CH 3522: Unit Operations Lab

Batch Drying

Batch - R, Group - 05
Date of Experiment: 5th March 2025
Date of Submission: 11th March 2025

Roll Numbers	Group Members
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1. Objective

- To analyze evaporation of water from a wet sand bed to study the batch drying process.
- To investigate the impact of varying air velocities on the evaporation rate.
- To determine the mass transfer coefficient (MTC) for different air velocities.
- To compare experimentally obtained MTC values with theoretical solutions

2. Introduction

Batch drying is a vital process in chemical engineering, used to remove moisture from solid materials through evaporation. In this experiment, the drying behavior of a wet sand bed is examined by monitoring the humidity levels of the incoming and outgoing air, as well as measuring the wet and dry bulb temperatures. Additionally, the study investigates the impact of varying air velocities on the drying rate, highlighting how improvements in mass transfer can enhance overall drying efficiency.

3. Theory

Drying is a critical operation in the production of chemical products and is employed in almost every facility manufacturing solids such as powders and granules. The process is typically carried out at several stages to eliminate moisture or solvents from raw materials, intermediate compounds, and finished products.

There are generally two types of drying systems: direct and indirect dryers. In direct drying, a warm or hot gas—usually air or an inert gas—is blown directly over the product in a continuous process. On the other hand, indirect drying is performed in a closed container that is heated by a circulating hot fluid, and this method can be conducted either in batches or continuously.

Batch drying is especially significant in the chemical and pharmaceutical industries. Not only does it effectively remove moisture from the product, but it also facilitates the recovery of solvents for reuse within the plant. Drying is often the most time-consuming stage in a production line, which typically includes reactors, evaporators, filters or centrifuges, and finally, the dryer before packaging. Consequently, the efficiency of the drying process has a major impact on the overall productivity of the facility.

Relevant Equations:

The mass transfer coefficient (MTC) is calculated using:

$$N = K_y(Y_s - Y) \tag{1}$$

Where,

N = molar flux of water in air flowing above the sand bed

K_y = mass transfer coefficient

Y_s = mole fraction of water in air at the surface of sand bed (it corresponds to saturation vapour pressure of water at that dry bulb temperature)

Y = average of the inlet and outlet mole fraction of water vapour in air

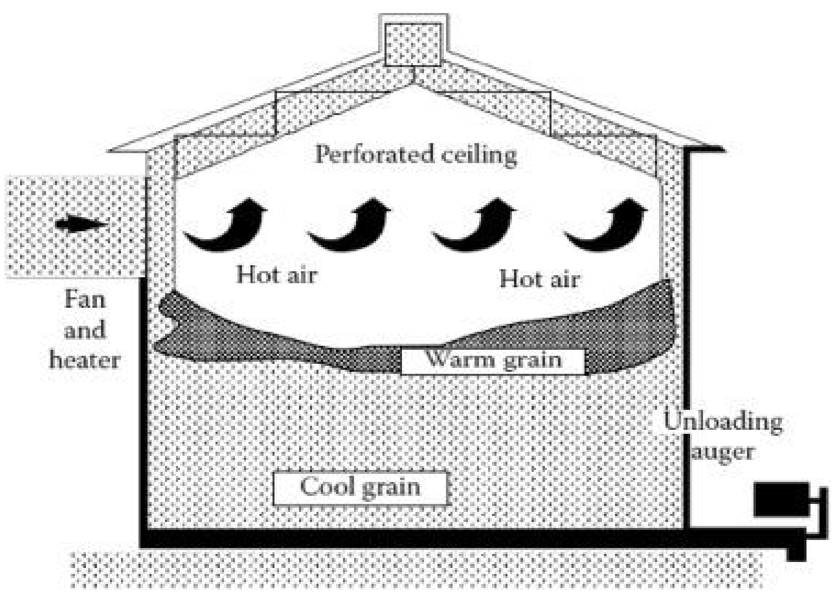


Figure 1: Batch Drying Phenomenon

The experimentally obtained mass transfer coefficient is compared with a theoretical value for the same using the following equation:

$$N_{Sh,\,avg} = \frac{K_c L}{D} = 0.0646(N_{Re,L})^{0.5}(N_{Sc})^{\frac{1}{3}} \tag{2}$$

