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Estimation of the Latent Heat of Adsorption and Rewetting During Deep Bed Grain Cooling

K. A. Ibupoto and [2]J. L. Woods
Department of Farm Structure, Faculty of Agric. Engin. Sindh Agriculture University, Tandojam, Pakistan, [2]Department of Agricultural and Environmental Sciences, University of Newcastle upon Tyne, UK

Abstract: The latent heat of adsorption (LHA) for barley has been estimated for the first time. The experiments were performed on a laboratory scale. The latent heat of adsorption estimated from the experiment is found to be 2485.5, 2393.1 and 2286.5 kJ/kg at 10, 14.8 and 19.2°C. The laboratory results showed a similar level of rewetting to the field data (lower than Deep Bed Simulation). The adsorption isotherms for barley should be measured as they are not currently available in the literature.

Key words: Barley, latent heat, adsorption, simulation, experiment

Introduction

Heat of adsorption is defined as the quantity of heat released when water vapour is adsorbed through the surface of the adsorbent. This is a measure of the heat or energy that is required to break the inter-molecular forces (Babbit, 1942). The heat of adsorption is thus an indication of the binding energy between the molecules of the water vapour and absorbent surface (Chung and Pfost, 1967). During the deep bed cooling process, there is a moisture adsorption on the grain, around the entry region as the high humidity cooling air is delivered. Due to the moisture adsorption, grain experiences a slight increase in temperature. The change in moisture content and the associated heat release during rewetting of the grain has a significant effect on the cooling process (Woods and McCallum, 1997).

As this study includes the laboratory experiment and its simulation. Hence, these experiments were designed to examine the difference in rewetting and heat of adsorption observed in laboratory experiments and simulation study. The detailed results of the laboratory experiments and their theoretical simulation for temperature, moisture content and the latent heat of adsorption are presented some where else (Ibupoto and Woods, 1999).

For the estimation of the latent heat of adsorption (LHA), the data has been processed with the assumptions outlined, theoretical approach and estimation procedure. The heat transfer coefficient and thermal capacity of the flask used for the estimation, were determined experimentally and are explained somewhere else.

It would be worthwhile to mention that first time latent heat of adsorption for barley has been estimated. Hence, the limited literature is found on this particular aspect.

Materials and Methods

Experimental procedure: The experiment was performed in the Heat and Moisture Transfer Laboratory, University of Newcastle upon Tyne, UK, to check the rewetting and heating processes of adsorption. A fresh, precleaned Pipkin variety of barley was selected for experiment, having a grain mass of 25 kg and flow rate of 300 liters/h. A Refrigeration flask was used as a grain bin and it was placed in the environmental chamber. Cold air at mean Berwick conditions i.e., 8°C, 84% Rh (Woods and McCallum, 1997) was produced in the well established Air Cooling Rig (Woods and Favier, 1993). Data logger was used to measure the data for temperature, moisture content and weight gained.

Before starting any real experimental run, the whole of the system was operated on a dummy bed to stabilize the air flow and air conditions in and around the empty flask. Air flow rate and inlet conditions were adjusted to the required values to be used in the experiments at Berwick (Woods and McCallum, 1997).

The flask was filled with previously weighed grains, sealed in plastic bags each of 5 kg. The flask was filled manually by taking the samples one by one from the incubator. From previous experience of trial runs, it was observed that grain temperature rises by 2°C during the transfer process hence the incubator was set at two degrees lower than the required grain temperature.

In order to fill the grain into the flask, it was necessary to open the environmental chamber partially and flask cap fully. While doing this, the inside chamber temperature rose by 3°C, as the filling process took about 20 minutes to finish. As soon as the flask was filled, its cap was closed air tight and the chamber door was replaced. The temperature of the chamber took 4-5 hs to settle down.

The balance was set to zero with some counter weights soon after the filling process. The air flow through the grain was switched on and adjusted quickly. The data logger was operated to register the different temperatures at intervals of 1 hr.

