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Full Paper

Aeration simulation of stored paddy by integrating desiccant tray unit into grain ventilation system

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Abstract: This research work suggested a method of reducing grain bulk temperature and avoiding moisture transfer in a storage bin during aeration of stored grain by using a desiccant tray unit. Air humidity was adsorbed by the desiccant unit and then reduced subsequently before entering the grain silo. The simulation program was developed based on the AERO program and the model of desiccant tray which assist users in the prediction of grain temperature and moisture content. According to the ambient air condition, the number of trays would be suitably calculated for storage conditions in humid tropical regions. The simulated result showed that 2 desiccant trays (3.5 kg of silica gel per tray) were appropriate for controlling air temperature and humidity of 18 tons of grain stored in a cylindrical silo at lower than 28 ^{o}C and 80% RH.

Keywords: simulation, aeration, silica gel, paddy, silo

Introduction

Temperature and moisture content of grain are considered as two of the most important factors affecting grain quality during storage or aeration. Ideally, moisture should not be gained or lost. It is known that in tropical countries, high ambient humidity causes grain deterioration in storage due to

Mj. Int. J. Sci. Tech. **2008**, *1*(Special Issue), 7-16

grain respiration and mould growth, which is a major problem on grain drying, particularly in the wet season. However, the temperature difference between grain bulk and ambient air causes the movement of grain moisture from high temperature to low temperature zone by natural convection. This regular moisture movement in stored grain increases the distribution of insects, mites and fungi and thus leads to the deterioration of grain quality [1]. About 5% of all grains are destroyed during storage by insects, mites and fungi, and in some tropical environments, spoilage exceeds 25% [2]. To maintain the quality of product for long term storage, insect and mould population growth should be controlled.

The cooling of grain by aeration system usually reduces the rate of insect and fungi population growth and preserves grain quality. In subtropical and temperate climate, the aeration system can be effected by the flowing of cool ambient air through the grain bulk [3]. Moreover, in tropical countries particularly in Asian countries such as Thailand, Vietnam, Indonesia and Malaysia, high ambient temperature and humidity reduce the performance of grain aeration system and the grain usually deteriorates due to its respiration and mold growth. To control air humidity, solid desiccants such as silica gel, zeolites, activated alumina and hygroscopic salts are generally used.

Many researchers studied the adsorption and regeneration performance of various types of solid desiccant [4-6]. For the application of solid desiccant in various processes, Popescu and Ghosh [7] and Rengarajan and Nimmo [8] applied rotary desiccant wheel for controlling air humidity in an air-conditioning system. Fu et al. [9] reported the energy consumption of a tea dryer having a rotary desiccant wheel. The energy could be saved at approximately 15% and the tea aroma and colour was better than those subjected to the conventional process. Kiatsiriroat and Tachajapong [10] designed a staggered tube bank of desiccant unit to reduce energy consumption of a heat pump. Nuntaphan, et al. [11] developed a tray-type desiccant unit to reduce energy consumption in hot air generation for longan drying.

However, there is little information about the application of solid desiccant for paddy storage from the literature. The device to reduce the enthalpy of air used for grain aeration before it is forced through the grain in dry ambient air under near isothermal condition was developed by Ismail et al. [6] Nevertheless, its performance was not reported for operating in the humid tropics [3]. Therefore, the objective of this study is to integrate the solid desiccant (silica gel) unit with the grain ventilation system with the aim to reduce grain bulk temperature and avoid moisture transfer in a storage bin during aeration in the humid tropical climate, thus maintaining the quality of the product for long-term storage.

Materials and Methods

Concept of integrating desiccant unit with paddy silo

Figure 1 shows the concept of applying the solid desiccant unit with the paddy silo. The air blower generates the air stream that flows along the wind tunnel and passes through the desiccant unit resulting in the reduction of leaving air humidity. The low-humidity air then flows into the silo leading to the reduction of grain temperature while controlling consequently the moisture content of grain.

Notice that the solid desiccant used in this work was silica gel and was used to fill up a multi-tray unit with each tray containing 3.5 kg of dry silica gel. Figure 2 shows the schematic diagram of a desiccant tray.

