ADSORPTION HEAT RECOVERY.

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1986.

I declare that this Thesis does not only conatin my own work but also was composed by me alone.

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ACKNOWLEDGEMENTS

To The Royal Norwegian Agency for Development,NORAD,for awarding me this Scholarship.

To The British Council for administering the scholarship;Your hospitality was very helpful indeed!

To my employer,The University of Dar-Es-Salaam for giving me study leave to attend this course.

To Dr Collin Pritchard,my supervisor and all staff of the Department of Chemical Engineering- Academic,Technical and fellow postgraduate students- for your invaluable assistance,guidance and encouragement.

To Helene,my wife and my daughter Martha,you both deserve belated thanks for your patience and understanding during my two years of absence from home.

Enock Masanja.

September 1986.

ERRATA

The following corrections are appended in the backcover pocket:

1. page 26
2. page 45
3. page 109

Also appended are:

- Sample table of data.
- Diagram of Adsorber bed showing thermocouple locations.(page 71a)
- Detailed flow-diagram of the procedure for parameter estimation as fig.2.5a.
- Figures A1-A10 giving bed temperature as function of bed axial distance with time as a parameter.

ABSTRACT

Drying accounts for a high proportion of the process industries' Energy use.It is energy intensive but inefficient.Most of the energy lost leaves in exhaust streams;mostly (typically 80%) in the form of Latent heat. Effective heat recovery from these streams requires that not only both the Latent and Sensible heats be recovered but also upgraded to a useful temperature as direct heat recovery is only possible at very low temperatures.

This study considers Adsorption Heat recovery using Magnesium Chloride as an adsorbent.The study shows that,using a feed stream of 30 to 60 °C and 50%RH an outlet stream of 80 to 100 °C and 10%RH could be achieved,suitable for recycling to a drying process.

SYMBOLS

a	Interfacial area per unit volume	$[m^2/m^3]$
A	Area	$[m^2]$
C	Discharge Coefficient	[-]
C	Cost	[$]
C	Concetration	$[mol/m^3]$
C_0	Inlet Adsorbate Concentration	$[mol/m^3]$
Ci	Intraparticle Adsorbate Concentration	$[mol/m^3]$
Cad	Adsorbed Adsorbate Concentration	$[mol/m^3]$
C	Specifc Heat	[J/kgk]
C_f	Fluid Specific Heat	[J/kgk]
Cp	Specific Heat at constant pressure	[J/kgk]
Cv	Specific Heat at constant volume	[J/kgk]
Cs	Solid Specific Heat	[J/kgk]
D,d	Diameter	[m]
Dp	Particle Diameter	[m]
dz	Elemental height increment	[m]
De	Effective Diffusivity in particle	$[m^2/s]$
Dax	Axial Fluid Dispersion Coefficient	$[m^2/s]$
D_G,Dv	Gas phase Diffusion Coefficient	$[m^2/s]$
G,G'	Gas Mass rate	$[kg/m^2s]$
G	Gibbs free energy	[J/kg]
H	Enthalpy	[J]
H_f	Heat of Formation	[J/kg]
h_G	Gas side Heat transfer Coefficient	$[W/m^2k]$
h_D	Gas side Mass transfer Coefficient	[m/s]
hp	Particle to Fluid Heat transfer Coefficient	$[W/m^2k]$

h_0	Overall Heat transfer Coefficient	$[W/m^2k]$
hr	Radiant Heat transfer Coefficient	$[W/m^2k]$
j_H	Chilton and Colburn j factor for Heat transfer	[-]
j_D	Chilton and Colburn j factor for Mass transfer	[-]
k	Thermal Conductivity	[W/mk]
ks	Solid Thermal Conductivity	[W/mk]
k_f	Fluid Thermal Conductivity	[W/mk]
ke°	Effective Thermal Conductivity of stagnant packed bed	[W/mk]
K_A	Adsorption Equilibrium Constant	$[m^3/kg]$
L	Length	[m]
Mm	Molecular Weight of mixture	[kg/kmol]
M_a	Molecular Weight of Air	[kg/kmol]
M_a	Total weight of Air	[kg]
M_{H2O}	Molecular Weight of Water	[kg/kmol]
M_b	Mass of Bed	[kg]
m	Mass flow	[kg/s]
Nu	Nusselt Number = $hpDp/k_f$	[-]
Nur	Radiant Nusselt Number = $hrDp/k_f$	[-]
P	Pressure	$[N/m^2,atm]$
Pr	Prandtl Number = $C_F\mu_F/k_f$	[-]
P_{gf}	Partial Pressure of inerts in gas stream	[atm]
Q	Volumetric Flow Rate	$[m^3/s,l/min]$
Rd	Reynolds Number at Orifice throat	[-]
Re	Reynolds Number = $Dp\varepsilon_b\rho_F U/\mu_F$	[-]
R	Particle radius	[m]
R_T	Tube,Bed radius	[m]
r	Radial distance variable in particle	[m]

s	Thickness	[m]
S	Specific Entropy	[J/kgk]
Sc	Schmidt Number = $\mu_F/Dv\rho_F$	[-]
Sh	Sherwood Number = k_FDp/Dv	[-]
T	Temperature	[°C,K]
T_F	Temperature in bulk Fluid phase	[°C,K]
Ts	Temperature in Adsorbent particle	[°C,K]
T_0	Room Temperature,Fluid Temperature at Bed inlet	[°C,K]
t	Time	[s]
U	Velocity	[m/s]
x	Axial distance	[m]
X	Bed Loading	[kg/kg]
x_R	Arbitrary axial distance taken as reference	[m]
λ	Latent Heat of Condensation	[kJ/kg]
ρ	Density	[kg/m^3]
ρ_f	Fluid Density	[kg/m^3]
ρ_s	Solid Density	[kg/m^3]
μ_f	Fluid Viscosity	[Ns/m^2]
ω	Specific Humidity	[kg/kg]
β	Orifice diameter to Pipe diameter ratio	[-]
γ	Expansion factor	[-]
α_{ax}	Axial Thermal Dispersion Coefficient	[m^2/s]
εr	Root mean square error	[-]
ε_b	Bed Voidage	[-]
ε_p	Intraparticle Voidage	[-]
τ	Time for Thermal wave to stabilise(Tail vanish)	[s]
$f_{t\rightarrow s}$	Laplace Transform	

$f_{s \rightarrow t}$	Inverse Laplace Transform

Subscripts

s	Saturation
f	Film/Interface
l	Liquid
G	Gas

CHAPTER 1

INTRODUCTION

1.1. Energy Cost

The drive towards energy efficiency that the industry is experiencing today,probably owes its impetus to the surge of prices of primary fuel-Crude Oil and Gas-in the early seventies.For example Crude petroleum price rocketed from 3.243 US$ per barrel in October 1973 to around 12.492 US$ per barrel in January 1974.See Table 4 /1/.Mean Crude Oil prices from 1970 to 1983 based on UK imports shown in figure 1.1 illustrates that, prices have in general,until only recently been rising.

1.2. Major Energy Consumers

The huge energy bills forced the Industry to adopt means of improving energy efficiency.Proper energy integration has since become the norm of new plant designs.Heat recovery units have found places in old plant retrofits, even small energy savings in major energy consumers can result into substantial financial savings.

The breakdown of energy consumption in the UK between 1977 and 1983 is given in Tables 1.1 and 1.2 .

Table 1.1: UK Energy Consumption .[MJ] 1977-1983.
Heat Supplied Basis.Source Tables 9-10 /2/.

Year		1977	1978	1979	1980	1981	1982	1983
Iron and	PJ	520	530	530	302	343	310	308
Steel	%	8.4	8.5	8.1	5.1	5.9	5.4	5.4
Total(other)	PJ	1887	1919	1914	1716	1571	1530	1479
Industries	%	30.6	30.7	29.4	28.8	27.1	26.7	25.9
Total	PJ	2407	2449	2444	2018	1914	1840	1787
Industry	%	39	39.2	37.5	33.9	33	32.1	31.3
Rest	PJ	3768	3797	4064	3946	3880	3887	3928
	%	61	60.8	62.5	66.1	67	67.9	68.7

Values converted from Therms.1Therm ≈ 105.5MJ.

Total (other) Industries imply all non Steel or Iron like Cement,Bricks, Chemicals,etc.

Rest include Transport,Domestic,Public,Agriculture,etc.

Table 1.2: Energy Consumption Breakdown,non Steel UK Industries.
Heat Supplied Basis.Units:[PJ].Source Table 9 /2/

Year		1979	1980	1981	1982	1983
Total Energy		1914	1716	1571	1530	1479
Eng.& Metal	a	6.7	6.6	6.3	5.8	5.5
Food,Drink& Tobacco	a	3.3	3.3	3	3	2.9
	b	11.3	11.5	11.2	11.3	11.2
Chemical and Allied Trade	a	7	7.3	7.3	7.3	7.3
	b	24.8	25.7	26.8	27.5	28.3
Textile,Leather and Clothing	a	2	1.6	1.5	1.5	1.5
	b	6.7	5.7	5.7	5.5	5.8
Paper,Printing & Stationery	a	2.1	2	1.7	1.6	1.5
	b	7.1	6.7	6.2	5.9	5.8
Bricks,Fireclay and Tiles	a	0.9	0.8	0.8	0.8	0.7
	b	3	2.8	2.9	2.9	2.9
China,Glass& Earthenware	a	1.1	1.1	1	1	0.9
	b	3.7	3.9	3.7	3.6	3.6
Cement	a	1.5	1.4	1	1.2	1.1
	b	5.1	4.8	3.8	4.6	4.3
Others	a	4.6	4.6	4.5	4.5	4.3
	b	15.7	16	16.6	16.8	16.8

Key: a – As percent of total Energy consumed.

b – As a but excluding Eng.& Metal.

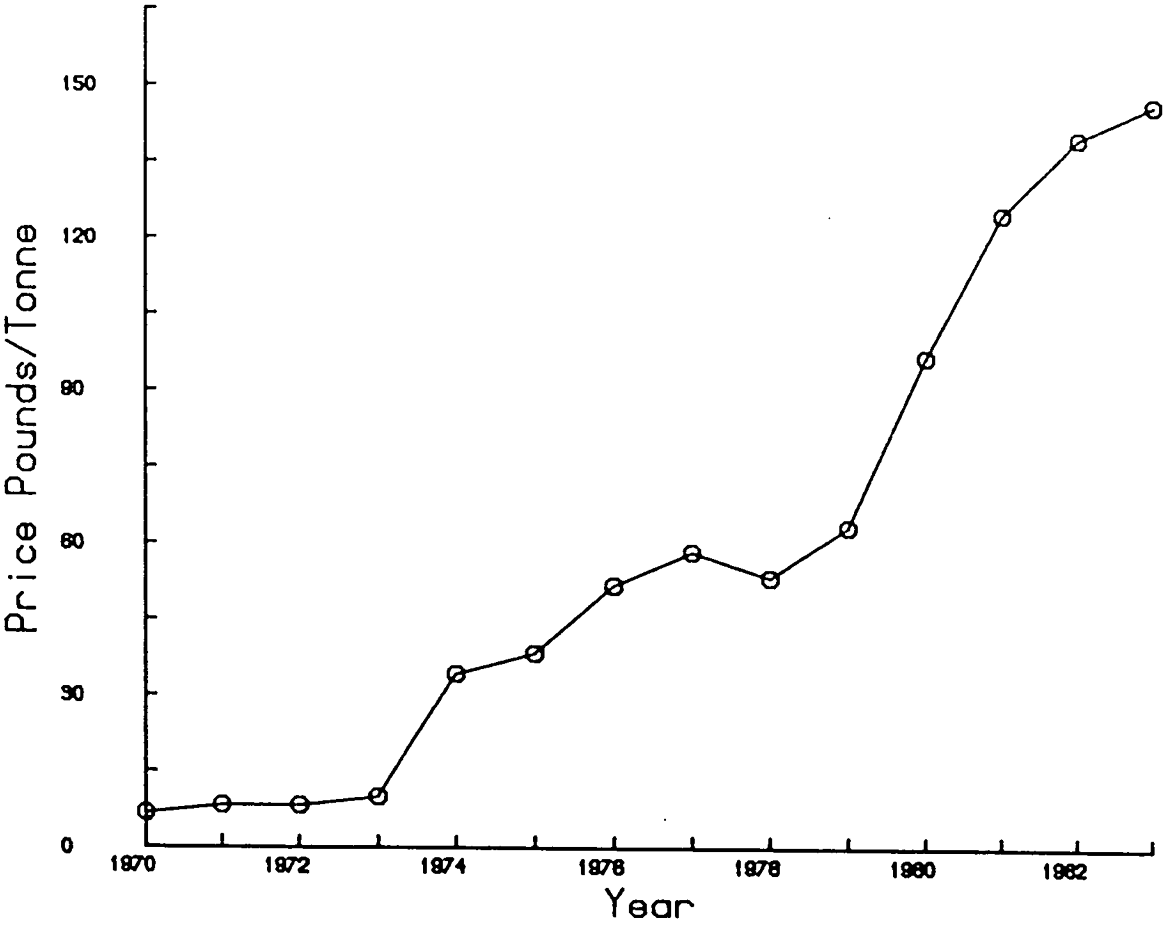
1.3. Drying:The Energy intensive Unit Operation

In all non metal Industries most of the energy consumed is related to drying or drying related unit operations.Examples below typify this fact.Values in 2 through 7 are based on heat supplied in the UK industry in 1980.

Fig.1.1 Crude Oil Prices 1970-1980

Based On UK Imports

Source Table 9-10 /2/



1. About 10% of USSR energy consumption is used in drying operations.See /3/.
2. 80-90% of total energy consumed in Building Brick industry is for drying and firing.See page 17 /4/.Some literature quote a figure of 92%.See page 36 chapter two /5/.
3. Of all energy used in Paper,Pulp and Board industry drying accounts for nearly 30%. /6/.
4. In Dairy industry,dry milk is produced by spray drying concetrated milk, consuming 25% of the total energy input.See page 20 chapter five /5/.
5. In Pottery,33% of the total energy input is used in drying,and 61% in firing.See page 63 chapter two /5/.
6. In Cement industry 92% of the energy used is used in calcining and drying.Page 13 chapter two /5/.
7. It is estimated that 5% of total UK energy consumption is used in drying./7/.

1.4. Energy Loss in Drying

Despite of being energy intensive,most drying processes are inefficient.Efficiencies may range from 20% in batch fluidised bed drying food additives,to 65% in brick dryers.In some specialised industries,like pharmaceutical tablet coat drying,low efficiencies of the order of 7% are typical.See /8/.

Exhaust gases from dryer are essentially warm and moist and they contain most of the energy lost.For example,in Building Brick dryers,between 40-70% of the energy lost is carried to the atmosphere by the exhaust gases.See page 45 chapter 2 /5/.This value can be as high as 75% in Milk spray drying /9/ and 87% in Paper,Pulp and Board drying machines.Page 80 /10/.

The form of energy lost depends on the exhaust gas temperature and humidity.In most cases the greatest amount is in the form of latent heat,eg, 79% in Paper drying,page 80 /10/,and 45% in Milk spray drying /9/.Thus unless exhaust gas temperature is very high,greater than say 100 °C,then the sensible heat is but a small proportion of the heat lost.

This can be shown theoretically by considering enthalpy h,of an air-water vapour mixture.If we define h=0 at any selected reference temperature, T_0,then the total enthalpy of the mixture,h_T is given by

$$h_T=C(T-T_0)+\omega\lambda(T_0) \tag{1.1}$$

Where

$$C=1.005+1.88\omega \tag{1.2}$$

Thus if R is the Latent heat to Total heat ratio,then

$$R=\omega\lambda(T_0)/[\omega\lambda(T_0)+C(T-T_0)] \tag{1.3}$$

Equation (1.3) can also be rearranged to give

$$\Delta T=(1-R)\omega\lambda(T_0)/RC = T-T_0 \tag{1.4}$$

Taking the reference temperature to be 0°C then $\lambda(0°C)=2501.6$kJ/kg Equation (1.3) gives loci of points (given by temperature and latent to total heat ratio) with equal humidity.See plot in figure 1.2.Equation (1.4) give loci of points (given by temperature and humidity) of equal latent to total heat ratio.These loci have been ploted in a psychrometric chart,figure 1.3 in which some known conditions of exhaust gases from true industrial processes have been indicated too. See also Tables 1.3 and 1.4 below.

Table 1.3: Air Temperature with Equal Latent to Total Heat Ratio.
Variable:Humidity.Equation (1.4).

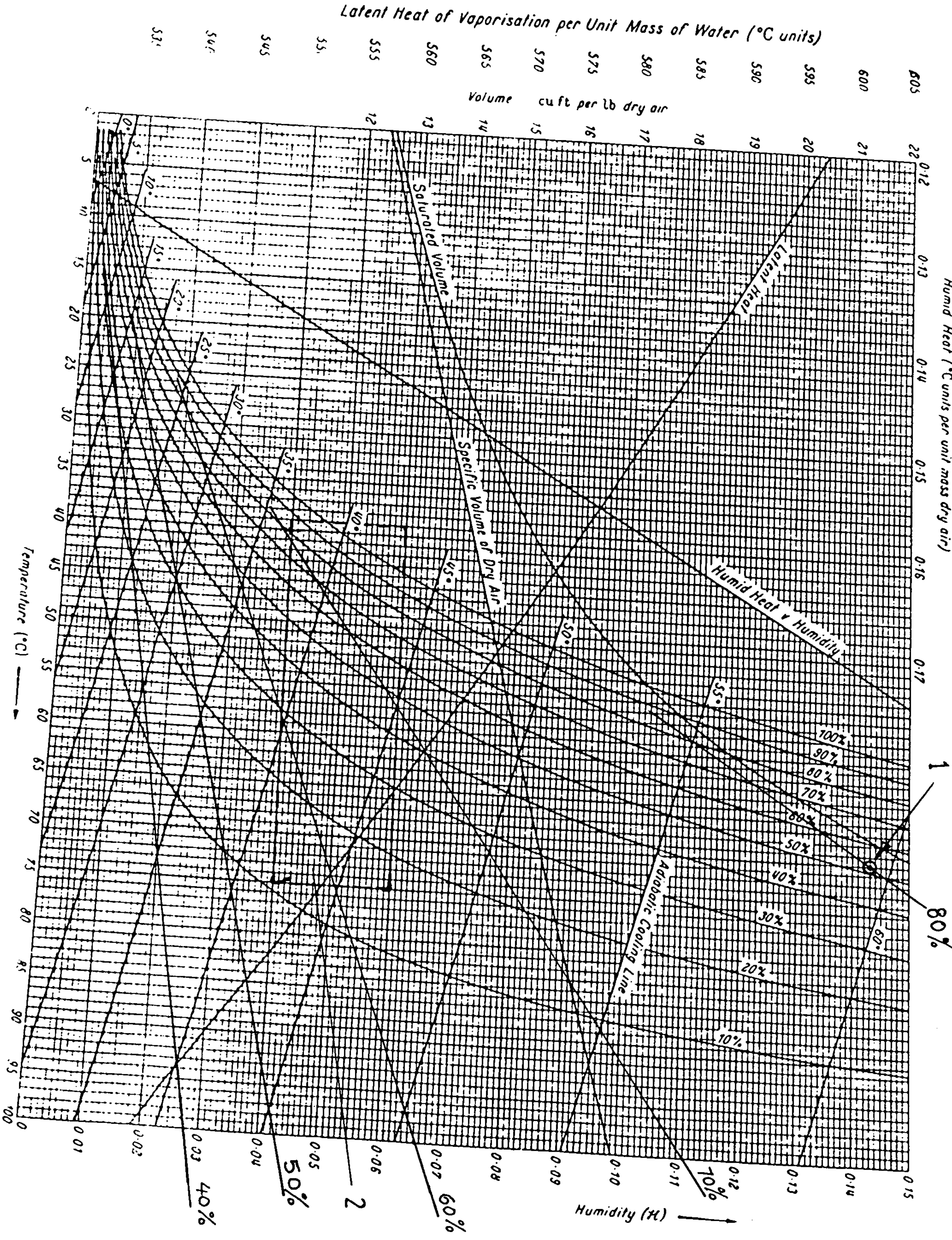
	Temperature °C				
ωkg/kg	R=0.4	R=0.5	R=0.6	R=0.7	R=0.8
0.01	37	24	16	10	6
0.02	72	48	32	21	12
0.03	106	71	47	30	18
0.04	139	93	62	40	23
0.05	171	114	76	49	28
0.06	201	134	90	58	34
0.07	231	154	103	66	39
0.08	260	173	115	74	43
0.09	288	192	128	82	48

Table 1.4: Latent Heat to Total Heat Ratio at Various Temperatures.
Parameter:Humidity.Equation (1.3).

	Ratio,R %			
ΔT°C	ω=0.02	ω=0.04	ω=0.06	ω=0.08
10	83	90	93	95
20	71	82	87	90
30	62	76	82	85
40	55	70	77	81
50	49	65	73	78
60	44	61	69	74
70	41	57	66	71
80	37	54	63	68
90	35	51	60	66
100	32	48	57	63

Fig.1.2:Psychrometric Chart.

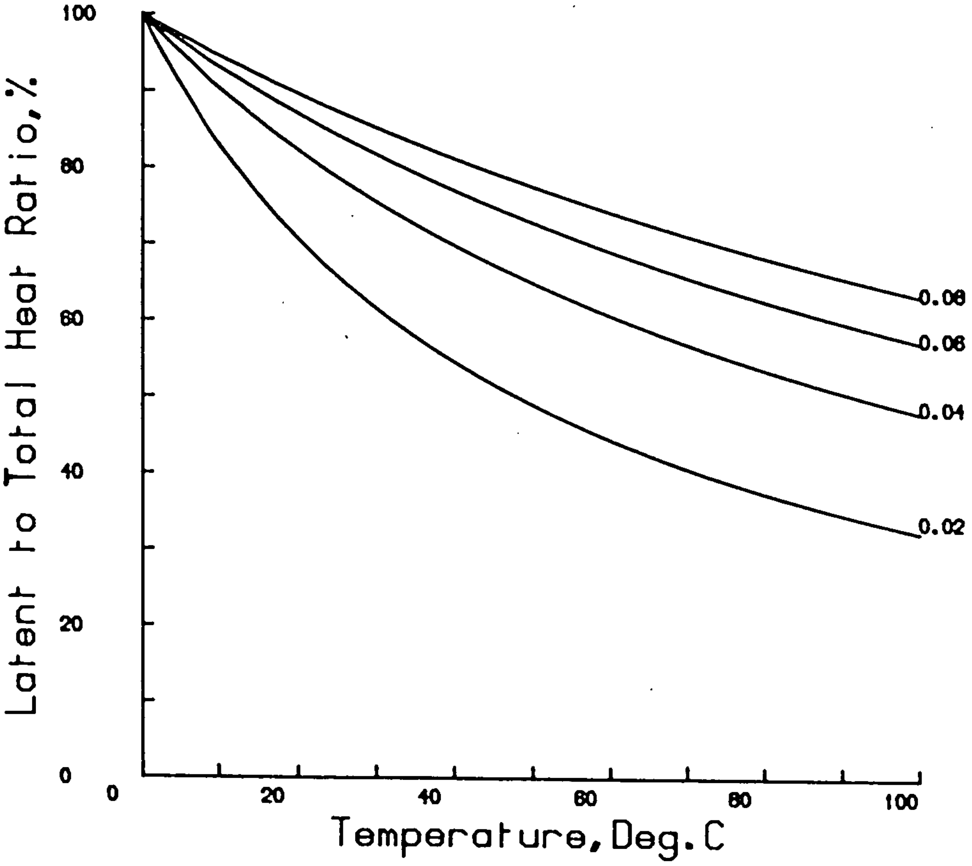
Latent Heat to Total Heat Ratio lines Inserted.



1 Exhaust from paper drying machine.
2 From milk spray drying.

Fig. 1.3 Latent Heat to Total Heat Ratio

Eqn. 1.3: Parameter is Humidity.



1.5. Exhaust Gas Temperature and Humidity

There are,in practice,diverse drying processes matched with a diversity of drying equipment.Exhaust gases conditions thus will vary from process to process.Some typical examples are enumerated below:

1. Paper,Pulp and board:Temperatures of exhaust can reach 70°C and humidity up to 0.28 kg/kg depending on amount and inlet temperature of drying gas./6/.
2. Milk spray drying:Dry bulb temperature ranges between 80 and 100°C.Absolute humidity ranges between 0.04 and 0.06 kg/kg giving a gas dew point of 30-40°C./9/.
3. Refractories industries:Exhaust gases are kept at 225-250°C to avoid corrosion. Page 25 /12/.

1.6. Heat Recovery from Exhaust Gases:Problems

There are inherent problems associated with heat recovery from moist gas streams.