Complete setup of experimental apparatus is shown in Ibupoto and Woods (1999).

Two of the experimental runs for heat of adsorption lasted about 336 h (2 weeks), being terminated when the balance showed zero moisture gain. The third one was interrupted after 216 h due to the occurrence of some error in the temperature control of the water tank. At the end of the experiments, sampling was performed with a vacuum sampler (220/240 V, 100 W & 50-60Hz) with minimum disturbance of the grain bed. Three samples of about 1 kg were taken from three levels; top, middle and bottom of the bed with the extension rod marked at required depths.

The dry bulb temperature of the cooling air and the grain bed were measured by using copper/ constanton thermocouples with an overall system accuracy within ± 0.7°C. Three thermocouples were used to monitor the air entry temperature; one at the flask entry and two of them at the bottom of the bed, inserted in the flexible air tubes. Another thermocouple was inserted in the outlet flexible air suction pipe to record the exit air temperature. For recording the bed temperature, eight thermocouples were positioned on the umbrella probe at a distance of 0.05 m, from each other. The mean temperature of the bed was taken as the average value of all the eight points. Three thermocouples were placed on the flask surface at three different positions; top, middle and bottom and the mean of them was taken as flask surface temperature. Also, ambient temperature was recorded by a thermocouple outside the environmental chamber.

The moisture content of barley was determined by using American Society of Agricultural Engineers Standard (ASAE S352.2). For each sample, five duplicate 20 g sub-samples of barley were dried at 130°C for 20 hrs in an oven and weighed to 0.0001 g. The average value was calculated on dry basis. he following points were considered for the determination of the latent heat of adsorption:

The temperature change, ΔTv is considered as the virtual additional temperature rise, the grain would have achieved if the flow and surface losses were zero.

For the determination of the enthalpy of the exit air, h_O, the isotherm equation for barley is used to get the Rh of the exit air, which is assumed to be in moisture equilibrium with the grain at exit (MC at exit = initial MC). This Rh is used with the measured exit temperature to get h_O.

For the determination of the enthalpy of inlet air, h_i, the dewpoint temperature is taken as the air temperature at the top of the tower to get humidity and is used with entry temperature (measured) to get h_i.

Tb is the mean grain bed temperature and T_f is the mean outside flask surface temperature.

The theoretical base for estimation of the latent heat of adsorption depends on the following equations. For the calculation of humidity, the following Eq. (1) is used (ASHRAE, 1989).

$$H = \frac{0.622 * P_v}{P_a - P_v} \quad \ldots\ldots\ldots\ldots\ldots\ldots 1$$

where H = humidity of the air, kJ/kg
P_a = atmospheric pressure, Pa
P_v = partial vapour pressure, Pa

In order to set required Rh conditions at the flask entry, the required dewpoint was determined from the psychometric tables. The air temperature leaving the saturation column was then controlled at this dewpoint temperature. The vapour pressure, P_v was then calculated from the specified Rh and the saturation vapour pressure at the air inlet temperature to the flask, using (ASHRAE, 1989) equation.

Enthalpy of the inlet and exit air is calculated by Eq (2), (ASHRAE, 1989)

$$h = T + H(2501 + 1.805T) \ldots\ldots\ldots 2$$

where h = enthalpy of the air, kJ/kg dry air
t = temperature of the air, °C

ΔT_v is the virtual additional temperature rise that would have occurred without flow and surface heat losses and is calculated from the following energy balance equation over a time increment Δt.

$$\Delta Tv = \frac{m_a (h_o - h_i) \Delta t + U A (T_b - T_f) \Delta t}{m_g C_{wg} + m_f C_f}$$

where m_a = mass flow of air, kg/s
h_o = enthalpy of the exit air, kJ/kg dry air
h_i = enthalpy of the entry air, kJ/kg dry air
U = heat transfer coefficient of the flask, kW/m^{2}K
A = area of the flask, m^2
m_g = wet grain weight at time, t, kg
C_{wg} = wet grain specific heat at time, t, kJ/kg K
$m_f C_f$ = thermal capacity of flask, kJ/ K

