CHAPTER 2

PRINCIPLES AND THEORIES

2.1 Closed-End Thermosyphon Heat Pipe

Closed-end two-phase thermosyphon is an effective heat transfer device that widely used in engineering applications. Heat obtained at the evaporator section by means of the evaporating mechanism is releasing at the condenser section by means of the condensing phenomena. Because the latent heat of vaporization of the working fluid is relatively high, a large amount of heat can be transported through the thermosyphon. The thermosyphon can mainly operate under the assistance of the gravity hence the heat transport capability of the thermosyphon is highly affected by the direction of the gravity as shown in Figure 2.1.

The actual overall rate of heat transfer, Q is then related by

$$Q = \frac{\Delta T}{Z_{total}}, \tag{2.1}$$

where ΔT is effective temperature difference between heat source and heat sink [K] and it can be denoted as

$$\Delta T = T_{so} - T_{si} - \Delta T_h, \tag{2.2}$$

where T_{so} is the heat source temperature [K],

T_{si} is the heat sink temperature [K].

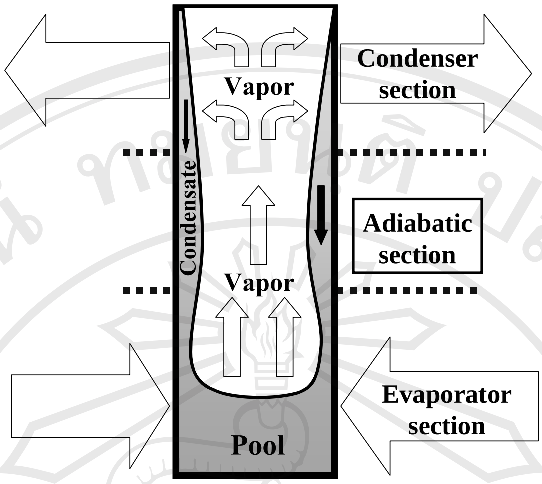

Figure 2.1 Thermosyphon (Dunn and Reay, 1982).

The mean temperature difference due to hydrostatic head, ΔT_h is given by

$$\Delta T_h = \frac{(T_p - T_v) \times F}{2}, \quad (2.3)$$

when F is filling ratio and it is defined as

$$F = \frac{V_l}{Al_e}, \quad (2.4)$$

V_l is volume of working fluid [m^3],

A is area cross section of the pipe [m^2],

l_e is the evaporator length [m].

The saturation temperature at the bottom of the pool, T_p is given by

$$T_p = T_v + \left(l_e \times F \times \frac{dT_s}{dH} \right), \quad (2.5)$$

when the term $\frac{dT_s}{dH}$ is the hydrostatic head which can be defined as

$$\frac{dT_s}{dH} = \frac{T_s g}{L}\left[\frac{\rho_l}{\rho_v} - 1\right], \tag{2.6}$$

when T_s is saturation temperature [K],

g is gravity at the earth's surface [m s^{-2}],

L is specific latent heat of working fluid [J kg^{-1}],

ρ_l is density of working fluid as liquid phase [kg m^{-3}],

ρ_v is density of working fluid as vapor phase [kg m^{-3}].

The vapor temperature of the working fluid, T_v is determined from

$$T_v = T_{si} + \left(\frac{Z_7 + Z_8 + Z_9}{Z_{total}}\right)(T_{so} - T_{si}) \ , \tag{2.7}$$

where Z_{total} is the overall thermal resistance of the thermosyphons can be represented by the idealized network of thermal resistances Z_1 to Z_{10} as shown in Figure 2.2.

