Heat Transfer Calculations

of a Thermosyphon

Introduction

Thermosyphons and heat pipes are used to transport large amounts of heat over a particular distance by using a two-phase fluid inside a hollow pipe. The more widely used heat pipe uses a wicking structure to transport the liquid back to the hot end whereas a thermosyphon is a simple hollow tube that uses gravity.

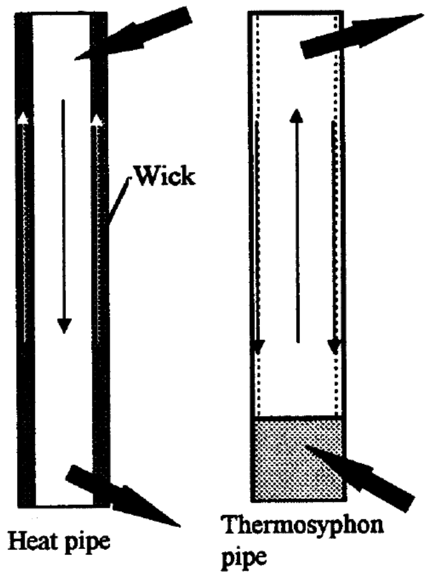

Figure 1. Comparison Between a Heat Pipe and a Thermosyphon [6]

The lack of a wicking structure makes the thermosyphon much less expensive than the traditional heat pipe. However, because of the integral role that gravity plays in the operation of the thermosyphon, it is only effective when the evaporator is below the condenser. In this article we will focus only on the non-looped single tube, known as the thermosyphon pipe, with water as the working fluid.

Thermosyphon Process

Heat is applied to the bottom end known as the evaporator section where the temperature difference between the wall and the fluid leads to pool boiling. The vapor from the pool rises due to buoyancy and travels through the middle, known as the adiabatic section. On the other end of the pipe, the condenser, the pipe is kept at a temperature colder than the saturation temperature of the vapor which causes it to condense on the walls. The increase in density and weight causes the condensate to fall back to the evaporator section to complete the cycle.

Limits/Design Points

Given the expected heat load and the temperature of the evaporator and condenser, we can calculate the remaining variables that can be used for designing the thermosyphon. The design decisions needed to make are:

1) Geometry: Diameter & wall thickness. The total length may be constrained by the application domain
2) Volume of fill liquid
3) Pressure (as related to saturation/boiling point temperature of the fluid)
4) Insertion length of the evaporator and condenser

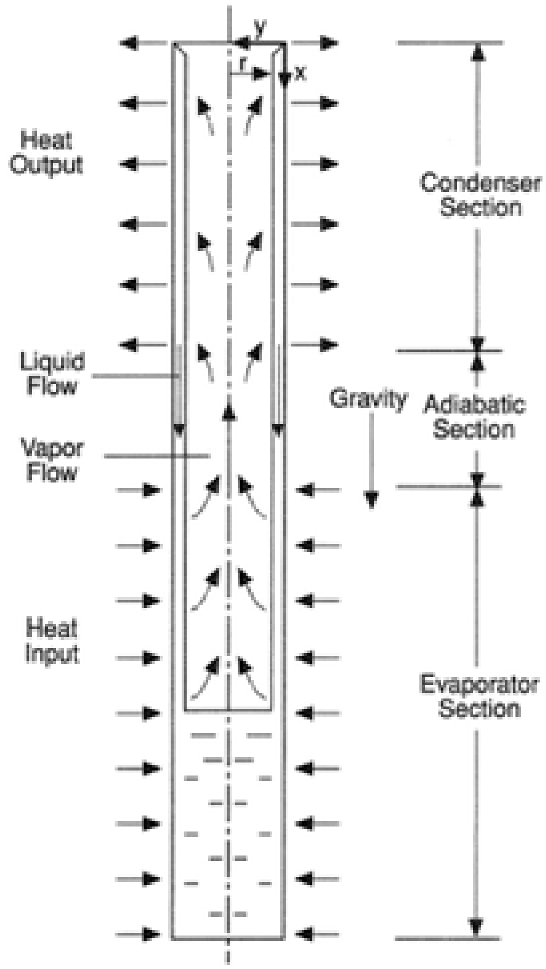

Figure 2. Vertical Two-Phase Thermosyphon [3]

The design points shown above are interconnected by the following limits under which the thermosyphon has to operate:

1) Flooding limit: the shear between the liquid and vapor cross-flow can increase to the point where the liquid does not fall. A similar limit in the traditional heat pipe is known as the capillary limit. The flooding limit can be best avoided by increasing the pipe diameter to the point the steam velocity is low. This limit is generally much more restricting than the sonic limit that can be experienced in heat pipes.
2) Boiling limit (dry out): If the liquid boils faster than the vapor condenses, entire thermosyphon will be filled with vapor

Flooding Limit

As mentioned above, the flooding limit can occur if the velocity of the vapor is too high and prevents the condensed liquid from falling down. The correlation shown in equations 1-3, as shown by Faghri et al. [2], finds the maximum allowable heat transfer for a given set of conditions. If the fluid properties are known, this correlation gives you a minimum pipe diameter required for a given power.

$$\dot{Q}_{max,flood} = \frac{T_b h_{lv} (\pi D^2_{pipe} \left[g\sigma(\rho_l - \rho_v)\right)^{1/4}\right]}{[\rho_v^{-0.25} + \rho_l^{-0.25}]^2} \tag{1}$$

$$T_b = \left(\frac{\rho_l}{\rho_v}\right)^{0.14} \tanh^2(B_o)^{1/4} \tag{2}$$

$$B_o = D_{pipe,in}\left[\frac{g(\rho_l - \rho_v)}{\sigma}\right]^{1/2} \tag{3}$$

Boiling Limit

Evaporator Section

Figure 3 shows the standard pool boiling curve. Researchers have discovered that staying to the left of the critical heat flux, i.e. nucleate boiling as shown in region II, maintains a steady pool boil [7].

