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# SIMULATION MODEL FOR INTERMITTENT FORCED AERATION OF STORED PADDY

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## ABSTRACT

The objective of this paper was to simulate the effect of intermittent forced aeration on cooling rate of stored paddy. Two-dimensional mathematical models were used to predict temperature in a paddy storage bin subjected to intermittent forced aeration.

Keywords: Rice, Simulation, Aeration, Intermittent.

## INTRODUCTION

The annual rice production in Taiwan is about 2,500,000 metric tons. Most of the paddy is stored as bulk or in bags in flat reinforced concrete warehouse operated by local farmer's associations. Every year, more than 500,000 tons of paddy are stored, and the storage periods range from 6 to 18 months.

In Taiwan, the paddy temperature at the upper layer in a warehouse without forced aeration always reaches 36 $^{o}$C to 40 $^{o}$C between December and April. The storage loss ranges from 0.165% to 2.406%, depending on the kind of storage warehouse. The milling yield of the stored paddy is around 77%. Average seasonal ambient air temperature in Taiwan is 15-30 $^{o}$C, and humidity is 75-90%.

Aeration of stored rice was initiated and gained great favor in the early 1920's (Smith, 1931). Calderwood et al. (1984) reported that rough rice was stored successfully up to 54 months with the help of aeration and control of stored-grain insects in a bin with a storage capacity of 9.52 tons.

Air flow rates adopted in cooling stored grain are between 0.052 and 0.15 $m^3$/min per ton of grain (Foster and Tuite, 1982; Mclean, 1980). The average design aeration for paddy in Southeast Asia is between 0.03 and 1.50 $m^3$/min per ton of paddy of moisture content ranging from 13% to 17% ( Teter,1981).

Bakker-Arkema and Bickert (1966) applied the analysis developed by Schumann (1929) to simulate deep-bed cooling of biological materials and reported that significant difference between experimental and theoretical temperature existed if mass transfer was ignored.

Sutherland et al. (1971) pointed out that little work had been devoted to the prediction of temperatures and moisture contents of grain subjected to forced air

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cooling. They incorporated both heat and mass transfer in a model to predict grain temperature and moisture and indicated that in aeration the majority of the grain bed was not cooled to the dry-bulb temperature of the inlet air, but tended to reach a temperature which was dependent on the air and grain moisture contents.

A one-dimensional storage simulation model for shelled corn was developed by Thompson (1972) to predict grain temperature , moisture content and dry matter decomposition. His model incorporated the following factors: heat and mass balance between the air and the inlet aerating air; equivalence between the equilibrium relative humidity of the grain and the relative humidity of air; grain respiration; and heat transfer through the bin.

Thorpe and Elder (1982) simplified Sutherland's (1971) model and applied a numerical method to predict grain temperature subjected to aeration with arbitrarily time varying air inlet conditions. They reported that good agreement was found between experimental data and numerical solutions for center-line grain temperature in a 100-ton silo.

Report on both heat and mass transfer in forced aeration of stored paddy in a packed bed was available for the two dimensional case (Lu et al., 1987). Lu (1992) carried out a field aeration experiments in a warehouse (30L x 12W x 4.5H m ) loaded with 916 tons of paddy in local Chung-hua County Farmer's Association. The average cooling rate of intermittent aeration was found 1.28 times higher than the continuous aeration. Although difference in cooling rates at upper and middle layers between continuous and intermittent aeration were small , the actual aeration time needed to bring the paddy temperature to a stable and lower point was much less in intermittent aeration.

## OBJECTIVE

The objective of this paper was to simulate the effect of intermittent forced aeration on cooling rate of stored paddy.

## MATERIALS AND METHODS

The unknown variables of air temperature, absolute humidity, solid moisture and temperature inside a packed bed during forced aeration are evaluated by solving equations derived from analyzing mass and energy balances on air and solid phases under assumptions that define the aeration system being modeled.

Some assumptions are necessary in order to develop a two dimensional mathematical model for describing cooling processes during forced aeration of paddy. These assumptions are listed as follows.

1) The porosity and bulk density are constant throughout the entire packed bed.
2) The air flow pattern in the packed bed is two-dimensional.
3) The thermal properties of air, water vapor and paddy are constant.
4) There is no heat conduction among particles of the paddy.
5) The bin walls and floors are insulated so there is no heat transfer from or to the outside environment.