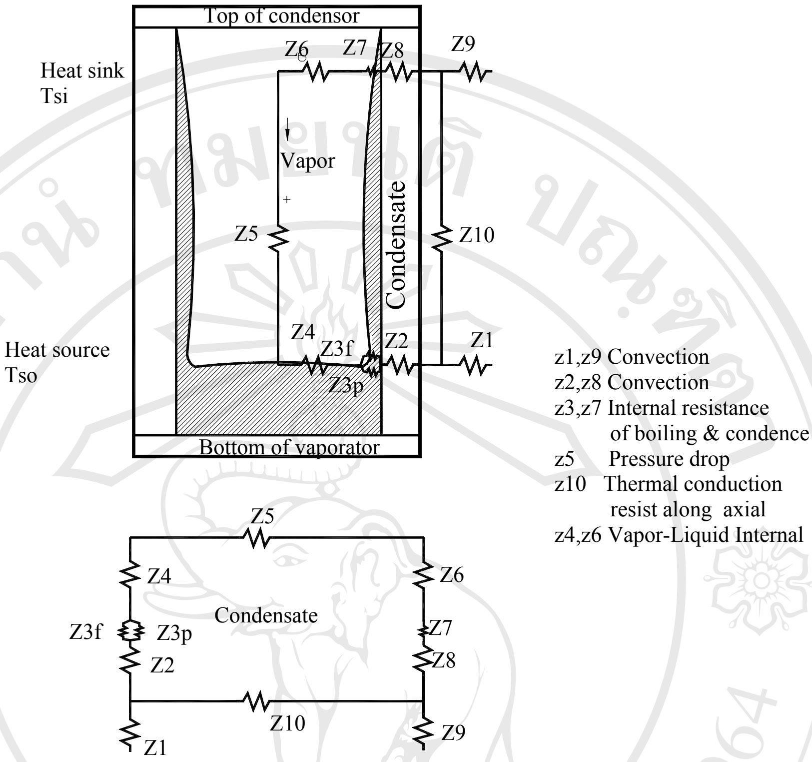

Figure 2.2 Thermal resistance and their locations.

The thermal resistances are arisen as follows

Z_1 and Z_9 are thermal resistances between the heat source and the evaporator external surface and between the condensers external surface and the heat sink, respectively, they are given by

$$Z_1 = \frac{1}{h_e A_e}, \tag{2.8}$$

and

$$Z_9 = \frac{1}{h_c A_c}, \tag{2.9}$$

when h_e is the convective heat transfer coefficient between evaporator and heat source [W m^{-2} K^{-1}],

A_e is the evaporator outer surface [m^2],

h_c is the convective heat transfer coefficient between condenser and heat sink [W m^{-2} K^{-1}],

A_c is the condenser outer surface [m^2],

Z_2 and Z_8 are the thermal resistances across the thickness of the contained wall in the evaporative and the condenser respectively are given by:

$$Z_2 = \frac{\ln(D_o / D_i)}{2\pi l_e k}, \tag{2.10}$$

and

$$Z_8 = \frac{\ln(D_o / D_i)}{2\pi l_c k}, \tag{2.11}$$

when D_o is the outside diameter of the tube [m],

D_i is the inside diameter of the tube [m],

l_c is the condenser length [m],

k is thermal conductivity of the tube [W m^{-1} K^{-1}].

Z_3 and Z_7 are internal resistances due to pool and film boiling of the working fluid which divides into

Z_{3p} is resistance from pool boiling which can be expressed as

$$Z_{3p} = \frac{1}{\Phi_3 g^{0.2} Q^{0.4} \left(\pi D_i l_e\right)^{0.6}}, \tag{2.12}$$

Z_{3f} *is* resistance from film boiling at the evaporator section which can be expressed as

$$Z_{3f} = \frac{CQ^{1/3}}{D_i^{4/3} g^{1/3} l_e \Phi_2^{4/3}}, \tag{2.13}$$

when Φ_3 is Figure of Merit (3)

$$\Phi_3 = 0.325 \times \frac{\rho_l^{0.5} k_l^{0.3} C_{pl}^{0.7}}{\rho_v^{0.25} L^{0.4} \mu_l^{0.1}} \left[\frac{P_v}{P_a}\right]^{0.23}, \tag{2.14}$$

C_{pl} is the specific heat at constant pressure of working fluid as liquid phase [J kg^{-1} K^{-1}],

ρ_v is density of working fluid as vapor phase [kg m^{-3}],

P_v is vapor pressure of working fluid [Pa],

P_a is atmospheric pressure [Pa].

Q is the rate of heat transfer [W]

C is constant of cylinder tube [C = (1/4)(3/π)$^{4/3}$ = 0.235],

Φ_2 is Figure of Merit (2)

$$\Phi_2 = \left(\frac{L k_l^3 \rho_l^2}{\mu_l}\right)^{1/4}, \tag{2.15}$$

k_l is thermal conductivity of working fluid as liquid phase [W m^{-1} K^{1}],

μ_l is viscosity of working fluid as liquid phase [N m^{-1}].

The conditions for using Z_{3p} and Z_{3f} as Z_3 are

if $Z_{3p} > Z_{3f}$ so

$$Z_3 = Z_{3p}, \tag{2.16}$$

if $Z_{3p} < Z_{3f}$ so

$$Z_3 = Z_{3p}F + Z_{3f}\left(1 - F\right). \quad (2.17)$$

Z_7 is resistance due to film boiling of working fluid at the condenser section and it can be calculated from

$$Z_7 = \frac{CQ^{1/3}}{D_i^{4/3} g^{1/3} l_c \Phi_2^{4/3}}. \quad (2.18)$$

Z_4 and Z_6 are the thermal resistances that occur at the vapor liquid interface in the evaporator and the condenser respectively. These values are always neglected in the calculation.