Finally, the latent heat of adsorption is calculated at each time step, Δt from the following equation based on energy balance (Woods, 1998) for the grain and flask:

$$Lads = \frac{(m_g C_{wg} T)_{j+1} - (m_g C_{wg} T)_j + m_f C_f ((T)_{j+1} - (T)_j) + (m_g C_{wg} + m_f C_f) \Delta T_v}{\Delta M} \quad \ldots 4$$

where j = iterative index so that $t = j \Delta t$
ΔM = change in mass of moisture, kg

In case of the theoretical latent heat of adsorption, the flask is ignored and grain is considered without losses, which is appropriate for the theoretical adiabatic grain bed.

Estimation procedure: A program was written in *Quick Basic* to calculate the latent heat of adsorption at each time step, in the light of the above mentioned points. To calculate the required parameters to be used for the estimation of the latent heat, the experimental data files were called as input files to the program and the calculations were made for a time step, Δt of 24 hrs for each input parameter and final latent heat value. In order to calculate the C_{wg} (specific heat of the wet grain), themoisture content at each time step was calculated from the weight gained in the experimental results. The specific heat of the wet grain, C_{wg} was then calculated from Disney (1954) equation. To test the above procedure for calculating the LHA, the above program was run on the simulation results for the flask conditions. For the simulated results, surface losses and the effect of flask thermal inertia were removed from Eqns (2) to (4).

Results and Discussion

Table 1 shows the temperature and humidity of the air entering the flask for each run. The process observed in all the runs was also simulated theoretically by using the developed model published somewhere else. In order to estimate the latent heat of adsorption, each experimental run and simulation was made at constant air temperature and humidity. During the experimental run, the temperature was recorded at hourly intervals by a data-logger and the balance reading was taken at an interval of 24 h, manually for weight gained. Moisture contents were determined after the termination of the experiment.

Table 1: Conditions of the entry air into the flask

Temperature into flask	Dewpoint into flask	Relative humidity into flask
10.0°C	7.5°C	85%
14.8°C	11.7°C	85%
19.2°C	17.2°C	85%

Temperature: The result show that the simulation and experimental temperature rise after the adsorption process at 10, 14.8 and 19.2°C. The curve for experimental temperature of the bed remained transient for the first week as it rose initially at a high rate for 48 h (2d) and then became a bit

Table 2: Comparison of the simulated and experimental moisture content at various temperatures for an initial moisture content of 0.1364 dec db.

Depth m.	MC at 10°C		MC at 14.8°C		MC at 19.2°C	
	Th	Exp	Th	Exp	Th	Exp
0.40	0.1385	0.1361	0.1385	0.1331	0.1394	0.1399
0.225	0.1385	0.1322	0.1385	0.1526	0.1396	0.1473
0.05	0.1938	0.1634	0.1707	0.1573	0.2028	0.1516
0.025	0.2366	0.1734	0.2243	0.1691	0.2320	0.1823
Mean of the bed	0.1768	0.1513	0.1680	0.1530	0.1784	0.1552

Table 3: Comparison of the highest values of the estimated LHA with Lw (pure water) from Mayhew and Rogers (1970)

Initial temp.	Mayhew and Rogers	Simulation	Experiment
10.0°C	2477.2	2455.2	2485.5
14.8°C	2465.5	2424.2	2393.1
19.2°C	2456.0	2369.2	2286.5

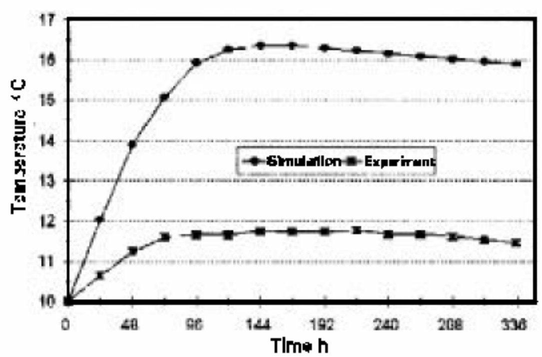

Fig. 1: Comparison of mean grain bed temperatures with time during the adsorption process at 10°C.