6) There are no temperature and moisture gradients in each paddy kernel.
7) There is no radiation heat transfer.
8) There are no changes in volume of air and paddy.
9) Thermal storage and moisture storage are defined as the changing rates of enthalpy and water vapor in the air, and are negligible.
10) The grain respiration heat is negligible in aeration and there is no heat generation by insect or microorganisms.

Equations for energy and mass balances are derived from an arbitrary differential control volume with unit thickness and dimensions in x and y directions. Dry air mass passing through a control volume of a stationary packed bed has components in the x and y directions.

The technique given by Holland and Liapis (1983) for describing general equations for energy and mass balances is adopted in developing the aeration models as following four equations (Lu et al., 1987):

$$\rho_a u \left( \frac{\partial W}{\partial x} \right) + \rho_a v \left( \frac{\partial W}{\partial x} \right) = - \rho_{sB} \frac{\partial M}{\partial t} \tag{1}$$

$$\frac{\partial \theta}{\partial t} = \frac{h_v (T - \theta)}{\rho_{sB} (C_{ps} + M C_{pw})} + \frac{(H_w - h_v)}{(C_{ps} + M C_{pw})} \frac{\partial M}{\partial t} \tag{2}$$

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = - \frac{h_v (T - \theta)}{\rho_a (C_{pa} + W C_{pv})} \tag{3}$$

$$\frac{\partial M}{\partial t} = - R \tag{4}$$

Those equations constitute the cooling model. These four equations will be solved for solid and air temperature by a finite difference method.

After aeration period, the non-aeration period is modeled by following equation by considering conduction heat transfer, respiration heat and neglecting natural convection. The model is shown as following:

$$\sigma \frac{\partial T}{\partial t} = \alpha \nabla^2 T + \frac{q''}{\rho_a c_{pa}} \tag{5}$$

Brooker's air pressure equation (Brooker, 1969):

$$\left[ \left( \frac{\partial P}{\partial x} \right)^2 + \left( \frac{\partial P}{\partial y} \right)^2 \right] \left( \frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} \right) - 2m \left[ \left( \frac{\partial P}{\partial x} \right)^2 \frac{\partial^2 P}{\partial x^2} + 2 \frac{\partial P}{\partial x} \frac{\partial P}{\partial y} \frac{\partial^2 P}{\partial x \partial y} + \left( \frac{\partial P}{\partial y} \right)^2 \frac{\partial^2 P}{\partial y^2} \right] = 0 \tag{6}$$

are used to solve numerically for pressure distribution inside the bed. After knowing the pressure inside the bed, the components of air velocity can be calculated.

Computer programs in FORTRAN are written for these governing equations that constitute the finite difference solutions to the cooling model and non-cooling model. The models are then verified by comparing the simulation results with experimental data.

A rectangular bin of the size of 0.9 m in width, 0.45 m in height and 0.01 m in depth was loaded with 25 kgs of short grain paddy of moisture 12% and put into a environmental controlling chamber. Two 0.05 m wide air inlets were located separately at 0.2 m from the left and right bottom corner of the bin. A blower forced the air of controlled temperature and humidity through a duct and air inlets into the packed bed of paddy in the experimental bin. The paddy temperature was measured and compared with the temperature predicted by the simulation model.

## RESULTS AND DISCUSSIONS

### Simulated temperature patterns during aeration

Stagnant or slow cooling areas can be identified by examining the temperature patterns. Hourly temperature patterns of a bin under forced aeration can be illustrated by drawing contour lines for the outputs of the models developed in this study. Figure 1 illustrates the temperature patterns after two hours of continuous aeration. The initial paddy temperature and moisture content are set at 40 $^{o}$C and 12%. During the aeration period, the inlet air temperature and relative humidity are set constant at 30 $^{o}$C and 80%. The static pressures for each of the two air inlets are set at 300 pascals and the aeration rate is 0.45 $m^3$/min per ton of paddy.

The slow cooling zones are those regions located between two adjacent ducts and regions near the left and right boundary characterized with stagnant air or low air velocity. These predicted slow cooling zones comply with the Perry's (1961) test report that indicated the last area to be cooled was between the ducts in an aeration bin.

### Hourly temperatures during intermittent aeration

Hourly temperatures at the upper, middle, lower, and bottom layers (locations are marked in figure 1) above the air inlet predicted by the cooling model involving both heat and mass transfer is illustrated in figure 2. The intermittent aeration process is set at one hour period, ie, one hour of fan-off non-aeration period after previous one hour fan-on aeration treatment. The initial paddy temperature and moisture content are set at 40 $^{o}$C and 12%. During the aeration and non-aeration period, the inlet air temperature and relative humidity are set at 30 $^{o}$C and 40%. Because of low air humidity, the temperature difference among different layers are significant. There is a slight increment of temperature during the non-aeration period.