Mj. Int. J. Sci. Tech. **2008**, *1*(Special Issue), 7-16

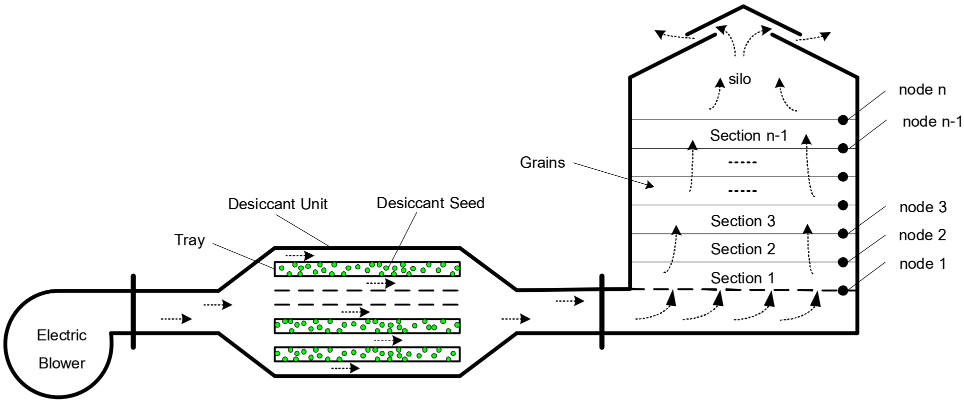

Figure 1. Concept of integrating a desiccant unit with a paddy silo

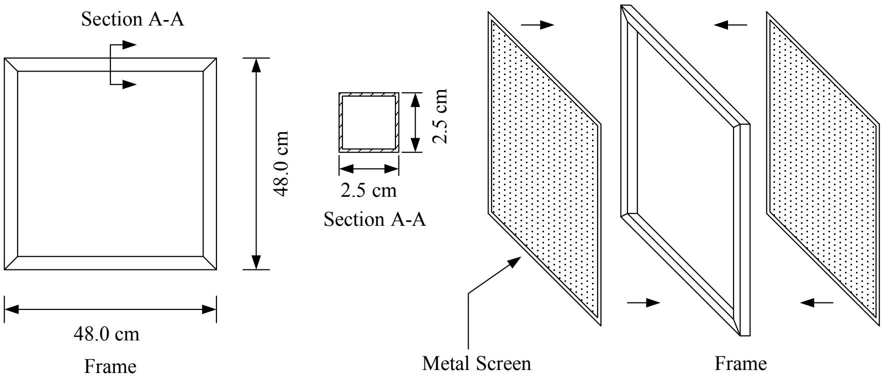

Figure 2. Schematic sketch of a desiccant tray

The Simulation program

Based on the concept of integrating the desiccant unit with the paddy silo as depicted in Figure1, the calculation method to predict the grain temperature and moisture content was developed as shown in Figure 3.

The input of the program was the conditioning of the ambient air stream, namely the air temperature, the air humidity and the mass flow rate. The next step was to predict the air condition leaving the desiccant unit by a desiccant model adapted from the adsorption and regeneration of the tray-type silica gel unit model developed by Hung et al.[12] In case of the adsorption process, the mass transfer model was calculated as:

$$MR_a = \exp\left(-at^{-0.20943}\right), \tag{1}$$

$$a = 0.017068\, \dot{m}_a^{-0.23538}\, W_{ai}^{-0.51849}\, T_{ai}^{0.93883}, \tag{2}$$

$$MR_a = \frac{\text{accumulated mass of moisture adsorbed in silica gel}}{\text{mass of dry silica gel}}. \tag{3}$$

