Research Paper

Experimental and theoretical study on dehumidification potential of clay-additives based CaCl2 composite desiccants

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HIGHLIGHTS

- Preparation and characterization of clay additives based CaCl2 composite desiccant is described.
- The exit air humidity ratio relative to inlet air humidity ratio is expressed in terms of percentage reduction in moisture.
- Process air relative humidity, air velocity and bed weight influences the dehumidification performance.
- Experimental results for percentage reduction in moisture are compared with theoretical mass transfer model.

ARTICLE INFO

ABSTRACT

Transported clay suitable for pot making is used as desiccant carrier. Additives like saw dust and horse dung are considered in particle preparation. Particles nearly spherical in shape are prepared manually and are dried under shadow and subsequently the particles are dried at different temperatures. These burnt particles are characterized for pore volume and surface area. The BET test reveals that clay particles subjected to 500 °C possess higher pore volume but clay-horse dung particles exhibit higher surface area. Heat treated particles of clay with additives are impregnated with CaCl2 solution of 50% concentration. The ratio of desiccant water content to surrounding layer water content varies from 14.09 to 75.34 for CaCl2 based composite desiccants. One dimensional PGC mass transfer model for process air through burnt clay – additives - CaCl2 desiccant bed is adopted. The RMSE of measured and predicted results for reduction of moisture content from the process air by composite desiccant beds are in the range of 3.26–13.2%.

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1. Introduction

Desiccant cooling and heating is an environmental friendly technology that can be used to condition the internal environment of buildings. They allow better indoor air quality [1,2]. Investigations have been carried out to determine the feasibility of desiccant dehumidification in air conditioning applications [3,4]. Desiccant based systems are widely used in adsorption of water vapor, organic solvent, toxic gases and thermal energy storage [4,5]. Jain et al. [6,7] have evaluated performance of liquid and solid desiccant cooling cycles for typical hot humid climates. Khedari et al. [8] studied the use of waste coconut coir as desiccant compared to chemical desiccants like silica gel in air conditioning systems. They showed that lower values of exit air temperature of coconut coir reduce the cooling load in open cycle air conditioning systems. The main components of desiccant based systems are desiccant and the bed configuration. To enhance the adsorption characteristics, liquid desiccants like calcium chloride, lithium chloride are impregnated into the pores of solid desiccant like silica gel, activated carbon and activated alumina [9,10], that results into composite adsorbents. The performance of composite adsorbents is compared with conventional desiccants [11]. A new family of composite adsorbent of water vapor based on impregnating hygroscopic salt into the pores of host inert materials like mined clay and starch is being researched [12,13]. This approach showed promising in utilizing natural resources such as starch and mined clay in the production of composite desiccant material. Rawangul et al. [13] have experimentally investigated the use of mature coconut coir as a desiccant for moisture adsorption in engineering application. Moisture adsorption isotherms of dried coconut coir were determined by static method. Beery et al. [14] reviewed the chemical and structural properties of starch based adsorbents for

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Nomenclature

a	specific surface area, m^{-1}
A_{sf}	total interfacial area available for heat and mass transfer, m^2
A	cross sectional area of bed, m^2
$c_{1e,in}$	inlet air specific humidity, g/kg of moist air
$c_{1e,out}$	exit air specific humidity, g/kg of moist air
c_{1s}	moisture fraction of the air in equilibrium with desiccant, g/kg of moist air
d_p	diameter of particle, m
D	diameter of desiccant bed, m
K	affinity constant
K_g	gas side mass transfer coefficient, kg/ m^2 s
L	length of the desiccant bed, m
$\dot{m}_a$	mass flow rate of gas mixture, kg/s
m_{b_i}	Initial mass of desiccant bed, g
P_v	partial pressure of water vapor, mm of Hg
P_{total}	total pressure, Pascal
P	perimeter of bed, m
q	water content of desiccant, g/kg dry desiccant
r_b	radius of desiccant bed, m
Re	Reynolds number
T_b	temperature of desiccant bed, °C
T_{1ein}	inlet air temperature, °C
T_{1eout}	exit air temperature, °C

v	process air velocity, m/s
W_{CaCl_2}	weight of calcium chloride, g
$W_{wet\ particle}$	wet weight of desiccant particle, g
$W_{dry\ particle}$	dry weight of burnt clay particle, g
W_{H_2O}	weight of water, g
W_0	Initial water content, g of water/kg of dry desiccant
RH	relative humidity
PGC	pseudo gas-side control
$RMSE$	root mean square error

Greek symbol

ε_b	bed porosity, %
ρ_a	density of air, kg/m^3
ρ_p	density of particle, kg/m^3
ρ_b	density of bed, kg/m^3
ε_p	particle porosity, %

Subscripts

in	inlet of the desiccant packed bed
out	outlet of the desiccant packed bed
o	initial value

water vapor adsorption. They concluded that the main parameters to increase the adsorptive capacity are porosity and surface area. There have been experimental studies related to addition of additives like sawdust to clay. Joshua Folaranmi [15] investigated the effect of additives on thermal conductivity of clay and suggested other additives such as animal dung and bentonite to improve the thermal conductivity of clay samples. Bentonite is a clay mineral which is used as filler in well drilling muds and a binder in foundry shops. Sturton et al. [16] have experimentally investigated the potential of bentonite, as drying agent for wheat and oats. Thoruwa et al. [17,18] carried humidification – dehumidification experiments on packed bed comprising bentonite with CaCl$_2$ desiccant under simulated tropical conditions. Based on their results they designed a prototype solar regenerative desiccant dehumidifying device employed for drying of cereal grains and crops. Citing the potential applications of CaCl$_2$ based desiccants, it is essential to know the performance characteristics of these desiccants. Various mathematical models have been proposed to assess the desiccant based humidification and dehumidification systems. Hamed [19] experimentally studied the isothermal adsorption of water vapor from atmospheric air using burnt clay impregnated with calcium chloride desiccants. The isothermal model for mass transfer is solved analytically for potential ratio and compared with experimental results. The modeling of transient heat and mass transfer characteristics of vertical packed burnt clay CaCl$_2$ desiccant is carried out by Ramzy et al. [20]. The models presented are pseudo gas controlled isothermal, pseudo gas controlled adiabatic and solid side resistance adiabatic models. Hiremath and Kadoli [21] have experimentally and theoretically studied the transient heat and mass transfer characteristics of vertical packed burnt clay CaCl$_2$ composite desiccant. Further they have characterized burnt clay with additives impregnated with CaCl$_2$ for properties like thermal diffusivity, thermal conductivity, specific heat and density [22].

Naturally available transported clay used for making pots is used as liquid desiccant carrier. Saw dust a by-product of saw mills and horse dung are employed as additives. Horse dung when mixed with transported clay is believed to impart strength to the

clay and enhance porosity which is suitable for making pots in northern part of Karnataka state, Vijayapur district. Experiments are conducted to find the transient heat and mass transfer characteristics of clay – horse dung – CaCl$_2$, clay – saw dust – CaCl$_2$ composite desiccant in relation to clay – CaCl$_2$ composite desiccant. The parameters like process air velocity and mass of the bed are varied during the experimental work. The theoretical model is solved for exit air humidity ratio and the results are compared with experimental results.

2. Preparation of clay based composite desiccant

Desiccants can take into them and then give up moisture to air, depending on the vapor pressure difference between the desiccant surface and the surrounding process air. In the present study the transported clay collected from a lake is used as liquid desiccant carrier. Saw dust and horse dung additives are cleaned and processed for contaminations. The clay material is segregated into three parts. The first portion is without any additives. The second portion with 20% horse dung and the third portion with 20% saw dust by weight. The weight is measured by using digital balance having a range 0.2–300 g and resolution of 0.01 g. The resulting clay and clay + additives material is mixed with water and kneaded thoroughly to bring to a form similar to dough. The pasty clay with additive materials is molded manually into spherical particles of 10 mm diameter. The green particles thus prepared are subjected to shadow drying instead of sun drying. In case of drying the particles under direct sunlight, the rate of surface evaporation is greater due to more flow of moisture towards the surface. When it is exposed to the direct sunlight, the evaporation of moisture from the particle is expected to be faster. This is due to large amount of heat received by the particle due to solar radiation. When the moisture evaporation becomes faster the strength of the bond of the constituents of the particles probably cannot withstand the fast evaporation rate of moisture and hence they give away. On the contrary when the particles are subjected to shadow drying the evaporation of moisture from the particle must be

taking place gradually. Due to such situation the bond strength of constituents is capable of preventing surface cracks. Based on the observation during sun drying and shadow drying, the particles are subjected to shadow drying. A gauge of copper material of 10 mm diameter is employed to check the correct diameter of particles produced. This enables us to separate the over-sized and non-uniform particles. The clay and clay additives spherical particles produced after shadow drying are stored in plastic boxes. Further to shadow drying, samples of clay, clay – saw dust and clay – horse dung particles are placed in a furnace and heat treated for one hour at temperatures ranging from 100 to 800 °C. After heating the particles for one hour, they are left to cool naturally in the furnace itself for 24 h. The influence of heat treated temperature was investigated as follows. Fig.1(a) and (b) shows the variation of weight reduction and change in porosity with temperature. Here the shadow dried samples are introduced into the furnace at temperatures ranging from 100 to 800 °C in step of 100 °C. Before subjecting to heating, the samples may contain pore moisture or mechanical moisture. With increase in temperature the shrinkage and moisture removal increases. For all the three samples the maximum loss in weight is recorded at 500–600 °C. As presented in Fig. 1(b), the apparent porosity values are estimated for samples heated from 300 to 800 °C. The porosity values are estimated using Archimedes principle that requires the measurement of dry weight, saturated weight and suspended weight in water. At 100 and 200 °C all the three samples gets dissolved into the water. However at 300 °C, except burnt clay samples other two samples retained their shapes that enabled measurement of suspended weight. From 300 °C all the samples retained their shapes and it is possible to record the suspended weight for porosity estimation. It is observed that porosity increases with increase in temperature up to 500 °C. The porosity increase is due to micro cracking. From 500 °C onwards the decrease in porosity is due to closure of micro cracks.