Where,

$N_{Sh,\,avg}$ = average Sherwood number

K_c = mean mass transfer coefficient

L = length over which mass transfer occurs

D = diffusivity of water in air

$N_{Re,L}$ = Reynold’s number

N_{Sc} = Schmidt number

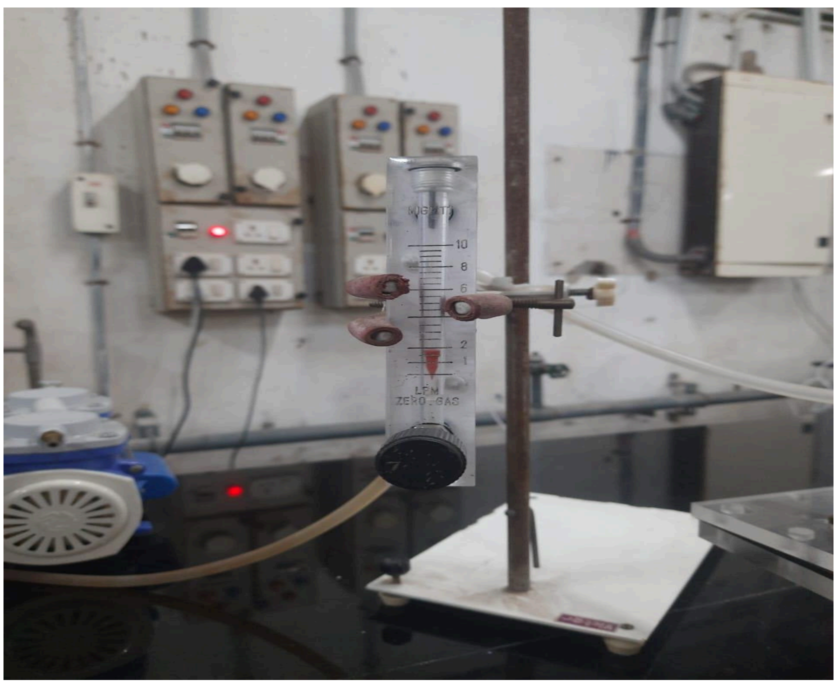


Figure 2: The flowmeter to check the inlet air’s volumetric flow rate

4. Apparatus Required

The apparatus and the chemicals used in this experiment are as follows,

- Batch drying setup, Spanner and Bolts
- Sand and Weighing Machine
- Distilled water, Pump, RH meter
- Connecting pipes, Teflon tape, Filler

5. Schematic of Experimental Setup

Experimental setup includes the following components and we have also provided the setup used during the experiment in figure 3.

- The batch drying setup consists of a controlled system where air is passed over a wet sand bed to study moisture evaporation. The system is enclosed and insulated using thermocol to prevent heat loss. The process starts with ambient air entering the setup through an inlet, which is regulated by a pump. The pump controls the airflow rate, ensuring consistent drying conditions.
- Inside the setup, a cavity filled with wet sand serves as the drying bed. Water is added to the sand until a thin layer of moisture remains on top. The drying chamber is tightly sealed using bolts, preventing any air leakage that could affect experimental accuracy.
- As the air flows over the wet sand, moisture evaporates and is carried along with the air towards the outlet. The air leaving the system contains the evaporated water, and its humidity is measured using an RH meter. The RH meter records wet bulb temperature, dry bulb temperature, dew point, and relative humidity of the exiting air.

Figure 3: Schematic diagram of Batch Drying Experiment

- The experiment is conducted at different airflow rates (2 LPM, 6 LPM, and 9 LPM) to analyze how air velocity affects the mass transfer coefficient and evaporation rate. The readings from the RH meter are taken at regular intervals until the system reaches a steady-state humidity value.

- The power supply ensures that the pump operates continuously, maintaining airflow through the drying chamber. By comparing the humidity measurements at the inlet and outlet, the moisture removal efficiency and drying rate can be determined.
- This setup allows for the study of mass transfer dynamics, helping understand the drying process and validating theoretical models related to batch drying.