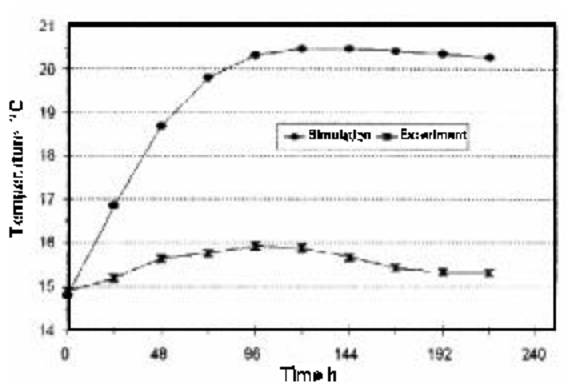

Fig. 2: Comparison of mean grain bed temperatures with time during the adsorption process at 14.8°C.

slower by 144 h (6d). The temperature became stable for about two days within 144-240 h followed by a slight decline. The temperature curves indicated about 2°C rise within two weeks (336 h) at 10°C, 1°C rise at 14.8°C and about 1.5°C at 19.2°C. There seems not much difference at the three temperatures, however, the curve at 10°C shows more smoothness. The theoretically simulated temperature curves

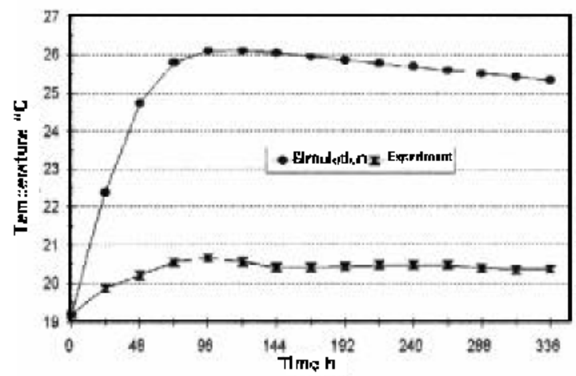

Fig. 3: Comparison of mean grain bed temperatures with time during the adsorption process at 19.2°C.

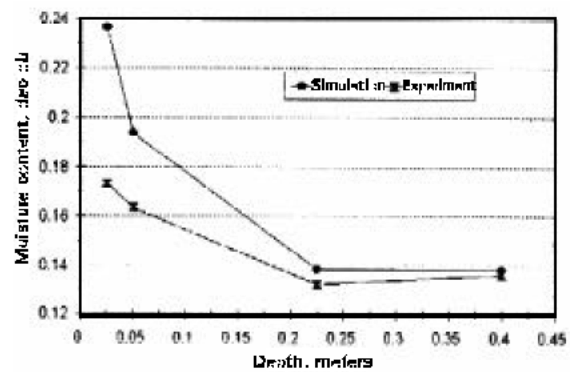

Fig. 4: Comparison of the moisture content profiles with time after the adsorption process at 10°C (336 hrs, initial moisture content, 0.1364 dec db.)