Firstly,gas side heat transfer coefficients are characteristicaly low demanding large heat transfer areas.This might make heat recovery from gas streams uneconomical.

Most exhaust gases from kilns and dryers are dirty and might contain acidic gases (SO_2 and some Fluorides).If such moist streams are cooled below their dew points,the condensate formed may present severe corrosion problems.In practice,such gas streams would be cooled to a few degrees about 10°C above their dew points.Thus,the latent heat which is the highest proportion is not recovered.

Dirty and fine particles as in exhaust from milk spray dryers may cause fouling of the heat transfer area.If a condensate is formed,sticky substances may be formed presenting additional cleaning difficulties.

Heat recovery from waste gases is of low grade compared to the heat that is actually needed in the process.Thus, if no ready use of this heat is available,the whole idea of heat recovery becomes unattractive.The possible end use is,in most cases,preheating incoming gas/air.But as humidity from the exhaust must not be passed over to the incoming air,direct contact heat exchange is not possible.Recuperative type exchangers have to be used,adding additional thermal resistance.Viability of this type of heat recovery is then determined by availability of cheap recuperators.

Exhaust gas humidity at given pressure of the stream determines the dew point of that stream.Thus even where the latent heat can be recovered (no corrosion problems),if the dew point is low, the latent heat so recovered will be available at low temperatures and unless upgraded to higher temperatures,this heat will be of little value.

1.7. Heat Recovery from Wet Gases:Methods

Successful heat recovery from moist (wet) gas streams must be capable not only of recovering the latent heat but also upgrading the heat to useful levels.

A unit that recovers heat and delivers it at a higher temperature is called a Heat Pump.Some of the Heat Pumps available are described below.

1.7.1. Refrigerative Dehumification

Refrigerative Dehumification Heat Pump can be driven either Mechanically or Thermally.Mechanical drives include Electrical driven Compressors and Compressors directly coupled to Internal Combustion engines.

In figure 1.4 an example of use of this type of Heat Pump in recovering heat from humid air from a drying chamber is shown.See also figure 6.25 /10/.

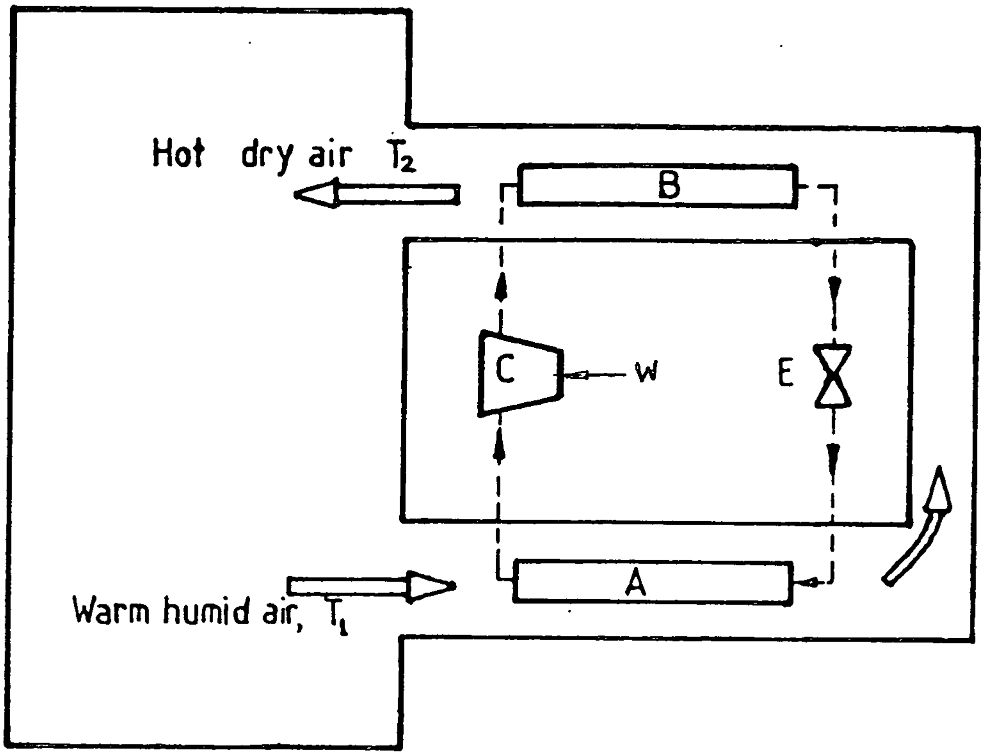


Fig.1.4: Heat Pump in a Dryer.

A–Heat Pump Evaporator.
B–Heat Pump Condensor.
C–Heat Pump Compressor.W is Work of Compression.
E–Heat Pump Expansion valve.

By passing the warm humid air over the Heat Pump Evaporator,A, the air is cooled below its dew point.Both Sensible and Latent heats are recovered.The condensate is drained off.The work of Compression in the Compressor,C upgrades the recovered heat to the condensor temperature.The dry cold air is then heated to temperature T_2 at the Condensor,B and recycled back to the drying chamber to pick more moisture.

The condensed Refrigerant vapours are expanded in valve E to give a vapour-liquid mixture which returns to the evaporator,completing the cycle.

The temperature lift,T_2-T_1,depends on the refrigerant and Heat Pump conditions(pressure and Temperature).

This type of Heat Pump is well developed,flexible and with current technology,easy to control.With suitable choice of refrigerant and proper control, high perfomance efficiencies can be achieved by matching power input to the compressor and the heating load.

In both Mechanical and thermally driven Heat Pumps,a fraction, normally small,of high grade energy is used to upgrade the low-grade heat recovered to a higher temperature.

A dimensionless quantity,the Coefficient of perfomance,C.O.P,is used to measure how many times more effective the Heat Pump is a supplier of heat than the high grade energy would be if used directly for heating.C.O.P is defined to be the ratio of the rate of heat rejection(at the condensor) to the mechanical power(or heat for heat driven Heat Pumps)drawn.Typical C.O.P values may range between 3 and 5 depending on type of Refrigerant and system conditions.See also /13/.

The advantage of Refrigeration Dehumification Heat Recovery system is its ability and reliability to offer precise humidity control in the drying chamber.This is particularly suitable where humidity control is required to control product quality such as in Timber drying and in Earthenware industries.

Refrigerants available allow only a limited temperature working range of 40–120°C.The large capital costs prohibit Heat Pumps of this type becoming universal pancea for energy saving.And in general Heat Pumps are only considered when other means of heat recovery have been exhausted or can not be applied.See also /14/.

1.7.2. Adsorption Heat Pump

In refrigerative dehumidification heat pump,the work of compression is essential to effect the upgrading (pumping) the heat.Adsorption Heat Pump, on the other hand owes its function to the Adsorption reaction being exothermic.

The driving force for adsorption of a component from a gaseous mixture on a solid adsorbent(and its subsequent desorption) is provided by the difference in the vapour pressure of the adsorbate in the bulk gas phase and in the adsorbent phase.The vapour pressure in the bulk phase is equal to the partial pressure of the adsorbate.

Thus,adsorption is favoured by low temperatures or high pressures. The reverse reaction,desorption, is favoured by high temperatures or low pressures.The process of adsorption/desorption can therefore be done by swinging temperatures from low to high-Temperature Swing Adsorption Process or by swinging pressure from high to low-Pressure Swing Adsorption Process.

In Temperature Swing Adsorption Process,when adsorption takes place,the adsorption zone travels along the bed,though at a low velocity.The heat given off-the Heat of Adsorption is analogous to the Latent heat in vapour condensation.This heat given off,raises the bed temperature so that the air,now with less adsorbate,is simultaneously warmed to higher temperatures.Thus like the adsorption zone,the temperature wave also travels along the bed.This process will continue until when the bed is saturated.The bed saturation depends on the equilibrium relationship between the vapour pressure of the adsorbate in the bulk gas and in the adsorbent.This relationship gives the bed capacity at a given pressure and temperature.This relationship is the adsorption isotherm. Examples of adsorption isotherms are given in figure 1.5.

Once the bed is saturated,it can not adsorb any more adsorbate. The adsorbed material has to be desorbed by changing process conditions-eg raise temperature or lower pressure.This process is called Regeneration.

Adsorption is thus essentially a batch operation though flow of adsorbate can be continuous.Thus at least two adsorbent beds are required with one bed on stream-adsorbing, while the second is being regenerated.

1.7.3. Adsorption/Regeneration Cycle Times

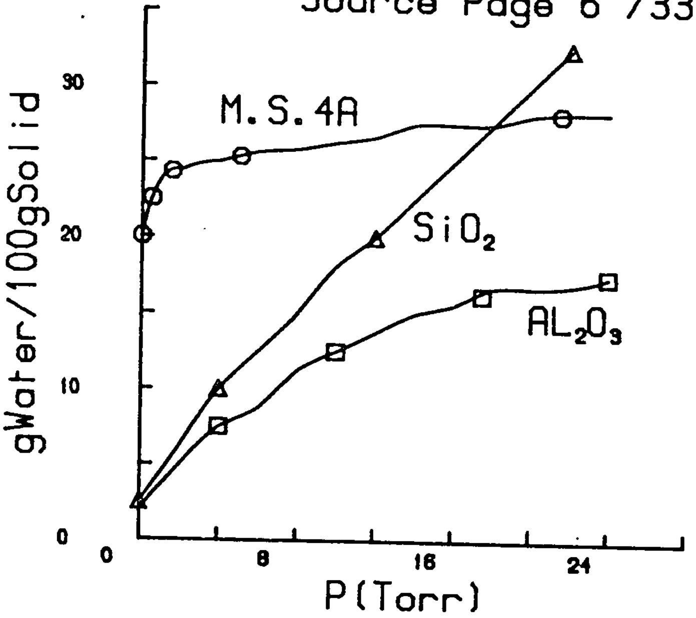
Adsorption time can vary from minutes to hours.but typically is one hour./15/.The cycle time in many cases is less that 12 hours./16/.

Regeneration time is often less that adsorption time./30/.But where regeneration takes longer more than two beds would be required if bed design was not based on the longer of the two cycle times.

1.7.4. Open and Closed Adsorption Heat Pumps

Alternative figures are given in figure 1.6 and 1.7.In Closed cycle adsorption,an external source of heat must be employed in regenerating the bed.In an Open cycle,it is possible to use part of the hot gas from the adsorption bed to regenerate the bed.In this case a supplementary heater might be required.

Fig.1.5 Equilbrium Isotherm For Water Vapour Sorption. Source Page 6 /33/.



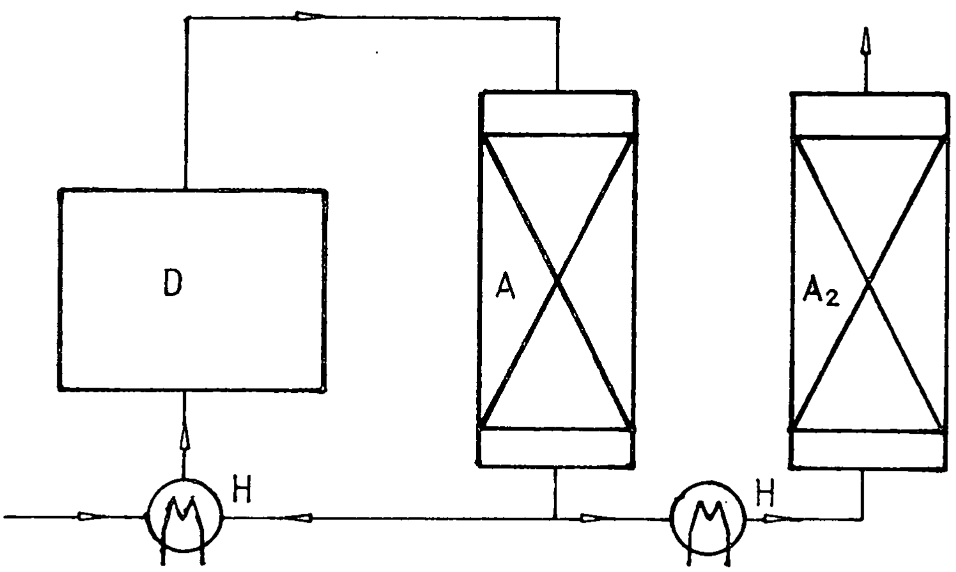


Fig.1.6:Open Cycle Adsorption Heat Pump-Coupled to Dryer.

D-Dryer;A-Adsorbent bed on line-Adsorbing.

A_2-Off-line bed-Under Regeneration.

H-Supplementary Heater.

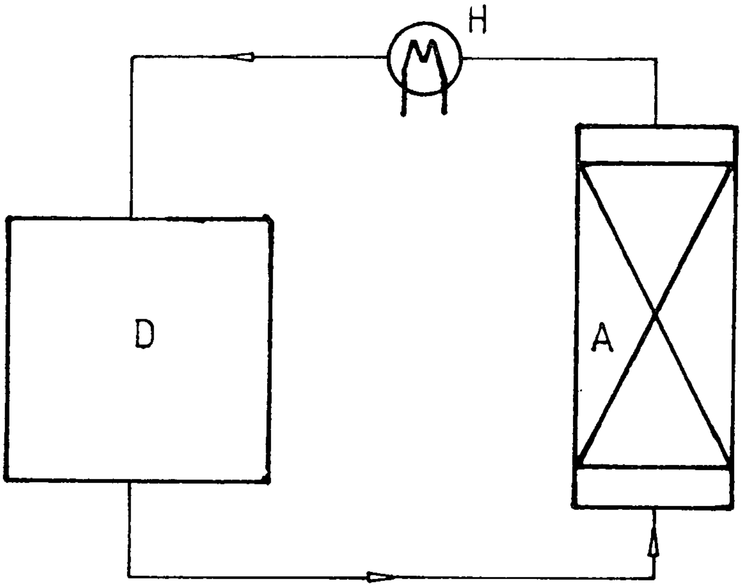


Fig.1.7:Closed Cycle Adsorption Heat Pump-Coupled to Dryer.

D-Dryer;A-Online bed-Adsorbing.

H-Supplementary Heater.

Off-line bed under Regeneration not shown.

1.7.5. Cost of Adsorption Systems

Almost all literature referenced adsorption systems are related to either Pollution control or solvent recovery-and not specifically to heat recovery.But since the nature of the process is similar the cost of these systems are quoted below to offer some picture on what sort of order of magnitude adsorption heat recovery systems would cost.

The costs given below are for Carbon (Activated) Adsorber system in 1977 US$.These costs are not valid for systems containing Hydrogen Chloride. See /15/.

For Adsorbent weight,W_c,lb

$$C=10000+721W_c^{0.481} \quad (1.5)$$

Equation (1.5) is valid for $250<W_c<10,000$.These are called Package Adsorbers.

For 10,000 < W_c 200,000 ,called Custom Adsorbers the cost is given by

$$C=50,000+0.277W_c^{1.20} \quad (1.6)$$

See also figures 1.8 and 1.9.

Table 1.5 give typical breakdown of annual costs for a typical adsorption unit using Activated Carbon.Costs are in 1979 US$.See /16/.

Fig.1.8 Cost of Package Adsorbers.
Stationary beds and Steam regeneration.
Source /15/.

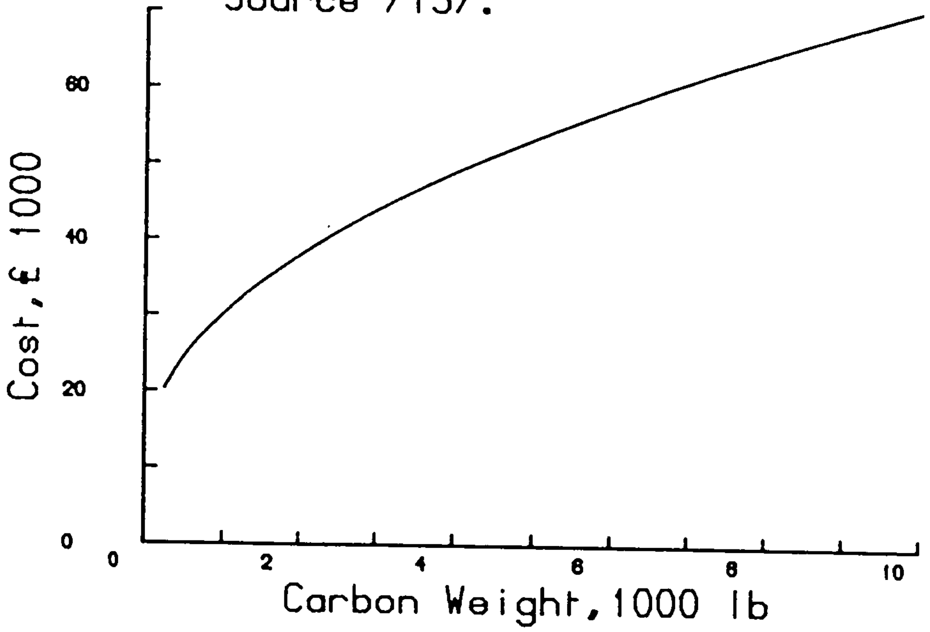


Fig.1.9 Cost of Custom Adsorbers.
Stationary beds and Steam regeneration.
Source /15/.

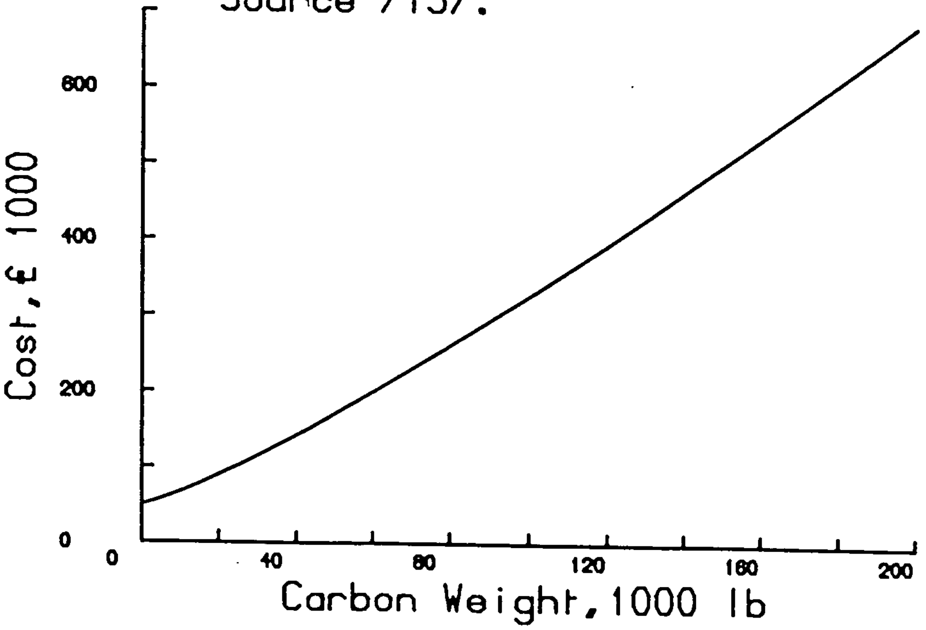


Table 1.5: Breakdown of Annual Cost of Typical Carbon Adsorber.
Cost in 1979 US$.Source /16/.

Flow rate,cfm	20000	10000	20000	10000
Feed conc.,ppm	1000	2000	500	1000
Capital Charges at 24%	$9600	$50400	$9600	5400
Utilities				
Steam at0.3lb/lbCarbon and at$4/1000lb	4300	4300	20100	20100
Electricity at5hp/1000cfm and at $0.04/kWh	25100	12500	25100	12500
Cooling Water,$.2gal/lb Steam and at $0.1/1000gal	4200	4200	2100	2100
Carbon replacement at 4yr Lifetime and at$1/lb	9000	4500	9000	4500
Total	$174600	$111900	$152300	$89600

It is important to point out that the cost of the adsorber unit would be depend among the following

1. The cost of construction material.Where there is corrosion problems,more expensive material of construction might have to be used.For example systems containing Hydrogen Chloride.
2. Type of Adsorbent,Amount and its Cost and its Regeneration efficiency.
3. Blower and automatic valves which would depend on feed-gas flow rates.
4. Location of the Adsorption unit in relation to the source of waste heat.This affects ductwork costs.

1.7.6. Reference to Previous Works

Adsorption as a process apart from its expanding application in pollution control and solvent recovery,it is extensively used in chromatography.Probably surprisingly,not so many work has been done on adsorption of water vapour as table 1.6 below shows.

Several mathematical models and solutions have been used to describe adsorption process.See /17/-/27/.Experimental works include the study of adsorption of Krypton and Argon on Graphitised Carbon,/28/,Adsorption of Propylene and 1-Butene and cis-2-Butene on Molecular Sieves,/29/.Adsorption of Carbon Dioxide on Activated Carbon,/30/,and on Molecular Sieves,/27/.Adsorption of Water by Cellulose material has been used to study the kinetics of water vapour sorption in freeze dried foods,/31/.Some of these experimental results are summarised in Table 1.6.

Table 1.6:Summary of Previous Work.

	Reference to Work				
	/27/	/28/	/29/	/30/	/31/
Adsorbate	CO_2	Ar Kr	C_3H_6 C_4H_8	CO_2	H_2O
Carrier(Bulk) Gas	N_2	N_2	N_2	N_2	Air
Pressure (atm)	1	1	1	1	1.7-2.6
Gas Feed Temperature °C	25		50	20	37
Max.Temp rise of Gas °C			30-47	2	3.2
Adsorbent	M.S.5A		M.S	C	Cell.
Heat of Adsorption kJ/kg			981	2358	
Overall Heat trans. Coeff. W/m^2k	14-46		20^a	2.7	
Bed length,m	0.27		0.915	0.25	
Column ϕ,m (material)	0.03 Cu		0.038	0.029 Poly	P.C

Key: a - Mean for C_3H_8.
C - Activated Carbon.

CU - Copper.

Cell. - Microcrystalline Cellulose.

P.C - Pressure Chamber.

Poly. - Polystyrene.

1.8. The Scope of this Research

This Research objective is to study heat recovery using an adsorption system.A brief exposition of adsorbents available is thus prerequisite.

1.8.1. Adsorbents

Adsorbents are materials that are capable of accumulating material usually gas on their surface.Essentially,adsorbents' function rely on their structure.See also /32/ and /33/.

A suitable adsorbent must be capable of reversibly and selectively adsorb large volumes of vapours.The selectivity to adsorb different species can be defined by a separation factor,α_{AB}

$$\alpha_{AB}=(X_A/X_B)/(Y_A/Y_B) \tag{1.7}$$

Where

X_A=concentration of component A in adsorbed phase.

X_B=concentration of component B in adsorbed phase.

Y_A=concentration of component A in bulk gas.

Y_B=concentration of component B in bulk gas.

Thus,Separation factor,like Relative Volatility in distillation is a measure of ease with which the components may be separated by adsorption. Separation factor has no quantitave relationship with the relative volatility. Unlike relative volatility which is fixed for give components,separation factor varies widely depending on adsorbents.

Practical adsorbents have adequate adsorptive capacity because they have enough pore volume.Normally pore volume distribution is controlled during manufacturing process.See figure 1.10 and 1.11.Pore size distribution strongly influences perfomance of some adsorbents like that of Activated Carbon.

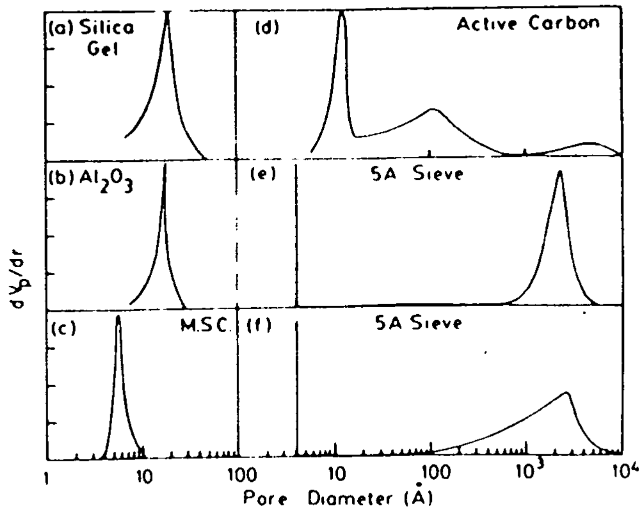
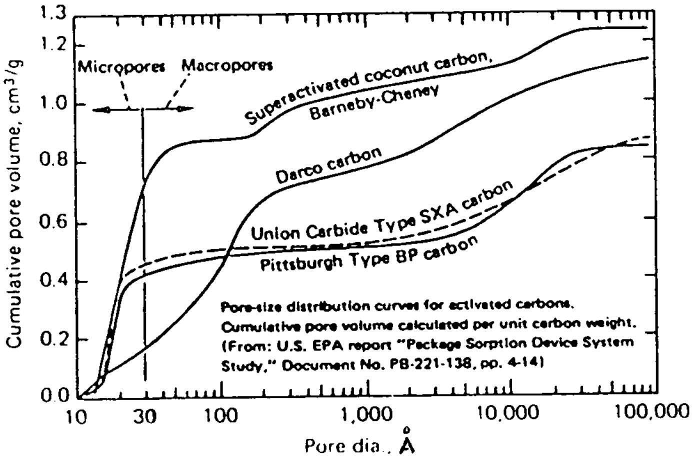


Fig.1.10: Pore Size Distribution.Source /33/.