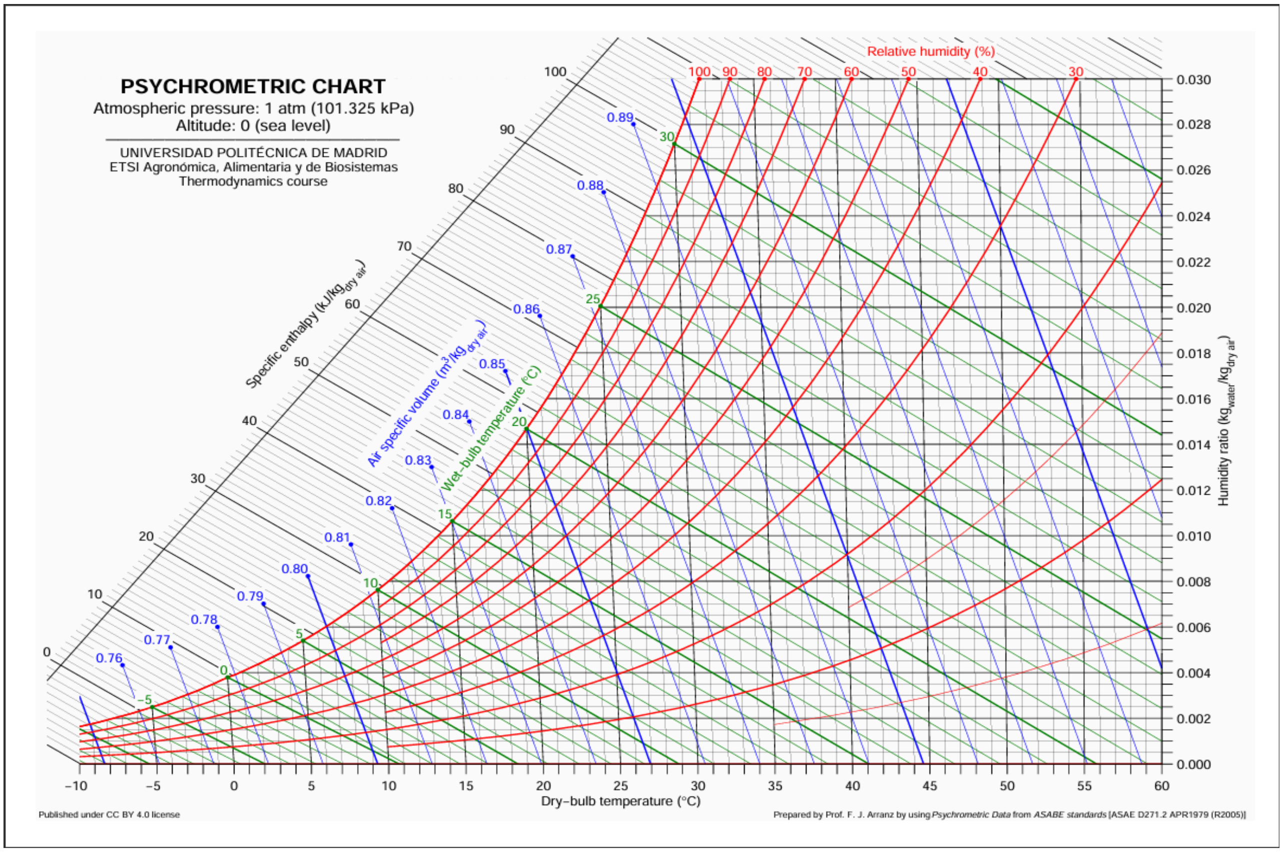


Figure 4: Psychrometric Chart to calculate several parameters using RH & Wet Bulb Temperature

6. Procedure

- Measure the RH of the inlet air using a RH meter.
- Measure the dimensions of the cavity in which the sand is to be filled to find its volume.
- Weigh the sand that is to be filled in the cavity.
- Measure the inner diameter of the pipes connected to the Batch drying setup (inlet and outlet pipes).
- Place the cavity in the setup.
- Fill the sand in the cavity till it completely fills and add water till a layer of it forms on the top.
- Measure the volume of water used in filling the sand filled cavity.
- Start closing the lid by tightening the bolts on the alternate corners and proceed in a diagonal way to ensure the lid is closed properly without any room for air leaks.
- Connect the pipes from the pump to the inlet of the setup and the outlet pipe to the RH meter.

- Switch On the pump and set the inlet air flow rate to 2 LPH.
- Take the readings for RH, wet bulb temperature, dew point and dry bulb temperature from the RH meter every minute.
- Continue the experiment till the RH value reaches a steady state.
- Repeat the experiment for inlet air flow rate values of 6 and 9 LPH as well.

7. Experimental Observations

The following table (refer to table 1, 2 & 3) contains the data collected while performing the experiment, corresponding to which the datasheet is also provided at the end of this report.

One thing to note is that the first data (at timestamp 0) in table 1 refers to the inlet condition at the starting.

The tabulated values are as follows,

Time	RH	T_{Wb} (℃)
0	52.8	22.9
1	59.4	25.3
2	59.3	25
3	59.4	24.7
4	59.7	24.5
5	60	24.4
6	60.1	24.4
7	60.3	24.3
8	60.6	24.4
9	61.6	24.5
10	62.6	24.7
11	62.9	24.7
12	62.9	24.7
13	62.8	24.7

14	62.9	24.7
15	62.9	24.7
16	63.3	24.8
17	63.3	24.8
18	64.2	24.9
19	64.4	25
20	63.9	24.9
21	63.7	24.8
22	63.9	24.8
23	64	24.8
24	64	24.8

Table 1: Experimentally Obtained Data for 2 LPM air flow rate

Time	RH	T_{Wb} (℃)
1	70.3	25.9
2	71.6	26
3	72.2	26.2
4	72.7	26.2
5	72.6	26.1
6	72.4	26.1
7	72.2	26.1
8	72.3	26
9	72.1	26
10	72.1	26

Table 2: Experimentally Obtained Data for 6 LPM air flow rate

Time	RH	T_{Wb} (℃)
1	78.4	27
2	77.6	26.9
3	76.5	26.7
4	75.3	26.5
5	73.6	26.3
6	71.5	25.9
7	70.1	25.8
8	68.7	25.5
9	68.2	25.4
10	67.3	25.2
11	67.1	25.2
12	67.1	25.2

Table 3: Experimentally Obtained Data for 9 LPM air flow rate

8. Sample Calculations

We show the calculations for the data obtained at time = 2 minutes when the volumetric flow rate of air is 2 liters per minute.

Air at Inlet

The inlet composition is assumed to be the same for all flow rates. The relative humidity RH value is 52.8% and the wet bulb temperature is $22.9\ ^oC$. From the Psychrometrics chart (figure 4) corresponding to these values we get the dry bulb temperature, which is $30.462\ ^oC$ or 303.61 K.

Humid ratio = $18.518\ g\ H_2O\ /\ kg\ Dry\ Air$

Mole ratio = $\frac{18.518}{18} mol_{H_2O}\ /\ \frac{1000}{28.96} mol_{dry\ air}\ = 0.02336$

This corresponds to the mole fraction value of 0.0228 of H_2O.

Vapor Pressure = Mole Fraction × $P_{atm}\ =\ 0.0228\ \times\ 1.01325\ \times\ 10^5\ Pa\ =\ 2312.714\ Pa$

Assuming ideal gas law to be valid, Molar flow rate of water vapor at inlet,

$$= \frac{P_{water\ vapor} \times Volumetric\ Flow\ Rate}{R \times T_{db}} = \frac{2.313 \times 10^3 \times (2\times10^{-3})\times(1/60)}{8.314 \times 303.61} = 3.054 \times 10^{-5}\ mol/s$$

Air at Outlet

At time $t = 2$ minutes, (at steady state) from the Psychrometric chart corresponding to the values of RH and wet bulb temperature, the dry bulb temperature comes out to be $31.520\ ^oC$.

Humid ratio $= 17.397\ g\ H_2O/\ kg\ dry\ air$.

