

CHAPTER IV

LOOP THERMOSYPHON

Loop thermosyphon (LTS) is a kind of thermosyphon which employs gravity to return the condensate back to the evaporator section by introducing the flow as one-way circuit in the loop container. In order to alleviate the energy use in the heat pump dryer system, a loop thermosyphon is introduced into the system. The LTS is the effective device to transfer heat by means of the latent heat of evaporation and condensation. The LTS is inexpensive, practical and requires no external power for operation. To alleviate some of energy consumption of the heat pump dryer, the loop thermosyphon was introduced to serve as an energy saver. Terdtoon *et al.* (1999) has introduced the loop thermosyphon into the conventional dryer system and commented that it can be used as a pre-heater unit suitable for industrial scale application.

For the heat pump dryer, no one has adapted loop thermosyphon as an energy saver. Hence, we focus on this aspect in this thesis. Two separate steps are as followed: First, construct the mathematical model of loop thermosyphon and simulate the suitable specification for heat pump dryer. Then, test the performance, given the details in this chapter. Secondly, construction and apply the loop thersyphon in the heat pump dryer and test to analyze the energy saving of the loop thermosyphon by comparing between heat pump dryer with and without loop thermosyphon (Chapter III).

4.1 Objectives of the mathematical model

- 4.1.1 To construct a simulation model, which can be used to simulate the loop thermosyphon and construct the loop thermosyphon experimental unit.
- 4.1.2 To evaluate the performance of the loop thermosyphon and find its suitability in the heat pump dryer unit.

4.2 Scope of the mathematical model

The appropriate loop thermosyphon was designed based on the condition of the cooling capacity of the heat pump dryer. From the heat transfer characteristics of the heat pump dryer at the minimum specific energy consumption and highest performance of heat pump system as discussed in chapter III, we can define the assumption of the mathematical modeling as follows:

4.2.1 The formulated model can be used to predict the trend of heat transfer of the loop thermosyphon at any condition.

4.2.2 The parameters forming this model will be specified to suit the constructional aspects and applied with the heat pump dryer. Because the data of integrated unit will be compared with the heat pump dryer without loop thermosyphon, all of the material data normally available in Thailand were used in the program. The parameters are;

The control parameters:

- Loop thermosyphon was made of copper tube with aluminum fin
- The evaporator and condenser section was 9.53 mm ID, 10 mm OD.
- 20 degree inclination angle
- Evaporator section and condenser section length was 410 mm
- Adiabatic section length was 1200 mm.
- Filling ratio 75% by volume of evaporator
- R-123 was the working fluid

The variable parameters were:

- Number of row (N_r)
- Number of colum(N_c)

From the N_r and N_c can calculate the loop of thermosyphon.

4.3 Structure of the mathematical model and computer program

Applying the principles and theory of heat transfer and basic governing equations, the mathematical model was established. The two-phase closed

thermosyphons concept was used for the analysis. Figure 4.1 shows the schematic diagram of the loop thermosyphon and its interior working conditions.

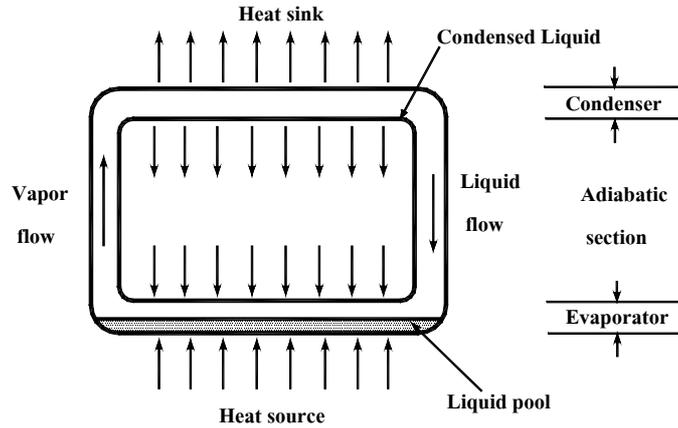


Figure 4.1 Schematically diagram of the loop thermosyphon

First, find the amount of heat that the loop thermosyphon must transfer out from the air before entering the evaporator of heat pump. This quantity can be obtained from the heat pump dryer in Chapter III. Also, establish values for the heat source temperature (T_{so}) and heat sink temperature (T_{si}) from Chapter III.

