Two-Dimensional Simulation of Temperature in Paddy Bulk Storage with Closed-Loop Oscillating Heat Pipes

Suppachai Chumnumwat[1] and Piyanun Charoensawan[2]

[1]Faculty of Engineering, Rajamangala University of Technology Lanna Phitsanulok,
Phitsanulok 65000, Thailand
[2]Department Department of Mechanical Engineering, Faculty of Engineering, Naresuan University,
Phitsanulok 65000, Thailand

[1]suppachaic@rmutl.ac.th, [2]piyanunc@nu.ac.th

Abstract. *The temperature distribution characteristic of 250 kg paddy was computational studied. The paddy was kept in the cylindrical bin with 0.7 m diameter and 1.0 m height and cooled by an array of closed-loop oscillating heat pipes (CLOHPs). The moisture content of paddy was 14% wet basis. CLOHPs were made of copper capillary tubes with 0.0014 m inside diameter and 0.0022 m outside diameter and filled with R134a at 50% of the total internal tube volume. The evaporator and condenser lengths of CLOHP were 1.0 m and 0.5 m respectively. CLOHPs were arranged in a circular form within the bin. The evaporator section was buried in the storage bin and the condenser section was exposed to the ambient air in order to remove heat from the respiration of paddy. The temperature distribution inside paddy bulk was numerical analyzed as the two-dimensional transient heat transfer in cylindrical coordinates (r, z, t) and the temperature of paddy in circumferential direction was supposed to be uniform. The temperature distribution within paddy bulk with CLOHP was investigated through 60 h and compared to the temperature distribution of system without cooling unit. The temperature difference of paddy inside the storage bin with and without CLOHPS was found in the range of 0.99-2.55%. The array of CLOHPs within paddy bin can remove the heat from grain during storage and reduce the bed temperature although there are a few temperature differences of paddy and ambient air. The thermal efficiency of simulated CLOHPs cooling system was about 45.2%*

Keywords:

Closed-loop oscillating heat pipe, paddy storage, temperature distribution

1. Introduction

The paddy is deteriorated during storage due to heat liberated from respiration process especially for the paddy after harvest in which the moisture content is high at 26.9% wet basis. After the drying process, the moisture content of paddy is reduced and kept at 14% wet basis which is the safety condition for a long storage time. The deficient paddy storage management induces important grain damage. Normally, the aeration with cool or ambient air is used to remove the heat from grain during storage and reduce the bed temperature. Because Thailand is in humid tropical climate and the rice cultivation is 2-3 times per year, the fan operating time is really long which follows by the high electricity expense per year. In order to decrease the operating cost of electricity consumption, the thermosyphon was applied as a cooling unit in paddy bulk storage [2]. The working fluid used was R22 at 100% filling ratio of evaporator volume. Although the bed temperature of paddy with the high moisture content was clearly reduced, the construction of tested thermosyphon was specific and complicated in order to add the evaporator and condenser areas and its design theory was restricted. Therefore a closed-loop oscillating heat pipe (CLOHP) which was one type of heat transfer device with high thermal performance [3-5] was concentrated in this research. Since it is made of a long capillary tube that is severally bent between the evaporator and condenser sections to form the meandering turns, there are simplicities of construction and an increase in the heat transfer surface area of CLOHP. Because of these advantages, CLOHP was widely investigated in cooling the small electronic devices [9], enhancing the performance of turbo charge diesel engine [10] and an application in waste heat recovery. The understanding of temperature distribution in the stored paddy is able to predict the grain deterioration potential. A numerical simulation model viz., a two-dimensional finite difference model, was developed to predict temperature in a paddy storage bin during the non-aeration period [1] and the aeration period [11] of the storage process. Recently the heat transfer model of paddy bulk with 26% wet basis was carried out in our previous research and it will be applied and developed for practical storage condition. In this research, a two-dimensional finite difference model was developed to investigate the temperature distribution in the 14% wet basis paddy storage bin with using CLOHPs as a cooling unit.

2. Mathematical Model and Computer Program

The temperature distribution inside paddy bulk was considered as the two-dimensional transient heat transfer in cylindrical coordinates (r, z, t) and the temperature of paddy in circumferential direction was supposed to be uniform as shown in Fig. 1.