The information obtained above is supplemented by measuring other texture properties such as pore volume and surface area. The BET (Brunauer–Emmett–Teller) analysis of the samples measures pore volume and surface area. The system utilizes the principle of static volumetric technique to obtain nitrogen gas adsorption/desorption isotherms at regeneration temperature of 200 °C. Fig.2 (a) and (b) shows the variation of surface area and pore volume with temperature. The test reveals that with increase in temperature from 500 °C to 800 °C, the surface area decreases. The addition of 20% horse dung with clay results in higher values of surface area at 500 °C. The BET surface area of burnt clay – sawdust samples is 59% less than the BET surface area of virgin burnt clay samples whereas the burnt clay samples surface area is 28% less than the

surface area of burnt clay horse dung samples. This indicates loss of a number of pores especially smaller pores for burnt clay sawdust particles. As shown in Fig. 2(b), the pure clay particles show higher values of pore volume at 500 °C. The pore volume of burnt clay increases by 62% and 36% as compared to clay saw dust and clay – horse dung particles. The pore analysis of samples indicated loss of small pores for burnt clay – sawdust samples. As a result, the internal surface area and pore volume of these samples are lower than virgin burnt clay and clay – horse dung samples. From Figs. 1(b) and 2(b), it is observed that the variation in porosity with temperature is much slower as compared to much change in physical volume. The total pore volume includes volume of open and closed pores. The change in apparent porosity only accounts the volume of open pores. Hence porosity variation with temperature is much less. The BET test accounts total pore volume. The physical volume of particles is much larger than the total pore volume. The increase in temperature causes less change in physical volume as compared large change in total pore volume. Hence the pore volume variation with temperature is much more than change in porosity.

Based on the results pertaining to weight reduction, porosity, surface area and pore volume, the three types of clay–additive particles are heated to a temperature of 500 °C. The number of clay and clay + 20% additive particles produced are about 3000. The profile projector is used measure the correct diameter of heated particles. The average diameter of about 100 particles measured by profile projector is 10.48 with a standard deviation of 1.63. The burnt particles are impregnated with $CaCl_2$ solution of 50% concentration. To ensure complete impregnation of $CaCl_2$ into the burnt clay and burnt clay additives particles, a soaking period of 24 h is adopted. After impregnation the particles are sticky in nature. Hence the impregnated samples are again dried at 100 °C and later on stored in air tight containers.

2.1. Microstructure of burnt clay – additives – $CaCl_2$ composite desiccant particles

The scanning electron microscopy (SEM) images of composite desiccant without and with impregnation at 5000× are shown in Fig. 3(a–c). With respect to the burnt clay particles, the SEM images of the desiccant particles without impregnation shows presence of large and smaller grains of clay constituting various elements with maximum Si, followed by Fe, Al, C, Ca, Mg and Na as minimum by weight. As noted, the surface morphology of composite desiccant with horse dung and saw dust additive appears to have created additional layer on the grains of clay giving a very coarse appearance in case of horse dung addition and smoother surface appear-
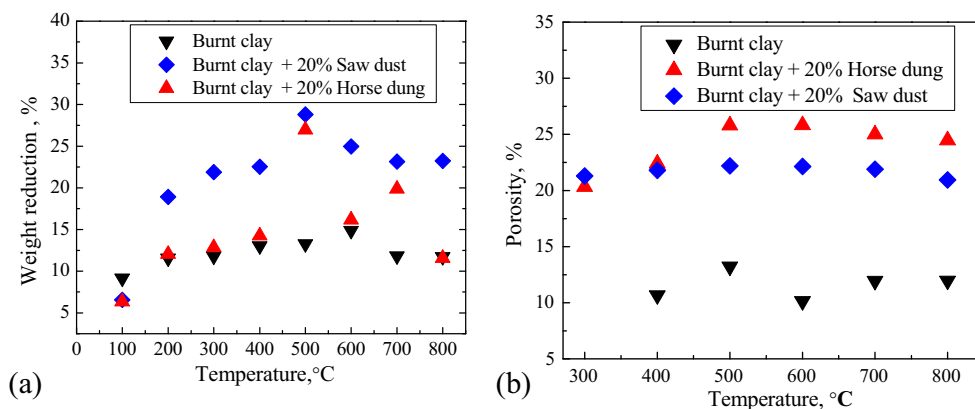

Fig. 1. Effect of burning temperature on burnt clay – additives particles (a) weight reduction and (b) porosity.
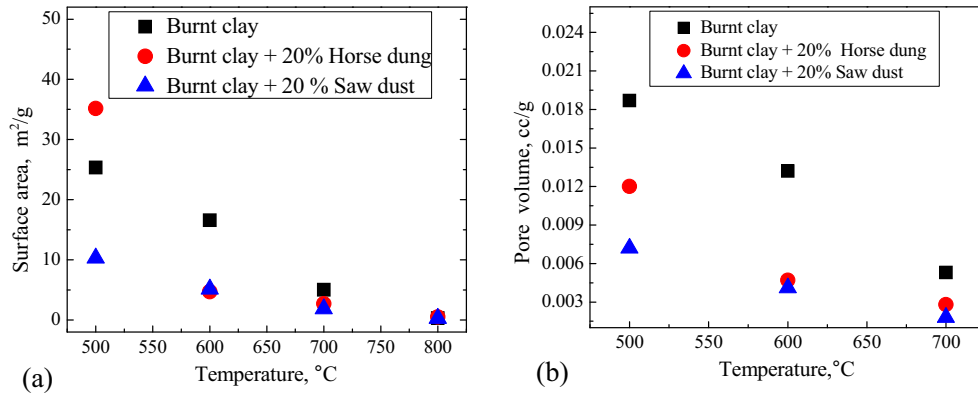
Fig. 2. Variation of (a) Surface area and (b) Pore volume with temperature for burnt clay + additives particles.

ance in case of saw dust additive. On impregnation the surface morphology in all three desiccants, the impregnation of $CaCl_2$ can be identified or recognized due to the additional layer deposited on the clay grains.

3. Determination of initial water content

The water content of composite desiccant particle is estimated as follows. The five particles are picked from the lot and ensured that these particles are completely dried by subjecting them to hot environment in a furnace at 500 °C. Each particle is weighed and average weight of five particles is noted, thus the dry weight of particles is determined. Five particles from the impregnated lot is chosen. The average wet weight of five samples is determined. By measuring the initial dry weight of clay additives particles before impregnation and final wet weight of composite desiccant particles after impregnation, the initial weight of water and weight of $CaCl_2$ is calculated on weight basis. For the solution of X concentration of $CaCl_2$, the initial water content of desiccant particles are estimated using the following equations.

$$X = \left(\frac{W_{CaCl_2}}{W_{CaCl_2} + W_{H_2O}} \right) \quad (1)$$

Weight balance for desiccant particles before and after impregnation is given by Eq. (1a) and solving Eq. (1) results in Eq. (2)

$$W_{\text{wet particle}} - W_{\text{dry particle}} = W_{H_2O} + W_{CaCl_2} \quad (1a)$$

$$W_{CaCl_2} = \left(\frac{W_{H_2O}}{\frac{1}{X} - 1} \right) \quad (2)$$

Substituting Eq. (2) in Eq. (1a) results in Eq. (3).

$$W_{\text{wet particle}} - W_{\text{dry particle}} = W_{H_2O} + \left(\frac{W_{H_2O}}{\frac{1}{X} - 1} \right) \quad (3)$$

Eq. (3) gives weight of water W_{H_2O} and the initial water content in grams of water vapor per kg of dry desiccant is given by

$$W_0 = \frac{W_{H_2O}}{W_{\text{dry particle}} + W_{CaCl_2}} \quad (4)$$

For the solution of 50% concentration the initial water contents estimated for burnt clay – $CaCl_2$, burnt clay – saw dust – $CaCl_2$ and burnt clay – horse dung-$CaCl_2$ composite desiccants are in the order of 63.79, 86.04 and 94.44 g_{water}/kg $_{dry\ desiccant}$ respectively.