Pore-size distribution curves for activated carbons. Cumulative pore volume calculated per unit carbon weight. (From: U.S. EPA report "Package Sorption Device System Study," Document No. PB-221-138, pp. 4-14)

Fig.1.11: Pore Size Distribution.Source /16/.

1.8.2. Silica Gel

See page 5 /33/.Silica Gel,like Activated Carbon,Alumina and Molecular sieves is a traditional adsorbent.

Silica Gel is a partially dehydrated form of polymeric colloidal Silicic Acid, $SiO_2.nH_2O$.The amount of water which is mainly chemically bound hydroxyl groups is up to 5% by weight.

The pore size ranges between 20 Å to 200 Å. The presence of the Hydroxyl group imparts a degree of polarity to the surface. The result of this makes the adsorbent adsorb polar molecules (eg Water,Phenols,Alcohols,Amines and Unsaturated Hydrocarbons) in preference to non polar molecules (eg Saturated hydrocarbons).

Capacity of Silica Gel at low temperatures is higher that that of Alumina.See also figure 1.5.Properties of commercially available Silica Gel are tabulated in Table 1.7.See also Table 1.8.

Table 1.7: Properties of Commercial Silica Gel.
Source page 176 /35/.

Apparent Density	0.7
Specific Gravity	2.1-2.3
Average Weight kg/m^3	609-641
Average Porosity %	50-65
Thermal Conductivity W/mk	0.144
Specific Heat kJ/kgk	0.92
Reactivation Temp.Range°C	150-175
Specific Surface sq.cm/g	6×10^6
Effective Bed Temperatures°C	4-32
Average Pore ϕ m	4×10^{-7}

Table 1.8: Silica Gel General Properties.
Source page 5 /33/.

	High Area Type	Low Area Type
Specific pore Vol.cc/g	0.43	1.15
Average Pore ϕÅ	22	140
Specific Surface sq.m/g	800	340
Particle Density g/cc	1.09	0.62

1.8.3. Activated Alumina

See page 7/33/.This is a high area porous Aluminium Oxide.It has a comparable affinity for water to Silica Gel but lower capacity at low temperature.At high temperatures however its capacity is higher than that of Silica Gel.

Activated Alumina is made by dehydration and recrystallisation of Bauxite ($Al_2O_3.3H_2O$) or the monohydrate at elevated temperatures.

Activated Alumina is thus favourable for high temperature use.It is however not favourable for high temperature use when compared to Molecular Sieves.

1.8.4. Activated Carbon

See page 7 /33/.This is made by Pyrolysis (thermal decomposition of Carbonaceous material) and then activated by steam or Carbon dioxide at 700-1100°C to remove Tarry Carbonisation products formed during pyrolysis.

This material, though, has little selectivity in adsorbing molecules of different sizes.It is non Polar and adsorbs non polar molecules in preference to polar ones.Some properties of this adsorbent are tabulated in Table 1.9.

Table 1.9: General Properties of Activated Carbon.
Source Page 7 /33/.

	Micropore	Mesopore	Macropore
Pore diameter,Å	<20	20-500	>500
Pore Volume,cc/g	0.15-0.5	0.02-0.1	0.2-0.5
Surface Area,sq.m/g	100-1000	10-100	0.5-2
Particle Density,g/cc	0.6-0.9	0.6-0.9	0.6-0.9
Porosity,%	40-60	40-60	40-60

1.8.5. Carbon Molecular Sieves

See page 8 /33/.This is prepared from Anthracite or Coal by controlled oxidation and subsequent thermal treatment.Molecular Sieves have effective micropores of diameter range between 4 Å and 9 Å.

This adsorbent is favourable for high temperature use.The small micropore diameter make it suitable for selective adsorption of molecules of different sizes though not as favourable as Zeolites.

1.8.6. Zeolites

This is a new development.It is a crystalline form of Alumino Silicates.Micropore size distribution is controlled by the crystal structure,It thus has virtually no pore size distribution.Pore sizes range between 2.8 Å and 7.4 Å making it very effective in selective adsorption of molecules of different size.

1.8.7. Others

There are Salts that show high affinity for water vapour and have been successefully used as dessicants.These include Calcium Chloride and Magnesium Chloride.They can be used as adsorbents though they do not fall under the classification of conventional adsorbents.They have probably not been used as adsorbents due to the fact that their structure is not stable, and it changes as more water vapour is adsorbed.

1.8.8. Adsorbent Capacity

Adsorption Capacity of Adsorbent depends on the Pressure and Temperature at which the adsorption process takes place.Adsorbent Capacity is refered to the Equilibrium amount adsorbed at that temperature and pressure.At Constant temperature the Adsorbent Capacity -Vapour Pressure relationship is called Adsorption Isotherm.See figure 1.5.At Constant Pressure ,the Adsorbent Capacity-Temperature relationship is called the Adsorption Isostere.See figure 1.12.

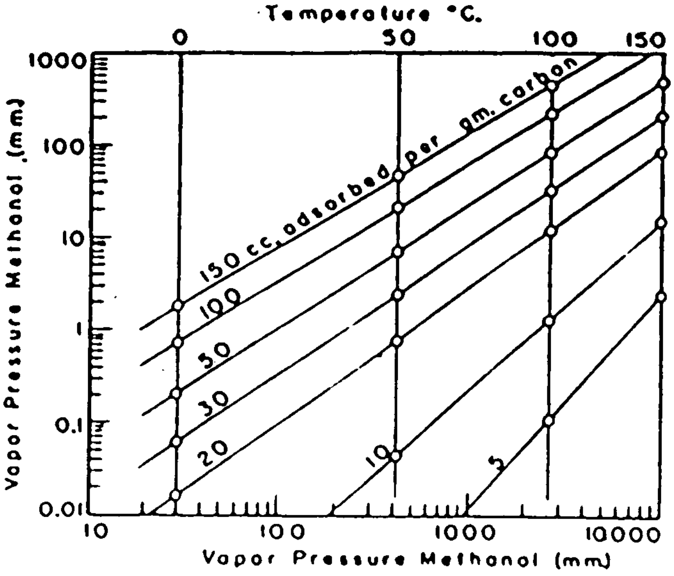


Fig.1.12: Isosteres of Methanol Adsorbed on Charcoal.Source /34/.

1.8.9. Heat of Adsorption and Adsorbent Temperature Rise

The magnitude of the Heat of Adsorption depends on the adsorbent and adsorbate.Some Literature values are given in Tables 1.10,1.11 and 1.12.See also Appendix of /35/.

The Temperature rise of the bed and gas depends on the adsorbent specific heat and the heat transfer coefficient in the bed for that given Heat of adsorption.These are not well documented.Some values are given in Table 1.6.

Table 1.10: Heats of Adsorption of Water by Carbon.
In cal/mole.Source Appendix /35/.

Temp. °C	E_i	E_L	E_L-E_i
-15	11100		
0		10740	
10	10000	10650	650
40	9300	10350	1050
80	8300	9940	1640
128	7200	9300	2160
187	5200		

Key: E_i - Average heat of Adsorption of first layer of adsorbed gas.

E_L - Heat of Liquefaction of gas.

Table 1.11: Heats of Adsorption of Gases by Charcoal.
In cal/mole.Source Appendix /35/.

Gas	Heat of Adsorption	Heat of Vaporization	Heat of Sublimation
Argon	3636	1504	4180
Nitrogen	3686	1250	
Carbon Monoxide	3146	1410	3715
Carbon dioxide	7300	2540	6100
Ammonia	7200	5000	7210

Table 1.12: Calorimetric and Isosteric Heats of Adsorption.
in cal/cc.Source Appendix /33/.

a,cc S.T.P	dq/da	Δq/Δa	at a,cc S.T.P
	CO_2 on Carbon		
1.82	0.363	0.345	0-2.3
4.02	0.344	0.324	2.3-11.3
10.3	0.311	0.324	2.3-11.3
19.72	0.293	0.305	11.3-22.6
28.87	0.281	0.300	22.6-33.4
34.07	0.288	0.294	33.4-43.9
38.14	0.285	0.294	33.4-43.9
41.4	0.290	0.294	33.4-43.9
44.9	0.287	0.292	43.9-50.8
	CH_3OH on Carbon		
29.7	0.615	0.619	0-21.7
65.4	0.563	0.553	21.7-47.4
65.4	0.563	0.542	47.4-75.3
126.5	0.533	0.524	75.3-127.4
	N_2 on Carbon		
1.5	0.198	0.195	0-3
3.5	0.171	0.209	3-5.5
4.6	0.214	0.209	3-5.5
5.6	0.200	0.205	5.5-7.7
8.1	0.203	0.210	7.7-13.5
	H_2O on Carbon		
0.41	0.423	0.381	0-20.6
1.49	0.459	0.381	0-20.6
4.21	0.465	0.381	0-20.6
16.3	0.481	0.474	20.6-60.7
191	0.507	0.472	60.7-102.1
198	0.502	0.467	102.1-143.8
208	0.508		

Key: a - Amount of gas adsorbed,cc.

dq/da - Isosteric(at constant pressure) Heat of Adsorpion.

Δq/Δa - Calorimetric Heat of Adsorption.

1.9. Choice of Magnesium Chloride and Process Conditions

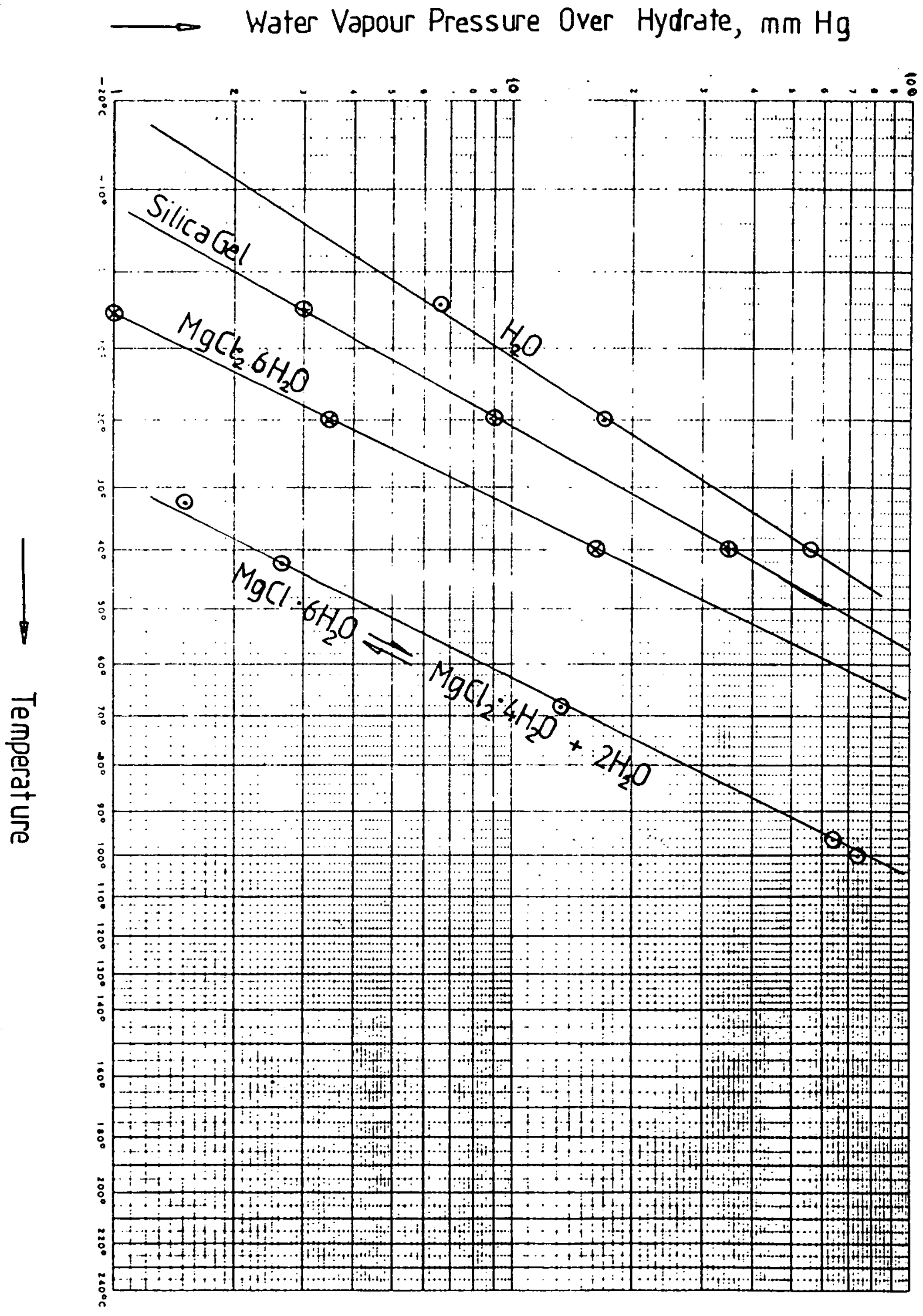
In this research,the choice of Magnesium Chloride as an adsorbent was based on its having Low Vapour Pressure.See figure 1.13 and /36/.Low Vapour Pressure implies that the vapour pressure difference between the sorbate,water vapour in the bulk gas and on the surface will be high and thus offer a high driving force for adsorption to take place.

The only disadvantage is that Magnesium Chloride,which is stable as a dihydrate or hexahydrate is not well documented as an adsorbent.

The process Conditions for investigation were chosen to be gas temperature of between 40-60 °C and saturated with water vapour.This choice is based on the fact that heat recovery from moist waste gases (exhausts) which are normally at a high temperatures would be carried out in conventional heat recovery units to recover the sensible heat and cooling the gases to a few degrees above their dew point and thus not recovering the Latent heat for reasons explained in detail under the problems of recovering heat from moist gas streams.

Fig.1.13 Vapour Pressure Data of Water and Water over Hydrate.

Source /36/.



CHAPTER 2

THEORY

2.1. Basic Principles

Adsorption is the accumulation of substance, usually gas, on solid surface.The Adsorption phenomenon can be studied by admitting gas-the Adsorbate into a closed vessel containing a known amount of adsorbing solid-The Adsorbent.If Pressure of the vessel,Temperature and weight of the adsorbent is followed with time then,the pressure of the vessel will fall as more adsorbate is adsorbed.The consequence of this will be an increase in adsorbent weight and rise in temperature.

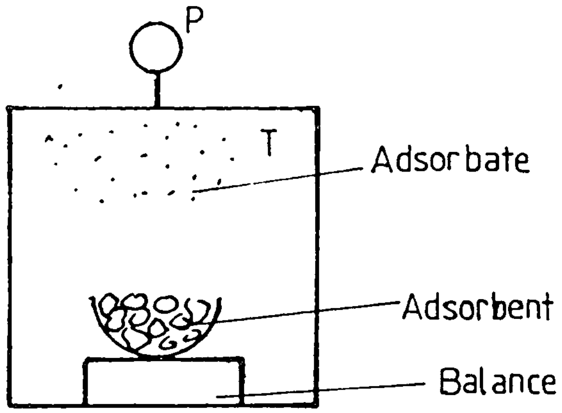


Fig.2.1: Sketch Illustrating Monitoring Adsorption.

This process will continue until an equilibrium is established between the adsorbate Vapour Pressure and the Amount of Adsorbate Adsorbed at that given temperature.

Thus if amount adsorbed per unit weight of adsorbate free solid is X then

$$X=f(T,P,Gas,Solid) \tag{2.1}$$

Or for given Adsorbate and Adsorbent

$$X=f(T,P)_{Gas,Solid} \tag{2.2}$$

It is important to mention that Adsorption can be Physical or Chemical.Physical Adsorption is normally rapid and reversible and significant only at relatively low Temperatures.Single or multiple layers of adsorbed material on the surface can be formed by formation of bonds that are somewhat weaker than those formed in Chemical Adsorption.In Physical Adsorption the magnitude of the heat of Adsorption is normally less than three times the Latent Heat of condensation.See page 29 /33/.

On the other hand,Chemical Adsorption is slow and more specific, which occurs during the process.There is a possibility of dissociation of adsorbed material.The process is irreversible and the Heat of Adsorption evolved can be higher than the Latent Heat of condensation by three orders of magnitude.See page 29 /33/.

In practice,most Adsorptive separation processes are Physical.This particular adsorption of Water vapour by Magnesium Chloride is taken as a Physical process.

Physical Adsorption is invariably Exothermic as,for any significant adsorption to take place,then Thermodynamics implies that $\Delta G<0$.Molecules of adsorbed gas on the solid surface have significantly less degree of freedom both in translational and rotational movements.thus $\Delta S<0$.

But

$$\Delta G=\Delta H-T\Delta S \tag{2.3}$$

Hence,since $\Delta G<0$ and $\Delta S<0$ and $T>0$,then ΔH must be less than zero. ie,the process is Exothermic.

2.2. Factors Affecting Adsorption

During adsorption the following happens

- The Adsorbate diffuses from the bulk fluid.In the process studied,water vapour diffuses from the carrier gas-air.
- The Adsorbate diffuses onto the solid surface.
- The Adsorbate diffuses inside the particle into intraparticle voids.

- Heat is simultaneously generated and is transfered from the particle to the bulk fluid and towards the wall.
- Some heat passes through the wall and insulation to the surroundings.

Thus although equilibrium data relationship as given by equation (2.1) and (2.2) is not complicated,the actual process is complex and affected by numerous factors.These include

1. Total pressure.
2. Physical and Chemical properties of Adsorbate.
3. Adsorbate feed(inlet) Temperature.
4. Gas inlet Humidity,ie Adsorbate feed concentration.
5. Type of Adsorbent:Physical properties,suitability,Total Capacity and useful capacity of the Adsorbent.
6. Size of Adsorbent particles.
7. Area of Adsorbent bed.
8. Thickness of Adsorbent bed.
9. Mass flow rate.
10. Presence or Absence of insulation.
11. The Initial Adsorbent temperature.
12. The magnitude of Heat generated and Corresponding temperature rise.
13. Final outlet Adsorbate concentration.
14. In Cyclic process:The Cycle length.

Factors 1-4 influence the magnitude of the Diffusion Coefficient and hence Mass transfer Coefficient as,the Diffusion of the adsorbate from the bulk fluid is the limiting value.

It is important to note that the fluid and bed temperature rise depend on heat transfer resistances.And since heat transfer from inside the the particle is by conduction and much faster than heat transfer from the surface to the bulk fluid through the external film on the particle,the true

Adsorption process is In fact never Isothermal.

2.3. Factors Affecting Regeneration

Before the Adsorbent material can be recycled for use,the Adsorbed material must be removed-ie,Desorbed.This process is Regeneration of the Adsorbent.Regeneration,like Adsorption can be done by varying Temperature or Pressure.This is explained in section 1.7.2.

In Thermal Regeneration,the following factors come into play

1. Temperature of Regenerating gas.
2. Regeneration gas flow rate.
3. Initial Adsorbent bed Temperature.
4. Pressure and Specific Heat of gas-Generating and Exit gases.
5. Heat losses.
6. Available time for Regeneration process.
7. Where Cooling of the regenerated bed is desired then the method of cooling is important.

2.4. Factors Under Investigation

The study of Adsorption of Water vapour on Magnesium Chloride in this research is limited to studying the influence of only a few factors. These are

a)Adsorption:- Gas inlet Temperature.

-Adsorbate inlet concentration.

-Gas flow rate.

b)Regeneration:-Regenerating gas Temperature.

-Regenerating gas Flow rate.

With this choice of factors to investigate,Mass and Heat balances are made and an experiment model selected.

2.5. Overall Mass and Heat Balances

Although actual mass and heat balances can be made from measured quantities during experiments,theoretical balances demand the knowledge of the reaction in question and adsorption isotherm in order to be able to predict the condition of the gas leaving the adsorption bed.All this information at present is not known.The adsorption of water vapour by Magnesium Chloride can be represented by the following general reaction equation

$$MgCl_2 + aH_2O \rightleftharpoons MgCl_2.aH_2O$$

Where the value of "a" ranges from 1 to 6.

The reaction presumably proceeds in stages.The heat evolved in fact might even restrict the extent of the adsorption reaction as Adsorption is an Equilibrium process and will cease once the vapour pressure of the adsorbate is equal to that of the adsorbed material on the surface.

There is no literature data for Magnesium Chloride that give information given by equation (2.2) ie as X=f(T,P).Thus equations for mass and heat balance are given below without actually giving some numerical values.

2.5.1. Mass and Heat Balance Equations

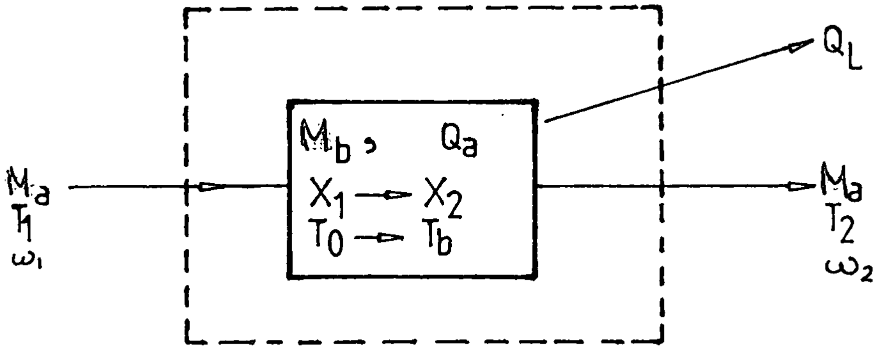


Fig.2.2: Balance Area

Water balance gives

$$M_a(\omega_1-\omega_2) = M_b(X_2-X_1) \tag{2.4}$$

If the amount of adsorbed water vapour is considered as condensed water vapour ie,liquid,then heat balance gives

$$M_bC_sT_o + M_a(1+\omega_1)Cp_1T_1+M_bX_1CwT_0=M_a(1+\omega_2)Cp_2T_2+M_bX_2CwT_b+M_bC_sT_2+Q_a+Q_L$$

Assuming $T_b \simeq T_2$ and neglecting heat loss(ie,$Q_L=0$) then the heat of Adsorption per kg of adsorbent,$\Delta H_a = Q_a/M_b(X_2-X_1) = Q_a/M_a(\omega_1-\omega_2)$ is

$$\Delta H_a = (1+\omega_1)Cp_1T_1/(\omega_1-\omega_2)-(1+\omega_2)Cp_2T_2/(\omega_1-\omega_2) \tag{2.5}$$
$$+C_s(T_0-T_2)/(X_2-X_1)+Cw(X_1T_0-X_2T_2)/(X_2-X_1)$$

Further for a special case where the gas is saturated with water vapour at inlet then

$$\omega_1 = f(T_1) = M_{H2O}/M_{air}.Ps/(P_T-Ps) \tag{2.6}$$

$$Ps = \exp[A-B/(T+C)] \tag{2.7}$$

T in °C;Ps and P_T in N/m^2

Where for $57<T<135$°C A=23.1863,B=3809.4 and C=226.7

For $0<T<57$°C A=23.7093,B=4111,C=237.7.See page 214 /42/.

2.5.2. Heats of Formation

Using the general reaction

$$MgCl_2 + aH_2O \rightleftharpoons MgCl_2.aH_2O$$

Different values of Heat of formation are calculated for several values of a using the relationship

$$\Delta H_f=\Delta H_f^\circ+\int_{T0}^{T} \Delta Cpdt \tag{2.8}$$

Where $\Delta H_f^\circ=\Delta H_f(\text{product})-\Delta H_f(\text{reactant})$ at 25°C with $MgCl_2.aH_2O$ as product and $MgCl_2$ and H_2O as reactants.Similarly,$\Delta Cp=Cp(\text{product})-Cp(\text{reactant})$.

The values calculated are based on the assumption of $T_0=25$°C and

$Cp(MgCl_2.aH_2O) \simeq Cp(MgCl_2) \simeq 1kJ/kgk$ and $Cp(H_2O) \simeq 1.9$ kJ/kgk.

Values of $\Delta H_f°$ are tabulated below.See page D-69 and D-73 /38/.

Table 2.1: Standard Heats of Formation (at 25°c)

Compound	Mol.Wt.kg/kmol	State	$\Delta H_f°$kcal/mol
$MgCl_2$	95.22	Solid	153.28
$MgCl_2.H_2O$	113.22	Solid	231.03
$MgCl_2.2H_2O$	131.22	Solid	305.86
$MgCl_2.4H_2O$	167.22	Solid	453.87
$MgCl_2.6H_2O$	203.33	Solid	597.28
H_2O	18	Gas	57.796

Table 2.2: Heat of Formation at Different a Values.