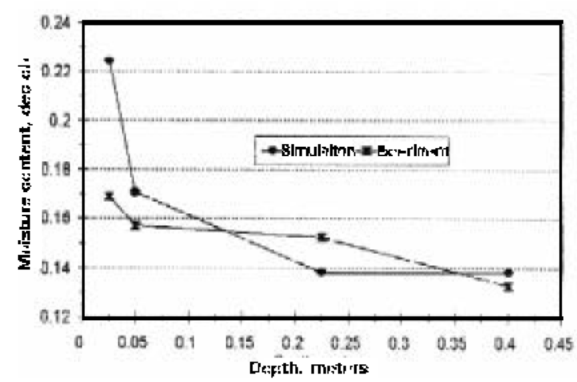

Fig. 5: Comparison of the moisture content profiles with time after the adsorption process at 14.8°C (216 hrs, initial moisture content, 0.1364 dec db)

have followed the same pattern and yielded highest position around 96-144 h (4-6d) then dropped gradually. Fig. 3 is slightly different from Fig. 1 and 2, where the simulated curve has shown a faster rate of rise and fall of the temperature. Simulated temperature is found to be over-predicted by 4-5°C from the experimental temperature at all initial temperatures.

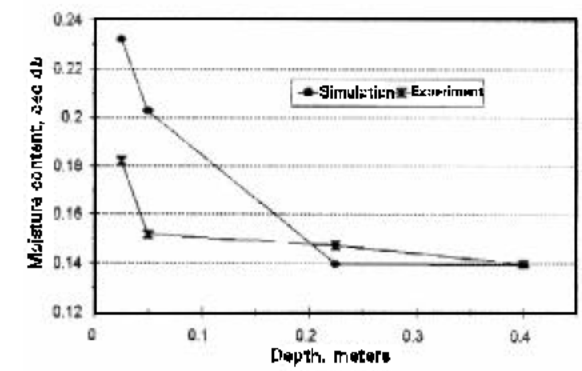

Fig. 6: Comparison of the moisture content profiles with time after the adsorption process at 19.2°C (336 hrs, initial moisture content, 0.1364 dec db).

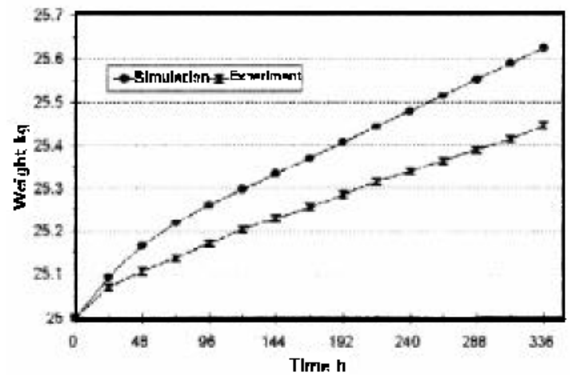

Fig. 9: Comparison of the increased weight with the time during the adsorption process at 19.2°C.

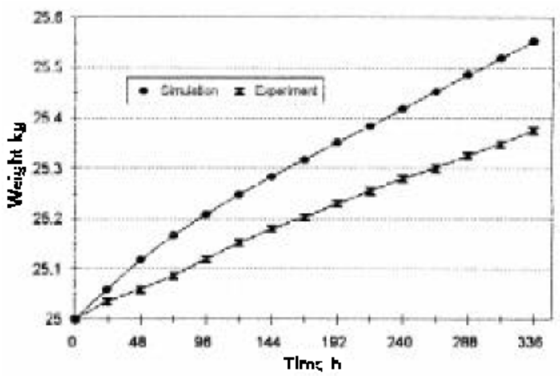

Fig. 7: Comparison of the increased weight with time during the adsorption process at 10°C.

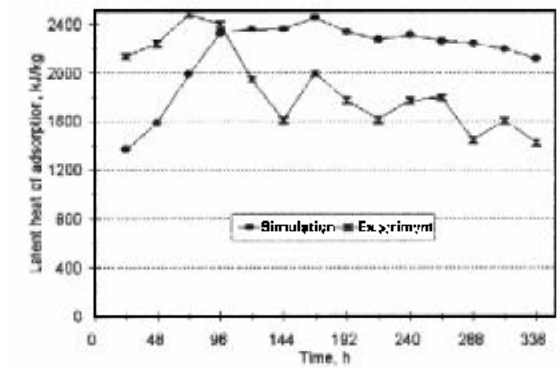

Fig. 10: Comparison of the latent heat of adsorption with time during the adsorption process at 10°C.