The equations for calculation of heat transfer characteristics of the loop thermosyphon are:

Find T_{so} and T_{si}

$$T_{so} = T_{do} + 273.15 \quad (4.1)$$

$$T_{si} = T_{eo} + 273.15 \quad (4.2)$$

Find the effective air velocity (V_{eff})

$$N_t = N_r * N_c \quad (4.3)$$

$$N_f = L_i / L_{fs} + 1 \quad (4.4)$$

$$A_f = 2 * N_f * (W_f * L_f - \pi * \frac{D_o^2}{4} * N_t) + 2 * N_f * L_f * T_f \quad (4.5)$$

$$A_b = N_t * (\pi * D_o * L_i - N_f * T_f * \pi * D_o) \quad (4.6)$$

$$A_t = A_f + A_b \quad (4.7)$$

$$A_{ff} = (L_i * L_f) - N_c * D_o * (L_i - N_t * T_f) - (N_f * L_f * T_f) \quad (4.8)$$

$$A_{fr} = L_i * L_f \quad (4.9)$$

$$L_{eff} = (S_t - D_o) / 2 \quad (4.10)$$

$$V_{eff} = (V_{air} * A_{duct}) / A_{fr} \quad (4.11)$$

Find H_{co} and H_{co}

The properties of air required are ρ_{air} , $C_{p,air}$, μ , K_{air} .

$$P_r = (C_p * \mu) / K_{air} \quad (4.12)$$

$$S_t = 0.036 * (L_{ff} * V_{ff} * \rho_{air} / \mu_{air})^{-0.2} * P_r^{-2/3} \quad (4.13)$$

$$H_f = S_t * C_p * V_{eff} * \rho_{air} \quad (4.14)$$

$$mL_{eff} = L_{eff} \sqrt{\frac{2 * H_f}{K_f T_f}} \quad (4.15)$$

$$\eta_f = \tanh(mL_{eff}) / (mL_{eff}) \quad (4.16)$$

$$N_u = B * C_z * R_e^m * P_r^{1/3} \quad (4.17)$$

$$N_u = H_b * D_o / K \quad (4.18)$$

$$H_b = (K * C_1 * C_2 * R_e^m * P_r^{1/3}) / D_o \quad (4.19)$$

$$G_{max} = \rho_{air} * V_{eff} * (A_{fr} / A_{ff}) \quad (4.20)$$

$$R_e = (D_o * G_{max}) / \mu_{air} \quad (4.21)$$

$$H_{co} = (\eta_f * A_f * H_f + A_b * H_b) / A_t \quad (4.22)$$

The C_1 , C_2 and m values depend on S_L/S_T which was calculated using the interpolation method. Depending on the condition whether it is staggered or aligned.

For H_{co} , the same equations except the temperature and air properties were used.

Calculations for one loop

$$N_{c1} = N_c / (N_c / 2) \quad (4.23)$$

$$N_{t1} = N_t / (N_r * N_c / 2) \quad (4.24)$$

$$L_{f1} = L_f / (N_c / 2) \quad (4.25)$$

$$W_{f1} = W_f / N_r \quad (4.26)$$

$$S_{e0} = A_t / (N_r * N_c / 2) \quad (4.27)$$

$$S_{co} = S_{e0} \quad (4.28)$$

For this thesis, the evaporator and condenser sections are equal.

$$L_e = L_i * (N_i / (N_r * N_c / 2)) \quad (4.29)$$

$$L_c = L_e \quad (4.30)$$

For this thesis, design $L_e = L_c$.

$$Z_1 = 1 / (H_{e0} * S_{e0}) \quad (4.31)$$

$$Z_9 = 1 / (H_{c0} * S_{c0}) \quad (4.32)$$

$$Z_2 = \ln(D_o / D_i) / (2 \pi * K * L_e) \quad (4.33)$$

$$Z_8 = \ln(D_o / D_i) / (2 \pi * K * L_c) \quad (4.34)$$

$$Z_t = Z_1 + Z_2 + Z_8 + Z_9 \quad (4.35)$$

Calculate T_v and ΔT

$$\Delta T = (T_{so} - T_{si}) \quad (4.36)$$

$$T_v = T_{si} + (Z_8 + Z_9) / Z_t * (T_{so} - T_{si}) \quad (4.37)$$

This step selects the working fluid and calculates its property.

$$H = S_t(\sin \beta) + D_i \quad (4.38)$$

Where, β is the angle of tube, for this thesis is 90 degree.

$$P_{p,1} = P_v + \rho_l * g * F * H \quad (4.39)$$

Where, F is filling ratios

From equation 4.39, we can find T_{p1}

Calculate the Q_{first} as follows:

$$T_s = (T_{p1} + T_v) / 2 \quad (4.40)$$

$$SS = T_s * g / H_{fg} * (\rho_l / \rho_v - 1) \quad (4.41)$$

$$T_{p2} = T_v + SS * F * H \quad (4.42)$$

$$T_p = (T_{p1} + T_{p2}) / 2 \quad (4.43)$$

$$\Delta T_h = (T_p - T_v) / 2 * F \quad (4.44)$$

$$\Delta T = (T_{so} - T_{si}) - \Delta T_h \quad (4.45)$$

$$Q_{\text{first}} = \Delta T / Z_t \quad (4.46)$$

Calculate Q_{new} by considering Z_3 (evaporator film thermal resistant) and Z_7 (condenser film thermal resistant).