Z_5 is the effective thermal resistance due to the pressure drop of the vapor as it flows from the evaporative to the condenser and it is rather small compared with Z_3 and Z_7.

Z_{10} is the axial thermal resistance of the wall of the container. This value is rather small and it is always neglected.

With the above assumptions, the overall thermal resistance could be simplified as:

$$Z_{total} = Z_1 + Z_2 + Z_3 + Z_7 + Z_8 + Z_9. \quad (2.19)$$

2.2 Nocturnal Long Wave Radiation

Electromagnetic spectrum (2008) stated that the electromagnetic (EM) spectrum is the range of all possible electromagnetic radiation. The "electromagnetic spectrum" (usually just spectrum) of an object is the characteristic distribution of electromagnetic radiation from that object. The thermal radiation is one of the electromagnetic radiation, occurs in the infrared range. The range of electromagnetic radiation has shown in Figure 2.3.

The infrared part of electromagnetic spectrum covers the range from roughly 300GHz (1 mm) to 400 THz (750 mm). It can be divided into three parts: far-infrared, mid-infrared and near-infrared.

Far-infrared, from 300 GHz (1 mm) to 30 THz (10 µm), the lower part of this range may be called microwaves. This radiation is typically absorbed by so-called rotational modes in gas-phase molecules, by molecular motions in liquids, and by phonons in solids. The water in the Earth's atmosphere absorbs so strongly in this range that it renders the atmosphere effectively opaque. However, there are certain wavelength ranges ("windows") within the opaque range which allow partial transmission, and can be used for astronomy. The wavelength range from approximately 200 µm up to a few mm is often referred to as “sub-millimeter” in astronomy, reserving far infrared for wavelengths below 200 µm.

Mid-infrared, from 30 to 120 THz (10 to 2.5 µm), hot objects (black body radiator) can radiate strongly in this range. It is absorbed by molecular vibrations, that is, when the different atoms in a molecule vibrate around their equilibrium positions. This range is sometimes called the fingerprint region since the mid-infrared absorption spectrum of a compound is very specific for that compound.

Near-infrared is in the range of 120 to 400 THz (2,500 to 750 nm). Physical processes that are relevant for this range are similar to those for visible light.

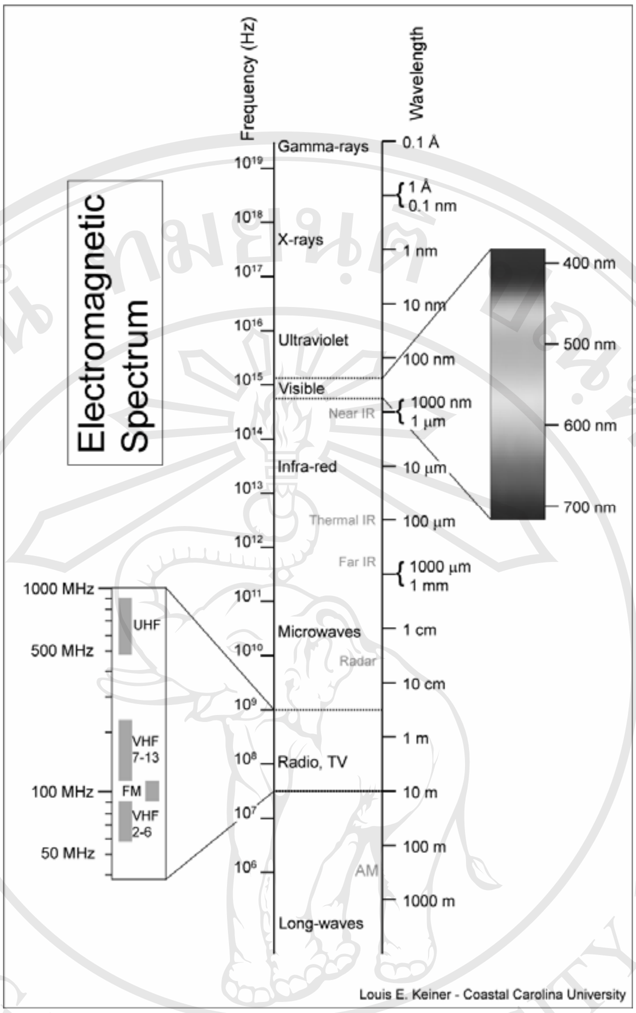

Figure 2.3 Electromagnetic spectrum ranges. (Electromagnetic spectrum, 2008)