Figure 3 and figure 4 compare the continuous aeration with the intermittent aeration at 1,2, and 3 hours interval by predicting paddy temperatures at locations respectively above the air inlet and between the two air inlet of the experimental bin. In this simulation study, the inlet air temperature and relative humidity are set at 30 $^{o}$C and 80%. It takes less aeration time in intermittent aeration than continuous aeration to bring the paddy temperature to the same level as shown in both figures 3 and 4. The cooling rate of paddy in intermittent aeration in warehouse was found faster than that in continuous aeration (Lu, 1992). Because of high air humidity, the temperature difference between successive aeration periods are not significant as observed in low humidity aeration as shown in figure 2.. There is a slight decrease of temperature during the non-aeration period at location between the two air inlets of the experimental bin as shown in figure 4.

Comparison of measured and predicted temperature

The predicted paddy temperature for bottom layer at location above the air inlet during the 5 hours of aeration treatment containing one-hour aeration and one-hour non-aeration is shown in figure 5.

The hourly temperatures at all of the four levels predicted by the model involving both heat and mass transfer agreed with the measured results. During the aeration and non-aeration period, the inlet air temperature and relative humidity are set at 30 $^{o}$C and 40%. Hourly temperature at the bottom layer predicted by the model matched closely with the measured temperature with a deviation less than 2 $^{o}$C.

## CONCLUSIONS

Two-dimensional mathematical models were used to predict temperature in a paddy storage bin subjected to intermittent forced aeration. The finite difference approach was used to solve a set of partial differential equations that make up the model. The bin used in simulating paddy temperature and gathering experimental data was a small experimental rectangular bin with two evenly spaced air inlets. The air entered at the bottom and exited at the top of the bin.

The cooling model which involves both heat, mass transfer and respiration heat, predicts paddy temperatures which compare well with the measured temperatures of the bin subjected to intermittent forced aeration. The temperature pattern during aeration indicates that the slow cooling zones are those regions located between two adjacent ducts and regions near the left and right boundary characterized with stagnant air or low air velocity.

## NOMENCLATURE

$C_{ps}$ - specific heat of dry air, kJ/kg-$^{o}$C

$C_{ps}$ - specific heat of solid, kJ/kg-$^{o}$C

$C_{pv}$ - specific heat of water vapor, kJ/kg-$^{o}$C

$C_{pw}$ - specific heat of liquid water, kJ/kg-$^{o}$C

$h_v$ - volumetric convection heat transfer coefficient, KJ/hr-m$^3$-$^{o}$C

$h_w$ - enthalpy of liquid water, kJ/kg

$M$ - dry basis moisture content of solid, kg water/kg dry solid
$m$ - constant
$P$ - pressure
$q''$ - respiration heat, W/m$^3$
$R$ - rate of water vapor transferred from the solids to air, kg water/kg dry solid - hr
$T$ - air temperature, $^oC$
$t$ - time, hr
$U$ - air superficial velocity in the x-direction, m$^3$/m$^2$- hr
$V$ - air superficial velocity in the y-direction, m$^3$/m$^2$- hr
$W$ - absolute air humidity, kg water vapor/kg dry air
$\alpha$ - thermal diffusivity
$\sigma$ - thermal inertia
$\rho_a$ - dry air density, kg/m3
$\rho_s$ - dry solid density, kg dry solid/m$^3$
$\rho_{SB}$ - bulk density of packed bed of paddy, kg/m$^3$
$\theta$ - solid temperature, $^oC$