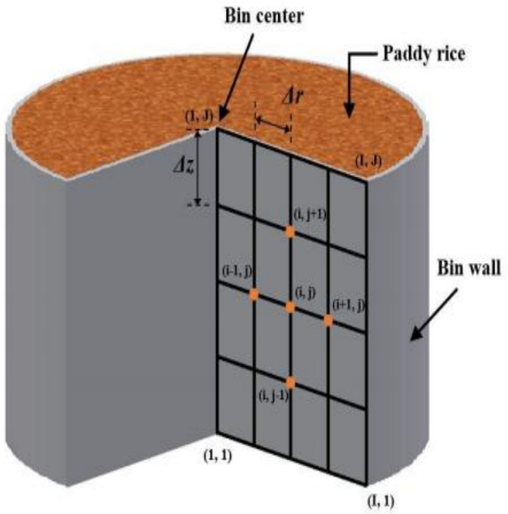


Fig. 1: Finite-difference discretization of a paddy storage bin

In order to simplify the model, it is necessary to suppose that the radiation heat exchange with surroundings is negligible. The ambient temperature is constant at 25˚C. The thermal energy generation is uniform within medium. The paddy moisture content is constant at 14% wet basis. The CLOHPs arrangement is defined in a circular form within the paddy storage bin and the distance between the adjoined CLOHPs in radial direction is 0.08 m as shown in Fig. 2. The evaporator sections are buried in the storage bin. The condenser sections are exposed to the ambient air in order to remove the respiration heat. The designed parameters of the paddy storage bin with using CLOHPs as a cooling unit are summarized in Table 1.

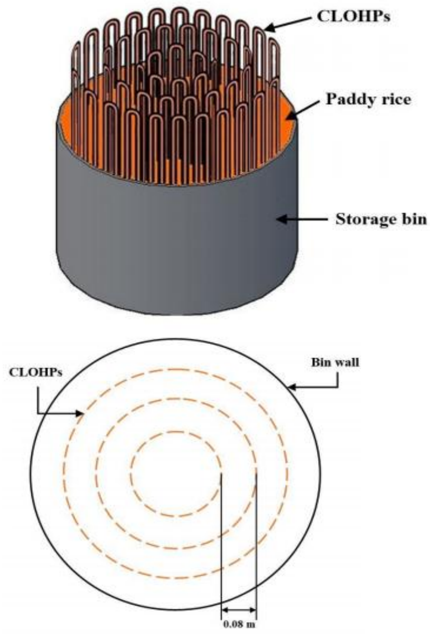


Fig. 2: CLOHPs arrangement in storage bin

Table 1: System specifications

Specifications	Dimensions
Mass of paddy	250 kg
Height of bin	1.0 m
Diameter of bin	0.7 m
Inner diameter of CLOHP	0.0014 m
Outer diameter of CLOHP	0.0022 m
Evaporator length of CLOHP	1.0 m
Condenser length of CLOHP	0.5 m
Number of CLOHP turns	20
Working fluid of CLOHP	R134a
Filling ratio of working fluid	50%
Initial temperature of paddy	26.5 °C
Paddy moisture content	14 % w.b.
Paddy storage time	60 h
Δr	0.0146 m
Δz	0.0416 m

The finite-difference equation for each nodal point in Fig. 1 was developed by applying energy balance to a control volume about the nodal region. That is

$$\dot{E}_g + \dot{E}_{in} - \dot{E}_{out} = \dot{E}_{st} \quad (1)$$

where E_g is the rate of thermal energy generated in the control volume due to respiration process of paddy. E_{in} is the rate at which thermal energy enter the control surface due to the heat conduction from adjoining nodes. E_{out} is the rate of thermal energy removed from the control surface by CLOHPs. E_{st} is the rate of change of internal thermal energy stored within the control volume of paddy.

The rate of thermal energy generated in the control volume due to respiration process of paddy was evaluated by using the expression as follow [7]:

$$\Delta T = \frac{15778(DML)}{c_p} \tag{2}$$

; where ΔT is the temperature increment due to heat generation in the paddy. c_p is the paddy specific heat and can be calculated as [8]:

$$c_p = 3.1 \times M_w + 1.2648 \tag{3}$$

; where M_w is the paddy moisture content. *DML* is the dry matter loss which indicates the amount of heat generated from respiration process. It is written as [7]:

$$DML = 1 - \exp(-Term) \tag{4}$$

; where

$$Term = A\left(\frac{t}{1000}\right)^C \exp[D(1.8T - 28)] \exp[E(M_w - 0.14)] \tag{5}$$

A = 0.001889, C = 0.7101, D = 0.0274, E = 31.63. t is the paddy storage time, T is the paddy temperature.