4. Experimental arrangement and procedure

The experimental set up to conduct dehumidification experiments is shown in Fig. 4. The set up consists of air compressor with reservoir, pressure line, air heating unit, humidification unit, orifice meter, vertical column and measuring instruments mounted at data measuring locations. Air collected from the air reservoir is allowed to enter at the bottom of vertical column through the pressure line. The experiments that can be conducted are adsorption and desorption (regeneration). To carry out the experiments, it is necessary to supply air along the test section which will have range of relative humidity, temperature and velocity. Accordingly, the process air has to be directed through different units and sections of the experimental set up. To achieve these objectives ball and gate valves have been used interchangeably. The desiccant particles are placed in the vertical column. The main parameters measured are relative humidity, temperature, pressure drop and mass flow rate of process air during dehumidification experiments. The relative humidity and temperature at bed inlet and exit is measured using calibrated Hygroflex hygro transmitter. The humidity transmitters at the bed inlet and exit are connected to computer through microcontroller interface. The transient values of humidity ratio and temperature of process air are written to excel file for every second of experiment duration. Volume flow rate of process air through the pressure line is measured using orifice meter of diameter 10.12 mm and coefficient of discharge of the orifice is 0.68. The K- type thermocouples are used to measure the temperature of process air. Infrared thermometer with range of 0–50 °C and accuracy of ±1.5% is used to measure temperature of the bed.

5. Performance parameters

The dehumidification performance of burnt clay with additives and impregnated with $CaCl_2$ desiccant bed is evaluated in terms of moisture removal rate which in turn depends on the inlet process air and exit air humidity ratios. The decrease in air humidity ratio is calculated from Eq. (5),

$$\text{Moisture removed} = \left(\frac{c_{1e,in} - c_{1e,out}}{c_{1e,in}} \right) \times 100 \quad (5)$$

Based on the vapor pressure, the moisture is transferred from desiccant surface to the surrounding air or vice versa. The vapor pressure relates the desiccant bed water content and relative humidity of surrounding air with equilibrium humidity ratio. The Antoine equation [19] is used to obtain isothermal data at different temperatures. The equilibrium vapor pressure p_v for clay – additives – $CaCl_2$ desiccant beds is given by
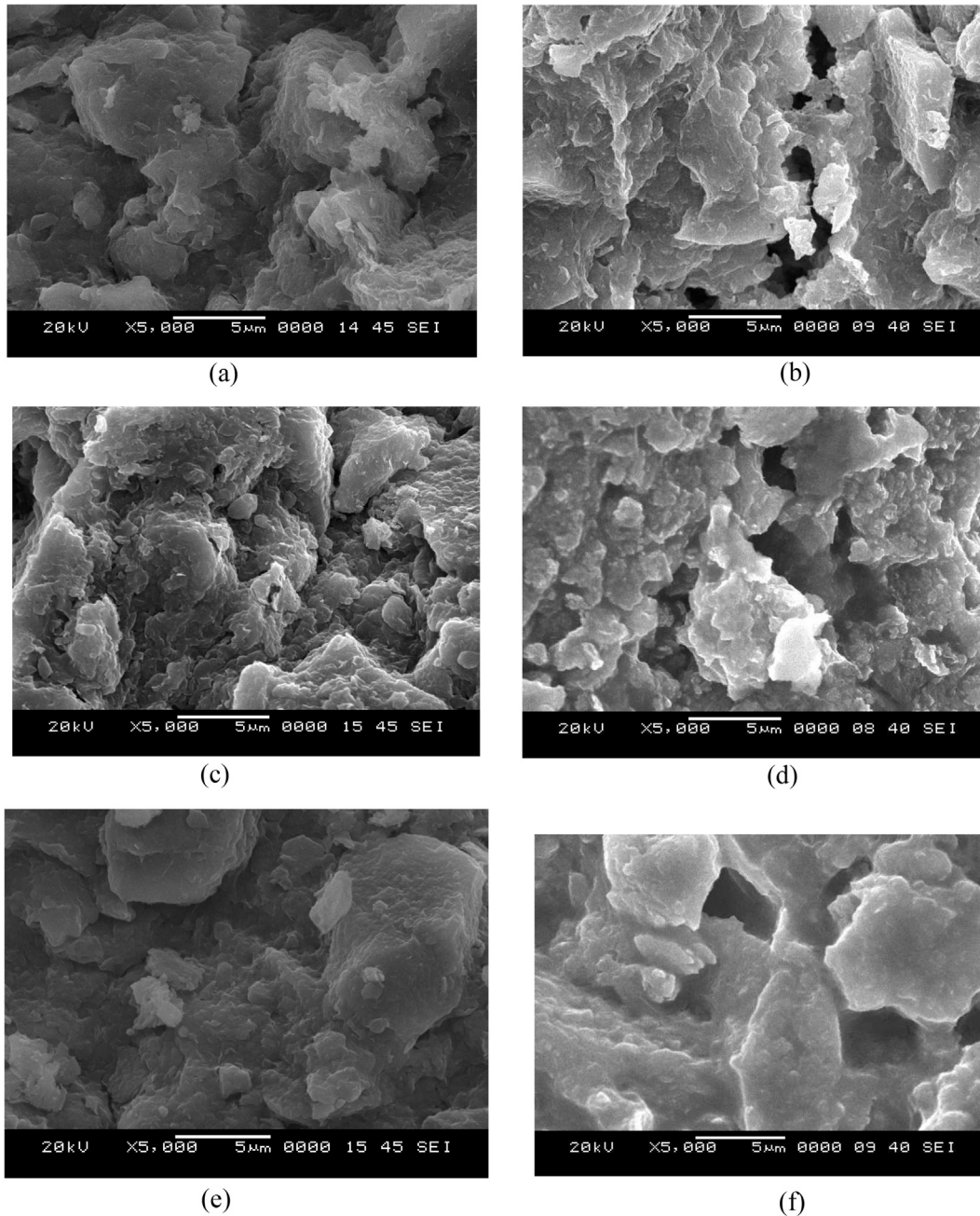
Fig. 3. Composite desiccant without and with impregnation (a, b) Burnt clay, (c, d) Burnt clay with horse dung and (e, f) Burnt clay with saw dust additive.

$$p_v = \exp\left[(a_0 + a_1 X) - \frac{(b_0 + b_1 X)}{(T_b + 111.96)}\right] \qquad (6)$$

$a_0 = 10.0624, a_1 = 4.4674, b_0 = 739.828, b_1 = 1450.96$ are regression constants. T_b is bed temperature and its range is from 10 to 65 °C and X is concentration and its range is from 0.2 to 0.5. The equilibrium moisture fraction is given by

$$c_{1s} = \frac{0.622 \times P_v}{P_{total} - 0.372 \times P_v} \qquad (7)$$

Affinity constant relates equilibrium humidity ratio and solute concentration at constant temperature. It signifies the ability of desiccant material to attract water vapor. The affinity constant as presented by Hamed [19] relates solute concentration in solid phase and fluid concentration at equilibrium and is given by

$$K = \left(\frac{q}{c_{1s}}\right) \qquad (8)$$

6. Experimental results and discussion

To have an insight into the heat and mass transfer performance characteristics of vertical packed burnt clay – additives – CaCl$_2$ composite desiccant beds, a number of experiments have been carried out and the transient values of exit air relative humidity and temperature are recorded with respect to inlet air humidity, temperature, velocity and for different bed weights. Two cases of dehumidification experiments are conducted.