$$Z_{3f} = 0.335 Q^{1/3} / (D_i * g^{1/3} * L_e^{4/3} * \Phi_2^{4/3}) \quad (4.47)$$

$$\Phi_3 = 0.32 * \frac{\rho_l^{0.65} * K_l^{0.3} * C_{pl}^{0.7}}{\rho_v^{0.25} * H_{fg}^{0.4} * \mu_l^{0.1}} \left[\frac{P_v}{P_a} \right]^{0.23} \quad (4.48)$$

$$Z_{3p} = \frac{1}{\Phi_3 * g^{0.2} * Q^{0.4} * (\pi * Di * Le)^{0.6}} \quad (4.49)$$

If $Z_{3p} > Z_{3f}$ Then

$$Z_3 = Z_{3f} * Z_{3p} / (Z_{3f} + Z_{3p}) \quad (4.50)$$

If $Z_{3p} < Z_{3f}$ Then

$$Z_3 = Z_{3p} \quad (4.51)$$

$$Z_7 = \frac{0.335 * Q^{1/3}}{Di * g^{1/3} * Le^{4/3} * \Phi_2^{4/3}} \quad (4.52)$$

Recalculate Z_t

$$Z_{t,new} = Z_t + Z_3 + Z_7 \quad (4.53)$$

$$Q_{new} = \Delta T / Z_{t,new} \quad (4.54)$$

Check Q_{new} with Q_{first} and iterate until $Q_{new} = Q_{first}$. Then check the limitation of internal limit. V_{iz-} , Q_{sonic} and $Q_{boiling}$. For the loop thermosyphon eliminate $Q_{counter-current}$ flow. Because it is a one way circuit.

After checking, then calculate Q_{total} .

$$Q_{total} = Q_{new} * N_c / 2 * N_r \quad (4.55)$$

$$E \text{ by } C = Q_{total} / \text{Cost} \quad (4.56)$$

Where,

$E \text{ by } C$ was the heat transfer per cost of construction of the loop thermosyphon.

4.4 The flow chart procedure of the mathematical program

First program is used to calculate the maximum heat transfer rate of the loop thermosyphon (Q_{total}). Second program is used to simulate the optimum $E \text{ by } C$ (energy by cost of construction) for constructing and performance evaluation.

4.5 Description of the program

The description of the whole program can be seen in Appendix B, as stated below:

This program is used to calculate the heat transfer of the loop thermosyphon (Q_{total}). After finding the conditions of heat excess from the system (Q_{excess}), then, it is used to calculate the Q_{total} . Compare Q_{total} with Q_{excess} . If not equal change the condition and iterate until $Q_{total} = Q_{excess}$.

The parameter was controlled for use in program before simulation. For example (in this thesis)

The control parameters are

- Format of tube (Aligned or staggered) was staggered
- Select working fluid (R-123 or R-134a) was R-123
- Adiabatic length (L_a) was 1.2 meter
- Price of bare tube was 50 Bath per meter
- Price of tube with fin 100 Baht per meter
- Airflow rate was 937 m³/h
- Temperature entering the condenser section (T_{si}) was 30 °C
- Temperature entering the evaporator section (T_{so}) was 60 °C
- Area of the duct (for calculate air velocity) was 0.215 m²
- Fin thickness was 0.00015 m
- Tube thickness was 0.0015 m
- Initial moisture content of the product (%wb) was 75 % wb
- Final moisture content of the product (%wb) was 20% wb
- In put the mass of the product (kg) was 120 kg
- Filling ratio was 75% of evaporator section
- Beta (degree) was 90 degree
- Out side diameter of tube (D_o) was 0.01 m (can get in market which set of fin)

The initial data are:

- Number of row (N_r)
- Number of column (N_c)
- Fin width (W_f)
- Distance between the fins (L_{fs})
- Distance between the tubes (S_t)

- Distance between the rows (S_i)
- Height of fin (L_f)
- Length of fin or Length of evaporator section (L_i)

The program calculates the water removed which in turn is used to calculate Q_{excess} . It is compared with Q_{total} from the loop thermosyphon. Simulate the optimum E by C, then change the condition, recalculate and compare the result with the first one and record the minimum E by C result.

From this study, the rate of maximum heat transfer to the cost of the construction of the LTS was used as one of the condition in establishing the optimum working condition. The model of the HPD was applied to the model of the LTS. Together, the combined model developed and simulated to find the minimum value of the total specific energy consumption of the system. The details will be explained in the next chapter.