Units kJ/kg.Equation (2.8)

Temp.T°C	a=1	a=2	a=4	a=6
40	11660	10447	8842	7900
50	11679	10466	8861	7920
60	11700	10485	8880	7939
70	11717	10504	8899	7958
80	11736	10523	8918	7977

These values are range from 3.3 to 5 times the Latent heat of condensation. Recall that in physical adsorption the heat of adsorption is normally less than three times the Latent heat of vapour condensation.

2.6. Experiment design

2.6.1. Experiment Air Flow Rate ranges.

In determining the air flow rate the limiting reaction is taken as the hydration of the anhydrous Magnesium Chloride to the hexahydrate. Thus the air flow rate must be capable of delivering the required amount of water vapour in the adsorption cycle time.ie,

$MgCl_2$ + $6H_2O$ $MgCl_2.6H_2O$

Molecular weight of $MgCl_2$,Water and $MgCl_2.6H_2O$ is 95.22 kg/kmol,18 kg/kmol and 203.22kg/kmol respectively.Thus the amount of water required to hydrate 1 kg of anhydrous Magnesium Chloride to the hexahydrate is

$m = 1\times6\times18/95.22 = 1.134$ kg.

But Adsorbent bed weight is 2.605 kg.See section 3.2.1.Therefore the total limiting amount of required water is

$m = 1.134\times2.605 = 2.954$kg.

In section 1.7.3 it was mentioned that typical adsorption cycle takes about one hour.Thus taking mean air density to be 1.092 kg/m^3 then the required air flow rate,m_a is

$m_a = 2.954/(1.092\times3600) = 7.494.10^{-4}$ m^3/s.

ie 45 l/min.Air flow rates required for different experimental adsorption cyle times are listed in table 2.3 below.

Table 2.3: Experiment Air Flow Rate Ranges

Time [hours]	0.5	1.0	1.5	2.0
Flow [l/min]	90	45	30	23

Rotameter for measuring air flow rate has a lower limit of 26.6 l/min.Thus the Experiment air flow range is taken as 26.6-90 l/min.

The experiment plan is to vary air flow rates (both in Adsorption and Regeneratin experiments) in the range of 0.3-0.6m/s.Also to use air inlet temperatureof between 30-60°C and Regeneration air temperature of between 120-160°C.

2.6.2. Differential Balances:Dynamic Model

During Adsorption,there is both Heat generation and transfer.The problem is thus that of unsteady Heat Transfer with Heat Generation.A model that describes unsteady Heat transfer with Heat generation has to be used.

There are many well developed unsteady heat transfer models. See page 243 /43/,eg the Schumann model,the Continuous-Solid Phase model (C-S model) or the Dispersion-Concentric model (D-C model).For solution of unsteady state heat transfer in packed beds,the D-C model is by far the most widely practiced model.See Chapter 7 /43/ and /30/.It is thus adopted here.

2.6.3. The D-C Model

In fluid flow through packed beds,fluid elements have different Velocity and Temperature gradients both in radial and axial direction.This difference in temperature gradient and in velocity and hence concentration gradient normally causes a reduction in driving force for Heat and Mass transfer.This difference in gradients,called Dispersion,if not accounted for in estimating transfer coefficients,then the Mass and Heat transfer perfomances might be over estimated.

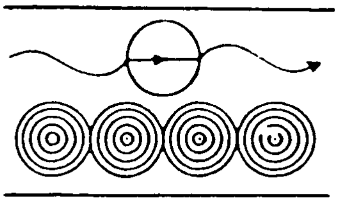
Radial Dispersion tends to equalise the difference in gradients and has no adverse effects on the Axial dispersion.See page 137 /44/ and /46/.

The D-C model suitability is based on the fact that it modifies the Nusselt number Heat transfer correlation and the Sherwood number Mass transfer correlation to account for the Axial Dispersion.

The theoretical development of the D-C model is based on the following assumption

- The fluid is in dispersed plug flow.
- Adsorbate fluid Concentration and Temperature profiles in the adsorbent particle are with centre-symmetry.Note that with this assumption.it means that there would be no conduction of heat or mass transfer in the Axial direction in the solid particle.To modify this orginal D-C model,Axial fluid Mass and Thermal dispersion coefficients are used.With the use of Axial dispersion coefficients,some authors have called this particular model as a Modified D-C model.See /30/.

- Intrapaticle diffusion rate is expressed in terms of the effective diffusivity and the gradient of the Adsorbate Concentration in the intraparticle fluid phase.The effective diffusivity,which consists of pore volume diffusion and surface diffusion is assumed to be constant(independent of concentration of adsorbate in the fluid phase within the particle voids or adsorbed).
- Adsorbate concentration in the bulk fluid is uniform at any one cross section.
- Temperature of the bulk fluid is uniform at any one cross section.
- Heat loss rate can be expressed in terms of the temperature difference between the bulk fluid in the bed and room temperature.
- All the parameters involved in Heat and Mass tranfer process in the Adsorption column are temperature-independent.This might be true only where the changes are minimum.



Fluid in Plug Flow,Particle Temperature with Radial symmetry.

Fig.2.3: Flow in D-C Model

The Mass balance gives

$$\partial C/\partial t=Dax\partial^2C/\partial x^2-U\partial C/\partial x-aDe/\varepsilon_b(\partial Ci/\partial r)_R \qquad (2.9)$$

$$\varepsilon_p\partial Ci/\partial t=De1/r^2\partial/\partial r(r^2\partial Ci/\partial r)-\rho_s\partial Cad/\partial t \qquad (2.10)$$

Where

$$Cad=f(Ci) \qquad (2.11)$$

$$De\partial Ci/\partial r=K_F(C-Ci) \text{ at } r=R \qquad (2.12)$$

Similarly for Heat balance

$$\partial T_F/\partial t=\alpha_{ax}\partial^{2}\underset{\wedge}{\overset{T_F}{}}/\partial x^2-U\partial T_F/\partial x-a/\varepsilon_b C_f\rho_f k_s(\partial T_s/\partial r)_R \tag{2.13}$$

$$-2h_0/R_T\varepsilon_b C_f\rho_f(T_F-T_0)$$

$$C_s\partial T_s/\partial t=k_s 1/r^2\partial/\partial r(r^2\partial T_s/\partial r)+(-\Delta H_a)\rho_s\partial Cad/\partial t \tag{2.14}$$

$$k_s\partial T_s/\partial r=h_p(T_F-T_s) \text{ at } r=R \tag{2.15}$$

Integration of equations (2.13) to (2.15) and rearranging gives

$$T_A^* = (-\Delta H_a)\rho_s f(C_0)aRR_T/6h_0 \tag{2.16}$$

$$\lambda_H^\circ = U/2\alpha_{ax}\{1-[(1+8\alpha_{ax}h_0/U^2R_T\varepsilon_b C_f\rho_f)]^{1/2}\} \tag{2.17}$$

T_A^* and λ_H° are calculated from either T_F^* or T_s^*.Where these are given by

$$T_F^*=\int_0^\infty(T_F-T_0)dt \tag{2.18}$$

Or

$$T_s^*=\int_0^\infty(T_s-T_0)dt \tag{2.19}$$

And

$$\exp(\lambda_H^\circ\Delta x)=[(T_F^*)_3-(T_F^*)_2]/[(T_F^*)_2-(T_F^*)_1] \tag{2.20}$$

$$T_A^*=[(T_F^*)^2-(T_F^*)_2^{\,2}-(T_F^*)_1(T_F^*)_2]/[2(T_F^*)_2-(T_F^*)_1-(T_F^*)_3] \tag{2.21}$$

$(T_F^*)_i$ is T_F^* at location i,eg

$(T_F^*)_1=T_F^*$ at $x=x_R$ where R is the reference,the first point where temperature is measured.$(T_F^*)_2$ is T_F^* at $x=x_R+\Delta x$,etc.

The actual Adsorption process can be thought to take place on infinitely many very small Adsorbing zones along the bed length.The first zone in contact with the adsorbate,say zone 1 in figure 2.4 ,starts to pick up the adsorbate, when it is saturated,the next zone,say 2,take over the picking of adsorbate. Thus a sort of concentration band or wave appears to move along the bed

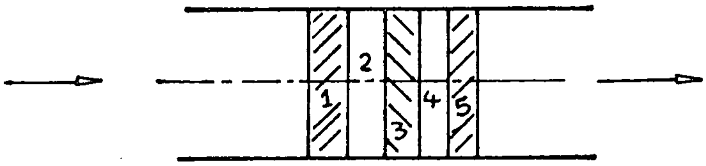


Fig.2.4: Sketch Showing Sequence of Adsorbing Zones.

Heat is given off when adsoption takes place,the Temperature of the bed and fluid at the adsorbing zone therefore rises and like the concentration wave also move along the bed length.Depending on the specific heat of the fluid and the adsorbent the temperature wave may lead or lag behind the concentration wave.If the fluid heat capacity is greater than that of the adsorbent,then the temperature wave front leads the concentration wave front.See page 805 /29/.

Using this fact,if temperature waves are monitored at three points, then the Overall Heat transfer coefficient,h_0 and the Heat generation term, $-(\Delta H_a)\rho_s f(C_0)a$,can be determined.

Where the Adsorption isotherm is known,the Adsorption equilibrium constant,K_A can be evaluated at the Adsorption mean temperature and the heat of Adsorption,$-(\Delta H_a)$ determined.Where the Adsorption isotherm is unknown,both the Adsorption equilibrium constant and the heat of Adsorption can be estimated using the temperature waves by a method explained below.

It is first assumed that the adsorption isotherm is Linear(ie,Low Adsorbate concentration in feed stream).Then,

$$f(Ci) = K_A Ci \tag{2.22}$$

And applying the Danckwerts boundary conditions at the bed inlet gives

$$U(C-C_0) = Dax\partial C/\partial x \quad \text{at } x = 0 \tag{2.23}$$

And

$$U(T_F-T_0) = \alpha_{ax}\partial T_F/\partial x \text{ at } x = 0 \qquad (2.24)$$

With the boundary conditions equations (2.22) to (2.24) the differential equations (2.9) to (2.13) can be solved to give calculated temperatures,say $T_{Fc}(x,t)$.By minimising the meansquare error,ε_r given by

$$\varepsilon_r = \surd[(T_{Fc}-T_F)^2/T_F^2]_{x,t} \qquad (2.25)$$

The unknown parameters of the adsorption isotherm,K_A,Dax,α_{ax} and the Heat of Adsorption can be estimated.

Solving the differential equations (2.9) to (2.13) using the boundary conditions,equations (2.22) to (2.24) by Laplace transformation and noting that in the experiment,the feed is a step input function,ie

$$C_0 = 0 \text{ and } T_0 = 0 \text{ at } t<0 \qquad (2.26)$$

And

$$T_0 = T_0 \text{ and } C_0 = C_0 \text{ at } t>0 \qquad (2.27)$$

By definition of Laplace transform (See also /45/).

$$f_{t\rightarrow s}df(t)/dt = sf(s)-f(0\_)$$

And

$$f_{t\rightarrow s}d^2f(t)/dt^2 = s^2f(s)-sf(0\_)-[df(t)/dt]_{t=0}$$

Note 0_ imply approach of t to zero from t<0.The inverse transformation,ie, the determination of a function from its transform is

$$f(t) = f_{s\rightarrow t}\ f(s) = 1/2\pi i\int_{Br}f(s)e^{st}ds = 1/2\pi\int_{\gamma-i\infty}^{\gamma+i\infty} f(s)e^{st}ds$$

Thus if $\Delta x/L \simeq 0$,then the bed is infinitely long and equations (2.9) to (2.15) can be integrated to give the required solution.ie

$$C(x,t)/C_0 = 1/2+2/\pi\sum_{n=1}^{\infty} 1/(2n-1).F_m(s)e^{st} \tag{2.28}$$

And

$$[T_F(x,t)-T_0]/C_0 = 2/\pi\sum_{n=1}^{\infty} 1/(2n-1).F_He^{st} \tag{2.29}$$

Where

$$s = (2n-1)\pi i/\tau \tag{2.30}$$

The concentration wave,$F_m(s)$ is given by

$$F_m(s)= f_{t\to s}\{C(x,t)/C_0\}=\exp(\lambda_m x)/[1-Dax\lambda_m/U] \tag{2.31}$$

Where

$$\lambda_m=U/2Dax\{1-\surd[1+4Dax/U^2(s+q_m)]\}$$

$$q_m=aDe/\varepsilon_bR[De/k_fR+f(\phi_m)]^{-1}$$

$$f(\phi)=(\phi\coth\phi-1)^{-1}$$

$$\phi_m=R[(\varepsilon_p+\rho_sK_A)s/De]^{1/2}$$

Note that

$$F_m(0)=1 \tag{2.32}$$

For the Thermal wave,$F_H(s)$

$$F_H(s)=f_{t\to s}\{(T_F(x,t)-T_0)/C_0\}=F_m(s)\overset{\beta}{\underset{\wedge}{\psi}}/\zeta \tag{2.33}$$

Other substitution are

$$\zeta=\alpha_{ax}\lambda_m{}^2-U\lambda_m-\xi U^2/4\alpha_{ax}{}^2$$

$$\beta=1-\exp[(\lambda_H-\lambda_m)x]\times[(\lambda_m-U/\alpha_{ax})/(\lambda_H-U/\alpha_{ax})]$$

$$\xi=4\alpha_{ax}/U^2\times[2h_0/R_T\varepsilon_b C_f\rho_f+s+q_H]$$

$$\psi=-(\Delta H_a)\rho_s K_A a\times[f(\phi_h)-f(\phi_m)]$$
$$\times[R\varepsilon_b C_f\rho_f(C_s/k_s-(\varepsilon_p+\rho_s K_A/De))]^{-1}$$
$$\times[(De/k_f R+f(\phi_m))\times(k_s/h_p R+f(\phi_H))]^{-1}$$

$$\lambda_H=[1-(1+\xi)^{1/2}]U/2\alpha_{ax}$$

$$q_H=ak_s[R\varepsilon_b C_f\rho_f(k_s/h_p R+f(\phi_H))]^{-1}$$

$$\phi_H=R(C_s\rho_s s/k_s)^{1/2}$$

Note

$$F_H(0)=0 \tag{2.34}$$

Other parameters are approximated using the following equations:

The particle to fluid heat transfer coefficient is approximated by the Nusselt number correlation,see page 293 /43/,ie,

$$Nu=h_pDp/k_f=2+1.1Pr^{1.3}Re^{0.6} \tag{2.35}$$

For Mass transfer coefficient,the Sherwood number correlation,see page 154 /43/is used to give

$$Sh=K_FDp/Dv=2+0.06Sc^{1/3}Re^{0.5} \tag{2.36}$$

The dispersion coefficients,for mass transfer,Dax and Thermal,α_{ax},are not very sensitive to variations of temperature, See page 1071 /30/,and can be approximated to be constant and equal to

$$\alpha_{ax}=ke^{\circ}/\varepsilon_b C_f\rho_f+.5DpU \tag{2.37}$$

Where

$$ke^{\circ}/k_f=0.707Nur^{0.96}(k_s/k_f)^{1.11} \tag{2.38}$$

Equation (2.38) is valid for $20<k_s/k_f<1000$ and $Nur<0.03$. See page 182 /43/.

Note in equation (2.38) the radiant Nusselt number is significant at higher temperatures where combined conduction and radiation heat transfer from the surface of a particle to neighbouring particles have to be considered.

Under expected experiment conditions,temperature not exceeding 120°C,$Nur\simeq 0$ and equation (2.38) reduces to

$$ke^{\circ}/k_f=0.707(k_s/k_f)^{1.11} \tag{2.39}$$

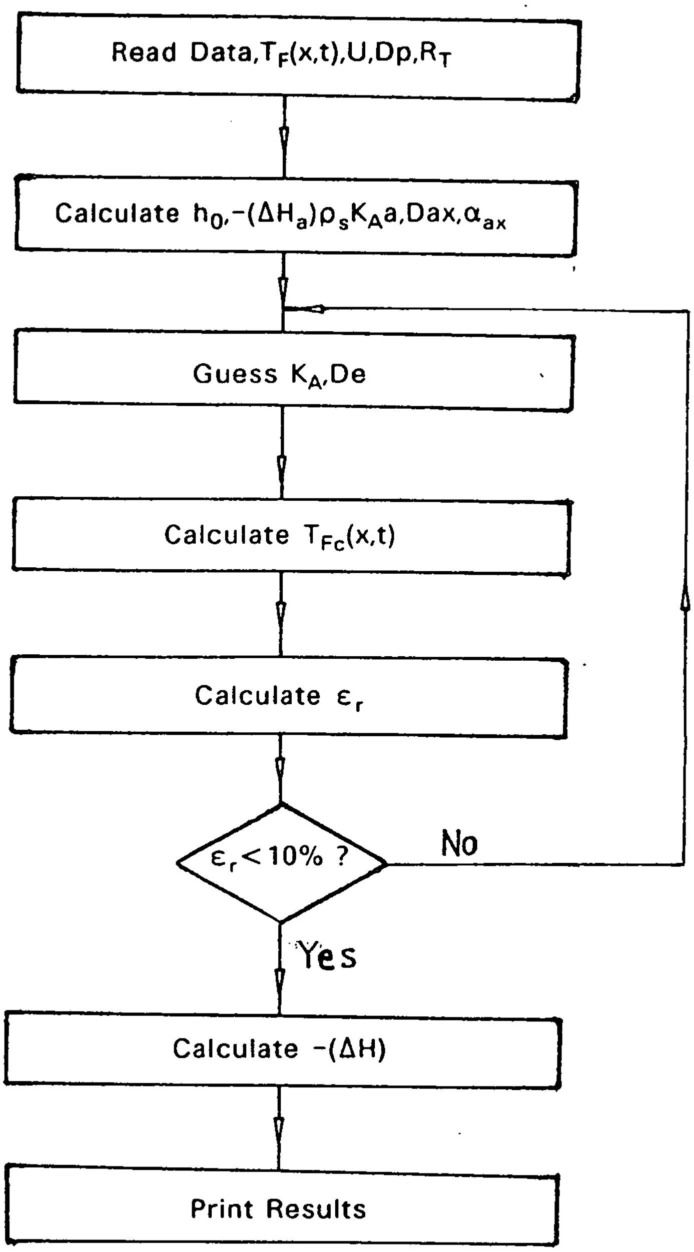
Dax,is ,see page 139 /43/,approximated from

$$Dax\varepsilon_b/Dv=20+0.5ScRe \tag{2.40}$$

Equation (2.40) is valid for $Re>5$.

The Algorithm to solve the problem is given below.In the Algorthim the Error minimising loop uses the error minimising "NAG" subroutine "E04FDF"available in the Edinburgh University Computing Library.

Fig.2.5:Algorithm-Solution method.



2.7. Heat Losses

The Heat loss from the bed can be estimated from the bed Temperatre,T_b and Room temperature,T_0 using the Fourier law of Heat conduction.This value of heat loss can then be used to correct the Heat of Adsorption and Regeneration calaculated by equation (2.5).

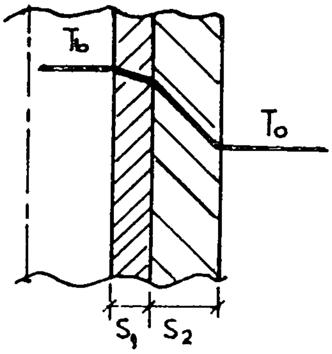


Fig.2.6:Sketch Showing composite wall(metal & insulation.)

The Heat loss,Q_L is given by

$$Q_L = A(T_b - T_0)/[s_1/k_1+s_2/k_2] \tag{2.41}$$

Where subscripts 1 and 2 refer to the metal and insulation respacectively.

CHAPTER 3

DIMENSIONING EXPERIMENT EQUIPMENT

In chapter two many factors affecting the adsorption process were listed.Few factors were selected to be studied in this research;. it was explained that the process would be investigated by monitoring air temperature and humidity both at inlet and outlet;bed weight;and bed temperature across the whole bed length.

Thus the experiment equipment must include a humidifying column to supply a stream of humid air,air flow measurement,humidity, temperature and weight measurement.

3.1. Constraints

The design was constrained by the availabilty of certain equipment and measuring instruments.These included:

1. Electronic top pan balance:For weight measurement.Available were Oertling GC62 and JC41 measuring a maximum of 6 kg and 4 kg respectively.Thus the total bed weight must be less than 4 kg.
2. Differential pressure transducer :An MKS Differential pressure transducer with maximum allowable pressure of 12.7mm (0.5 in) water. thus the pressure drop across the orifice plate must be less than 12.7mm water.
3. Glass column:For use as a humidifying column:
   Diameter:0.152m (6 in)
   Height 1.524m (60 in)
4. Packing material:13mm (1/2 in) Ceramic Rasching rings.

3.2. Dimensioning of Equipment

3.2.1. Adsorption Bed Tube:Diameter and Length.

A light weight metal,Aluminium tube was selected.Aluminium has the additional advantage of being corrosion resistant to Magnesium Chloride;normally less than 0.005 in per year.See Table 23.3 /37/.Available was a 2 inch (outside diameter) tube.

From page 11-12 /37/:

Wall thickness = $2.413.10^{-3}$m (0.095in)

Inside cross section area = $1.66.10^{-3}m^2$ (2.573 sq.in)

Weight/length steel = 0.877kg (1.934 lb)

Weight factor for Aluminium =0.35

From page B-94 /38/ mean density of $MgCl_2.6H_2O$ = $1569kg/m^3$

Total weight/m $=\underbrace{0.877 \times 0.35}_{\text{metal}}+\underbrace{1.66.10^{-3} \times 1 \times 1569}_{\text{solids}}$ kg

=0.307 +2.605 kg

=2.912 kg

Therefore take 1.2m length tube.Maximum length filled with solids 1m.

Hence total weight = .307 ×1.2 +2.605 kg ≈ 3 kg

This leaves allowance for the weight of insulation,metal straps,thermocouples,etc.

Summary:

Tube outside diameter = $5.08.10^{-2}$m

Tube inside diameter = $4.597.10^{-2}$m

Tube length = 1.2m

Material:Aluminium

3.3. Orifice Plate

A clean,square-edged hole was selected for reasons of simplicity and ease of manufacture.The disadvantages include high pressure drops,non-linearity and low accuracy.The problem of non-linearity may be offset by using a computer to calculate the flow using a high order polynomial.

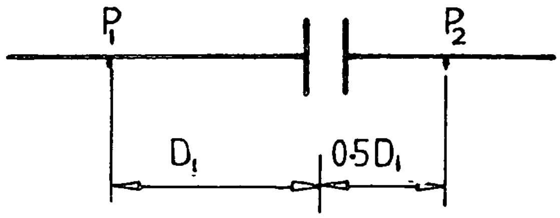


Fig.3.1:Sketch of Pressure Taps for Orifice Meter.

For orifice,the pressure tappings are generally one pipe diameter upstream and one half pipe diameter downstream.

The practical equation for weight rate of discharge adopted for use for gas is:See page 107 /40/.

$$M=Q\rho_1=\rho_2 CA_2\gamma[2(P_1-P_2)\rho_2/(1-\beta^4)]^{1/2} \qquad (3.1)$$

For given Orifice type

$$C=f(\beta,Rd) \qquad (3.2)$$

For radius tapping (pressure taps at 1D and 0.5D upstream and downstream respectively) C = 0.63-0.67 and is nearly constant if the Reynolds number at the throat,Rd is greater than 30,000.For transitional zone the value of discharge coefficient is not constant and it is advisable to establish it by calibration.See page 5-12 /37/.

Charts eg Fig.3.2,tables or empirical equations can be used to estimate this value.A consistent equation; that is, one for use with any type of orifice is:See page 491 /39/.