Hence the mole ratio comes out to be 0.027989.

Mole fraction of water $= \frac{0.027989}{1+0.027989} = 0.02723$.

Pressure at outlet $= 0.02723 \times 1.01 \times 10^5\ Pa = 2758.8507\ Pa$.

Molar flow rate of water vapor

$$= \frac{P_{water\ vapor} \times Volumetric\ Flow\ Rate}{R \times T_{db}} = \frac{2.758\times10^3\times(2\times10^{-3})\times(1/60)}{8.314\times304.67} = 3.63 \times 10^{-5}\ mol/s\ .$$

Rate of evaporation = Molar flow rate out − Molar flow rate in

$$= 3.63 \times 10^{-5} - 3.054 \times 10^{-5}\ mol/s = 5.7649 \times 10^{-6}\ mol/s.$$

Area of evaporation $= 6.25 \times 10^{-4} m^2$.

Molar flux $(N) = \frac{Rate\ of\ evaporation}{Area\ of\ evaporation} = \frac{5.7649\times10^{-6}}{6.25\times10^{-4}} = 0.009224\ mol/m^2.s$

Now saturation water vapor pressure at this temperature ($31.520\ ^oC$) is 4.633 kPa.

Since, $N = K_Y(Y_S - Y)$

$Y_S = \frac{4.633\times10^3}{1.01325\times10^5} = 0.04572,\ \ Y = (0.0228 + 0.02723)/2 = 0.0250$

Therefore, $K_Y = 0.44564\ mol/m^s.s$

Volumetric flow rate $= \frac{P_{sat}}{RT} = 1.829\ mol/m^3$.

$K_{c,exp} = \frac{K_Y}{volumetric\ flow\ rate} = 0.2436\ m/s$.

Theoretical correlation for MTC

From the experimental setup we have the following parameters,

$L = 0.025m,\ \ Ac = \pi \times (0.006/2)^2 = 2.8274 \times 10^{-5} m^2$ (cross sectional area).

Also from literature we get the following properties of air,

$\rho = 1.293\ kg/m^3,\ \ \mu = 1.598 \times 10^{-5}\ m^2/s,\ \ D = 2.26 \times 10^{-5} m^2/s.$

Velocity of air = $\frac{Volumetric\ flow\ rate\ of\ air}{Cross\ sectional\ area} = \frac{2\times10^{-3}\times(1/60)}{Ac} = 1.1789\ m/s$

$N_{Re,L} = \frac{\rho v L}{\mu} = 2384.78$

$N_{Sc} = \frac{\mu}{\rho D} = 0.5468$

Therefore the theoretical value of the mass transfer coefficient comes out to be (using eq 2),

$K_{c,theo} = \frac{D}{L} \times 0.646 \times (N_{Re,L})^{0.5} \times (N_{Sc})^{1/3} = 0.02332\ m/s.$

9. Results & Discussions

The complete results for all the tabulated data are provided in the following tables,

Time (min)	Humid Ratio (%)	Molar Flux (mol/m^2s)	Experimental K_Y (mol/m^2s)	Experimental K_C (m/s)	Theoretical K_c (m/s)
1	17.796	0.0105	0.4981	0.2690	0.02332
2	17.397	0.0092	0.4456	0.2436	0.02332
3	17.059	0.0082	0.4095	0.2283	0.02332
4	16.856	0.0076	0.3904	0.2211	0.02332
5	16.769	0.0073	0.3850	0.2201	0.02332
6	16.778	0.0074	0.3879	0.2220	0.02332
7	16.682	0.0071	0.3791	0.2188	0.02332
8	16.821	0.0075	0.4024	0.2316	0.02332
9	17.019	0.0082	0.4463	0.2581	0.02332
10	17.332	0.0092	0.5063	0.2923	0.02332
11	17.357	0.0093	0.5162	0.2990	0.02332
12	17.357	0.0093	0.5162	0.2990	0.02332
13	17.349	0.0093	0.5130	0.2968	0.02332
14	17.357	0.0093	0.5162	0.2990	0.02332
15	17.357	0.0093	0.5162	0.2990	0.02332
16	17.506	0.0098	0.5435	0.3142	0.02332

17	17.506	0.0098	0.5435	0.3142	0.02332
18	17.697	0.0104	0.5887	0.3415	0.02332
19	17.832	0.0108	0.6098	0.3523	0.02332
20	17.673	0.0103	0.5782	0.3343	0.02332
21	17.539	0.0099	0.5572	0.3235	0.02332
22	17.556	0.0100	0.5640	0.3281	0.02332
23	17.564	0.0100	0.5675	0.3305	0.02332
24	17.564	0.0100	0.5675	0.3305	0.02332