Mj. Int. J. Sci. Tech. **2008**, *1*(Special Issue), 7-16

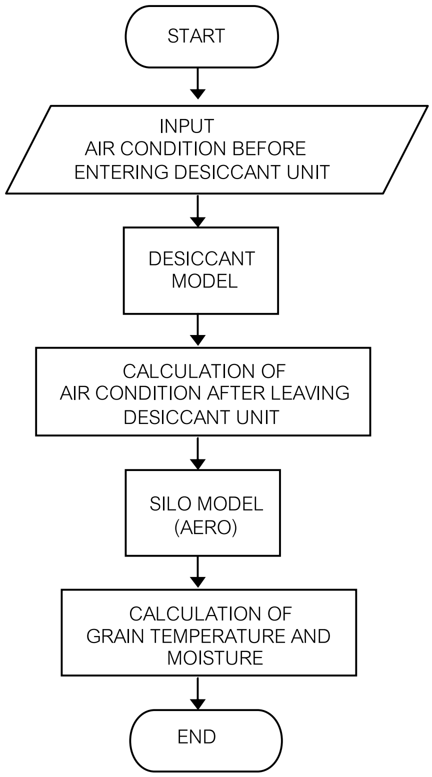

Figure 3. Calculation flowchart of the simulation program

where, t = time (min), m_a = mass flow rate of air per one tray ($kg.s^{-1}$), W_{ai} and T_{ai} = inlet humidity ratio ($kg_{water}.kg_{dryair}^{-1}$) and inlet temperature of air (^oC), respectively. By using this mass balanced model, the outlet humidity ratio could be calculated.

In the case of the heat transfer model, Hung, et al. proposed the empirical model as:

$$Q_d = -21.25766 + 2.10383X - 0.00971X^2 + 0.0000148463X^3, \quad (4)$$

$$X = \exp(at^{-0.24852}), \quad (5)$$

$$a = 354.8 \times \dot{m}_a^{0.11071} W_{ai}^{0.097897} T_{ai}^{0.78378}. \quad (6)$$

where Q_d = heat transfer during adsorption process (W). Notice that the outlet temperature of air was increased due to the heat of sorption. From Eqs. (4)-(6), the outlet temperature of air could be calculated by using the energy balance model.

The outlet conditions of air leaving the desiccant unit were the input parameters of the silo model. In this research, the simulation program of Lopes, et al. [13], namely 'AERO', acted as the silo model and was used for predicting the complex changes in the stored grain system under various conditions and for evaluating the operation of the aeration system. This model was related to the air psychrometric relationship with the mass and energy balances. The differential equations that described the heat and mass transfer in an aerated bulk of grain were expressed as:

Mj. Int. J. Sci. Tech. **2008**, *1*(Special Issue), 7-16

$$\frac{\partial T_g}{\partial t}\left\{\rho_b\left[c_g + c_w U\right] + \varepsilon\rho_a\left[c_a + R\left(c_w + \frac{\partial h_v}{\partial T_a}\right)\right]\right\}$$
$$= \rho_b h_s \frac{\partial U}{\partial t} - u_a\rho_a\left[c_a + R\left(c_w + \frac{\partial h_v}{\partial T_a}\right)\right]\frac{\partial T_g}{\partial y} + \rho_b\frac{dm_s}{dt}\left(Q_r - 0.6h_v\right) \tag{7}$$

$$\frac{\partial U}{\partial t}\rho_b = -\rho_a u_a\frac{\partial R}{\partial y} + \frac{dm_s}{dt}\left(0.6 + U\right), \tag{8}$$

where c_a = specific heat of air (J.kg^{-1} ^{o}C^{-1}), c_g = specific heat of dry grain (J.kg^{-1} ^{o}C^{-1}), c_w = specific heat of water (J.kg^{-1} ^{o}C^{-1}), h_v = latent heat of vaporization of water (J.kg^{-1}), h_s = differential heat of sorption (J.kg^{-1}), U = grain moisture content (%) on a dry basis, m_s = grain dry matter loss (%), Q_r = heat of oxidation of grain (Js^{-1}m^{-3}), T_a = air temperature in equilibrium with the grain (^{o}C), t = time (s), u_a = aeration air velocity (m.s^{-1}), R = humidity ratio of air (kg$_{water}$.kg$_{dryair}$$^{-1}$), y = vertical coordinate (m), ε = grain porosity (decimal), ρ_a = density of intergranular air (kg.m^{-3}), ρ_b = bulk density of the grain (kg.m^{-3}), and T_g = grain temperature (^{o}C).