6.1. Analysis of dehumidification experimental results for burnt clay CaCl$_2$ composite desiccants

The transient variation of exit air humidity ratio and temperature as function of inlet air humidity ratio and temperature is presented in Fig. 5(a) and (b). During these two experimental runs the
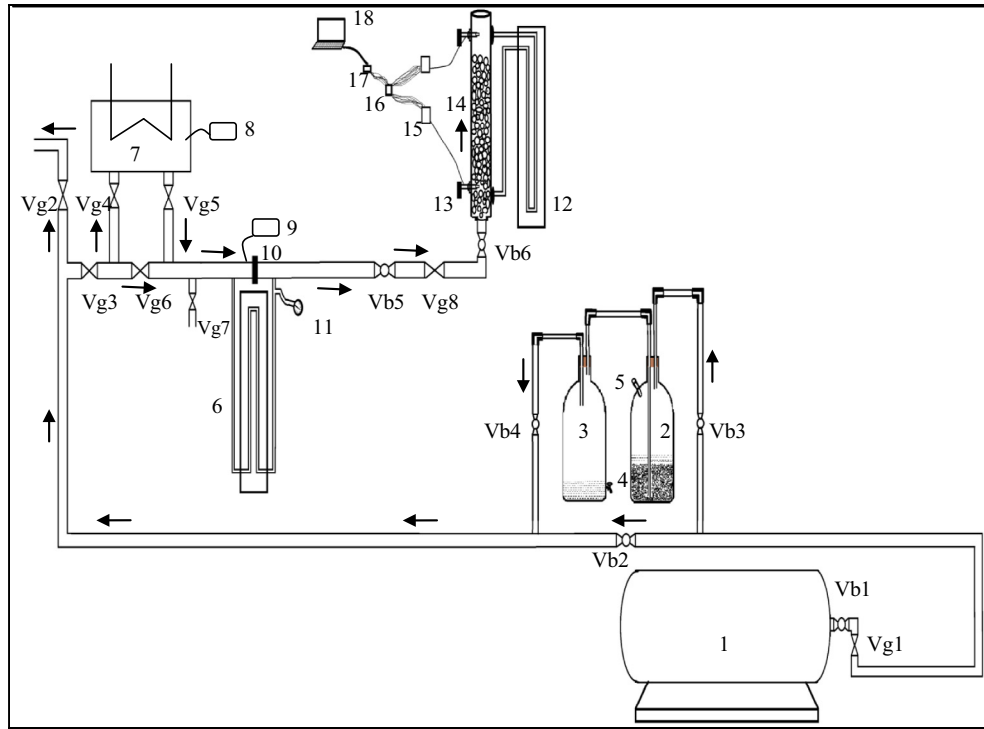
Fig. 4. Detailed schematic layout of experimental set up. 1. Air Compressor 2. Humidifier 3. Moisture damper 4,5. Water line 6,12. U-tube manometer 7. Air heating unit 8, 9. K- type thermocouples 10. Orifice meter 11. Pressure gauge 13, 15. Hygrotransmitter 14. Desiccant column 16, 17. Aurdino with voltage divider 18. computer. Ball valve: Vb. Gate valve: Vg.

desiccant particles are used for the first time. The process air with relative humidity of 80–90% is introduced into the burnt clay – CaCl2 desiccant bed. The humidity level of process air reduces to a value of 46% towards the end of process. It can be seen that the outlet, inlet air humidity ratio and temperature with adsorption time have similar trend. For example, the exit air humidity ratio firstly decreases and then increases with time and later on decreases steadily with time. During the initial period, that is, from 0 to 80 s, the ratio of outlet to inlet air humidity ratio is less than one and adsorption process has occurred. Consequently during this period vapor pressure on the desiccant surface is less than the vapor pressure of process inlet air. Because of this the mass transfer direction will be from air to desiccant surface. At 1 m/s the

maximum reduction in moisture occurs when the process time is below 100 s, whereas at 2 m/s minimum value of exit air humidity ratio is observed at process time slightly more than 100 s. In between 100 s and 400 s there is a transition from unsteady state to steady state. From 400 s onwards the capability of the bed to adsorb moisture is very minimal. During initial stages of operation the water vapor or moisture content of process air transferred to the bed gets condensed into the pores and capillaries of desiccant particles. The condensation results in the release of heat and that in turn increases the process air temperature.

With progress in time the bed water content increases and the exit air temperature decreases and would attain temperature near to that of inlet air temperature. At 1 m/s the maximum rise in exit
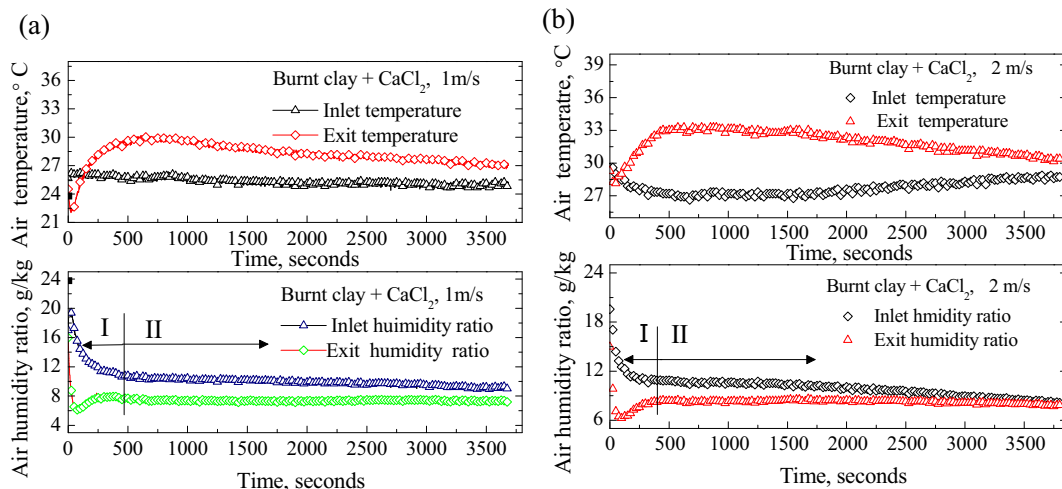

Fig. 5. Experimental time variation of exit air temperatures and humidity ratio for burnt clay with additives CaCl2 impregnated packed vertical bed.

air temperature with respect to inlet air temperature is 4 °C at process time of 630 s. At the end of two hours of process time the temperature difference between inlet air temperature and exit air temperature is 2 °C. The increase in bed water content is about 11.58 g with respect to initial bed weight of 400 g. At 2 m/s the rise in exit air temperature with respect to inlet air temperature is 6 °C at about process time of 550 s. At the end of two hours of process the exit air temperature is 1.6 °C higher than inlet air temperature. The bed weight increases from 400 g to 416.8 g.

The experiments conducted depend on outdoor conditions of lab. The inlet air humidity ratio and temperature of air let into the bed varies as time progresses. In order to access the mass transfer performance during the dehumidification process, a moisture removal from the process air is expressed as percentage of moisture reduction. As a result the evaluation of the dehumidification process for different variables like, inlet air velocity, and weight of the bed can be discussed irrespective or independent of the laboratory conditions. The reduction in moisture content of air is evaluated in percentage moisture reduction by Eq. (5). As shown in Fig. 6(a) and (b) the measured absolute humidity and temperature of air at bed inlet and exit are presented graphically in terms of percentage change in moisture at every interval of time. During initial period of adsorption the moisture removal for 1 m/s increases from 8 to 61% and then decreases value of 28%. The decrease is due to variation in bed temperature, bed water content and $CaCl_2$ concentration during the process. During initial stages of process the bed is dry and moisture uptake increases. The lower

vapor pressure on the dried bed surface results in transfer of moisture from air to desiccant surface. With progress in time the bed water content increases and bed temperature drops. Due to this vapor pressure on desiccant surface increases and moisture transfer potential from air to bed decreases. With progress in time the bed gets saturated and operates at constant temperature. With advancement in time the moisture removal rate tends to become steady and ultimately it decreases the bed moisture uptake capacity. At 2 m/s the reduction in moisture content of air increases from 20 to 52% and then onwards decreases to a value of 18%. Irrespective velocity of flow of air through the bed the maximum reduction occurs at process time which is below 500 s. From then on wards adsorption process continues to proceed till the saturation of desiccant bed.

Fig. 7(a) and (b) illustrates the adsorption behavior of burnt clay $CaCl_2$ bed at different velocity of process air. At lower velocity that is less than 1 m/s, the bed is active enough to take moisture. The bed moisture uptake capacity increase gradually up to 300 s. From then onwards moisture uptake capacity decreases and then remains constant with progress in time. At velocities higher than 1 m/s, the beds are hyper active within an initial time span of 150 s. From then onwards moisture transfer rate decreases sharply at 200 s. Between 200 and 400 s there is a gradual decrease in moisture uptake capacity. For the remaining period moisture removal capacity decreases and the desiccant beds continues to adsorb till saturation. The increase in bed water content with respect to a initial bed weight of 400 g are 7.09 g, 11.58 g,
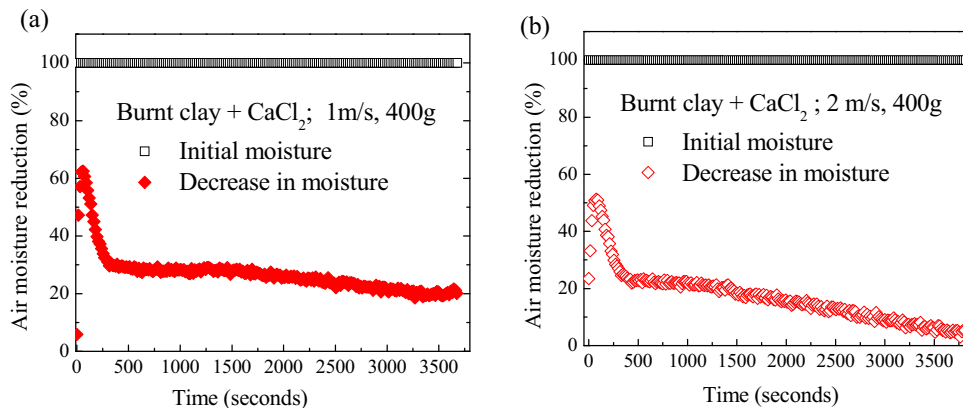