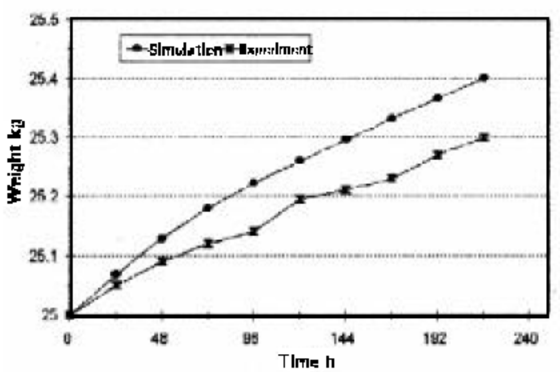

Fig. 8: Comparison of the increased weight with the time during the adsorption process at 14.8°C.

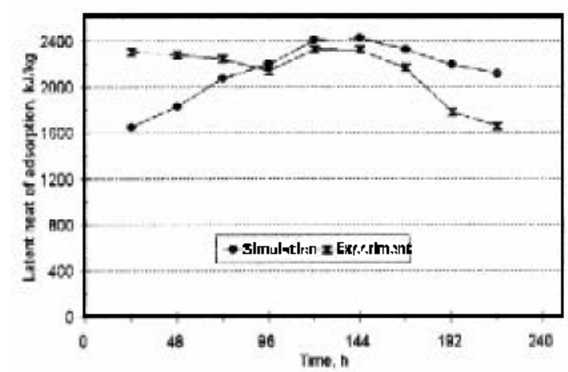

Fig. 11: Comparison of the latent heat of adsorption with time during the adsorption process at 14.8°C.

Moisture content: Fig. 4-6 show the comparison of the theoretical and experimental moisture content profiles at different levels of the bed. The highest moisture content for the experiment is found to be at the bottom of the bed around 0.025m and the lowest at the top of the bed around 0.40m and about the same pattern is followed by the simulation. Some drying is found at 10°C whereas some rewetting at 19.2°C both in the middle of the bed. Theoretically simulated MC over-predicts the experimental MC significantly in the bottom layers for all grain temperatures. This gives rise to the higher simulation temperatures observed above. The high simulated and lower experimental moisture contents clearly confirm the same observation for the field results of Berick 1993-4 (Woods and McCallum, 1997). However, there is not much difference in the simulated and observed MC in the middle and top of the bed.

The range of the MC difference between the simulation and the experiment is from 4.97 to 6.32 at the bottom of the bed

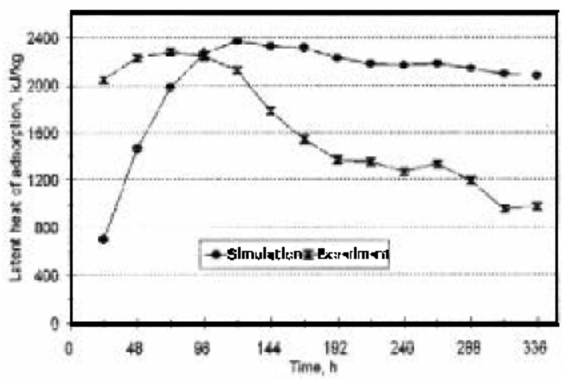

Fig. 12: Comparison of the latent heat of adsorption with the time during the adsorption process at 19.2°C.

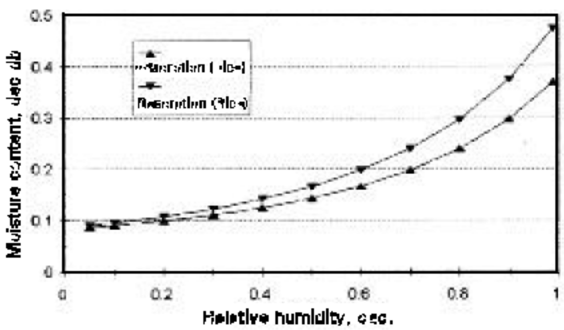

Fig. 13: Adsorption and desorption isotherms for rice at 10°C.