The partial differential equations that described the heat and mass transfer in bulk paddy were solved by using the numerical analysis as:

$$T_{ginew} = T_{gi} + \frac{\Delta t}{\rho_b(c_g + c_w) + \varepsilon\rho_a[c_a + R_i(c_w + dh_v)]} \times \left(\begin{array}{l} h_s\left(-\rho_a u_a\left(\frac{R_i - R_{i-1}}{\Delta y}\right) + dm_s(0.6 + U_i\right) \\ + \rho_b dm(Q_r - 0.6h_v) - u_a\rho_a(c_a + R_i(c_w + dh_v)) \\ \times\left(\frac{T_{gi} - T_{gi-1}}{\Delta y}\right) \end{array}\right), \tag{9}$$

$$U_{inew} = U_i + \frac{\Delta t}{\rho_b}\left(-\rho_a u_a\left(\frac{R_i - R_{i-1}}{\Delta y}\right) + \frac{dm_s}{dt}(0.6 + U_i)\right). \tag{10}$$

where i = the node under consideration, dh_v / dT_a = differential of latent heat with relation to temperature, dm_s / dt = rate of dry matter loss, Δt = time interval (s), and Δy = section length (m). The bulk of paddy was divided into sections in the vertical direction (direction of air flow), as shown in Figure 1. The section limits were called nodes and at the first node it was assumed that the equilibrium condition for mass and temperature existed between the aeration air and the surface of the paddy bulk. This configuration tended to over-estimate the moisture content value of the first grain section. However, this problem was minimised by estimates of temperature and moisture content of the first section using Lagrangian interpolation technique for considering the first four nodes. During the simulation process, the paddy moisture content and temperature were calculated after each time interval for each section in an iterative way.

The software AERO was used to evaluate the feasibility of applying the desiccant tray for aeration of the stored grain in the humid tropics. The predicted results for the average temperature and

Mj. Int. J. Sci. Tech. **2008**, *1*(Special Issue), 7-16

moisture content of the stored grain under selected aeration conditions were obtained by running the simulation program. The input parameters for running the computer program are presented in Table 1.

Table 1. Input data for running aeration simulation

Item	Data
Grain bulk	
stored product	paddy
density of grain kernels, kg.m^{-3}	576.00
safe moisture content, % wb	13.00
initial moisture content, % wb	13.00
grain bulk with initial uniform temperatures, ^{o}C	35.00
mass of grain, ton	18.00
Silo	
diameter, m	3.90
length of grain bed, m	2.50
number of section	20
Variable air ambient conditions	
inlet temperature, ^{o}C	26-30
inlet relative humidity, %	70-90
Aeration airflow, m^3.min^{-1}.ton^{-1}	0.3
Desiccant unit	
mass of silica gel in each tray, g	3,500
number of tray	2-10

Results and Discussion

The results obtained from the simulation program by using the input conditions listed in Table 1 are shown in Figires 4-6. Notice that the replacement time of desiccant tray was every 3 hours. The temperature and relative humidity of air after leaving the desiccant unit were hourly-average values and were taken as input parameters of the silo model. Hence, the grain temperature could be calculated from the average grain bulk temperature. The grain moisture was taken from the value of the first grain section near the plenum chamber of the silo.

Figure 4 shows the simulation results in the cases of 0, 2, 4 and 10 desiccant trays. The inlet temperature of air and its relative humidity were kept constant at 28^{o}C and 80% respectively. The air flow rate was 0.1 kg.s^{-1} (or 0.3 m^3.min^{-1}.ton^{-1}). Generally, it could be seen that the temperature of the grain decreased with the number of used trays from 35^{o}C to 29^{o}C in a 20-hour duration. In addition, it was also found that the effect of the number of desiccant trays was only slight at the time interval of 0-

Mj. Int. J. Sci. Tech. **2008**, *1*(Special Issue), 7-16

20 hours on the average temperature of grain. However, when the aeration time was more than 20 hours, the grain temperature with 10 trays was approximately 1°C lower than without desiccant.

Regarding the effect of desiccant tray on the moisture content of grain, there was a slight change of moisture content of grain found by using 2 trays. In the case of 4 and 10 trays at 30 hours, the grain was excessively dried at approximately 11.5% and 8.5% moisture content respectively. Besides, it was obvious that the moisture content was increased with aeration time if the desiccant was not used owing to the high inlet air humidity. The appropriate moisture content of grain in the silo should be about 13% wet basis (Table 1). It is therefore suggested that 2 trays are sufficient to reduce the grain bulk temperature and to avoid moisture transfer in a storage bin during stored grain aeration.