Fig. 6. Experimental time variation of exit air moisture content relative to inlet air humidity ratio for vertical packed burnt clay $CaCl_2$ bed.
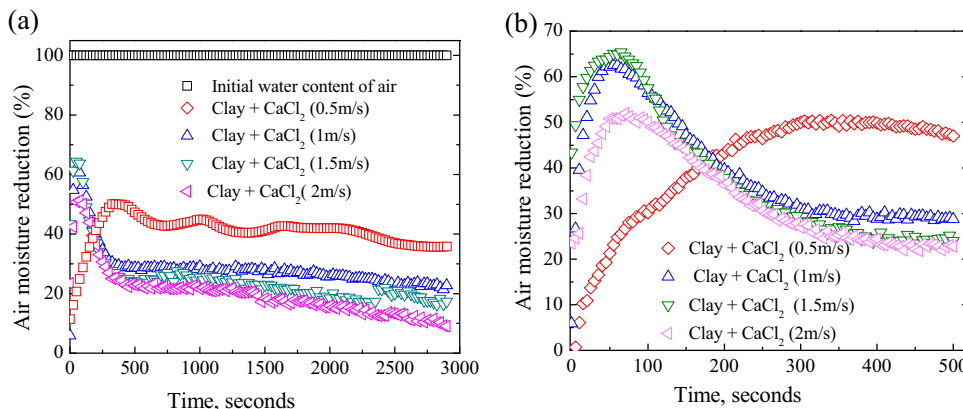

Fig. 7. Transient variation of process air moisture reduction at different velocities for burnt clay with $CaCl_2$ impregnated packed vertical bed (a) and (b) details during 0–500 s.

14.34 g and 16.89 g at 0.5 m/s, 1 m/s, 1.5 m/s and 2 m/s respectively.

Fig. 8(a) and (b) shows the transient variation of change in moisture content of air for bed weights of 250, 500 and 750 g. The process air velocity to the bed was maintained at 0.5 m/s and 1 m/s. The composite desiccants used during these experiments had already undergone adsorption process. The inlet air humidity level was low of the order 18 to 25%. It is seen that increasing bed height increases the moisture removal rate. However the amount of moisture adsorbed by the bed is greatly influenced by the velocity of the process air. When the velocity of the air across the bed 0.5 m/s the amount of moisture adsorbed is considerably large when compared to the bed operated at process air velocity of 1 m/s.

6.2. Analysis of dehumidification experimental results for burnt clay – horse dung – CaCl$_2$ desiccant bed

Fig.9(a) and (b) shows the transient variation of change in moisture content of air for burnt clay horse dung additives CaCl$_2$ composite desiccant beds. The various experimental parameters are similar to that described for burnt clay CaCl$_2$ desiccant beds. However at bed inlet air velocity of 0.5 m/s during the initial adsorption times of 250 s the bed with 750 g is more active compared to the beds of 500 g and 250 g. Beyond 250 s the desiccant beds of 750 g and 500 g are more or less have the same adsorption capacity. Overall the characteristics of adsorption curves are similar to the adsorption characteristics of burnt clay CaCl$_2$ desiccant beds.

6.3. Analysis of dehumidification experimental results for burnt clay – Saw dust – CaCl$_2$ desiccant bed

Fig. 10(a) and (b) shows the transient behavior of the burnt clay – saw dust – CaCl$_2$ desiccant bed. As shown Fig. 10 (a), the desiccant bed of 500 g weight shows considerable increase in dehumidification of process air as compared to 250 and 750 g beds. This is contrasted when compared to burnt clay – CaCl$_2$ and burnt clay – horse dung – CaCl$_2$ beds. Apart the beds of 250 g and 750 g have same capacity of moisture adsorption.

6.4. Analysis of dehumidification experimental results for burnt clay – additives – CaCl$_2$ desiccant bed

Effect of additives like saw dust and horse dung to the transported clay for dehumidification potentiality is examined. Fig. 11 (a) presents the adsorptive behavior of nearly new clay additives composite desiccant beds subjected to higher humidity levels. Fig. 11(b) presents the details of the transients of during the initial stages, 0–250 s, of the adsorption process. It is clear that the adsorption process is highly dependent on the composition of desiccant particle. The beds are more or less equally active to take moisture from process air during initial time period of 0–250 s. The increase in bed water content with respect to initial bed weight of 400 g are 13.72 g, 14.34 g and 15.12 g for clay, clay horse dung and clay saw dust additives composite desiccant beds.

Experimental runs are undertaken for composite beds with varying mass as 250, 500 and 750 g. For each bed the velocity of process air was maintained at 0.5 m/s and 1.0 m/s. The desiccant
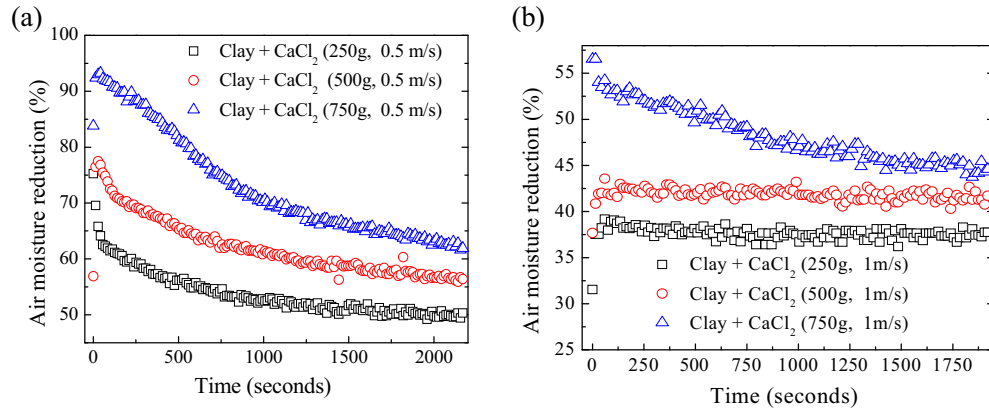

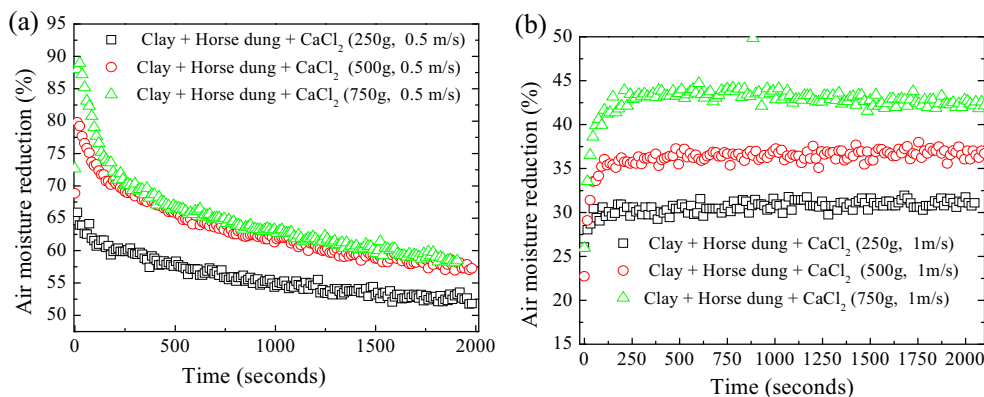**Fig. 8.** Transient variation of reduction in moisture content for clay – CaCl$_2$ bed.