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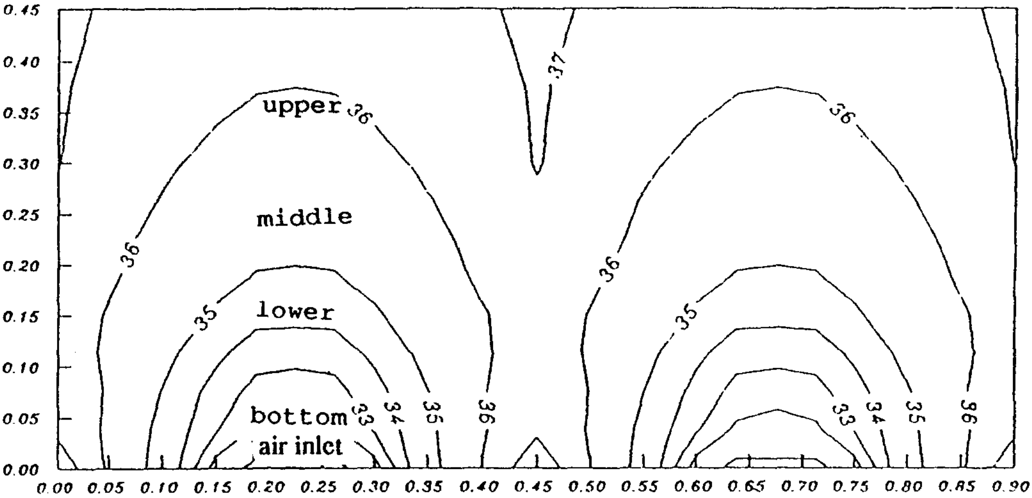

Figure 1. Temperature pattern after two hours of aeration predicted by the heat and mass transfer model.

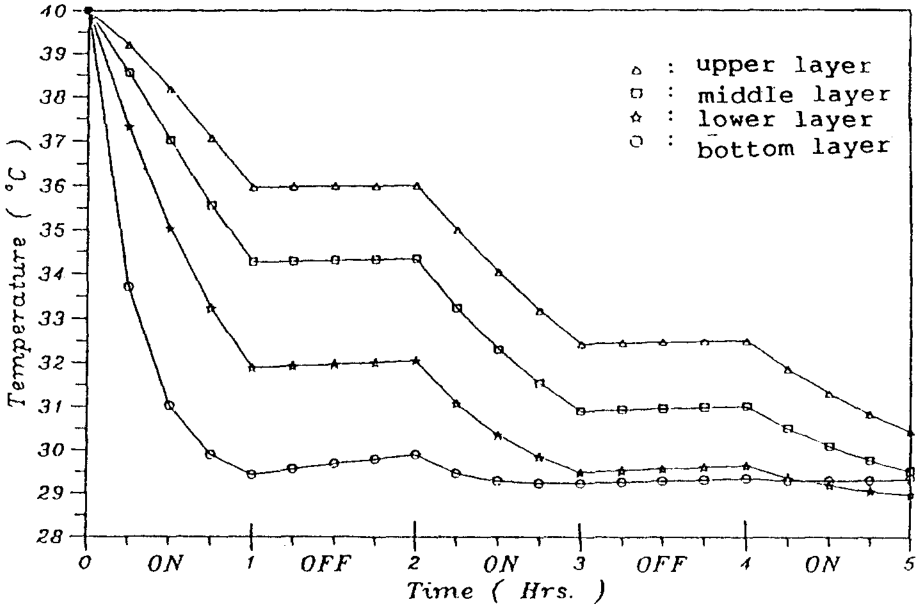

Figure 2. Temperature variation above air inlet during intermittent aeration (air temperature 30 °C, humidity 40%).

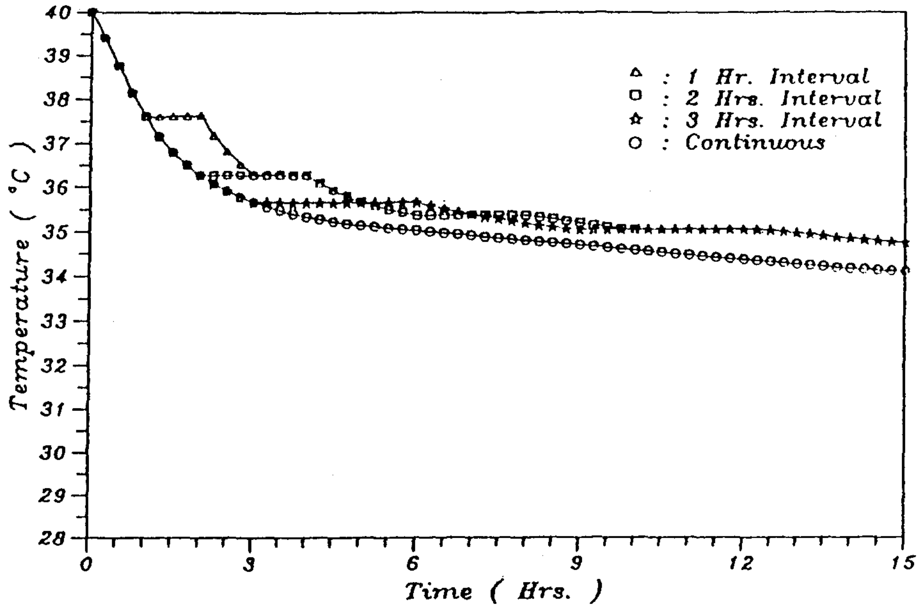

Figure 3. Comparison of temperature variation above air inlet for continuous and intermittent aeration (air temperature 30 °C, humidity 80%).