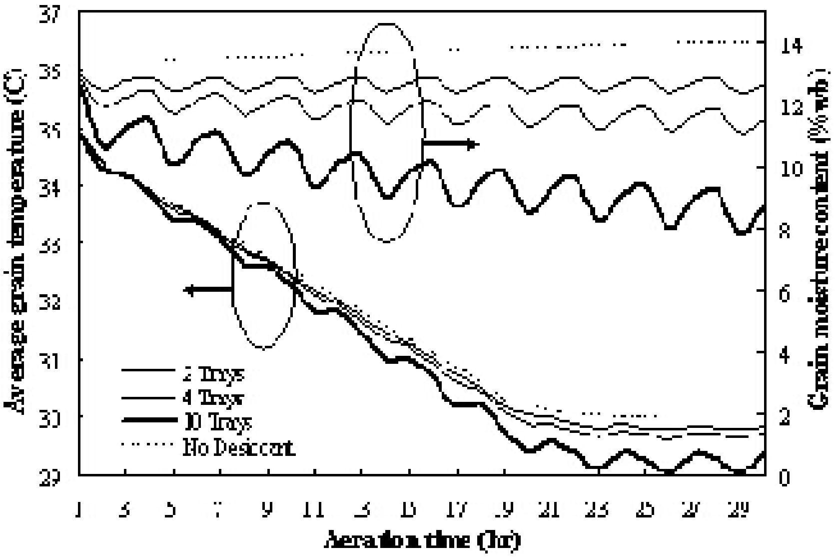

Figure 4. Effect of desiccant tray on temperature and moisture content of grain

Figure 5 illustrates the effect of inlet air temperature on the average temperature and moisture content of grain. In this case, 2 desiccant trays were used. The relative humidity and temperature of inlet air were 80% and 26-30°C. It was found that the grain temperature and moisture content were directly and inversely proportional respectively to the inlet air temperature. Compared to Figure 6 in which the inlet temperature of air was 28°C and the relative humidity was varied between 70-90%, it could be seen that higher humidity of air resulted in higher grain moisture content and grain temperature. The temperature difference between grain and air was about 4°C at 90% RH, which was lower than that of 6°C at 70%RH. The wet grain was found at 90% RH. The results from Figures 5-6 can be explained by the mass transfer phenomenon as follows.

The mass transfer of moisture from the grain to the air could be expressed as [14]:

$$R_g = \frac{h_m A_g}{R}\left(\frac{P_{mg}}{T_{mg}} - \frac{P_{ma}}{T_{ma}}\right) \tag{11}$$

where R_g = mass transfer rate of moisture from the grain to the air (kg.s^{-1}), h_m = mass transfer coefficient (m.s^{-1}), A_s = surface area of grain (m^2), R = ideal gas constant (J.kg^{-1} K^{-1}), P_{ma}, P_{mg} and T_{ma}, T_{mg} = pressure (Pa) and temperature (°C) of water vapour in the air and at the grain respectively.

Mj. Int. J. Sci. Tech. **2008**, *1*(Special Issue), 7-16

In the condition of high air humidity, the increase of the pressure of water vapour in the air resulted in the low mass transfer rate between grain and air. As a result, the grain gained high moisture content. In addition, the mass transfer rate in Eq.11 was correspondingly increased with the increase in air temperature. In this case, therefore, the moisture content in the grain should be reduced.

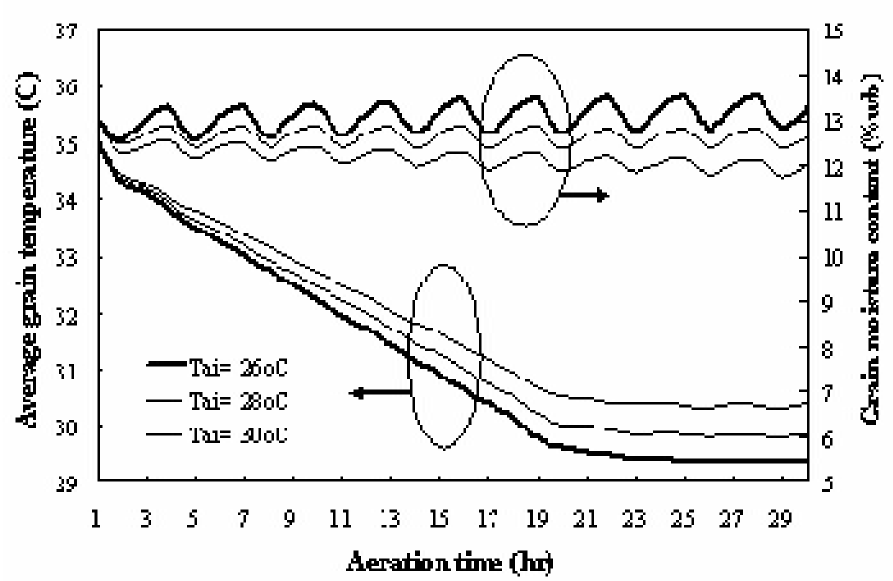

Figure 5. Effect of inlet air temperature on temperature and moisture content of grain