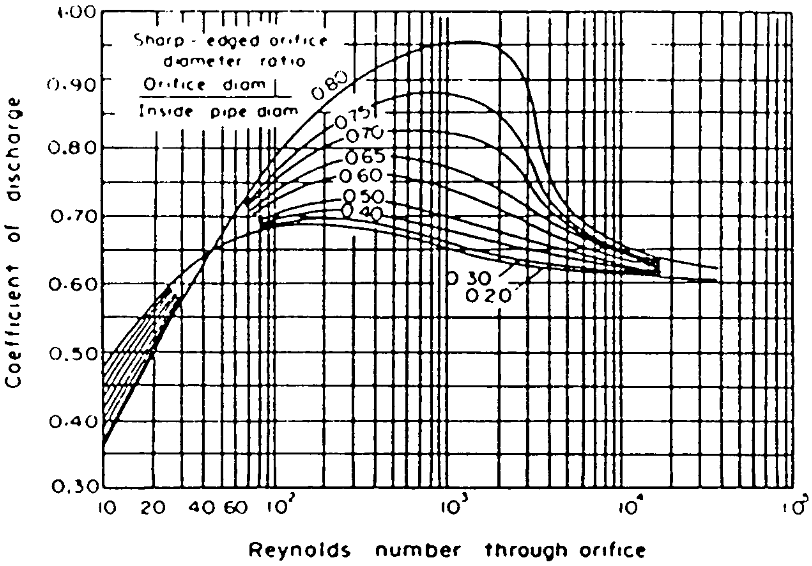


Fig.3.2:Discharge Coefficients of Orifice Meter.Source /40/.

$$C=0.5959+0.0312\beta^{2.1}-0.184\beta^{8}+0.0029\beta^{2.5}(10^{6}/Rd\beta)^{0.75}+0.09L_1\beta_1\beta^{4}/(1-\beta^{4})-0.0337L_2\beta^{3} \quad (3.3)$$

Where

L_1 = Dimensionless location of upstream tap with respect to the upstream face of the orifice face.

L_1 = 0 for corner taps,1 for radius taps at 1D and 0.5D and 1/D for flange taps.

L_2 = Dimensionless location of downstream tap with respsect to the downstream orifice face.

L_2 = 0 for corner taps,1/D for flange taps and 0.5-s/D for radius taps at 1D and 0.5D.

For orifice meter,the expansion factor is given by. See page 5-13 /37/.

$$\gamma=(0.41+0.35\beta^{4})\times(1-r)/k \quad (3.4)$$

Where

$$r=P_2/P_1 \quad \text{and} \quad k=Cp/Cv \quad (3.5)$$

Equation (3.3) is solved for different values of Rd with β as a parameter. Note that

$$Rd=D_2U_2\rho/\mu \quad (3.6)$$

But

$$\beta=D_2/D_1 \quad (3.7)$$

And for continuity

$$A_2U_2=A_1U_2 \quad (3.8)$$

Where

$$Ai=\pi Di^{2}/4 \text{ and } Ui=Q/Ai \tag{3.9}$$

Equations (3.7),(3.8) and (3.9) in (3.6) gives

$$Rd=4Q\rho\left(\beta\pi\mu D_1\right)^{-1} \tag{3.10}$$

Pipe diameter,D_1 = 0.021m (Regular Copper 3/4 in nominal diameter)

Orifice thickness s = 2 mm (Assumed).

Air viscosity $\mu = 2.5.10^{-5}$ Ns/m^2

Air density ρ = 1.092 kg/m^3

Results are tabulated in Table 3.1.

Table 3.1: Discharge Coefficient as Function of Flow Rate.
Parameter:Diameter Ratio.See Equation (3.3)

Q	Coefficient of Discharge							
l/min	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
10	0.61	0.64	0.68	0.75	0.84	0.95	1	1
20	0.61	0.62	0.65	0.69	0.75	0.82	.91	1
30	0.6	0.62	0.64	0.67	0.71	0.77	.84	.98
40	0.6	0.61	0.63	0.66	0.69	0.74	.8	.92
50	0.6	0.61	0.63	0.65	0.68	0.72	.78	.89
60	0.6	0.61	0.62	0.64	0.67	0.71	.76	.86
70	0.6	0.61	0.62	0.64	0.67	0.7	.75	.85
80	0.6	0.61	0.62	0.64	0.66	0.69	.74	.83
90	0.6	0.61	0.62	0.63	0.66	0.69	.73	.82
100	0.6	0.61	0.62	0.63	0.65	0.68	.72	.81

Note that the values of discharge coefficients in the table are limited to unity even where the evaluated value was greater than one. This is from the definition of the discharge coefficient.

But maximum allowable pressure drop across the orifice is

12.7mm(0,5 in) water.See under constraints. Taking a safety margin of 10%,the the maximum working pressure drop is :

$$\Delta P=P_1-P_2=0.9\times 12.7.10^{-3}\times 9.81\times 1000=112.1N/m^2$$

Since the pressure drop is marginal,then $r = P_2/P_1 \simeq 1$ and $\rho_1 \simeq \rho_2 = \rho$ Equation (3.1) imply

$$C^2\beta^4/(1-\beta^4)=Q^2\rho^2/(2\rho^3\pi^2\Delta PD_1^4/16) \qquad (3.11)$$

But maximum pressure drop is expected at maximum flow rate Maximum flow Q = 90 l/min.See chapter two. Therefore

$$C^2\beta^4/1-\beta^4 \simeq 7.7.10^{-2} \qquad (3.12)$$

Result of equation (3.12) are tabulated in Table 3.2.

Table 3.2: Discharge Coefficient as Function of Diameter Ratio.
Equation (3.12):At Maximum flow of 90 l/min.

β	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
C	6.91	3.06	1.71	1.07	0.72	0.49	0.33	0.2	0

From figure 3.1,for $\beta \simeq 0.6$, $C>0.6$.Therefore take $\beta=0.6$

Hence ,Orifice diameter,$D_2=\beta\times D_1=0.021\times 0.06=0.013m$

Summary:

Piping:Regular Copper 19.05 mm (3/4 in)nominal diameter.

Pipe inside diameter = 0.021m

Orifice diameter = 0.013m

Orifice thickness = 0.002m

Orifice shape:Square-edged hole.

3.4. Humidifying Column

The purpose of the humidifying column is to produce a stream of humid air.As in all humidifier design,only the gas outlet humidity and temperature is specified.(Not final water temperature as would be the case for cooling towers).See also chapter 11 /40/.

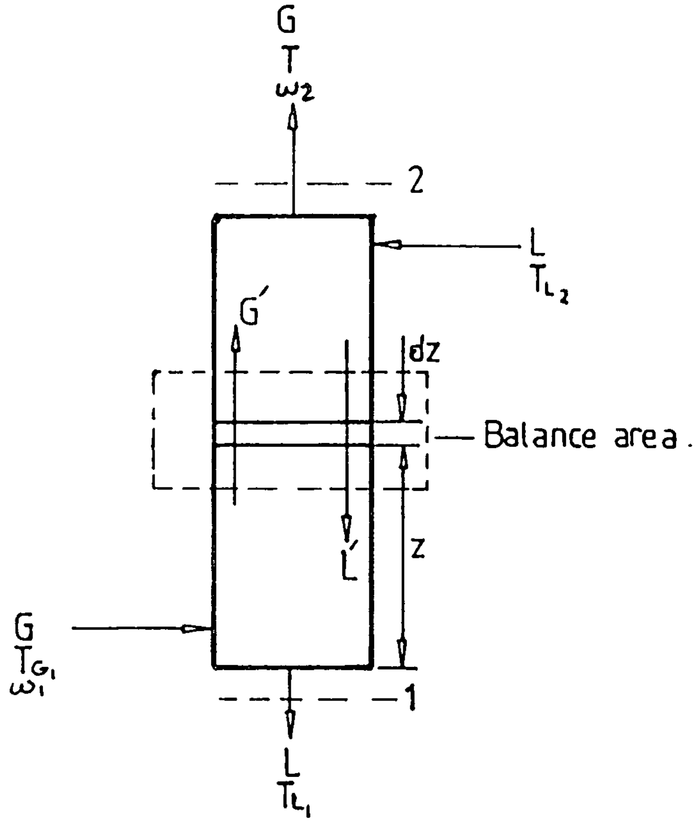


Fig.3.3: Flow in Humidifying Column.

Water balance gives

$$G'd\omega=dL' \tag{3.13}$$

Energy balance results in

$$G'dH_G=L'dH_L \tag{3.14}$$

Assuming that only a small amount of water is evaporated,then the amount of make up water is small and the temperature of circulating water approaches the adiabatic saturation temperature,T_s and remains constant.

Thus

$$T_{L1}=T_{L2}=T_f=T_s=\text{constant} \tag{3.15}$$

Thus $dT_L=0$ and $\omega_f=\omega_s$
Also

$$H_G=C(T_G-T_0)+\omega\lambda \tag{3.16}$$

Also

$$H_L=C_L(T_L-T_0) \tag{3.17}$$

Thus

$$dH_G=CdT_G+\lambda d\omega \tag{3.18}$$

And

$$G'dH_G=LC_LdT_L \tag{3.19}$$

Assuming physical properties of water do not change appreciably over the column height,these equations can be integrated to give

$$G'(H_{G2}-H_{G1})=L'C_L(T_{L2}-T_{L1}) \tag{3.20}$$

In contacting the gas and the liquid,there is both mass and heat transfer from the bulk of the liquid through the gas-liquid interface to the gas phase.

Thus the heat transfer from the bulk liquid to the interface is given by

$$h_L adz(T_L-T_f)=L'C_LdT_L$$

And with equation (3.15)

$$dT_L/(T_L-T_s)=h_L adz/L'C_L \tag{3.21}$$

Heat transfer from liquid-gas interface to the gas phase gives

$$h_G adz(T_f-T_G)=G'CdT_G$$

And with equation (3.15) gives

$$dt_G/T_s-T_G=h_G adz/G'C \qquad (3.22)$$

If column is completely wet,then,the heat transfer area is equal to the mass transfer area.Thus for mass transfer from the liquid-gas interface to the gas is

$$h_D \rho adz(\omega_f-\omega)=G'd\omega$$

And with equation (3.15)

$$d\omega/(\omega_s-\omega) = h_D \rho adz/G' \qquad (3.23)$$

Integration of equation (3.22) and equation (3.23) and rearranging gives

$$(T_{G1}-T_{G2})/(T_{G2}-T_s)=1-e^{-h_G az/G'C}$$

ie

$$T_{G2}=(T_{G1}+AT_s)/(A+1) \qquad (3.24)$$

Where

$$A=1-e^{-h_G az/G'C} \qquad (3.25)$$

Also

$$(\omega_2-\omega_1)/(\omega_s-\omega_1)=1-e^{-h_D \rho az/G'}$$

ie,

$$\omega_2=\omega_1+B(\omega_s-\omega_1) \tag{3.26}$$

Where

$$B=1-e^{-h_D\rho az/G'} \tag{3.27}$$

Thus for a given column diameter and packing material,the condition of the gas at the outlet (which is specified by the humid air required) depends on the height of packing,z.The column packing can therefore be calculated on heat transfer basis,equation (3.24) or mass transfer basis, equation (3.26).Normally,the larger value resulting from the two methods would be used.

The heat and mass transfer coefficients are approximated by

i)Gas side heat transfer coefficient,h_G:

Taecker and Hougen method (See page 18-38 /37/) for Raschig rings gives

$$j_H=1.148Re^{-0.48}=(CG/k)^{2/3}\times h_G/CG \tag{3.28}$$

Where

$$Re=G/\mu\times\surd A_p \tag{3.29}$$

ii)Gas side mass transfer coefficient,h_D:

Same method gives for mass transfer

$$j_D=1.07Re^{-0.41}=h_DP_{gf}M_m/G\times(\mu/\rho D_G)^{2/3} \tag{3.30}$$

Equations (3.28) and (3.30) are valid for $70<Re<3000$

Possible air flow rates can range from 26.5l/min to 90l/min and maximum temperature of 60°C,saturation humidity at this temperature is 0.15kg/kg.See chapter two.

Thus taking ambient temperature to be 25°C physical fluid properties can be evaluated at mean temperature of (60+25)/2 = 42.5°C,say

40 °C.

Air density, ρ = 1.092 kg/m^3

Air viscosity, μ = 2.10^{-5}Ns/m^2

Air Prandtl No., Pr = Cμ/k = 0.71

Air specific heat, C = 1000J/kgk

Gas side Diffusion Coeff. D_G = 2.112.10^{-5}m^2/s

Water density, ρ = 1000kg/m^3

Water viscosity, μ_L = 6.10^{-4}Ns/m^2

Air molecular weight, M_m = 29kg/kmol

Column Diameter, D = 0.152m

Rasching ring size, d = 0.013m

Rasching ring wall thickness, s = 1.588.10^{-3}m

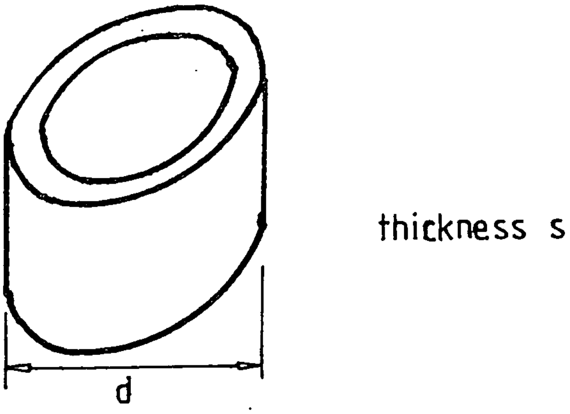


Fig.3.4: Sketch of Rasching Ring.

External area, $A_p = \pi d^2 + 2s\pi d + 2sd$

$= \pi \times 0.013^2 + 2 \times 1.588.10^{-3}(\pi \times 0.013 + 0.013)$

$= 7.019.10^{-4}$m^2

Taking mean air flow rate of 55l/min then

$G = 55 \times 4 \times 1.092/(1000 \times 60 \times \pi \times 0.152^2)$

$= 5.506.10^{-2}$kg/m^{2}s

Which gives

$$Re=G/\mu\sqrt{A_p}=5.506.10^{-2}/2.10^{-5}\times\sqrt{7.019.10^{-4}}=73$$

With equation (3.28) gives

$$h_G=1.148\times73^{-0.48}\times1000\times5.506.10^{-2}\times0.71^{-2/3}=13.7\ w/m^2k$$

For mass transfer coefficient,approximate P_{gf}=1atm.(low vapour content in the vapour phase).$M_m \simeq M_a$=29kg/kmol.

Equation (3.30) gives

$$h_D=1.07\times73^{-0.41}\times5.506.10^{-2}/29\times(2.10^{-5}/(1.092\times2.112.10^{-5}))^{-2/3}$$

ie,$h_D=3.8.10^{-4}$m/s

Using these values of h_G and h_D with equations (3.24) and (3.26) air outlet temperature and humidity is calculated as a function of column packing height,z.Results are tabulated in Table 3.3.

Table 3.3: Air Outlet Conditions as Function of Packing Height,z
Parameter:Circulating Water Temperature.Equations (3.24) and (3.26)

z[m]	Water Temperature,°C							ω(60°C)
	40	50	60	70	80	90	100	kg/kg
0	25	25	25	25	25	25	25	0.141
0.1	30.6	34.4	38.1	41.9	45.6	49.3	53.1	0.141
0.02	31.4	36.4	41	45.5	50.1	54.7	59.2	0.141
0.03	32.2	37.1	41.9	46.7	51.6	56.4	61.2	0.141
0.04	32.4	37.3	42.3	47.2	52.1	57.1	62	0.141
0.05	32.5	37.4	42.4	47.4	52.4	57.3	62.3	0.141
0.06	32.5	37.5	42.5	47.5	52.4	57.4	62.4	0.141
0.07	32.5	37.5	42.5	47.5	52.5	57.5	62.5	0.141
0.08	32.5	37.5	42.5	47.5	52.5	57.5	62.5	0.141
0.09	32.5	37.5	42.5	47.5	52.5	57.5	62.5	0.141

The required height for duty specified is found to be about 0.1m. Thus a realistic value of 1m is taken.

3.4.1. Check for Flooding

Using generalised pressure drop correlation figure for example see page 492/41/,a check can be made to see whether the column runs below flooding conditions.See figure 3.5.

$$K_4=42.9G^2F_p(\mu_L/\rho_L)^{0.1}/[\rho_v(\rho_L-\rho_v)] \qquad (3.31)$$

Taking maximum flow rate of 90l/min this gives

$$G=90\times4\times1.092/(1000\times60\times\pi\times0.152^2)=0.09\ \mathrm{kg/m^2s}$$

This gives

$$K_4=42.9\times0.09^2\times640\times(6.10^{-4}/1000)^{0.1}/[1.092(1000-1.092)]=0.05$$

From figure 3.5 it can be seen that this value is far below the range at which flooding is likely to occur.Hence non-flooding requirements are fulfilled.

Summary

Column diameter = 0.152m

Packing height = 1m

Packing size = 0.013m(1/2in)

Packing material:Ceramic Rasching rings

The flow sheet is given in figure 3.6

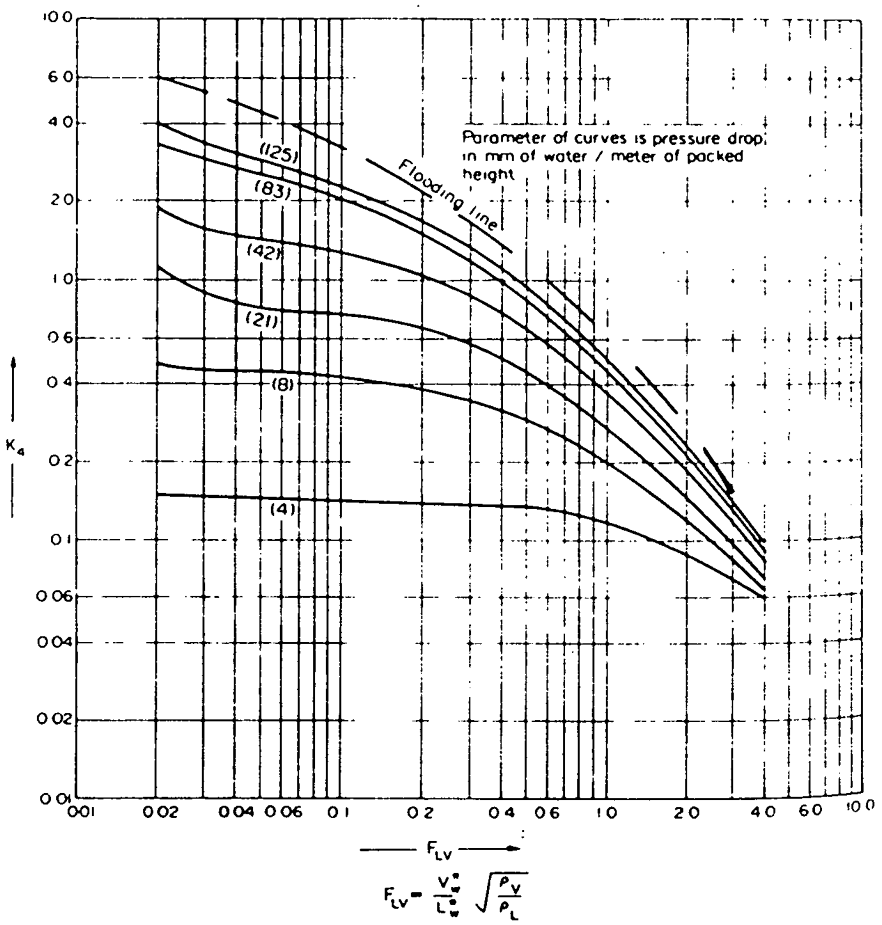
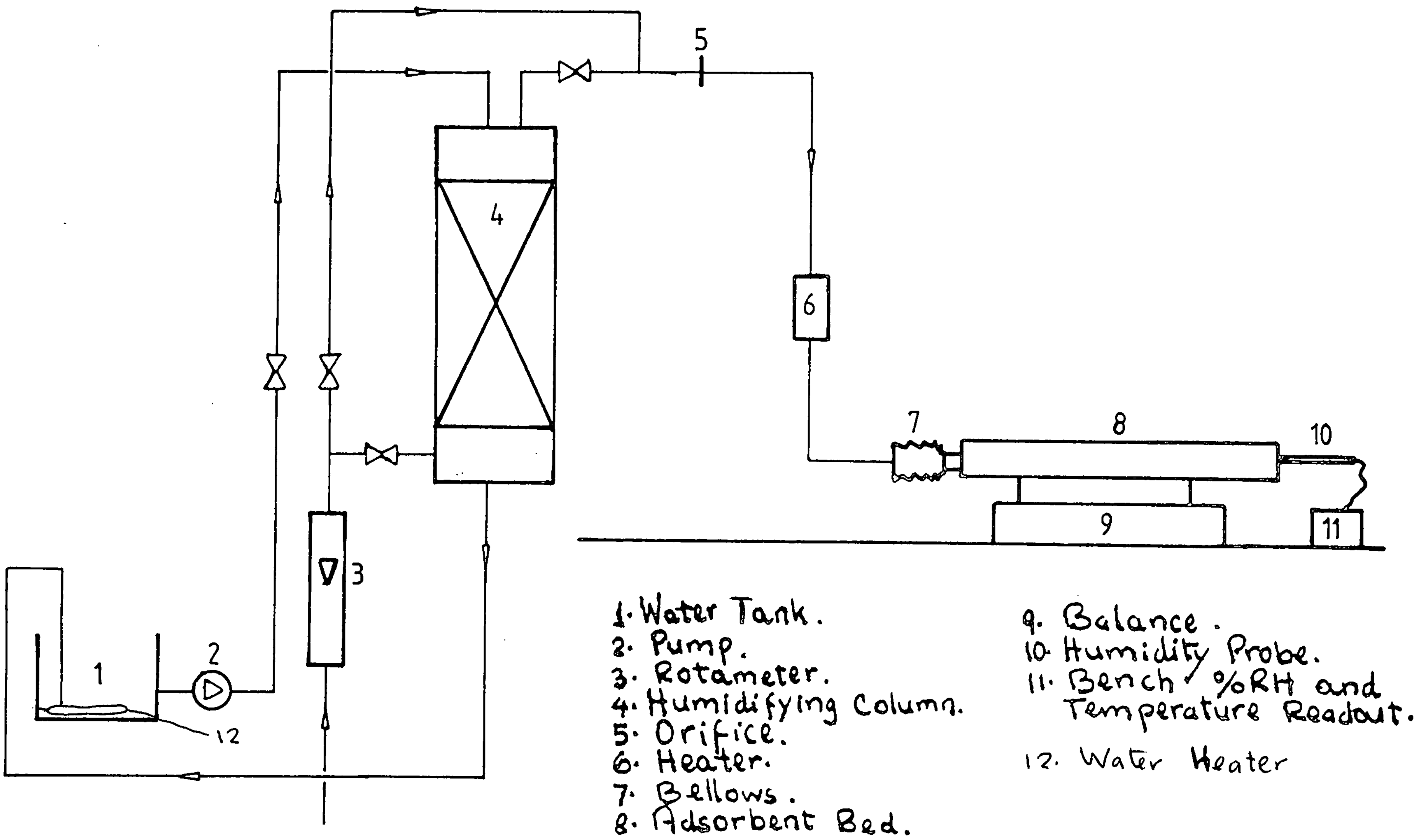


Fig.3.5:Generalised Pressure Drop correlation.Source /41/.

Fig 3·6 Flow Sheet



CHAPTER 4

EXPERIMENT AND MEASUREMENT METHODS

Experiments to study the adsorption process of water vapour on Magnesium Chloride in this research are done by monitoring air flow,humidity and temperature at inlet and outlet,adsorbent weight and temperature of adsorbent across the whole bed length with time.This is done using the following equipment:

4.1. General Data Collection

All experimental data except air outlet humidity were collected by a Commodore " PET 4032 " Computer using the 8 Bit parallel user port and the IEEE bus.Data collected by the computer was collected as running averages of readings in that time interval.

4.2. Temperature

All temperature measurement were done using grade two thermocouple of type K.These have a standard accuracy of ± 2.2 °C in the range of 0-270 °C.

Using a CIL Microsystems PCI 1002 thermocouple amplifier the thermocouple voltage is fed into the PET as a twelve bit signal via the PET IEEE bus.The thermocouple amplifier range of 0-3 mV output corresponding to 0-4000 bits is used.(other ranges 0-10 mV and 0-100 mV are available).A suitable subroutine supplied by CIL Microsystems is used to convert the voltage to temperature using a fourth order polynomial.

4.2.1. Temperature Measurement Accuracy and Sensitivity.

Temperature range :0-100 °C

Amplifier output range 0-3 mV

Sensitivity 1 bit in 4000

Accuracy $\simeq \pm 100 \times 1/4000$

$\simeq \pm 0.024$ °C

4.3. Weight

Top pan electronic balances type GC62 and JC41 by Oertling weighing a maximum of 6 kg and 4 kg respectively.The weight is transfered to the PET as an 8 bit signal through the 8 bit parallel user port of the computer.

4.4. Air Flow

Process air is supplied from the compressed air line.The air flow is measured both by a Rotameter and Orifice.

Rotameter tube, of metric tube size 18 with Duralumin float type A size 18 (Diameter 18.70 mm and 3.85 gm weight) was used.A calibration chart supplied by the manufacturers,KDG flowmeters was available for use.