Table 4: Results when the air flow rate is 2 LPM

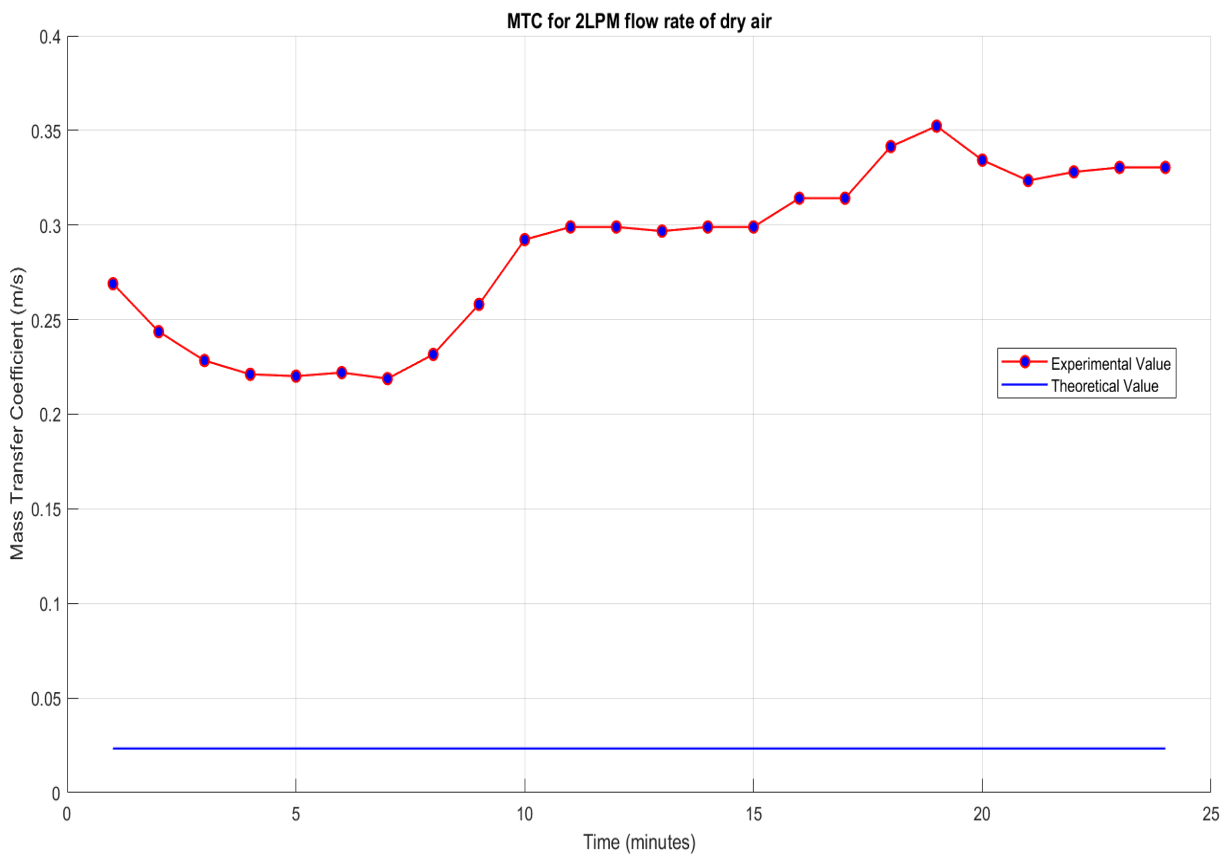


Figure 5: Plot showing the variation of mass transfer coefficients with time for 2 LPM air flow rate

Time (min)	Humid Ratio (%)	Molar Flux $(mol/m^2 s)$	Experimental K_Y $(mol/m^2 s)$	Experimental K_C (m/s)	Theoretical K_c (m/s)
1	19.387	0.0478	2.9288	1.7014	0.04039
2	19.622	0.0501	3.1587	1.8480	0.04039
3	19.923	0.0529	3.3313	1.9370	0.04039
4	19.960	0.0534	3.4080	1.9906	0.04039
5	19.825	0.0521	3.3549	1.9695	0.04039
6	19.810	0.0519	3.3226	1.9467	0.04039
7	19.795	0.0518	3.2928	1.9259	0.04039
8	19.675	0.0507	3.2687	1.9248	0.04039
9	19.660	0.0505	3.2368	1.9023	0.04039
10	19.660	0.0505	3.2368	1.9023	0.04039