The rate of change of internal thermal energy stored within the paddy control volume can be expressed as:

$$\dot{E}_{st} = \rho c_p \frac{dT}{dt} dV \tag{6}$$

; where ρ is the paddy density and can be calculated as [8]:

$$\rho = 171.02 \times M_w + 560.16 \tag{7}$$

The rates of heat conduction between adjoining nodes in the radial direction (q_r) and axial direction (q_z) were evaluated from Fourier's law,

$$q_r = -k_{eff} A \frac{\partial T}{\partial r}, \quad q_z = -k_{eff} A \frac{\partial T}{\partial z} \tag{8}$$

; where k_{eff} is the effective thermal conductivity of paddy and can be calculated as [8]:

$$k_{eff} = 0.27 \times M_w + 0.0653 \tag{9}$$

A is the heat transfer area. $\partial T/\partial r$ and $\partial T/\partial z$ are the temperature gradients in r and z directions respectively.

The rate of thermal energy removed from the control surface by CLOHP was calculated from the non-dimensional empirical correlation given by Charoensawan et al., 2007 [6]:

$$Ku = 2.13 \times 10^{-9} \mathrm{Pr}_l^{0.75} Ja^{*-0.38} Bo^{-0.84} Ka^{0.58} (k_c/k_a)^{1.21} \tag{10}$$

; where k_c/k_a is the ratio of the thermal conductivities of the coolant at the required temperature and the ambient air at 25˚C. Pr_l is Prandtl number of liquid. *Ka* is Karman number. *Ja** is modified Jacob number. *Bo* is Bond number. *Ku* is Kutateladze number that can be written as [6]:

$$Ku = \frac{q''}{h_{lv}\rho_v\left(\frac{\sigma g(\rho_l - \rho_v)}{\rho_v^2}\right)^{\frac{1}{4}}} \tag{11}$$

; where h_{lv} is the latent heat of vaporization of working fluid, ρ_l and ρ_v are the liquid and vapor densities of working fluid respectively, g is the gravitational acceleration, σ is the surface tension and q'' is the radial heat flux of CLOHP that can be calculated as [6]:

$$q'' = \frac{q}{2n\pi D_i L_e} \tag{12}$$

; where q is the heat transfer rate of CLOHP and n is the number of turns. All properties of working fluid used in these dimensionless parameters were evaluated at an operating temperature of CLOHP.

In order to obtain all nodal finite-different equations, the following initial and boundary conditions were considered:

$$\frac{\partial T}{\partial r} = 0 \quad \text{for } r = 0 \tag{13}$$

$$T(r,z,0) = T_0(r,z) \quad \text{for } t = 0 \tag{14}$$

$$-k_{eff}\frac{\partial T}{\partial r} = h_e(T - T_a) \quad \text{for } r = 0.35 \tag{15}$$

$$-k_{eff}\frac{\partial T}{\partial z} = h_s(T - T_a) \quad \text{for } z = 1 \tag{16}$$

$$-k_{eff}\frac{\partial T}{\partial z} = h_i(T - T_a) \quad \text{for } z = 0 \tag{17}$$

; where h_e, h_s and h_i are the convective heat transfer coefficients on the bin wall, the grain top surface and the grain bottom surface respectively and can be obtained from the previous research [1]. T_0 is the initial paddy temperature. T_a is the ambient air temperature. The computational steps for modeling the system are described in Fig. 3. The simulation model of stored paddy with and without CLOHPs was studied. The temperature distribution inside paddy bulk was analyzed along the storage time of 60 h for five representative temperature points shown in Fig. 4.

3. Results and Discussion

3.1 Paddy storage with and without CLOHPs

The dependency of average temperature of paddy stored in the bin on time is shown in Fig. 5. The paddy temperature increases from 28˚C to 31.5˚C in the storage time of 20 h and then it is nearly constant. This might be because the rate of heat generation in paddy is high until 20 h and after that it decrease. In addition, the simulation data obtained in this research is compared to the experimental data given by Dussadee et al. (2004) [2]. It is seen that the simulation data entirely agrees with the experiment result and the standard deviation is ±2.2%. Therefore the two-dimensional finite difference simulation model developed in this research can predict the temperature distribution in a paddy storage bin.

Fig. 6 shows the evolution of predicted paddy temperature for different points. The paddy temperatures with and without CLOHPs at point S1, S2, S3, S4 and S5 were indicated above in Fig. 4. The paddy temperature difference between with and without CLOHPS for point S1, S2, S3, S4 and S5 were calculated as 2.55%, 1.31%, 1.47%, 1.45% and 0.99% respectively.