Fig. 9. Transient variation of reduction in moisture content for clay – horse dung- CaCl$_2$ bed.
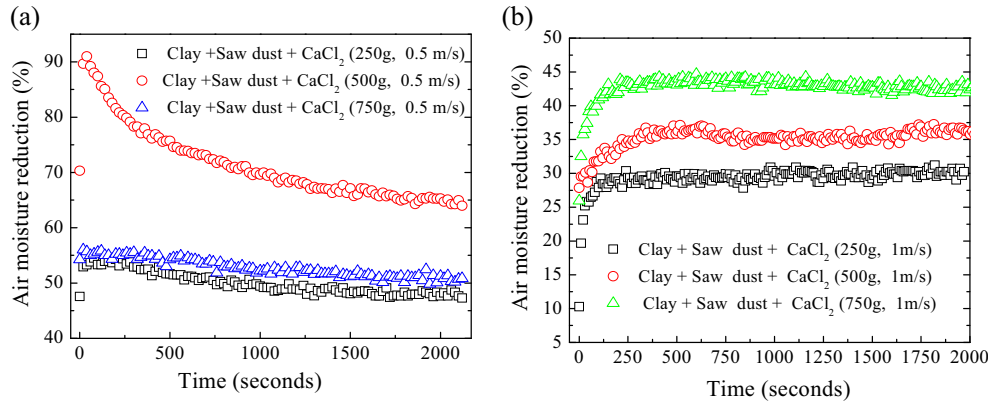
Fig. 10. Transient variation of reduction in moisture content for clay – saw dust – CaCl$_2$ bed.
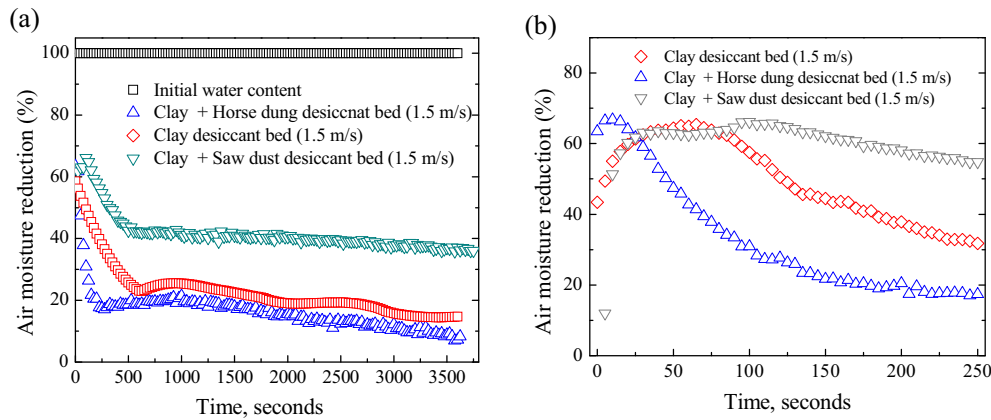

Fig. 11. Transient variation of moisture reduction from process air due to various composite desiccant in a packed vertical bed, mass of composite desiccant being 400 g.

samples introduced into the vertical column are those which have been already subjected to few number of adsorption process and subsequently regenerated. Experiments are conducted at the process air humidity ranging from 18 to 25%. From Fig.12(a), (c) and (e) at lower velocities of 0.5 m/s each of the composite desiccant perform differently depending on the weight of the bed. For example for a bed of 750 g burnt clay CaCl$_2$ is performing much better compared to burnt clay horse dung CaCl$_2$ and burnt clay sawdust CaCl$_2$ composite desiccant beds. When the process air velocity is 1.0 m/s as presented in Fig. 12(b), (d) and (f), moisture reduction in process air is better for burnt clay CaCl$_2$ bed irrespective of the quantity of desiccant. The beds operating at lower velocity of 0.5 m/s shows higher moisture reduction than beds operating at 1 m/s. As cooling effect predominates at higher velocities the vapor pressure difference between the desiccant surrounding air and desiccant surface decreases significantly. Because of this the bed moisture intake capacity is low at higher velocities. Higher pore volume and moderate surface area for burnt clay particles and the retention of CaCl$_2$ into pores results in higher dehumidification rates as compared to other two desiccant beds. At drying temperature of 500 °C the addition of horse dung to transported clay increases the surface area with moderate pore volume. The clay – CaCl$_2$ with horse dung additive shows similar bed behavior as that of clay-CaCl$_2$ desiccant bed. The addition of saw dust neither increases the pore volume nor the surface area. However experimental runs of clay – CaCl$_2$ bed reveal higher dehumidification capacity at every interval of time. This is evident from the fact that the visual examination of clay - CaCl$_2$ desiccant particles

shows deteriorated surface which is exposed to flow of process air. The surface deterioration and descaling is due to increased number of cycles of use. However the burnt clay-horse dung-CaCl$_2$ composite desiccant particles show greater degree of structural integrity and thermal stability as compared to other two desiccant particles. With increased use of clay-sawdust-CaCl$_2$ desiccant particles, the surface turns powdery.

7. Analysis of affinity constant

The affinity constant relates the desiccant moisture content and the moisture content in the layer surrounding the desiccant particle. It characterizes the isotherm property of desiccant material. The isotherm correlation which is required in the theoretical modeling relates the bed water content and equilibrium relative humidity at constant temperature. The moisture ratios in terms of affinity constant are evaluated using Eq. (8). Fig. 13 shows the affinity constant for burnt clay – additives – CaCl$_2$ composite desiccants in vertical packed bed and its value varies from 14.09 to 75.34. The BET analysis reveals higher pore volume for burnt clay – CaCl$_2$ desiccants as compared to burnt clay – additives desiccants. Higher pore volume results in lower values of moisture ratios for burnt clay-CaCl$_2$ desiccant bed. From the experimental results it is clear that lower moisture ratio for burnt clay – CaCl$_2$ samples bed exhibits higher adsorptivity. The affinity constant that is moisture ratios for burnt clay saw dust CaCl$_2$ and burnt clay – horse dung – CaCl$_2$ beds are being higher resulting in lesser adsoprtivity.
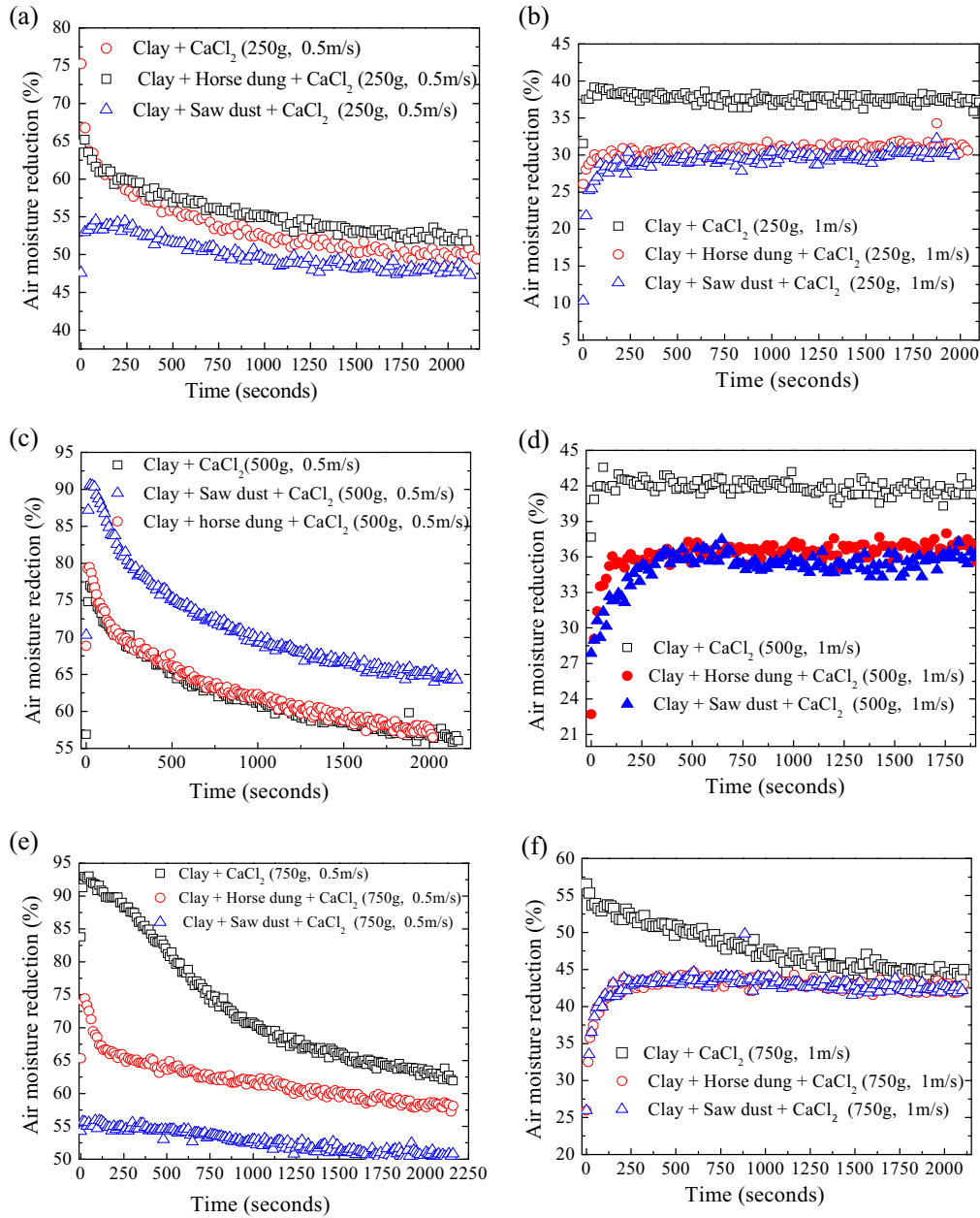
Fig. 12. Comparison of transient variation of reduction in air moisture content for burnt clay – additives – CaCl₂ composite desiccant beds.
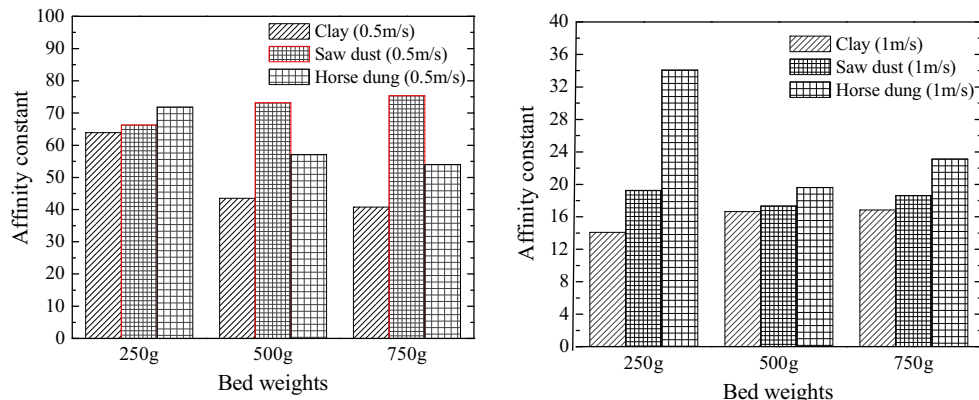