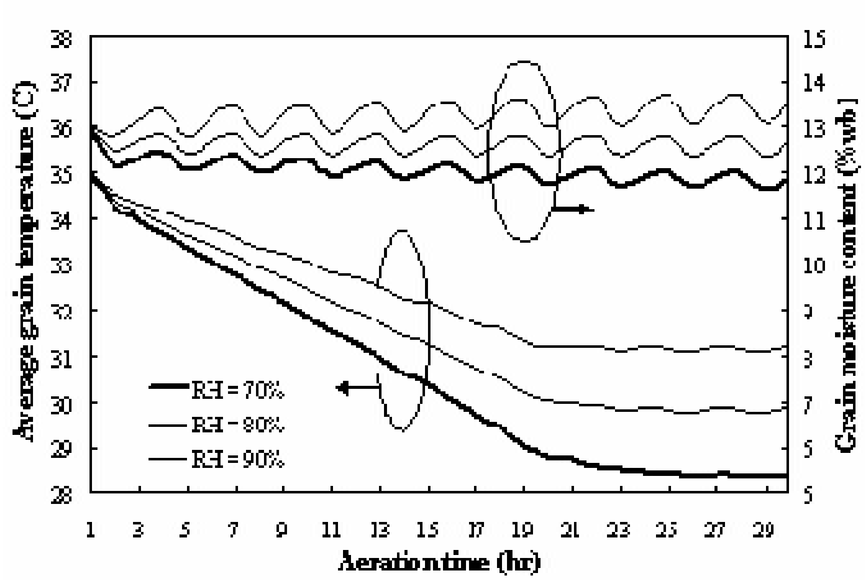

Figure 6. Effect of inlet air humidity on average temperature and moisture content of grain

It was highlighted that with T_{ai} = 30°C from Figure 5 and %RH = 70% from Figure 6, the grain moisture content was being excessively low. On the other hand, with T_{ai} = 26°C from Figure 5 and RH = 90% from Figure 6, the grain was dampened.

Mj. Int. J. Sci. Tech. **2008**, *1*(Special Issue), 7-16

Moreover, the simulated grain moisture content curves shown in Figures 4-6 were much transient. This might lead the reader to think that there was some kind of instability in the desiccant tray model of the simulation program, as described in Figure3. It is noticed from Eqs (1) to (6) that Eqs (1), (2) and (3) gave the result of moisture adsorbed. Eqs (4), (5) and (6) were used to calculate the temperature of air leaving the desiccant tray, which was the inlet air for aeration. From that result, these values were then taken as input data of the model developed by Lopes et al., namely "AERO", by using the energy and mass balance models. In fact, the simulated relative humidity was varied as the simulated temperature at each time interval, then the predicted moisture content was simulated by the Chung-Pfost EMC equation [1] depending upon whether these parameters changed quickly. The simulated curves of the grain moisture content were also shown in Figures 4-6. It is noted that the replacement time of the desiccant tray was every three hours. Moreover, in practice, the value of grain moisture content did not change as fast as the simulated result [15]. Therefore, the predicted moisture content curves did not generate the instability in the simulation program.

Conclusions

The simulation results above proved the concept of using desiccant for stored grain aeration in the humid countries. It can be concluded that the application of a desiccant unit for reducing the air humidity before entering the silo can control the grain temperature and moisture content during aeration. In case of the air temperature and humidity of about 28^{o}C and 80% RH respectively, using 2 desiccant trays was sufficient. Therefore, according to the ambient air condition, the number of trays could be suitably calculated for safe storage conditions in humid tropical regions.

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Mj. Int. J. Sci. Tech. **2008**, *1*(Special Issue), 7-16

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