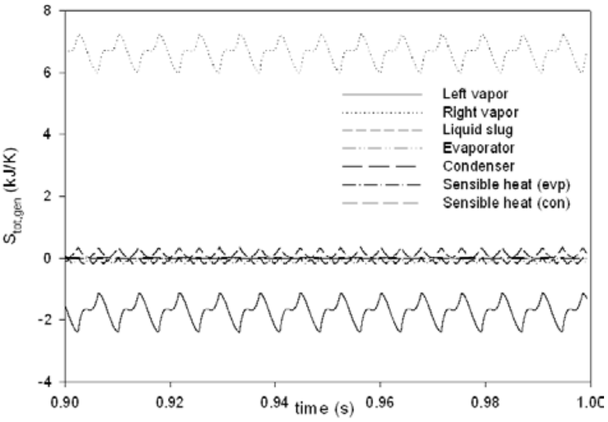
As a result, the change in the vapor plugs 1 and 2 is noticeably larger than the others in the entropy generation, and the initial vapor temperature has a significant effect on the change of the entropy generation in the U-shaped PHP.

Figure 3 demonstrates the effect of the pressure loss at the bend on the entropy generation. The pressure loss coefficient of 0.31 is used in the calculations when the curvature radius (r) of the bend is 5.83mm as shown in Fig. 1 (Ma et al., 2008). In the startup stage, the entropy generations have the same frequency with or without the pressure loss at the bend in the vapor plug 1 and 2, respectively. However, in the final stage, the frequency of the entropy generation with the pressure loss is faster than that without the pressure loss. The reason is that the pressure drop prevents the liquid slug from moving in the PHP. Thus, the pressure loss at the bend has a significant effect on the frequency, while it does not affect the amplitude of the entropy generation.

Unlike the cases for the two vapor plugs, the entropy generation of the liquid slug with time is a little difference of the entropy generation with or without pressure loss at the bend. The amplitude difference is about 0.004 kJ/K, and the frequency difference is almost constant. Figure 3 also shows the entropy generations due to the evaporation, the condensation and the sensible heat with or without the pressure loss in the vapor plugs 1, 2 and liquid slug, respectively. In other words, they present the effect of the latent heat and the sensible heat on the entropy generation with or without the pressure loss in the heating section and the cooling section. The entropy generation in the startup stage is almost constant regardless of the existence of the pressure loss at the bend. However, the frequencies with the pressure loss are still faster than those without the pressure loss in the final stage.



(a) Total entropy without pressure loss at final stage



(b) Total entropy generation with pressure loss at final stage

Figure 3. Total entropy generation with or without pressure loss at bend

The difference of the entropy generations due to the friction is small. Therefore, the friction can be ignored in the entropy generation. As a result, the entropy generations are almost the same regardless of the pressure loss. However, the frequencies of the entropy generation with the pressure loss are quicker than those without the pressure loss at the bend.

5. CONCLUSIONS

The entropy generation in the U-shaped PHP has been investigated in consideration of the initial temperatures and the pressure loss at the bend. The entropy generations are calculated from the variations of vapor mass, the liquid temperature, latent heat, sensible heat, and friction. In result, the entropy generations are sensitively affected by the initial temperature, and the variation of the vapor mass is the main cause of the entropy generation. The amplitude of the entropy generation is irrelevant to the pressure loss at the bend. However, the frequency of the entropy generation with the pressure loss is faster than those without the pressure loss.

NOMENCLATURE

c_p	Specific heat at constant pressure, J/kg-K
d	Diameter of heat pipe, m
h	Convection heat transfer coefficient of liquid slug, W/m^{2}K
k	Thermal conductivity, W/m^2-K
L	Length, m
L_p	Length of liquid slug, m
m	Mass of vapor plugs, kg
$\dot{m}$	Mass flow rate, kg/s
Nu	Nusselt number
Q	Heat capacity, kJ
$Q_{in,s,l}$	Sensible heat transfer into liquid slug, W
$Q_{out,s,l}$	Sensible heat transfer out of liquid slug, W
r	Curvature radius of bend, mm
s	Specific entropy, kJ/kg-K
S	Entropy, kJ/K
t	Time, s
T	Temperature of liquid slug, K
v_p	Velocity of liquid slug, m/s
x_p	Displacement of liquid slug, m

Greek symbols

Δ	Difference
ρ	Density, kg/m^3
τ_l	Shear stress, N/m^2

Subscripts

0	Initial condition
l	Liquid

v	Vapor plug
e	Evaporation
c	Condensation
in	Enter
out	Exit
lat	Latent heat
sen	Sensible heat
v	Vapor plug
f	Friction
gen	Generation
tot	Total

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