Table 5: Results when the air flow rate is 6 LPM

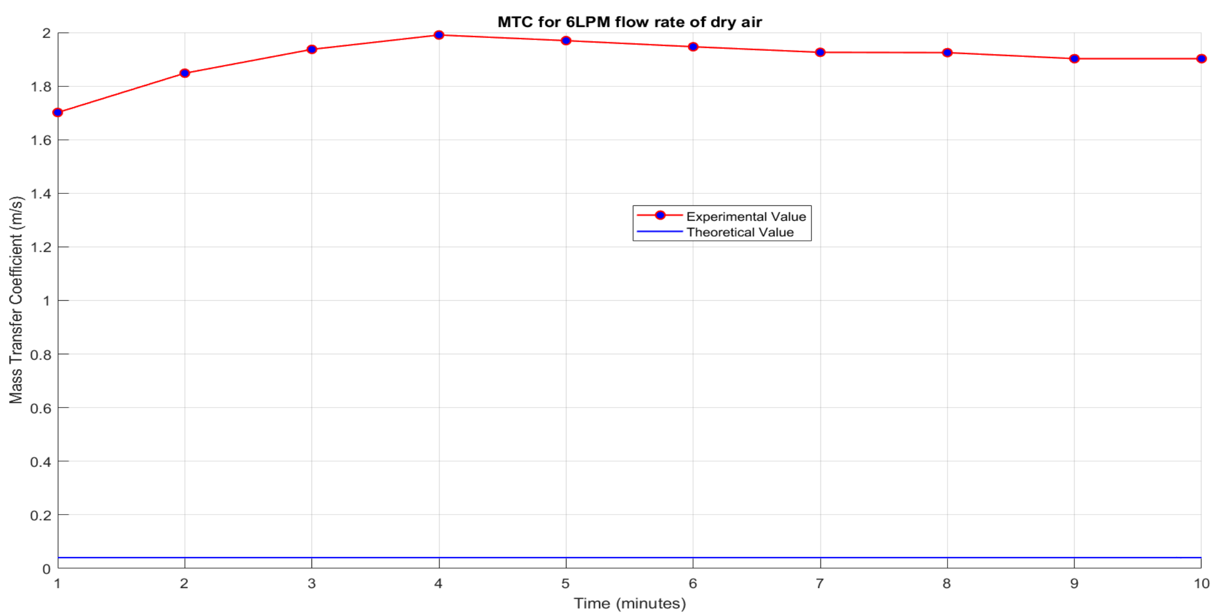


Figure 6: Plot showing the variation of mass transfer coefficients with time for 6 LPM air flow rate

Time (min)	Humid Ratio (%)	Molar Flux $(mol/m^2 s)$	Experimental $K_Y\ (mol/m^2 s)$	Experimental K_C (m/s)	Theoretical K_c (m/s)
1	21.432	0.1015	7.1201	4.1854	0.04947
2	21.240	0.0987	6.8207	4.0033	0.04947
3	20.893	0.0937	6.3944	3.7597	0.04947
4	20.542	0.0886	5.9478	3.4987	0.04947
5	20.157	0.0829	5.3937	3.1595	0.04947
6	19.488	0.0733	4.6588	2.7387	0.04947
7	19.256	0.0697	4.2928	2.5042	0.04947
8	18.776	0.0628	3.8220	2.2383	0.04947
9	18.615	0.0605	3.6636	2.1479	0.04947
10	18.303	0.0560	3.3700	1.9819	0.04947
11	18.287	0.0557	3.3316	1.9550	0.04947
12	18.287	0.0557	3.3316	1.9550	0.04947