For water at atmospheric pressure, the critical heat flux is in the range of 950—1300 kW/m² [8].

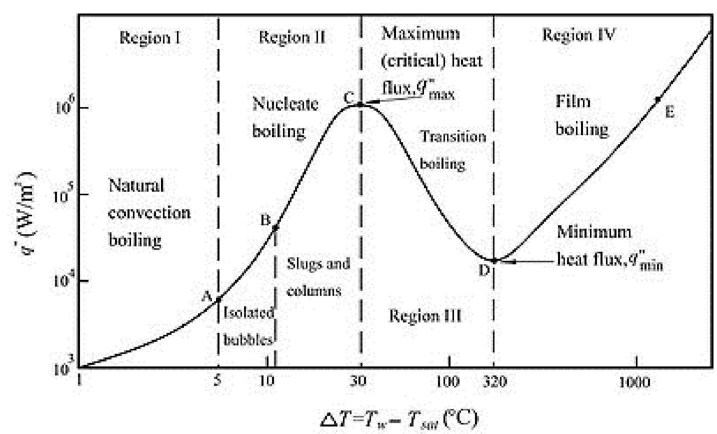

Figure 3. Pool Boiling Heat Flux vs Temp Difference [11]

To calculate the specific critical heat flux, use the correlation from Sun and Leinhard [9] as shown in equation 4. The minimum evaporator section length can then be found such that the resulting heat flux is less than the critical heat flux as shown in Equation 5.

$$Q''_{CHF}=0.149\rho_v\text{-}\rho_{lv}\left[\frac{\sigma g(\rho_l-\rho_v)}{\rho_v^2}^{1/4}\right] \tag{4}$$

$$L_{evap}\geq\frac{\dot{Q}}{\pi D_{pipe}Q''_{CHF}} \tag{5}$$

Condenser Section

Most common type of condensation on a cold wall results in "film condensation" for which one can use Nusselt's condensation correlation, as shown in equation 6, to find the heat transfer coefficient as a function of condenser length [4]. Combined with the first law analysis for the evaporator section as shown in equation 7, one can determine the right condenser length. Note that the heat transfer, Q, is the same for the evaporator and condenser sections.

$$Nu=\frac{h_cL_c}{K_l}=\left[\frac{\rho_l(\rho_l-\rho_v)gh_{lv}L_c^3}{4\mu_lK_l(T_{sat}-T_{c,i})}\right]^{1/4} \tag{6}$$

$$\dot{Q}=h_c(2\pi R_{pipe,i}L_c)(T_{sat}-T_{c,i}) \tag{7}$$

Where $T_{c,i}$ refers to the temperature inside the pipe in the condenser section which can be calculated by the cylindrical conduction equation shown in Equation 8.

$$T_{c,i}=T_c-\frac{\ln\left(\frac{D_{out}}{D_{pipe,i}}\right)}{2\pi LK}\dot{Q} \tag{8}$$

Fill Volume

An incorrect initial fill volume in a thermosyphon can similarly lead to dry out or flooding limit even if the remaining variables are correctly set. For the thermosyphon in the vertical orientation, the fill volume should be 20-80% of the evaporator volume. There are varying views on whether an optimal fill volume exists within that range; a starting point of 50% fill volume is recommended.

Thermosyphon Orientation

The thermosyphon uses the force of gravity to transport condensed liquid back to the evaporator section. For that reason, one would intuit that the completely vertical orientation would serve as the most optimal performance and the completely horizontal orientation, if at all functional, to be the least.

However, several studies have found that the optimal orientation exists in the middle of the two angles. The results vary as to the range in which the optimum exists. For example, Emami et al. [1] found that an orientation of 60◦ from the horizontal has a performance 5-10% better than the vertical set up whereas their predecessors Terdtoon et al. [10] found the optimum to lie between 70-80 degrees.

Since the pipe orientation maybe a function of the larger design criterion and application geometry, the smaller differences in performance may not be as useful. For example, to get a 5% increase in performance, it may be easier to increase the diameter of the thermosyphon by 2.5% than to change the angle by 10-40◦.

Conclusion

A thermosyphon is a simple device that can be used to transfer large amounts of heat without moving parts. The limitations of the device are similar to those of a traditional heat pipe with a wicking structure. Using the correlations and equations shown in this section one can get a basic understanding of the right thermosyphon pipe to use for a particular application.

Greek Symbols

ρ_l	Density of liquid phase [kg/m³]
ρ_l	Density of vapor phase [kg/m³]
σ	Surface Tension of liquid [N/m]

Nomenclature

B_o	Bond number as defined by equation 3
$D_{pipe,in}$	Inner diameter of the thermosyphon pipe [m]
D_{out}	Outer diameter of the thermosyphon pipe [m]
g	Gravitational Constant, [9.8 m/s^2]
h_c	Heat transfer coefficient for condensation [W/m^2-K]
h_{lv}	Enthalpy of evaporation [J/kg-K]
K_l	Thermal Conductivity for the liquid [W/m-K]
L_{evap}	Length of the evaporator section [m]
Nu	Nusselt number
Q''_{CHF}	Critical Heat Flux in pool boiling [W/m^2-K]
Q	Heat Transfer rate [W]
T_c	Temperature outside the thermosyphon pipe in the condenser region [K]
$T_{c,i}$	Temperature inside the thermosyphon pipe in the condenser region [K]
T_{SAT}	Saturation/boiling temperature of the liquid [K]

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