A specially designed Orifice plate was used to measure air flow. An MKS Differential Pressure Transducer was used to log the pressure difference to the PET computer via a CIL Microsystems PCI 1002 amplifier that generates a twelve bit signal.The Differential Pressure Transducer ,type 223BD-0001A SPCA is marketed under the trade name Baratron.This uses a ±15 VDC input to give a 0-5VDC output corresponding to 0-12.77mm (0-0.5 in) water. The Differential Pressure Transducer was industrially calibrated by the suppliers.The Orifice was calibrated against the Rotameter.

4.5. Humidity

A Humidity probe type CH12 by Lee-Integer was used.This was connected to a bench percent relative humidity and temperature readout type DHL supplied by the same.The probe accuracy was checked to be good against humidity chambers in the Department of Forestry at the University of Edinburgh.

4.6. Regeneration Air Temperature Control

A precision digital temperature controller type TC201 by Servomex was used to control the power supply to the 3Kw regenerator air heater.

The controller power supply can be varied manually between 105 and 250 VAC .The controller offers a derivative time constant of 0-150 seconds and a proportional band of 0.1-30 °C both of which are adjustable.

The regeneration air temperature is sensed by a Platinum grade two resistance thermometer.

4.7. Initial Moisture Content Of Adsorbent

A vacuum moisture testing machine was used to determine the initial moisture content of the sample.The machine is type DL275 make of Townson and Mercer Ltd.

4.8. Sample Preparation

The sample was prepared by crushing and sieving.The sample size taken was d>1mm and d<3.2mm.In all calculations a sample mean size of 2mm was assumed.

4.9. Sources of Errors

1. The tube holding the adsorbent was connected to the air supply tube by a bellows.See figure 3.6.This type of connection may lead to mechanical errors in weight measurement.it was found that the weight measurements were virtually non reproduceable.For example at static condition (no air flowing) a 5 gm weight when placed on either end produced weight difference of up to 530 gm. But this change was still not reproduceable.Bed weight in result evaluation is thus calculated from mass balance using the measured outlet humidity.

2. Air flow:Air leaks on the downstream of the Orifice meter are not accounted for in measurement and evaluation of results.

3. Humidity:Humidity measurements were recorded manually.Thus while readings recorded automatically by the computer are recorded as running averages in the time interval,humidity measurements are not averaged.

CHAPTER 5

EVALUATION OF RESULTS AND ESTIMATION OF PARAMETERS

5.1. Mass and Heat Balance

In the experiments the following parameters were measured:

- Temperature:Inlet,Outlet and 10 points along the bed length.
- Outlet Humidity as percent relative humidity,%RH and Temperature.
- Bed Weight.This,as explained under section 2.9 is not used in evaluation of results.

The recorded paired data of Temperature and %RH are used to calculate the corresponding partial pressure,Pv of water vapour in the air stream.

$$Pv = \%RH \times P_s/100 \qquad (5.1)$$

The saturation pressure,P_s at any temperature is calculated using equation (2.7) and the outlet humidity,ω_2 using value of Pv in equation (2.6)(with M_{air} = 29 kg/kmol and M_{H2O} = 18 kg/kmol.).Then using equation (2.4) the corresponding bed loading is calculated.Values are tabulated for each experiment and are plotted as graphs of Bed loading vs Time and Temperature vs Time in figures 5.1 to 5.10 (for Adsorption experiments) and figures 5.11 to 5.13 (for Regeneration experiments).

The Heat of Adsorption and Regeneration are evaluated using equation (2.5) and the following values:

C_s = 1000J/kgk

Cw =4184J/kgk

The values are then corrected by adding the amount of heat lost calculated using equation (2.41) with the thermal conductivity of metal(Aluminium) and thickness equal to 222W/mk and $2.413.10^{-3}$m respectively.The thermal conductivity of fibreglass insulation is 0.72W/mk and the insulation thickness is 25mm.Resulting values are tabulated for each experiment and the apparent variation of Heat of Adsorption with total amount adsorbed plotted in figures

5.14 to 5.23.

5.1.1. Adsorption Temperature and Moisture pick-up Profiles

Figures 5.1 to 5.10 show similar trends.The time taken for the Outlet Temperature and Humidity to reach a maximum value is called Breakthrough time. From these graphs,it can be seen that the breakthrough time(for the feed conditions and flow rate used in the experiment) is about 30 minutes.

After breakthrough,the bed and outlet temperature become nearly equal and continue to fall.The bed and outlet temperature becoming equal can probably be attributed to high particle-to-fluid heat transfer coefficients. See under section 5.2.

In all experiments,at the end,the maximum bed loading reached is about 0.5 kg/kg except in figure 5.6 which reaches nearly 0.6kg/kg.This suggests that in the reaction

$$MgCl_2 + aH_2O \rightleftharpoons MgCl_2.aH_2O$$

With Molecular weight for $MgCl_2$ and water 95.22kg/kmol and 18kg/kmol respectively,then the Molecular weight of $MgCl_2O.aH_2O$ is 95.22+a×18 kg/kmol.For bed loading X = 0.5 kg/kg,then

$$a = 0.5 \times 95.22/18 = 2.645$$

Thus "a" : 2<a<3.Note that the Bed loading initially was not zero.The actual change in bed loading is only about half of 0.5 and thus "a" is between one and one and a half.

5.1.2. Regeneration Temperature and Drying Profiles

Figures 5.11 to 5.13 show similar trends.Throughout the 100-minute period of these experiments,the bed loading is still falling.The temperature profiles suggest that the bed and outlet temperature approach the regeneration air temperature asymptotically.

5.1.3. Variation of Apparent Heats of Adsorption

The heat of Adsorption is expected to be initially very large, probably around 7000kJ/kg(see below) and to fall as adsorption progresses. (See also page 7 /35/.) Some of the experimental results conform to this pattern.(See figures 5.16,5.17,5.18 and 5.20.) The rest show an initial rising trend before starting to fall.No logical explanation has been found for this observation.

It was explained under section 2.1 that in physical Adsorption,the heat of Adsorption is normally as high as three times the Latent heat of Condensation.Taking a value of 2260 (100°C)kJ/kg as the Latent heat of Condensation,the heat of Adsorption is expected to be as high as 6780kJ/kg and likely to be within the range $2260<\Delta H_a<6780$kJ/kg.Most of the values calculated are within this range.

Fig. 5.1: Experiment Results: Date 28/11/85.

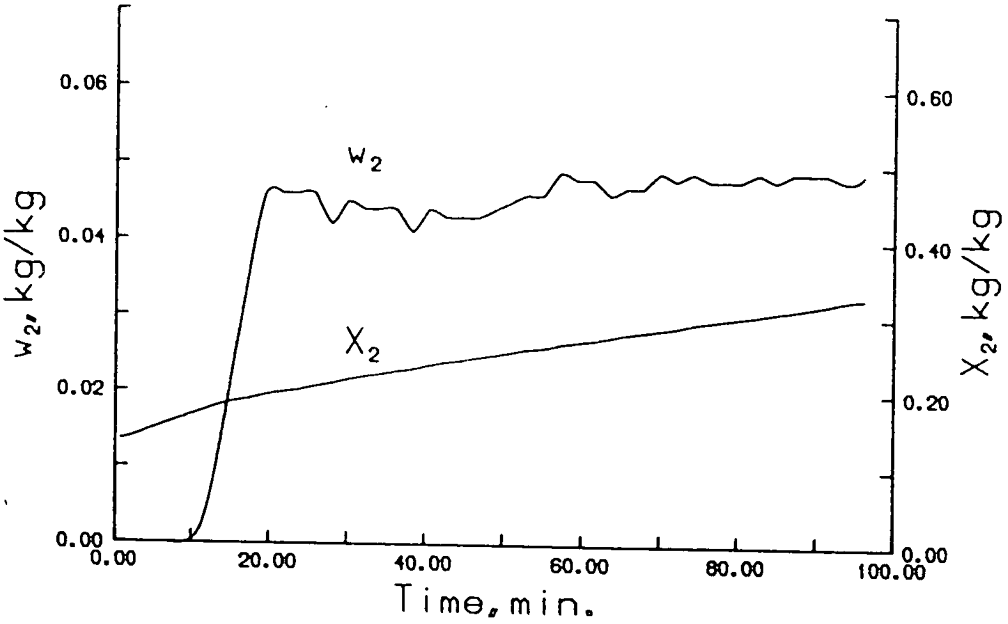
Adsorption

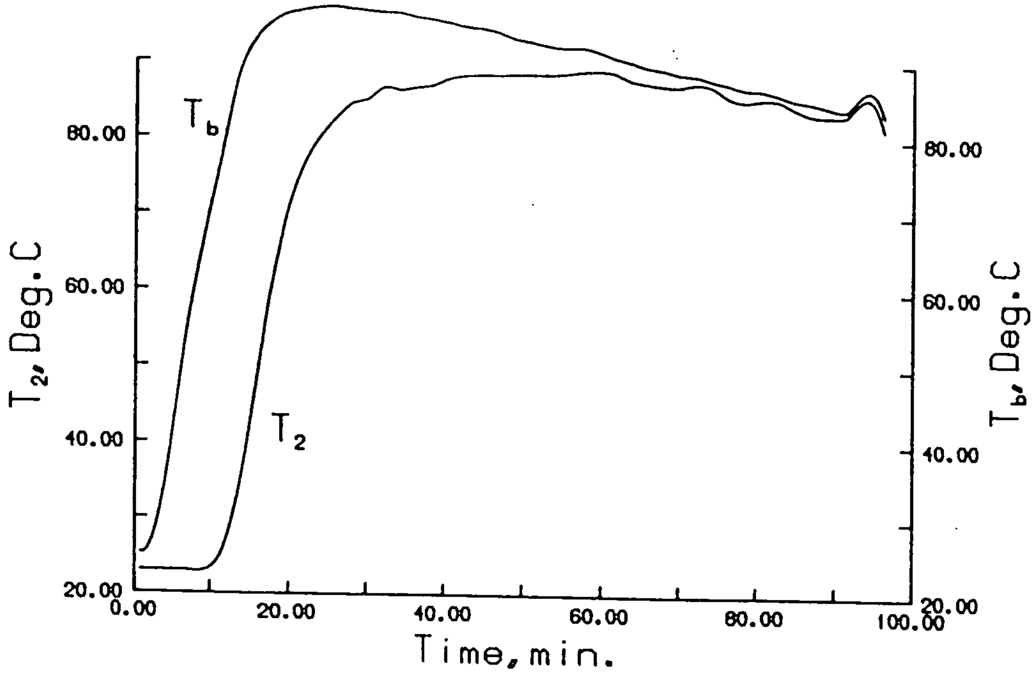
$X_1 = 0.133$ kg/kg

$T_1 = 52$ Deg. C

$w_1 = 0.095$ kg/kg

$Q = 32.47$ l/min ($U = 0.326$ m/s)





In figures 5.1 to 5.10 curves are through points after every two minutes. See sample data table in pocket

Fig.5.2:Experiment Results:Date 03/12/85.

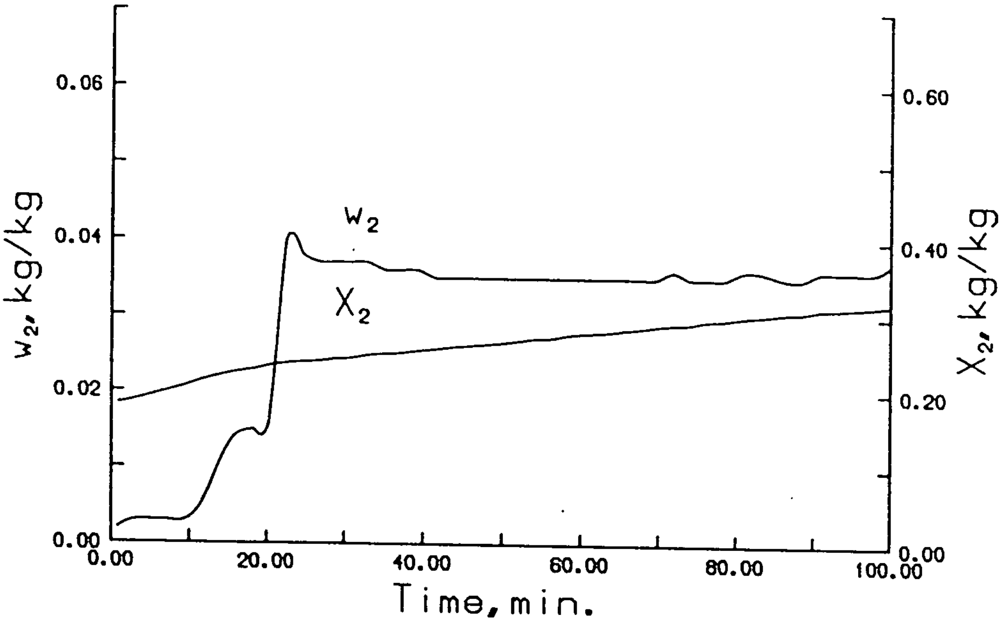
Adsorption

X_1 = 0.182 kg/kg

T_1 = 44.6 Deg.C

w_1 = 0.06 kg/kg

Q = 39.147l/min(U = 0.393 m/s)



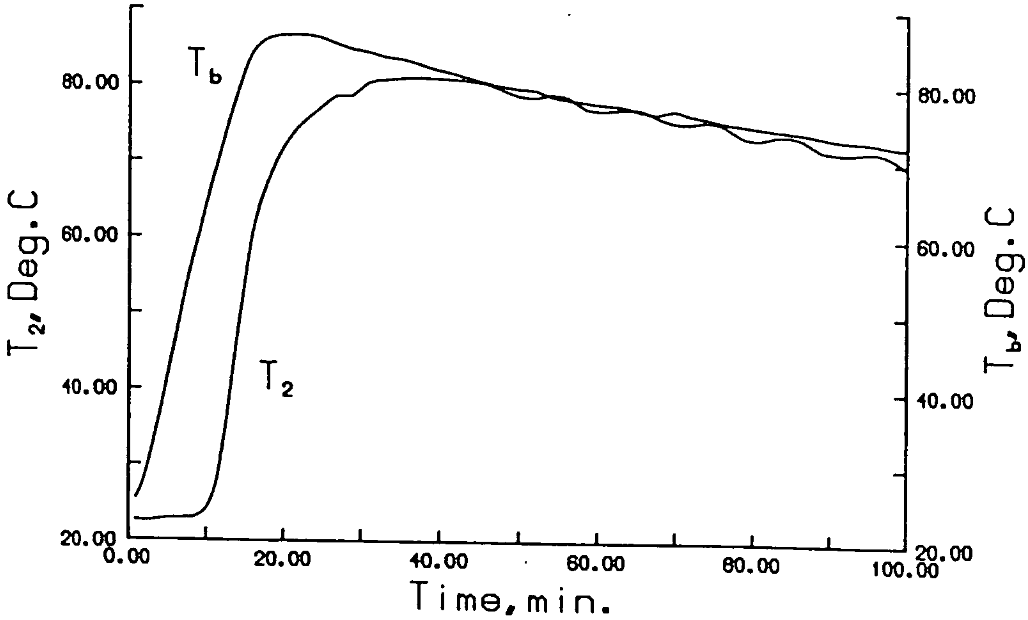


Fig.5.3: Experiment Results: Date 05/12/85.

Adsorption

X_1 = 0.244 kg/kg

T_1 = 45.5 Deg.C

w_1 = 0.068 kg/kg

Q = 39.147 l/min (U = 0.393 m/s)

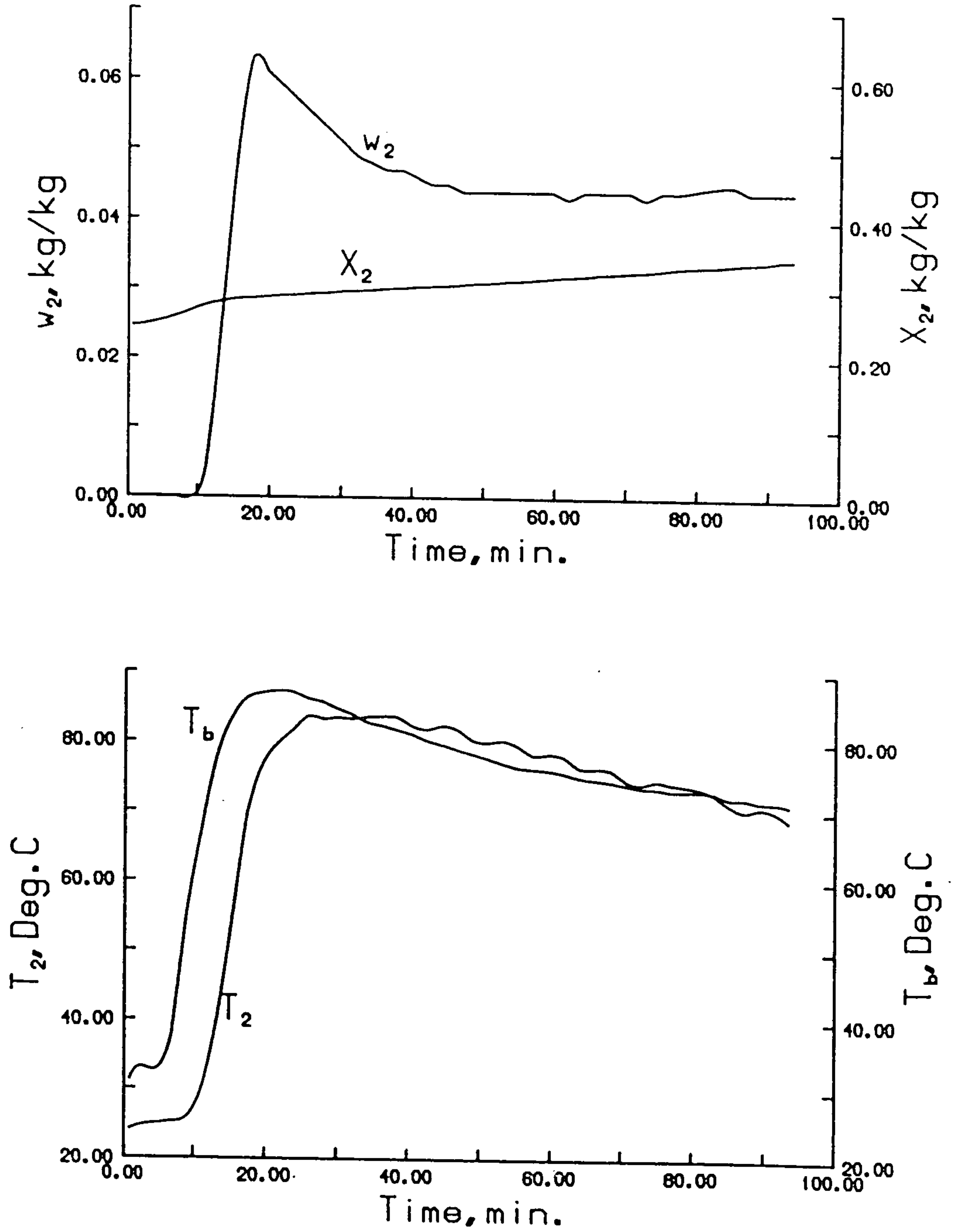


Fig.5.4:Experiment Results:Date 18/01/86.

Adsorption

X_1 = 0.17 kg/kg

T_1 = 44.4 Deg.C

w_1 = 0.062 kg/kg

Q = 39.147 l/min(U = 0.393 m/s)

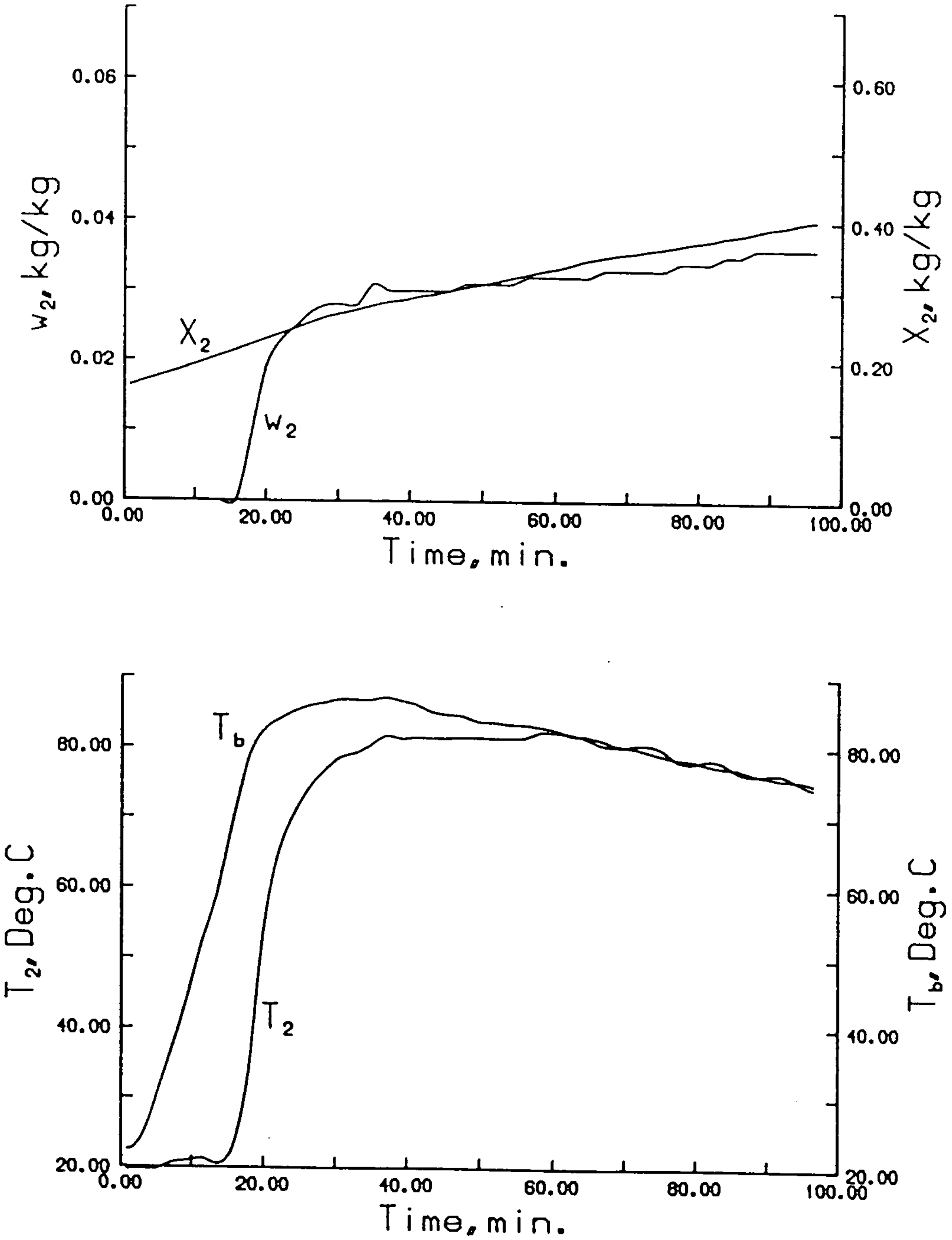


Fig.5.5:Experiment Results:Date 13/01/86.