Table 6: Results when the air flow rate is 9 LPM

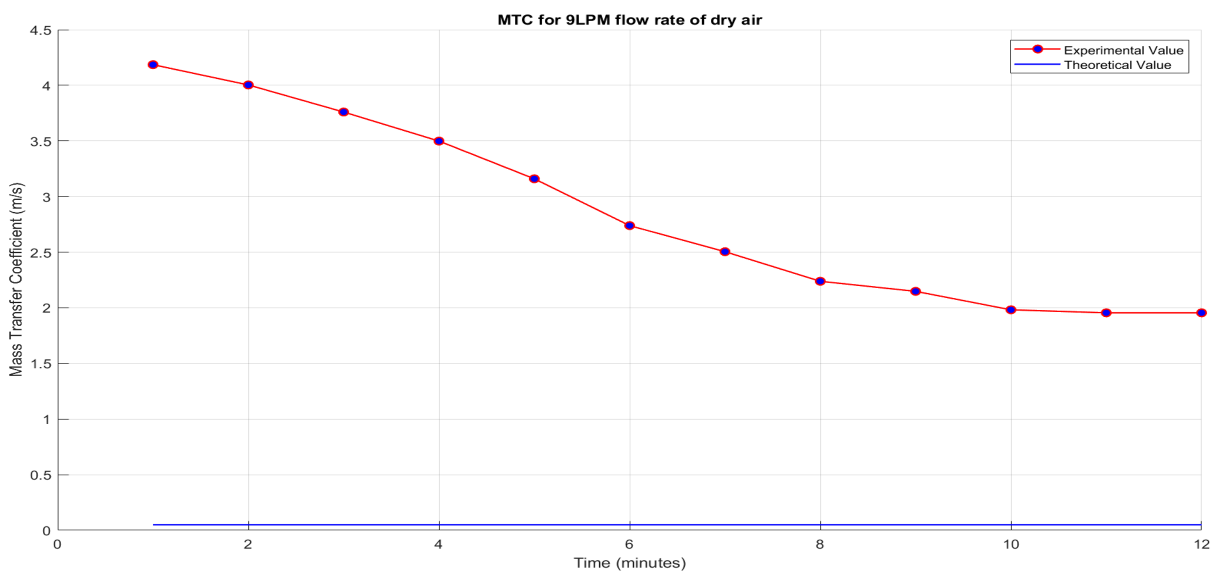


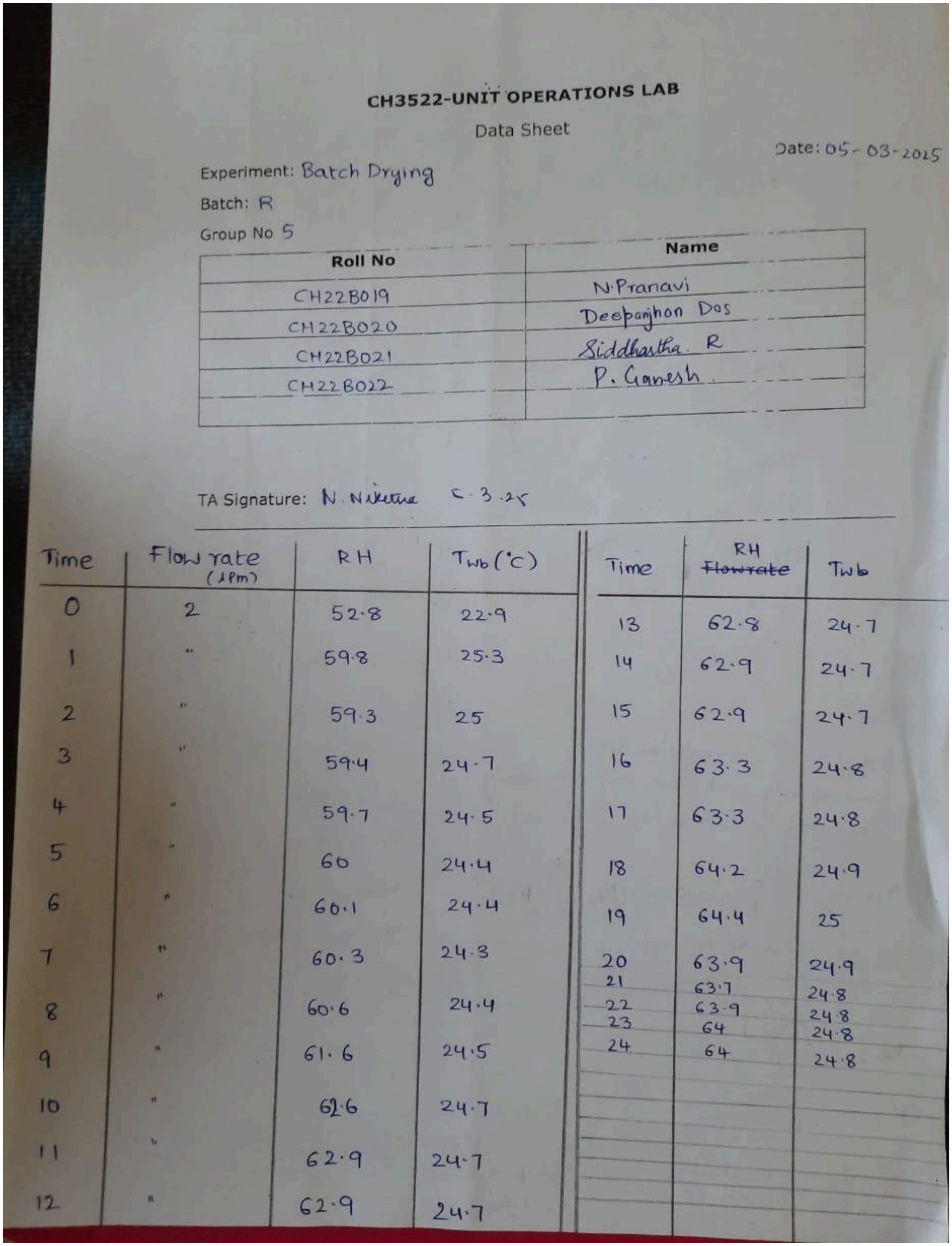
Figure 7: Plot showing the variation of mass transfer coefficients with time for 9 LPM air flow rate

10. Conclusions

- On increasing the air flow rate, the mass transfer coefficient increases and the relative humidity of exiting air increases since more moisture gets evaporated faster.
- After a threshold, the relative humidity of outgoing air reaches a steady value as the air's moisture holding capacity is met and equilibrium is established.
- Both experimental data and theoretical calculations indicate that by increasing the airflow rate we get higher mass transfer coefficient. This trend highlights the direct influence of airflow on enhancing moisture removal efficiency in the drying process.
- The difference between the experimental and theoretical mass transfer coefficient values can be due to simplifications in the theoretical model, measurement errors, or unnoticed losses in the setup.

11. References

I. Resource from Moodle.
II. Engineering Toolbox to get the diffusion coefficient and other constant values of air.
III. Psychrometric Chart at different altitudes and atmospheric pressure.
IV. Online Interactive Psychrometric Chart to obtain the Humid Ratios and Dry Bulb temp.
V. Engineering Toolbox to obtain the water vapor saturation pressure at different temperatures.
VI. Perry, R. H., & Green, D. W. (2008). Perry's Chemical Engineers' Handbook, Eighth Edition. McGraw-Hill. Mass Transfer P. 5-63 to obtain the theoretical correlation.
VII. The GitHub repository contains all the related data & coded scripts used for calculations.