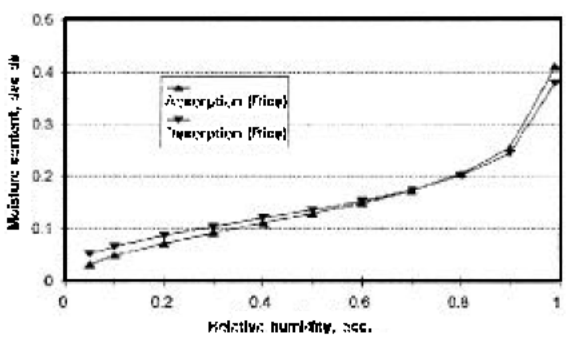

Fig. 14: Adsorption and desorption isotherms for wheat at 10°C.

and mean bed MC from 1.5 to 2.55% (Table 2). Compared mean moisture content is taken as an average of four points at four depths of the bed after 336 hrs (14d) at 10 and 19.2°C and 216 hrs (9d) at 14.8°C, after the completion of the adsorption process.

Weight gained: The comparison of the weight gained due to rewetting at the bottom of the bed, is shown in Fig. 7-9. The curves at 10, 14.8 and 19.2°C are found to be smooth for the theory and experiment, apart from some variations at 14.8°C in the experiment. The total weight increase in two weeks is recorded as 0.553 and 0.375 kg at 10°C and 0.625 and 0.445 kg at 19.2°C, for the simulation and experiment

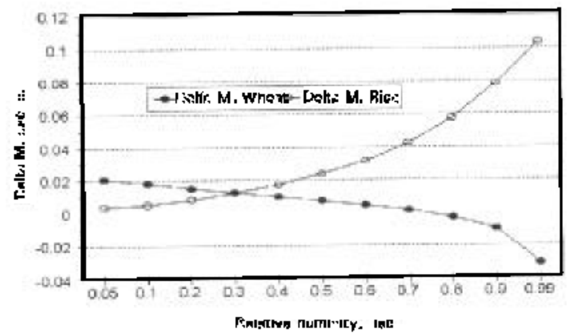

Fig. 15: Difference of adsorption and desorption isotherms at 10°C.

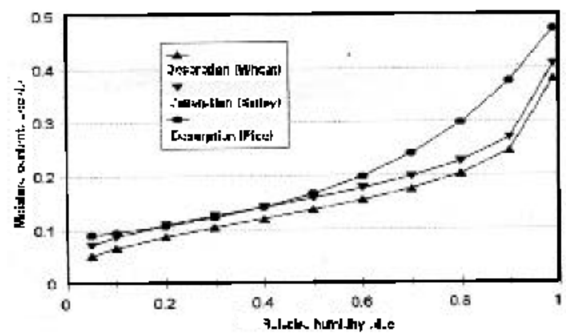

Fig. 16: Desorption isotherms for wheat, barley and rice at 10°C.

respectively. The weight increases at the rate of 0.023 and 0.0156 kg/day for simulation and experiment at 10°C and 0.026 and 0.0185 kg/day for simulation and experiment at 19.2°C.