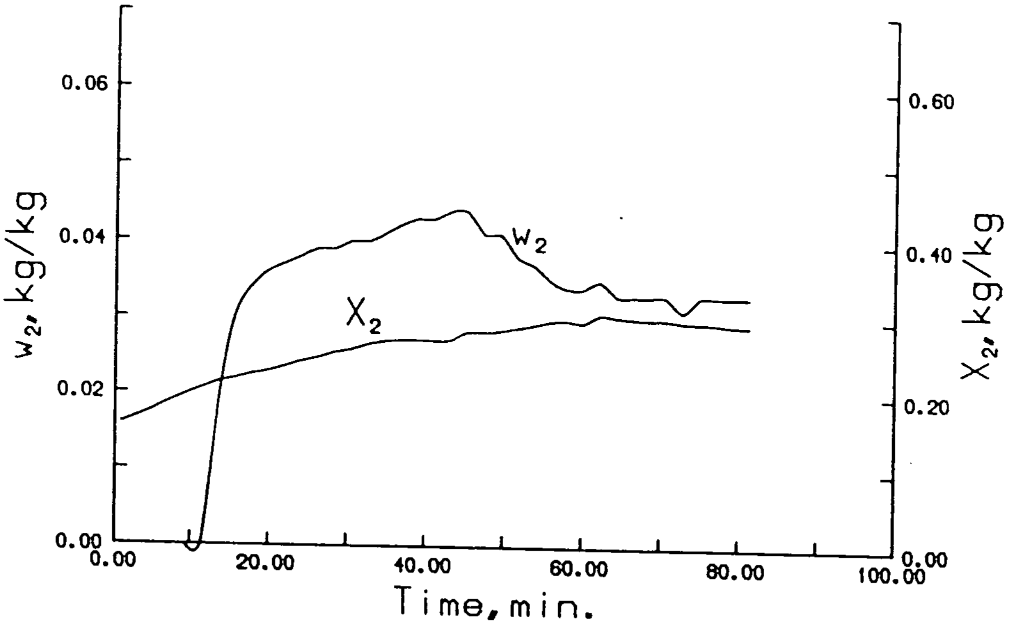
Adsorption

X_1 = 0.156 kg/kg

T_1 = 48 Deg.C

w_1 = 0.077 kg/kg

Q = 39.147 l/min(U = 0.393 m/s)



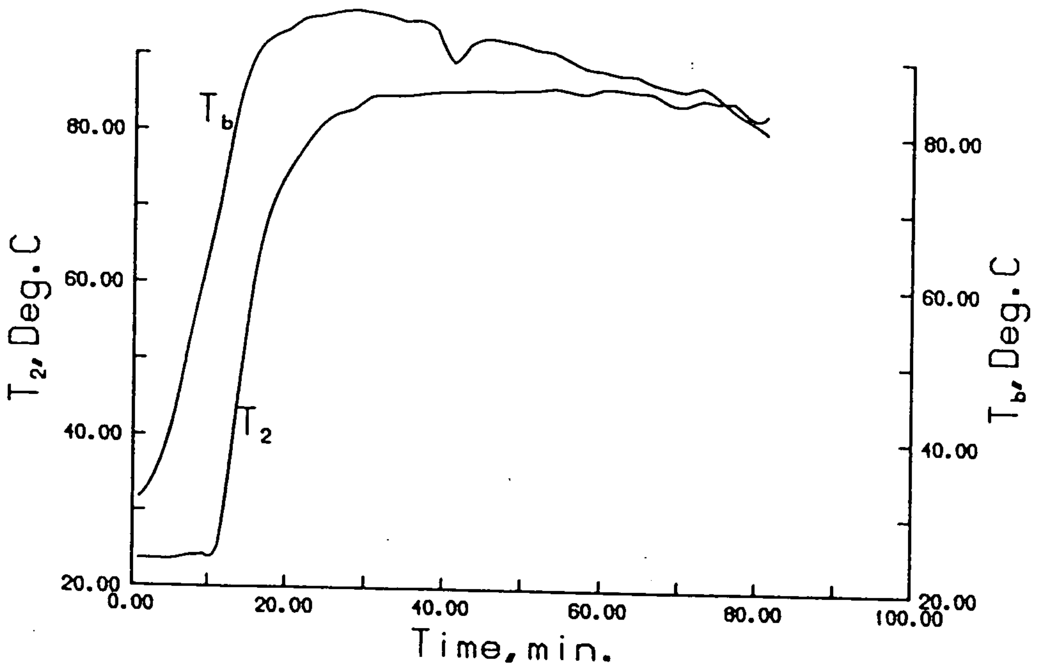


Fig.5.6:Experiment Results:Date 26/02/86.

Adsorption

X_1 = 0.224 kg/kg

T_1 = 52.3 Deg.C

w_1 = 0.094 kg/kg

Q = 39.147 l/min(U = 0.393 m/s)

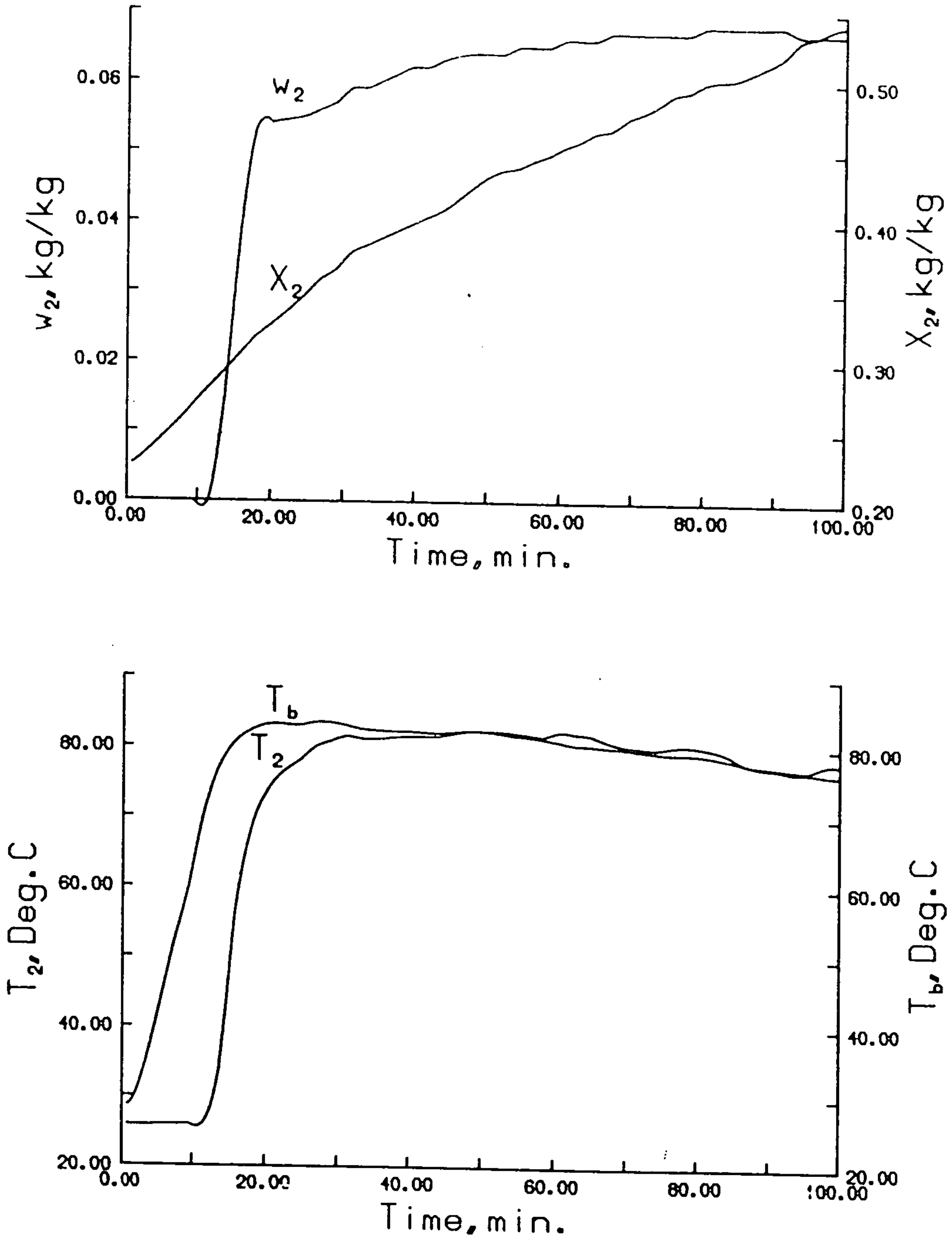


Fig.5.7:Experiment Results:Date 28/02/86.

Adsorption

X_1 = 0.144 kg/kg

T_1 = 54.4 Deg.C

w_1 = 0.092 kg/kg

Q = 39.147 l/min (U = 0.393 m/s)

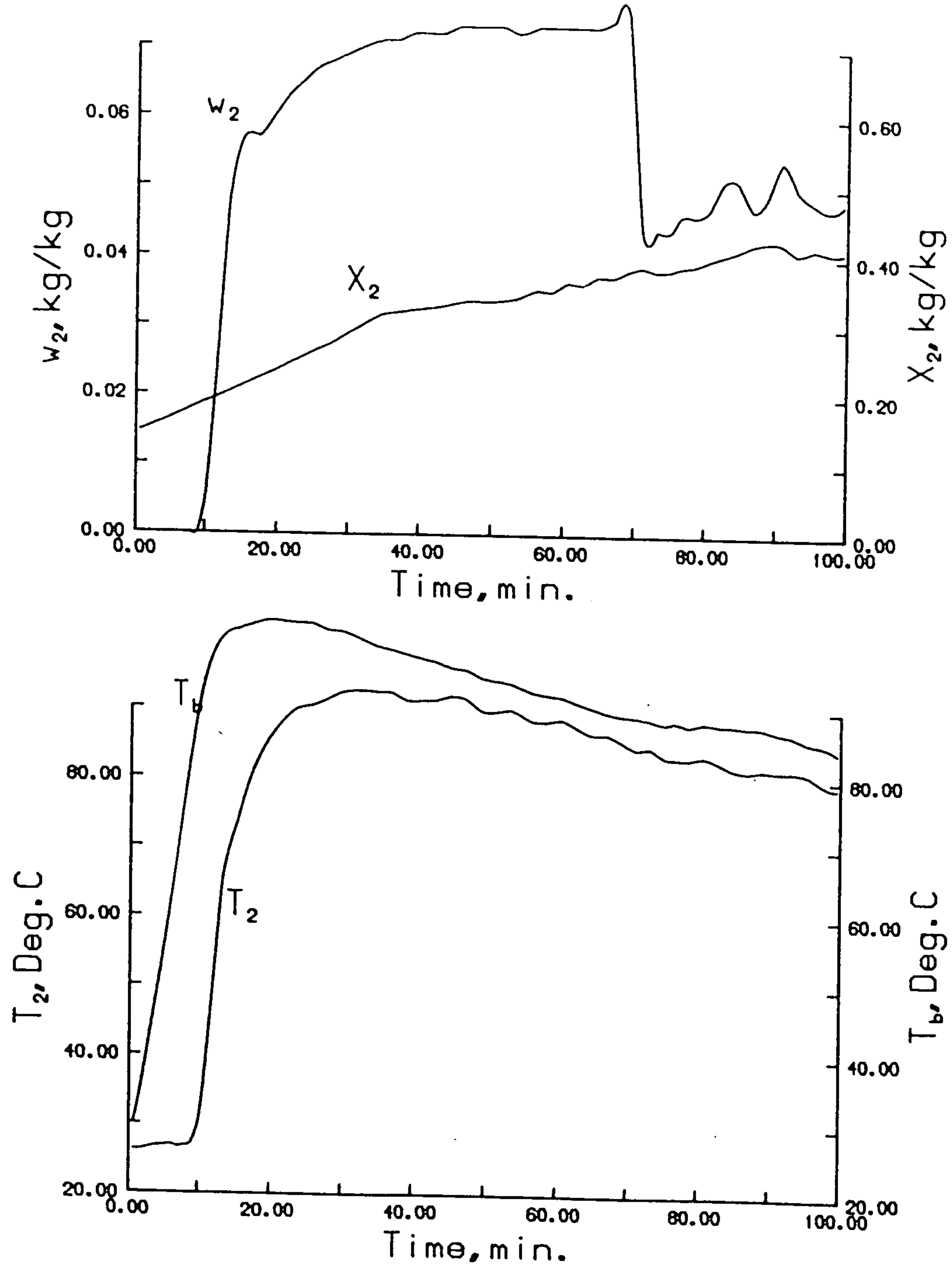


Fig.5.8:Experiment Results:Date 05/03/86.

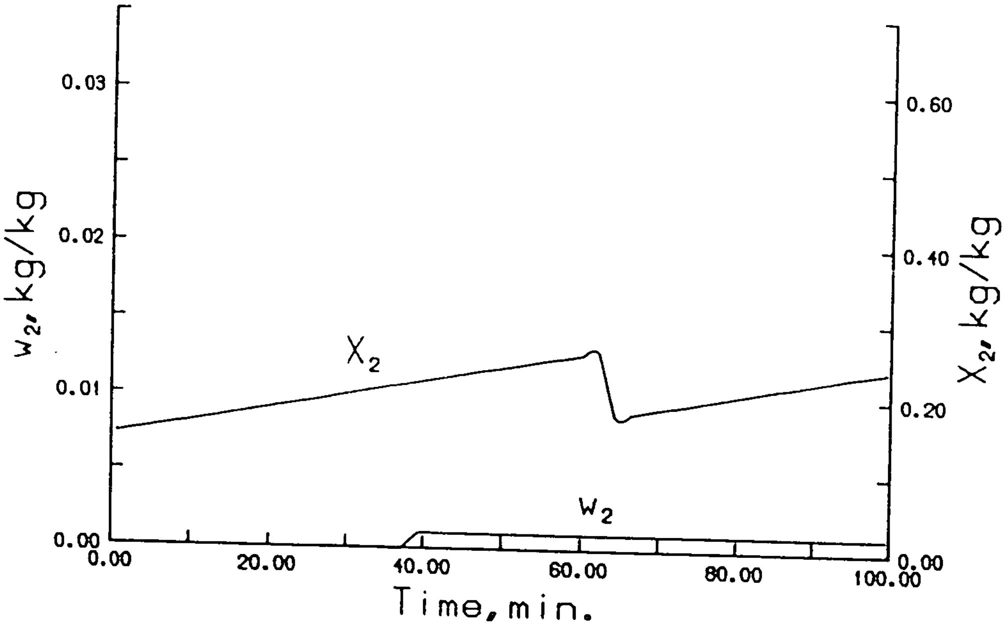
Adsorption

X_1 = 0.146 kg/kg

T_1 = 34.2 Deg.C

w_1 = 0.035 kg/kg

Q = 39.147 l/min(U = 0.393 m/s)



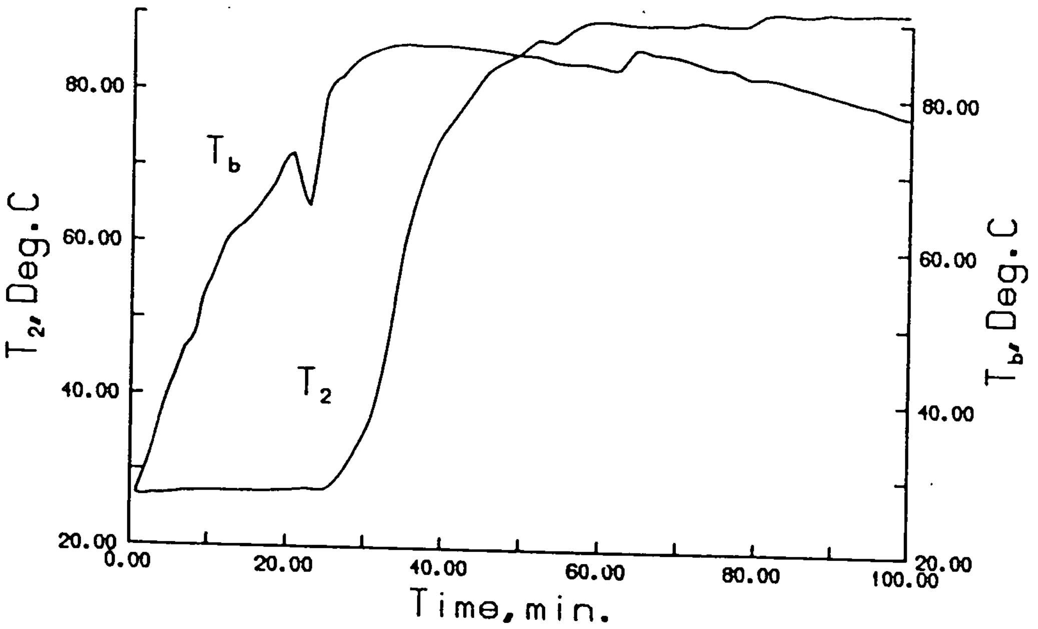


Fig.5.9:Experiment Results:Date 26/03/86.

Adsorption

X_1 = 0.198 kg/kg

T_1 = 47.8Deg.C

w_1 = 0.077

Q = 45.457 l/min(U = 0.456 m/s)

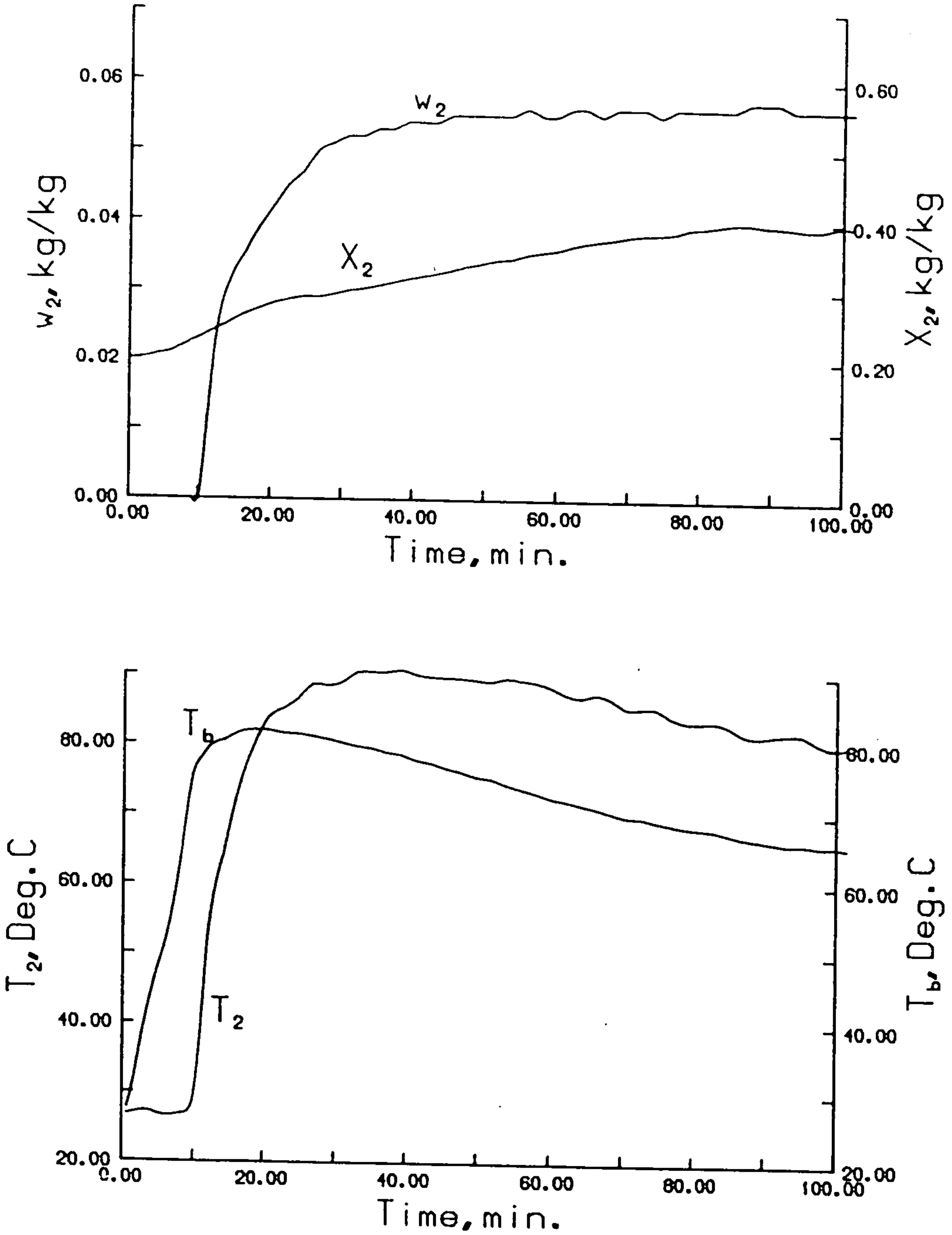


Fig.5.10:Experiment Results:Date 27/03/86.

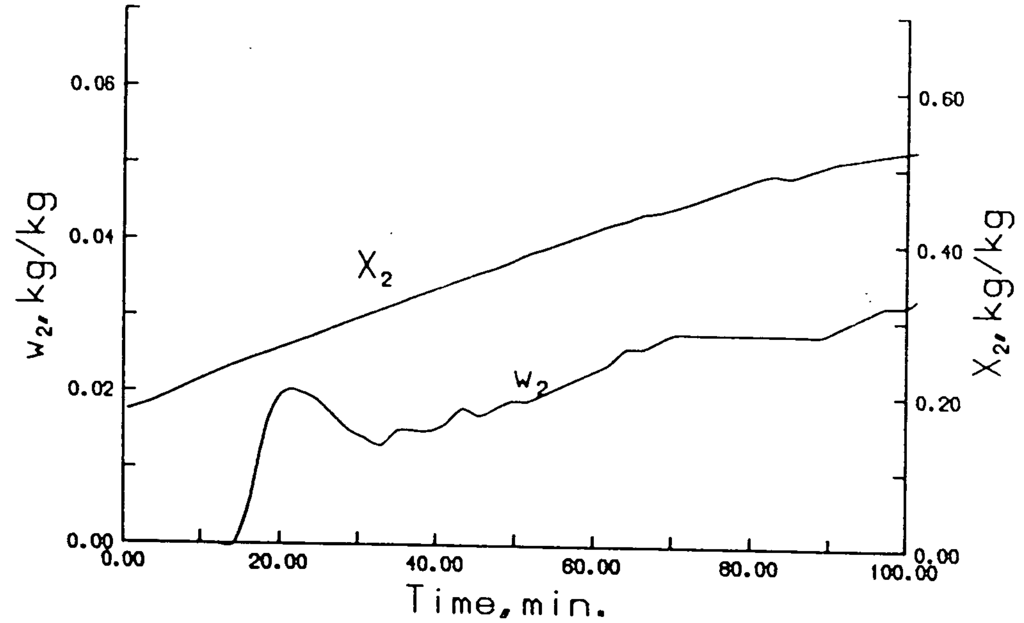
Adsorption (Bed without insulation)

X_1 = 0.173 kg/kg

T_1 = 44.6 Deg.C

w_1 = 0.064 kg/kg

Q = 39.147 l/min(U = 0.393 m/s)



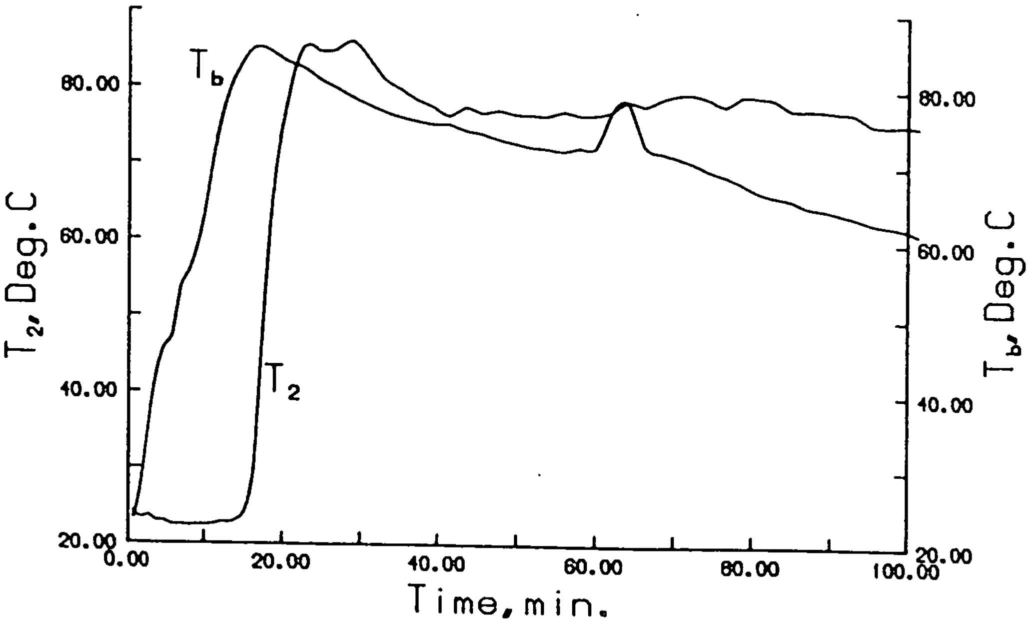


Fig.5.11:Experiment Results:Regeneration.