CH3522-UNIT OPERATIONS LAB

Data Sheet

Date: 05-03-2025

Experiment: Batch Drying

Batch: R

Group No 5

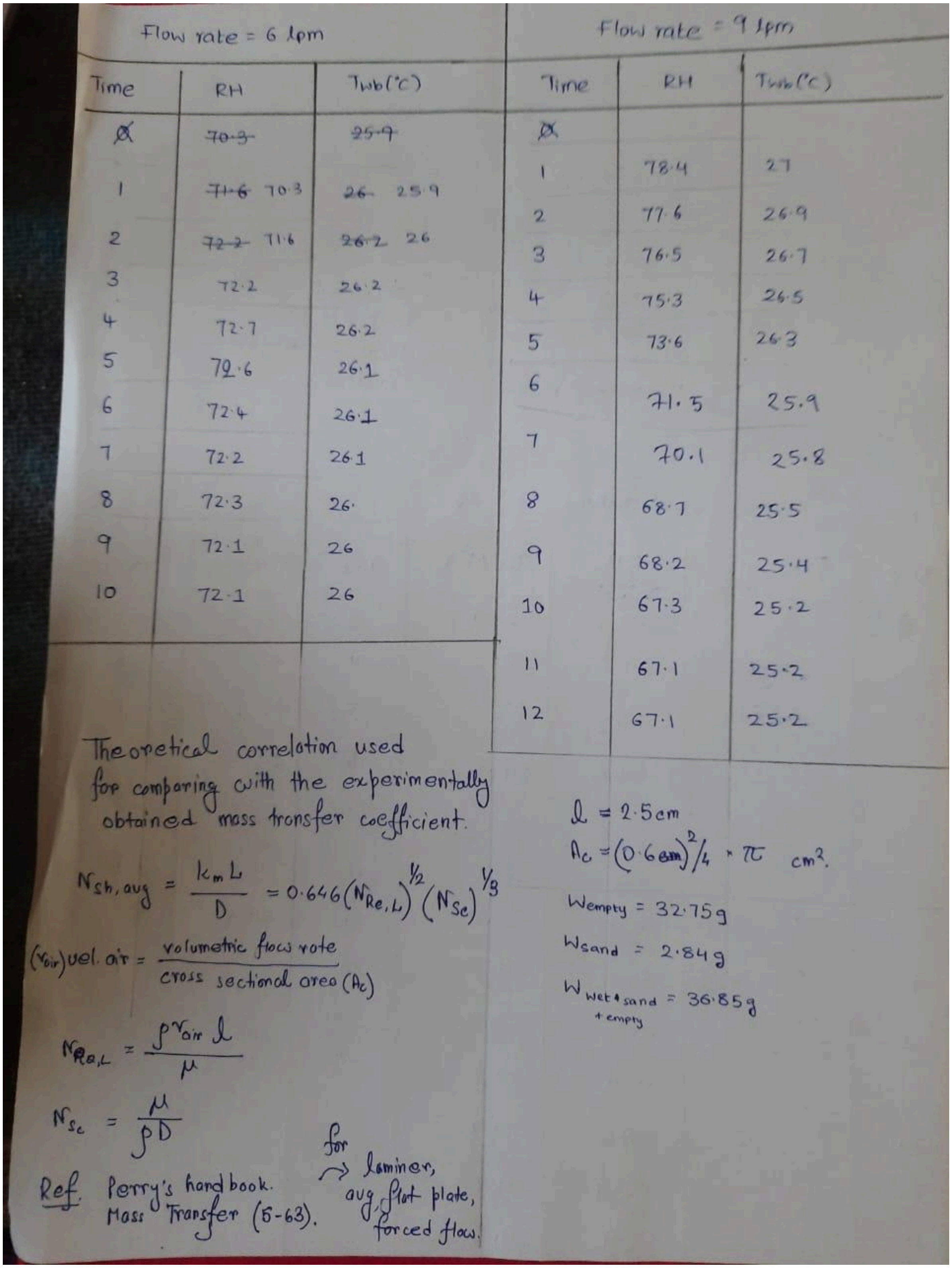
Roll No	Name
CH22B019	N.Pranavi
CH22B020	Deepanjhon Das
CH22B021	Siddhartha. R
CH22B022	P. Ganesh

TA Signature: N. Niketha 5.3.25

Time	Flow rate (lpm)	RH	T_{wb} (°C)
0	2	52.8	22.9
1	"	59.8	25.3
2	"	59.3	25
3	"	59.4	24.7
4	"	59.7	24.5
5	"	60	24.4
6	"	60.1	24.4
7	"	60.3	24.3
8	"	60.6	24.4
9	"	61.6	24.5
10	"	62.6	24.7
11	"	62.9	24.7
12	"	62.9	24.7

Time	RH ~~Flowrate~~	T_{wb}
13	62.8	24.7
14	62.9	24.7
15	62.9	24.7
16	63.3	24.8
17	63.3	24.8
18	64.2	24.9
19	64.4	25
20	63.9	24.9
21	63.7	24.8
22	63.9	24.8
23	64	24.8
24	64	24.8

Figure : Datasheet containing Lab-Data.



Flow rate = 6 lpm

Time	RH	T_{wb}(°C)
Ø	~~70.3~~	~~25.9~~
1	~~71.6~~ 70.3	~~26~~ 25.9
2	~~72.2~~ 71.6	~~26.2~~ 26
3	72.2	26.2
4	72.7	26.2
5	72.6	26.1
6	72.4	26.1
7	72.2	26.1
8	72.3	26.
9	72.1	26
10	72.1	26

Flow rate = 9 lpm

Time	RH	T_{wb}(°C)
Ø		
1	78.4	27
2	77.6	26.9
3	76.5	26.7
4	75.3	26.5
5	73.6	26.3
6	71.5	25.9
7	70.1	25.8
8	68.7	25.5
9	68.2	25.4
10	67.3	25.2
11	67.1	25.2
12	67.1	25.2

Theoretical correlation used for comparing with the experimentally obtained mass transfer coefficient.

$$N_{Sh,avg} = \frac{k_m L}{D} = 0.646 (N_{Re,L})^{1/2} (N_{Sc})^{1/3}$$

$$(v_{air})\ \text{vel. air} = \frac{\text{volumetric flow rate}}{\text{cross sectional area } (A_c)}$$

$$N_{Re,L} = \frac{\rho v_{air} l}{\mu}$$

$$N_{Sc} = \frac{\mu}{\rho D}$$

Ref. Perry's hand book. Mass Transfer (5-63). → for laminar, avg, flat plate, forced flow.

$l = 2.5$ cm

$A_c = (0.6\text{ cm})^2/4 \times \pi$ cm^2.

$W_{empty} = 32.75$ g

$W_{sand} = 2.84$ g

$W_{wet+sand+empty} = 36.85$ g

Figure : Datasheet containing Lab-Data.