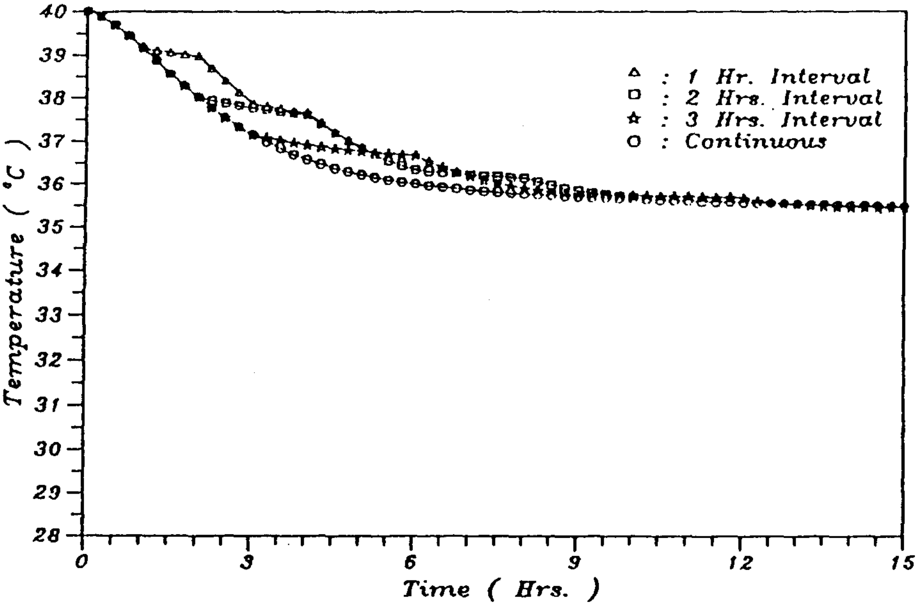

Figure 4. Comparison of temperature variation between air inlets for continuous and intermittent aeration (air temperature 30 °C, humidity 80%).

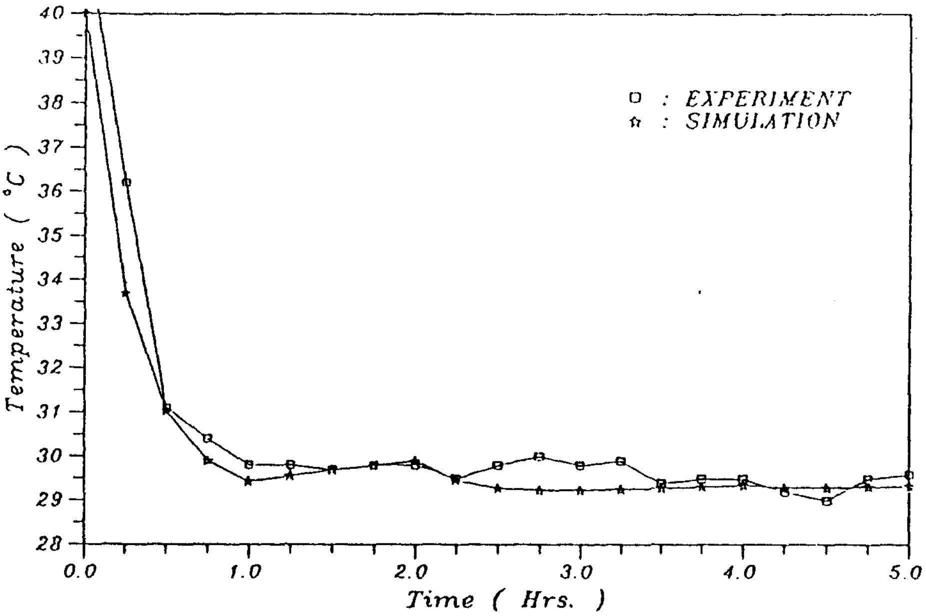

Figure 5. Comparison of predicted and measured temperatures at the bottom layer above air inlets during intermittent aeration (air temperature 30 $^{o}$C, humidity 40%).