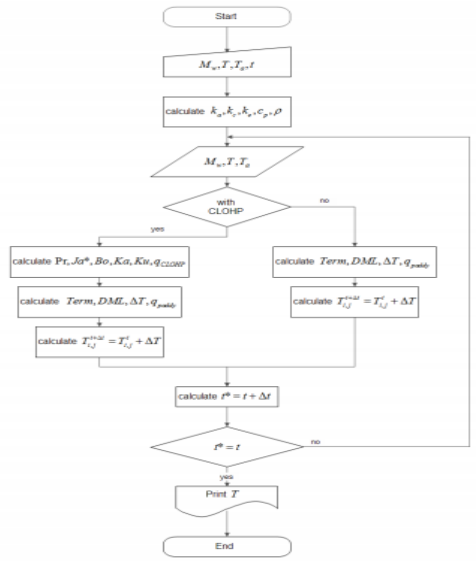


Fig. 3: Computational steps for modeling.

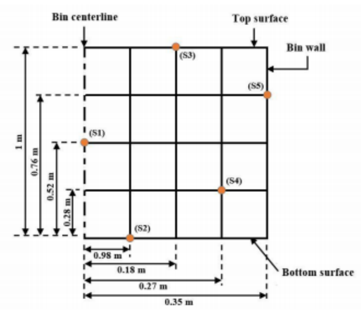


Fig. 4: Positions of temperature in paddy storage bin.

3.2 Temperature distribution inside paddy bulk with and without CLOHPs

At the initial time, the paddy temperature stored in the bin is uniform at 26.5˚C for with and without CLOHPs. The maximum temperature always occurs in the middle bed region of storage bin. The temperature decreases with an increase in the r-direction distance from centerline of storage bin as shown in Table 2.

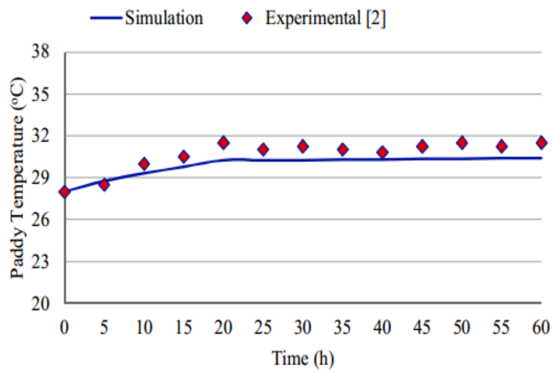
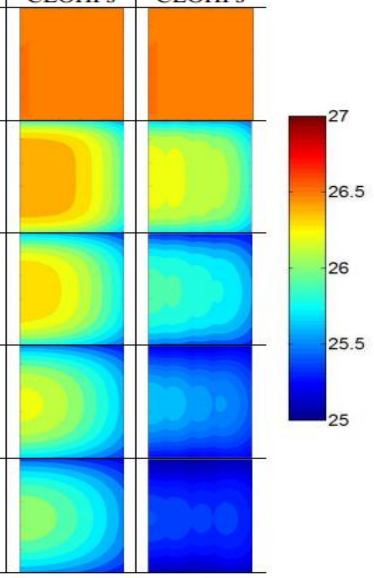


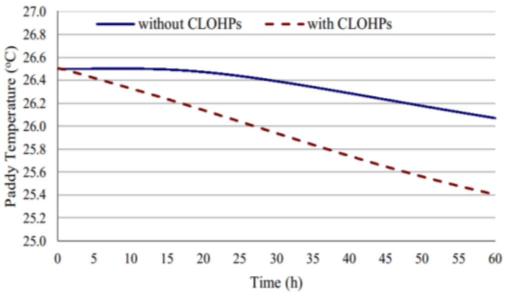
Fig. 5: Dependency of average temperature of paddy stored in the bin on time

For paddy bulk without CLOHPs, with the longer the storage time, the temperatures of all points within medium gradually decrease. The maximum temperature occurs in the middle region of bin and the value was about 26˚C. The minimum value occurs at the bin wall and the top and bottom surfaces of paddy. The value is about 25.7˚C at 60 h.