For this research, the radiation is occurred in the far-infrared range. The net radiative heat transfer at the surface of the radiator to the night sky can be expressed as:

$$\dot{Q}_{radiation} = \varepsilon \sigma A \left(T_{rad}^4 - T_{sky}^4 \right) \quad , \tag{2.20}$$

where $\dot{Q}_{radiation}$ is the net radiative heat loss [W],

ε is the emissivity of the radiator surface,

σ is the Stefan-Boltzmann constant [5.670 x 10^{-8} W m^{-2} K^{-4}],

A is the radiator surface area [m^2],

T_{rad} is the radiator temperature [K],

T_{sky} is the equivalent sky temperature [K].

T_{sky} is defined as the temperature of a black body radiator emitting the same amount of radiative power as the sky, which is difficult to measure. As data are not available for most locations, it may be more convenient to calculate approximate values of the sky temperature, based on the meteorological data.

Bliss (1961) suggested a formula to find T_{sky} when it was the function of the ambient temperature and the dew point temperature as

$$T_{sky} = T_a\left[0.8 + \frac{T_{dp} - 273}{250}\right]^{1/4}, \tag{2.21}$$

where T_a is the ambient temperature [K],

T_{dp} is the dew point temperature [K].

Swinbank and Rohy (1963) presented a correlation to find T_{sky} when it was the function of only ambient temperature as

$$T_{sky} = 0.0552T_{air}^{1.5}. \tag{2.22}$$

The sky emissivity may be calculated as a function of the dew point temperature, Clark and Berdahl (1980) presented empirical correlation from their experiment as

$$\varepsilon_{sky} = 0.006T_{dp} + 0.74. \tag{2.23}$$

Martin and Berdahl (1984) suggested a formula to find the sky emissivity when it was the function of dew point temperature as

$$\varepsilon_{sky} = 0.711 + 0.56\left(\frac{T_{dp} - 273.15}{100}\right) + 0.73\left(\frac{T_{dp} - 273.15}{100}\right)^2. \qquad (2.24)$$

Berdahl and Martin (1984) expressed the night sky emissivity as a function of the dew point temperature and the relative humidity for cloudless atmospheres $\left(\varepsilon_{sky} = \varepsilon_0\right)$ as

$$\varepsilon_0 = 0.711 + 0.0056 \cdot T_{dp} + 0.000073 \cdot T_{dp}^2 + 0.013 \cdot \cos\left(\frac{2\pi t_m}{24}\right), \qquad (2.25)$$

when

$$T_{dp} = C_3 \frac{\left[\ln(RH) + C_1\right]}{C_2 - \left[\ln(RH) + C_1\right]}, \qquad (2.26)$$

where t_m is the number of hours from midnight in solar time [Hr],

RH is the relative humidity [%],

T_a is the ambient temperature [ºC],

$C_1 = \left(C_2 \cdot T_a\right)/\left(C_3 + T_a\right)$,

C_2 = 17.08085,

C_3 = 234.175.

The experimental data for this work covers for -20 ºC < T_{dp} <+30 ºC, when (T_{sky} - T_a) < 5 K in a hot and humid sky climate and (T_{sky} - T_a) < 30 K in a cold, dry climate.

The presence of clouds increases the atmospheric absorbance and hence the emittance. Martin and Berdahl (1984) also described the correlation for overcast conditions and sky emissivity (ε_{sky}) was a function of the fractional cloud cover, the cloud emittance and the temperature difference between surface and cloud base as

$$\varepsilon = \varepsilon_0 + (1-\varepsilon_0)\varepsilon_c n \exp\left(-\frac{z_c}{z_*}\right), \quad (2.27)$$

where z_c is the cloud base height [km],

z_* is the reference cloud base which is set to be 8.2 [km],

n is the cloud amount of sky covered by non-transparent clouds which is in the range $0 < n < 1$ and can find by

$$n = N/8, \quad (2.28)$$

when N is the total cloud amount in integers, $0 \le N \le 8$,

ε_c is the hemispherical cloud emittance that assumed to be 1 for low and medium high clouds. For cirrus clouds, and 4 km < z_c <11 km the equation can be express as

$$\varepsilon_c = 0.74 - 0.084(z_c - 4), \quad (2.29)$$

and for z_c > 11 km

$$\varepsilon_c = 0.15. \quad (2.30)$$

Vimolrat and Kiatsiriroat (2004) showed that the sky temperature model of Bliss (1961) was appropriate for Thailand weather condition. In this study, we select this model for the whole calculation.