Fig. 13. Affinity constant for vertical packed burnt clay – additives – CaCl₂ beds.
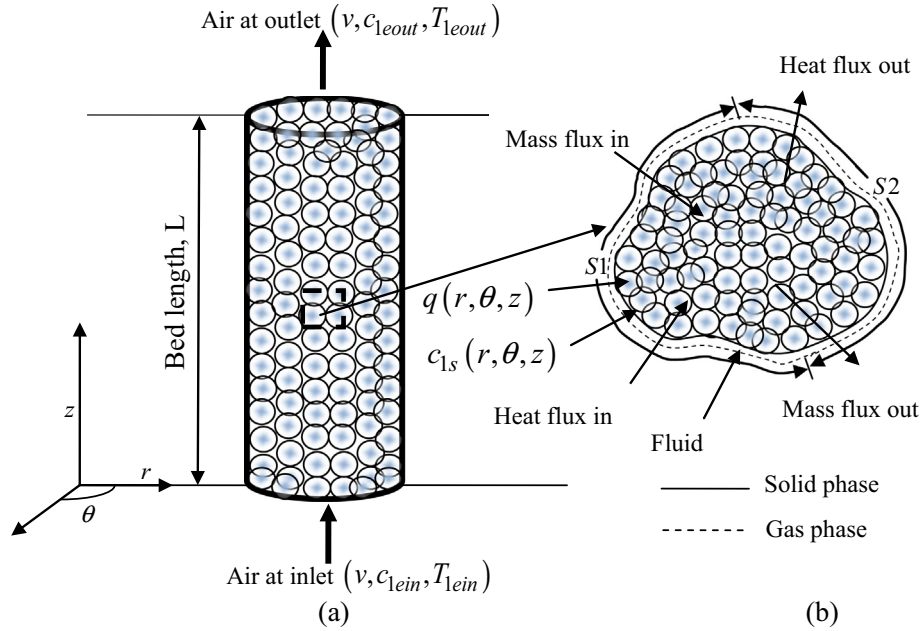
Fig. 14. (a) Physical system of packed desiccant bed and (b) Arbitrary control volume showing gas phase and solid phases.

8. Mathematical modeling of heat and mass transfer for burnt clay-additives-CaCl₂ dehumidifier

In order to make use of the experimental results, mass transfer model is developed. From the experimental results it is evident that the burnt clay – additives – CaCl₂ composite desiccant bed operates at an average temperature that varies in the range of 2–5 °C. The present study models and refines mass transfer isothermal model to get an insight into the overall behavior of the system [19]. The physical system is shown in Fig. 14(a). The bed is of cylindrical shape and fixed vertically. The bed containing spherical desiccant particles is defined in the domain $[0 - L]$ and $[0 - D]$ m.

Compressed air with a velocity v m/s is allowed to pass through the bed at temperature T_{1e} °C; the moisture fraction of inlet air is c_{1e} kg/kg of dry air. For one dimensional analysis, the air flow is assumed to be in axial z direction. The control volume in the direction of flow is shown in Fig. 14(b). The solid line represents the solid phase and the dotted line represents gas phase. The moisture fraction of gas phase built around the desiccant particles is c_{1s} kg/kg. The solid phase water content is q kg/kg of dry desiccant. The heat and mass fluxes entering and leaving the control volume are represented across surfaces $S1$ and $S2$. For the model development the governing equations for solid and gas phases of the physical system can be derived as follows.

8.1. Gas phase and solid phase mass balance

The mass balance equations are written for spatial variation of moisture fraction of operating air and transient variation in water content of desiccant particles. Mass balance equations are written for species water vapor of process air. As shown in Fig. 14(b), consider an arbitrary region of fixed V bounded by surface s. Let ds be the elemental area of the surface. Let ρ be the density of some quantity for which we wish to make a balance. $\hat{n}$ be the unit normal to the surface. $S1$ and $S2$ are the control surfaces, across which net influx and out flux of mass are represented in gas and solid phases. $((\rho_a c_{1e})v)_{in}$ and $((\rho_a c_{1e})v)_{out}$ are the mass fluxes of species, water vapor entering and leaving the control volume in gas phase.

$((\rho_p q)v)_{in}$ and $((\rho_p q)v)_{out}$ are the mass fluxes of water entering and leaving the control volume in solid phase in the flow direction. Writing mass balance of the species water vapor for fixed control volume in gas and solid phases.

Rate of accumulation of species in V = Net rate of influx of species into V + Rate of generation of species in V

$$\iiint_V \varepsilon_b \frac{\partial}{\partial t} \rho_a c_{1e} dV + \iiint_V (1 - \varepsilon_b) \frac{\partial}{\partial t} \rho_a c_{1e} dV$$
$$= \iint_S - (\rho_a c_{1e} v) \cdot \hat{n} ds + \iiint_V Q_g dV \qquad (9)$$

$$\iiint_V \varepsilon_b \frac{\partial}{\partial t} \rho_p q dV + \iiint_V (1 - \varepsilon_b) \frac{\partial}{\partial t} \rho_p q dV$$
$$= \iint_S - (\rho_p q v) \cdot \hat{n} ds + \iiint_V Q_g dV \qquad (10)$$

The above expressions are simplified using Gauss divergence theorem and equating the integrand itself to zero results in following set of equations

$$\left[\varepsilon_b \frac{\partial \rho_a c_{1e}}{\partial t} + (1 - \varepsilon_b) \frac{\partial \rho_a c_{1e}}{\partial t} + \nabla \cdot (\rho_a c_{1e} v) - Q_g \right] dV = 0 \qquad (11)$$

$$\left[\varepsilon_b \frac{\partial (\rho_p q v)}{\partial t} + (1 - \varepsilon_b) \frac{\partial (\rho_p q v)}{\partial t} + \nabla \cdot (\rho_p q v) - Q_g \right] dV = 0 \qquad (12)$$

Eqs. (11) and (12) are simplified to obtain the governing equations with following assumptions and considerations.

(1) Assuming rate of generation $Q_g = 0$ and neglecting mass transfer in radial and angular directions.
(2) Since solid phase loses no material and generates none, the rate of accumulation of moisture in the desiccant bed is equal to the total mass flux over the particles and is given by solid phase balance.
(3) The moisture is transferred from the bulk air stream to the particle surface by the means of convection, and hence the net mass flux over the desiccant particle is given by $n_s = K_g(c_{1s} - c_{1e})$.

Table 1
Parameters for bed and process air for the theoretical solution.