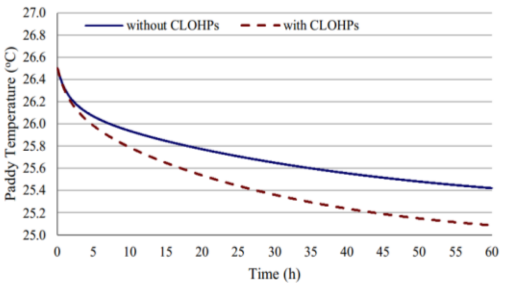
Table 2: Temperature distribution inside paddy bulk

Time (h)	Without CLOHPs	With CLOHPs
0		
15		
30		
45		
60		

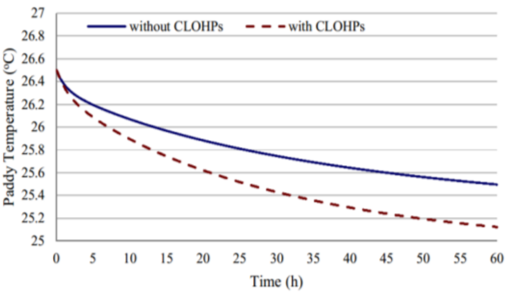




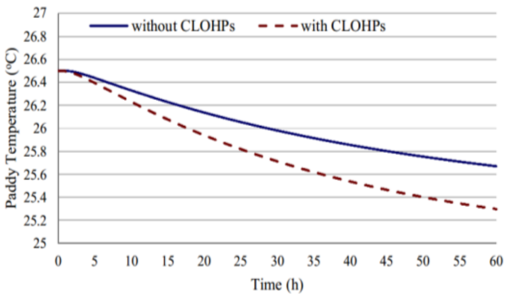
(a) At point S1



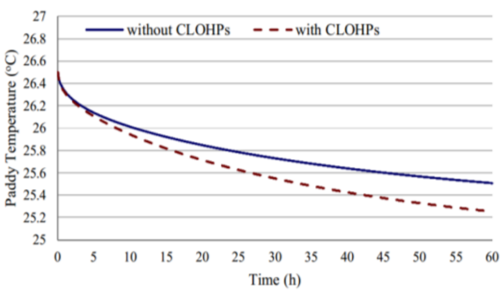
(b) At point S2



(c) At point S3



(d) At point S4



(e) At point S5

Fig. 6: Comparison of paddy temperature with and without CLOHPs at each position.

For paddy bulk with CLOHPs, with the longer the storage time, the temperatures of all points within medium steeply decrease. At 60 h the paddy temperature in the middle region of bin is reduced to about 25.3˚C. The minimum temperature occurs at the bin wall and the top and bottom surfaces of paddy and the value is about 25˚C at 60 h. After that the paddy had temperature equal to the ambient temperature. Therefore the array of CLOHPs within paddy bin can remove the heat from grain during storage and reduce the bed temperature although there are a few temperature differences of paddy and surrounding. It was found that the thermal efficiency of CLOHPs cooling system for 250 kg paddy was about 45.2%.

4. Conclusions

From all results, the conclusions are:

- The developed model can be used to predict the temperature inside 250 kg and 14% wet basis paddy bulk stored in the cylindrical bin with and without CLOHPs as a cooling unit.

- The temperature difference of paddy inside the storage bin with and without CLOHPS was found in the range of 0.99-2.55%.

- The minimum temperature occurs at 60 h with the average value of 25.4˚C. The lowest value occurred at the bin wall and the top and bottom surfaces of paddy are as same as the ambient temperature.

- The array of CLOHPs within paddy bin can remove the heat from grain during storage and reduce the bed temperature although there are a few temperature differences of paddy and air. The thermal efficiency of CLOHPs cooling system for 250 kg paddy was about 45.2%.

- The developed model can be applied to predict the temperature distribution in cylindrical bin with and without CLOHPs for investigate the deterioration from respiration process of the other grains storage.

5. Acknowledgement

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Bibliography

Piyanun Charoensawan received her Ph.D. in Mechanical Engineering from Chiang Mai University (CMU), Thailand, in 2003. She is currently an Associate Professor at the Faculty of Engineering, Naresuan University, Thailand. Her research interests include heat pipe science and technology, boiling heat transfer, two-phase flow, solar energy and energy conservation.

Suppachai Chumnumwat received his M.Eng. in Mechanical Engineering from Naresuan University (NU), Thailand, in 2012. He is currently a lecturer at the Faculty of Engineering, Rajamangala University of Technology Lanna Phitsanulok, Thailand. His research interests include heat transfer, heat pipe, and solar energy technology.