Latent heat of adsorption: The comparison of the simulated and experimental latent heat of adsorption (LHA) with time after the adsorption process at the three initial temperatures are shown in Fig. 10-12. The experimental results show zigzag curves for the latent heat values with greater variation during the first week. The variations reduce with time and somewhat smoother curves are observed. Compared to the experiment, the simulated curves are smooth with small fluctuations. It would be worthwhile to mention that the simulated and experimental curves follow a similar pattern and after achieving maximum values of LHA, they decline until termination. The highest latent heat of adsorption during 96-144 h (4-8d) is found and recorded (Table 3) for both simulation and experiment. The highest value is observed during the early stages when temperature rise is maximum and the heat loss errors are relatively small. The maximum temperature rise can be attributed to the adsorption of the moisture. When the moisture content of the material is very low, practically all of the adsorbed moisture will be in the first layer and hence, will have a high heat of adsorption. As the moisture content is accumulated layer by layer and the release of heat of adsorption is gradually decreased (Young and Nelson, 1967). The results of the latent heat of condensation of water (pure) by Mayhew and Rogers (1970) are close to the results of this study.

Adsorption correction: The adsorption correction for barley is described by the results predicted from the isotherm equations for rice, wheat and barley.

The MC hysteresis effect increased with the increase of Rh and the desorption isotherm seemed higher than the adsorption by the difference of about 0.06-0.07 dec db at around 0.8 dec Rh for rice data (Fig. 13). However, the wheat data (Fig. 14) showed a difference of 0.005-0.02 dec db. The difference of both the isotherms for rice and wheat is plotted in Fig. 15. The comparison of the desorption data for rice, wheat and barley is shown in Fig. 16. The data clearly indicated the desorption MC predicted for barley was about 1-2.5% higher than for wheat and rice.

For rice and wheat, the difference of MC prediction by the desorption and adsorption isotherms was confirmed by the Fig. 13-15. The higher MC prediction of barley crop was confirmed from the desorption isotherm in Fig. 16 and it is clearly necessary to determine the adsorption data for barley.

Discussion

Some variations in grain temperature are observed after 96 h (4d) at 14.8 and 19.2°C. However, a straight curve is maintained at 10°C which means that as the initial temperature increases, the stability of the temperature rise decreases (Fig. 1-3).

The experimental levels of rewetting are similar to those observed in the field. The results also show that the theoretically simulated MC, as for the field simulation is over-predicted compared with experimental for which there is no clear known reason. However, it could be the desorption data for barley used in the simulation as there is no data available on barley adsorption.

Adsorbed molecules of water on the adsorbent behave like pure water at higher moisture contents and as the moisture content increases, the net heat of adsorption approaches zero (Chung and Pfost, 1967; Young and Nelson, 1967). Heat of adsorption found by Chung and Pfost (1967) ranged from 2.83 to 0.26 k cal/g mole (370.2878-34.019 kJ/kg) for the corn within the moisture content range of 4-20% at 31°C. The latent heat observed by them was the additional energy required to adsorb water into grain. Mayhew and Rogers (1970) has reported the latent heat of condensation (pure water) as 2477.2, 2465.5 and 2456.0 kJ/kg at 10, 15 and 19°C. Gallaher (1951) developed the equation for the latent heat of vaporization and correlated this with moisture content for wheat grain. However, the latent heat of adsorption determined in the present study is a combination of the latent heat of water and the additional energy required to adsorb water into grain. Latent heat of adsorption from the theoretical simulation at 10, 14.8 and 19.2°C in this study, is found to be a maximum of 2455.2, 2424.2 and 2369.2 kJ/kg, respectively and the latent heat of adsorption, determined from the experiment is observed at a maximum of 2385.5, 2393.1 and 2286.5 kJ/kg at 10, 14.8 and 19.2°C, respectively. The literature has revealed that very little research has been conducted on the latent heat of adsorption, particularly on barley grain by experiment. The results shown in Table 3 by Mayhew and Rogers (1970) are from the experimental data for pure water. Woods and McCallum (1997) have reported the release of heat of adsorption associated with rewetting, which affected the grain cooling during their field experiments, but did not estimate the magnitude of the latent heat of adsorption. This is the first time that the latent heat of adsorption for barley has been estimated by experiment and the same is simulated theoretically. Experimental results are in good agreement with the results of Mayhew and Rogers (1970).

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