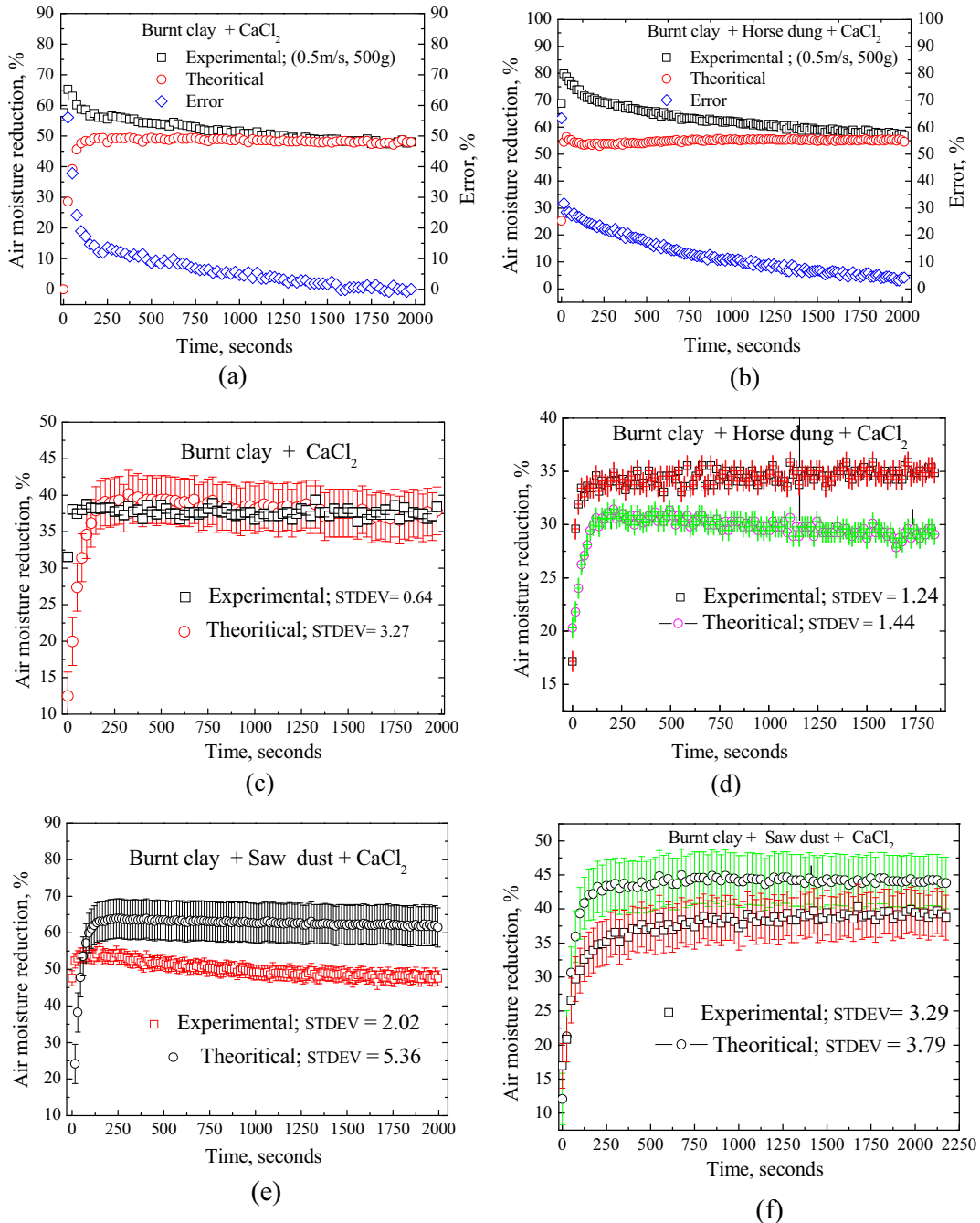| Desiccant bed	T_b (°C)	$c_{1e,in}$ (g/kg)	ε_b	K	m_{b_i} (g)	v (m/s)
Burnt clay + CaCl$_2$ [Fig. 15(a)]	15.92	3.76	0.40	33.17	500	0.5
Burnt clay + horse dung + CaCl$_2$[Fig. 15(b)]	14.89	3.67	0.32	57.11	500	0.5
Burnt clay + CaCl$_2$[Fig.15(c)]	18.45	3.99	0.35	26.55	250	1
Burnt clay + horse dung + CaCl$_2$[Fig. 15(d)]	20.14	3.96	0.33	34.07	250	1
Burnt clay + saw dust + CaCl$_2$[Fig. 15(e)]	11.83	3.67	0.26	66.26	250	0.5
Burnt clay + saw dust + CaCl$_2$[Fig. 15(f)]	16.76	3.66	0.48	42.06	500	0.5

Fig. 15. Comparison of experimental and theoretical results for burnt clay – additives – CaCl$_2$ beds.

(4) Lumped element model or lumped parameter system is adopted that is at a given time the spherical particle is at constant temperature.

(5) The bed water content is a function of fluid concentration at equilibrium with the adsorbed phase and its magnitude is given by the isotherm equation, $q = Kc_{1s}$.

(6) Heat of adsorption is generated by the condensation of water vapor within the pores of desiccant particle. Heat of adsorption is assumed to be totally generated in the composite desiccant particles [23].

The set of governing equations which are derived for predicting the system behavior are

$$\frac{\partial c_{1e}}{\partial z} = \frac{K_g P(c_{1s} - c_{1e})}{\dot{m}_a} \tag{13}$$

$$\frac{\partial c_{1s}}{\partial t} = \frac{K_g P(c_{1e} - c_{1s})}{A\rho_b K} \tag{14}$$

Eq. (13) represents the governing equation for water vapor species conservation (moisture conservation) in gas phase. Eq. (14) represents the governing equation to find the equilibrium moisture concentration at any time. It represents rate of change of moisture content in interfacial layer with accumulation of moisture in the interfacial layer. The associated boundary and initial conditions for Eqs. (13) and (14) are

Boundary condition : $c_{1e}(z = 0, t) = c_{1e0}$ (15)

Initial condition : $c_{1s}(z, t = 0) = c_{1s0}$ (16)

The governing equations are linear coupled first-order deferential equations; a numerical solution is obtained for air moisture reduction at any time step. Given the input information, namely, the process air and bed properties, mass flow rates, air humidity ratio, solution concentration, to the mathematical model output is obtained using the above equations by a finite difference method. By knowing the input conditions at the bottom i.e. entry of the dehumidifier column, outlet conditions at the top, i.e. exit of the bed are then obtained by carrying out time step-by-step analysis.

8.2. Auxiliary correlations

The bed porosity is calculated using calculated using the relation [23]

$$\varepsilon_b = 1 - \frac{\rho_b}{\rho_p} \tag{17}$$

The accumulation of moisture in the desiccant particles is highly dependent upon mass transfer coefficient at air and desiccant interface and specific surface area of desiccant particle. The specific surface area is defined as ratio of surface area to volume of desiccant particle and is given by

$$a = \frac{6(1 - \varepsilon_b)}{d_p} \tag{18}$$

The amount of area that is total bed surface area available for heat and mass transfer inside the bed for the given volume for moisture transport is evaluated as

$$A_{sf} = a \times 3.142 \times r_b^2 \times L \tag{19}$$

The perimeter of the bed is given by

$$P = \frac{A_{sf}}{L} \tag{20}$$

The gas side mass transfer coefficient for intra particle moisture transport is given by [23]

$$K_g = 0.704 \times \rho_a \times v \times Re^{(-0.51)} \tag{21}$$

8.3. Comparison of experimental and numerical results

Table 1 lists the experimental parameters for bed and process air as input to the theoretical model. Fig. 15(a)–(f) gives the comparison between calculated and experimental values for reduction in moisture content of process air. The results are shown with relative error and standard deviation error bars. Considering all the composite desiccant, the numerical values of the moisture reduction from process air with respect to experimental determination had a root mean square error in the range of 8.12–13.2% at 0.5 m/s and 3.26–5.97% at 1 m/s velocity of process air. The theoretical results obtained using Eqs. (13) and (14) exhibit reasonably a trend similar to that of the experimental results. The deviations between experimental and theoretical results may be due to the estimation of affinity constant. It is a function of bed water content and bed temperature. The estimation of bed water content as a function of time is needed. The isotherm property of the desiccant material used needs to be developed. In experiments inlet air humidity ratio is measured by humidity sensor. The theoretical value of reduction in air moisture content is calculated as a function of experimental inlet air humidity ratio as measured by humidity sensor. The data measured by sensors may have distortions and are reflected in the theoretical results.

9. Conclusions

In the present study, the naturally available transported clay used for making pots in the northern parts of Karnataka state, India is used as a liquid desiccant carrier. Apart, saw dust and horse dung are added to transported clay. The effect of operating parameters on the vertically packed burnt clay – additives – $CaCl_2$ composite desiccant beds is experimentally and numerically investigated. The following conclusions can be drawn:

1. At drying temperature of 500 °C the burnt clay $CaCl_2$ desiccant particles exhibits more pore volume whereas burnt clay horse dung additive desiccant particles shows maximum surface area.
2. Test results show that dehumidification performance decreases with increasing air mass fluxes. This is because of high air velocities lead to reduced residence time in the dehumidifier and result in limited mass transfer rates between moist air and to the desiccant surface.
3. It was observed that with number of cycles of use of desiccant particles, the surface gets descaled for burnt clay impregnated with $CaCl_2$ particles. Retaining structural and thermal stability promotes repeated use of clay horse dung additives composite desiccant particles. On repeated use of the clay-sawdust-$CaCl_2$ desiccant particles tends to become powdery.
4. At higher humidity of process air the heat liberated during the adsorption process going to decrease the moisture removal rate of clay additives based composite desiccants. Whereas for process air with lower humidity, the sensible heat transferred to the bed from process air will decrease the mass transfer potential towards the bed.
5. The theoretical results for percentage reduction in moisture content show trends similar to that of experimental results of burnt clay additive based $CaCl_2$ composite desiccants. The RMSE are higher when the process air velocity is 0.5 m/s.

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