Date 12/06/86 :Expt.no 1

Air Flow = 59.71 l/min (U = 0.594 m/s)

Regeneration Air Temperature = 143 Deg.C

Initial Bed Loading = 0.149 kg/kg

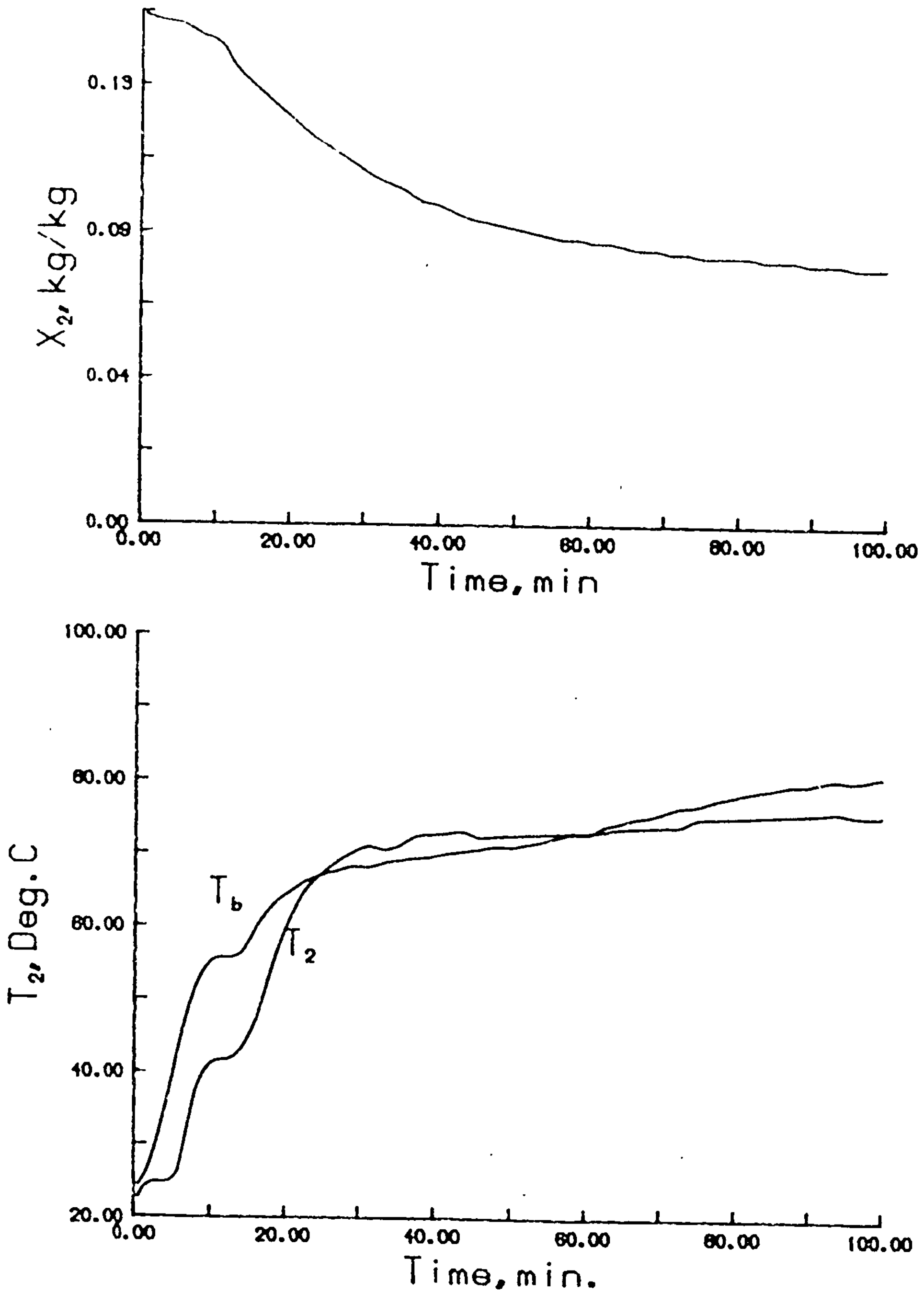


Fig.5.12:Experiment Results:Regeneration

Date 12/06/86 :expt.no3

Air Flow = 45 l/min (U = 0.452 m/s)

Regeneration Air Temperature = 144 Deg.C

Initial Bed Loading = 0.149 kg/kg

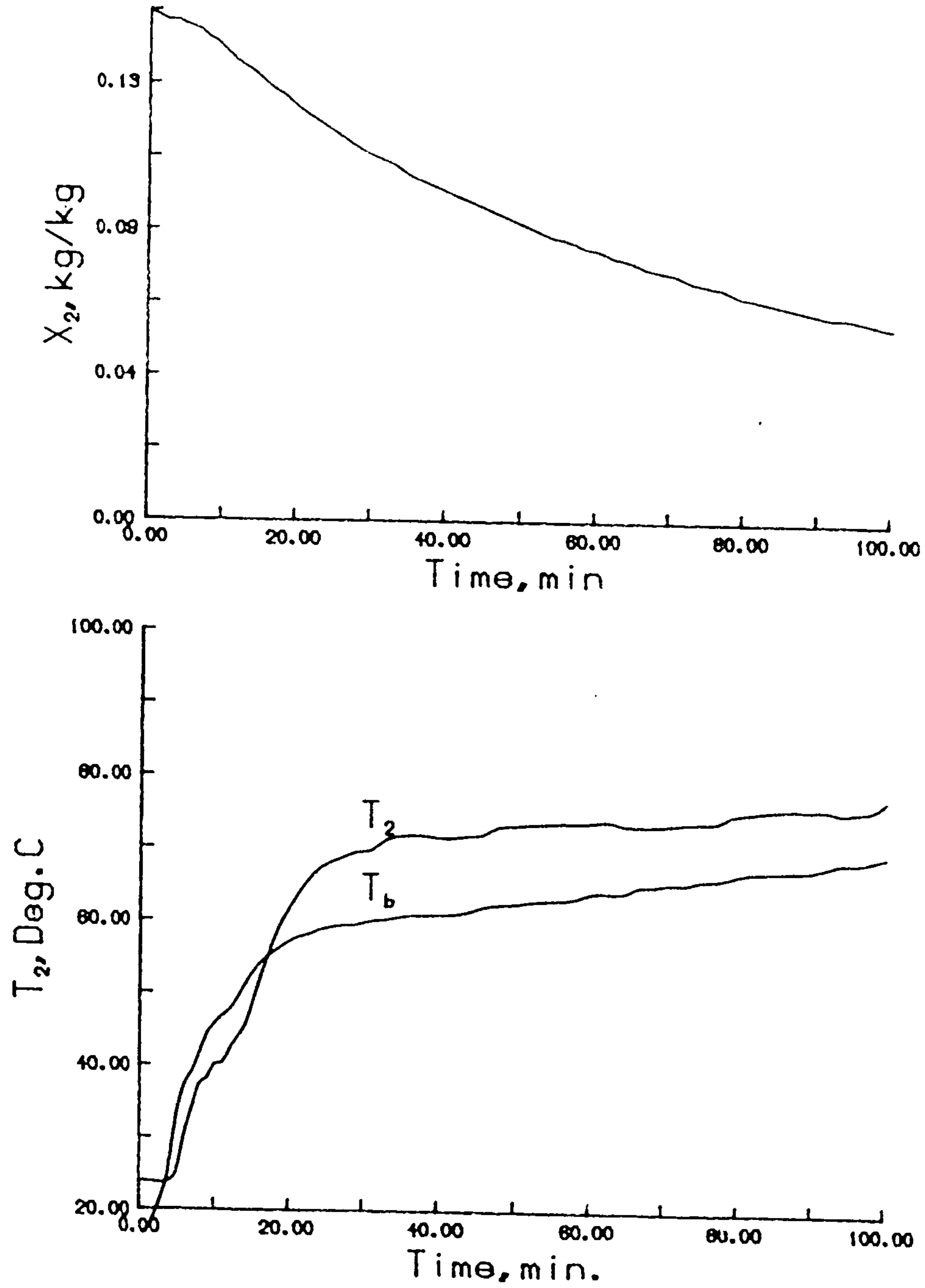


Fig.5.13:Experiment Results:Regeneration
Date 13/06/86
Air flow = 45 l/min (U = 0.452 m/s)
Regeneration Air Temperature = 164 Deg.C
Initial Bed Loading = 0.148 kg/kg

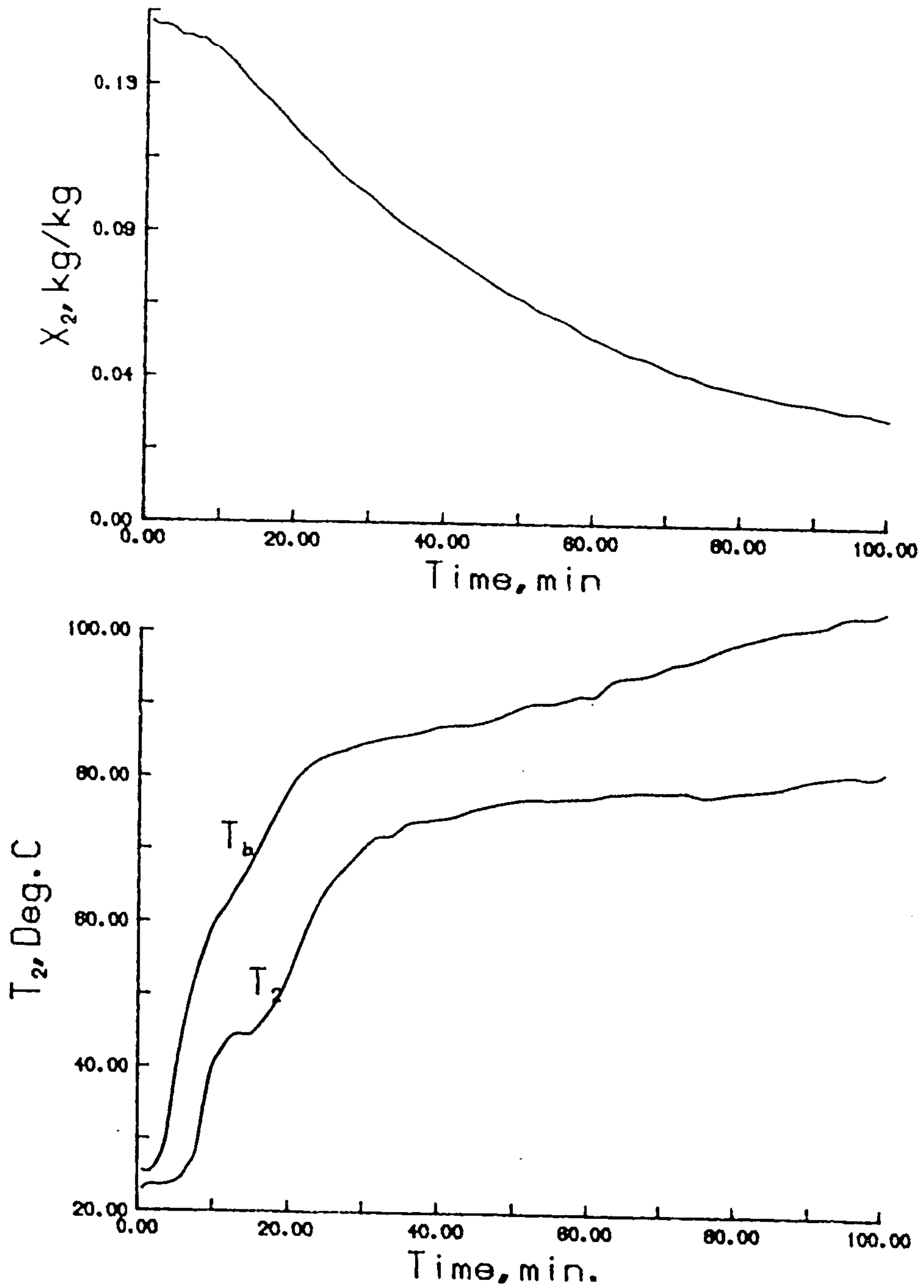


Fig.5.14:Experiment Results:Date 28/11/85.

Adsorption

X_1 = 0.133 kg/kg

T_1 = 52 Deg.C

w_1 = 0.095 kg/kg

Q = 32.47l/min(U = 0.326m/s)

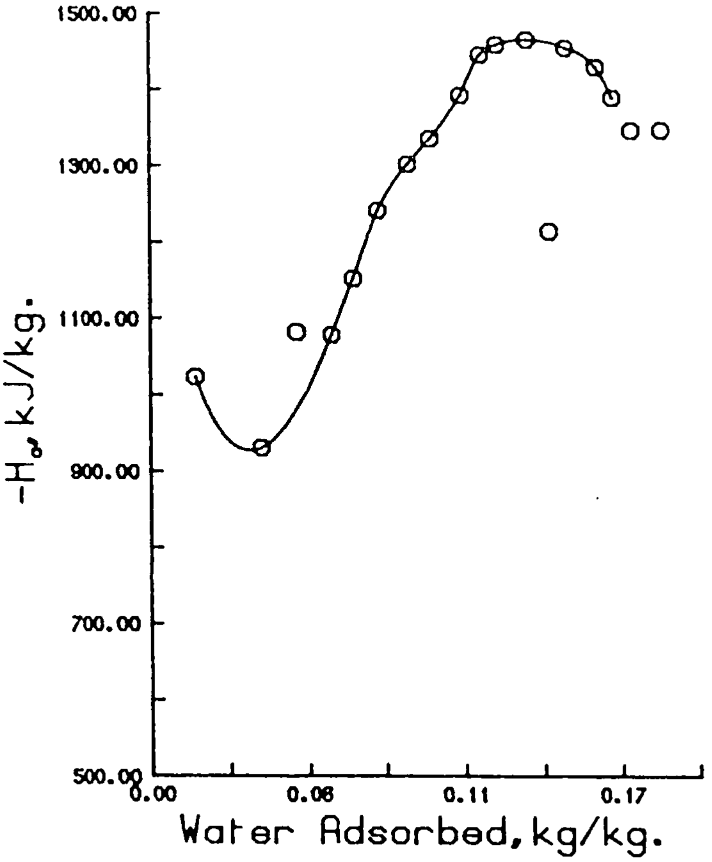


Fig.5.15:Experiment Results:Date 03/12/85.

Adsorption

X_1 = 0.182 kg/kg

T_1 = 44.6 Deg.C

w_1 = 0.06 kg/kg

Q = 39.147l/min(U = 0.393m/s)

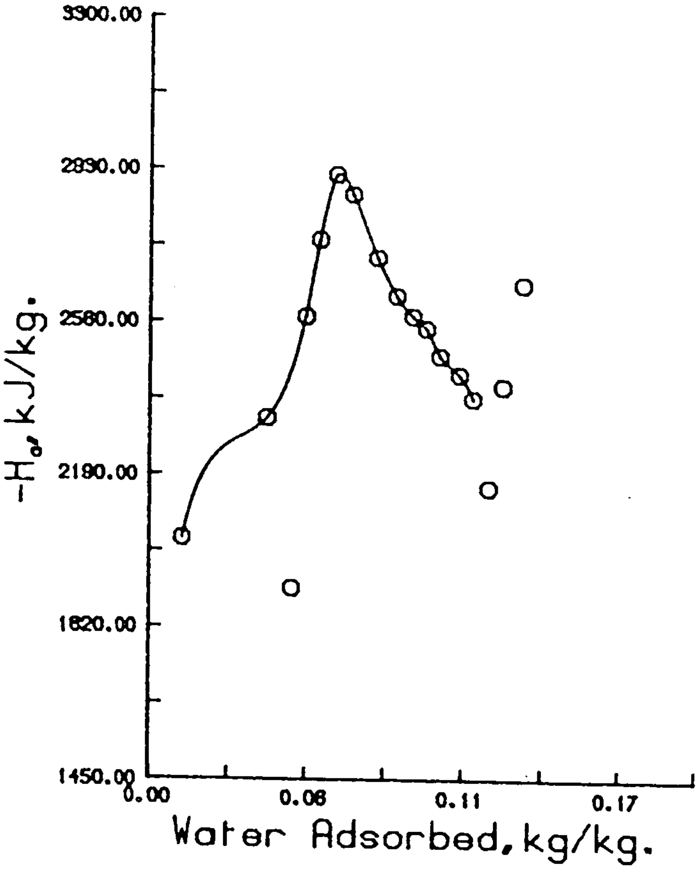


Fig.5.16:Experiment Results:Date 05/12/85.

Adsorption

X_1 = 0.244 kg/kg

T_1 = 45.5 Deg.C

w_1 = 0.068 kg/kg

Q = 39.147 l/min(U = 0.393m/s)

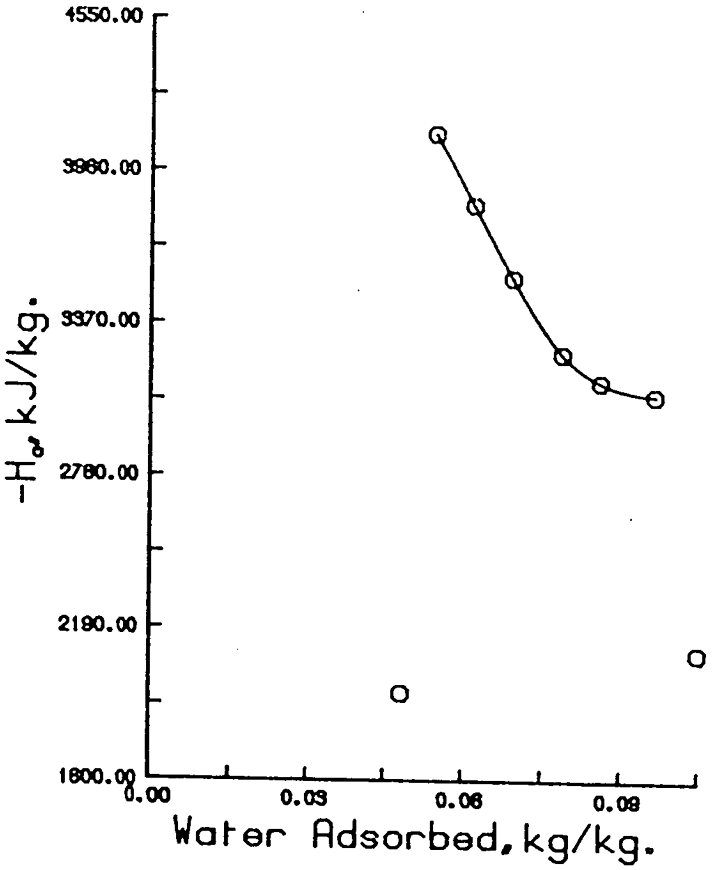


Fig.5.17:Experiment Results:Date 13/01/86.

Adsorption

X_1 = 0.156 kg/kg

T_1 = 48 Deg.C

w_1 = 0.077 kg/kg

Q = 39.147 l/min(U = 0.393m/s)

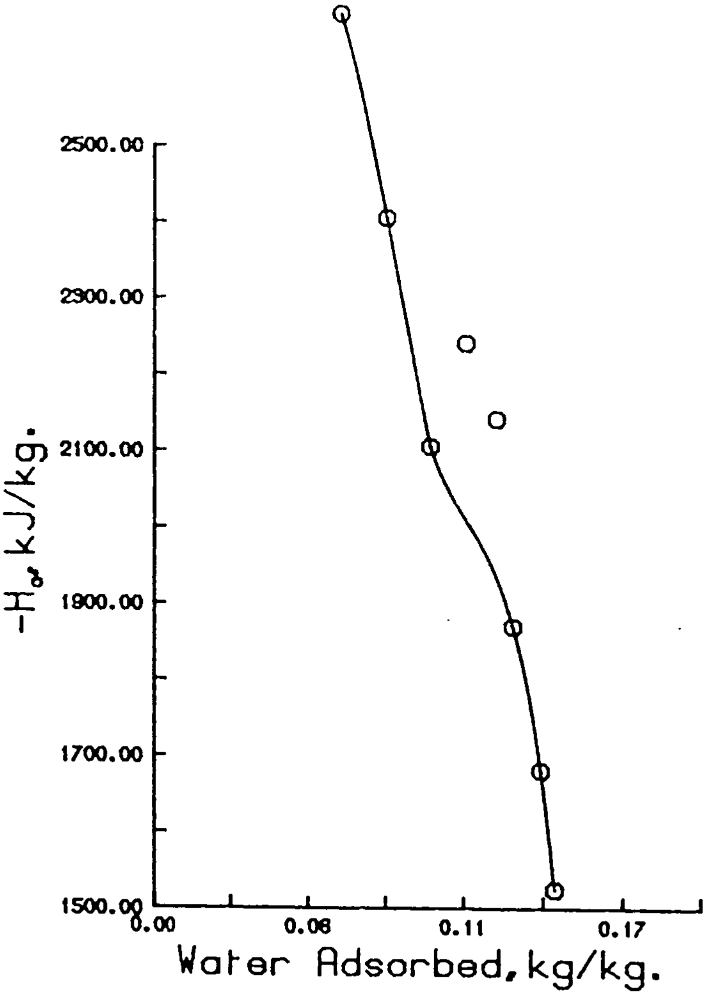


Fig. 5.18: Experiment Results: Date 18/01/86.

Adsorption

X_1 = 0.17 kg/kg

T_1 = 44.4 Deg.C

w_1 = 0.062 kg/kg

Q = 39.147 l/min (U = 0.393 m/s)

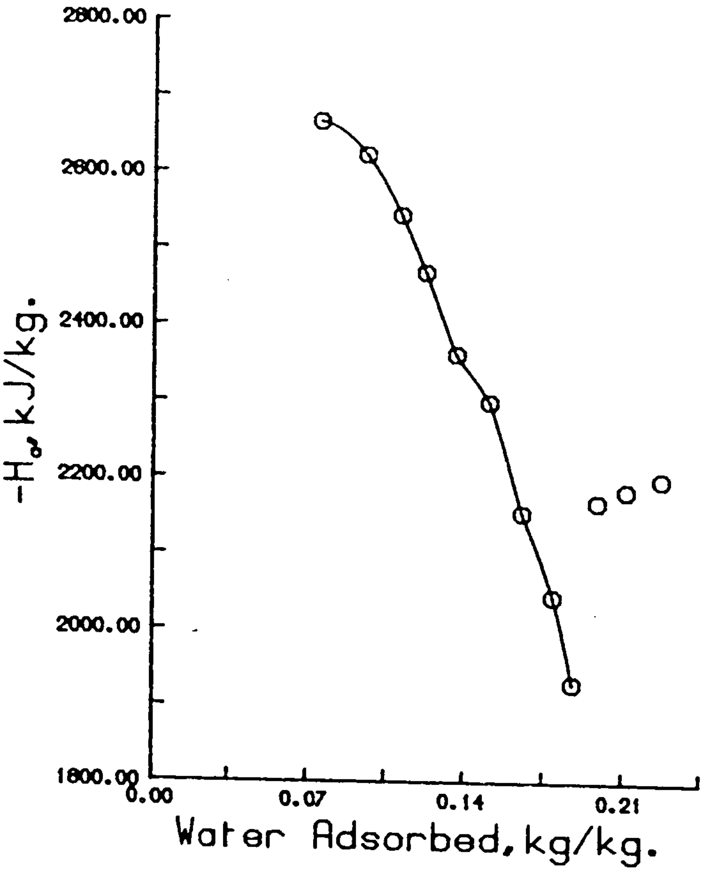


Fig.5.19:Experiment Results:Date 26/02/86.

Adsorption

X_1 = 0.224 kg/kg

T_1 = 52.3 Deg.C

w_1 = 0.094 kg/kg

Q = 39.147l/min(U = 0.393m/s)

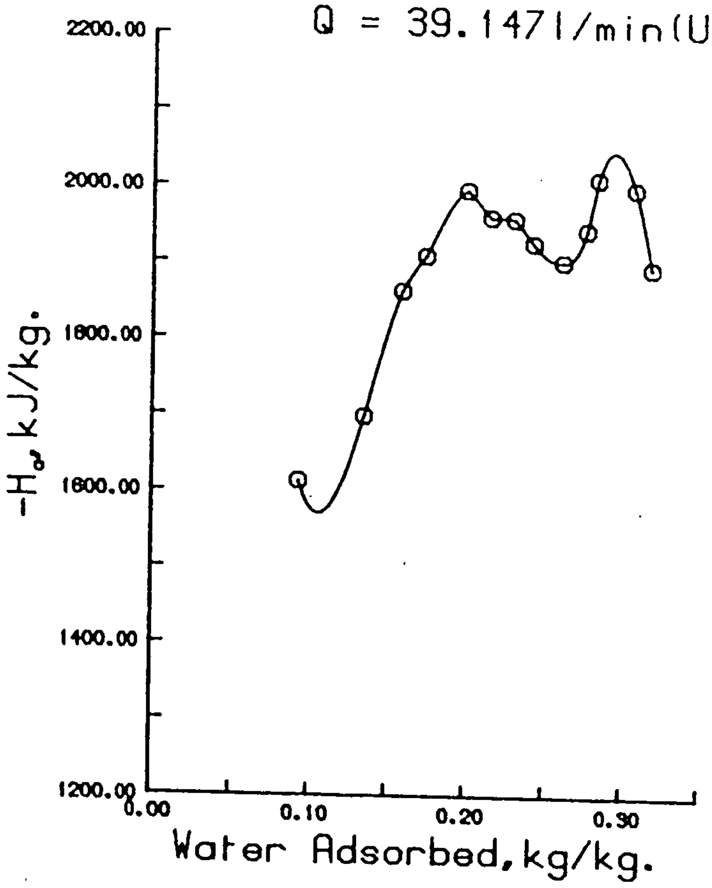


Fig.5.20:Experiment Results:Date 28/02/86.

Adsorption

X_1 = 0.144 kg/kg

T_1 = 54.4 Deg.C

w_1 = 0.092 kg/kg

Q = 39.147l/min(U = 0.393m/s)

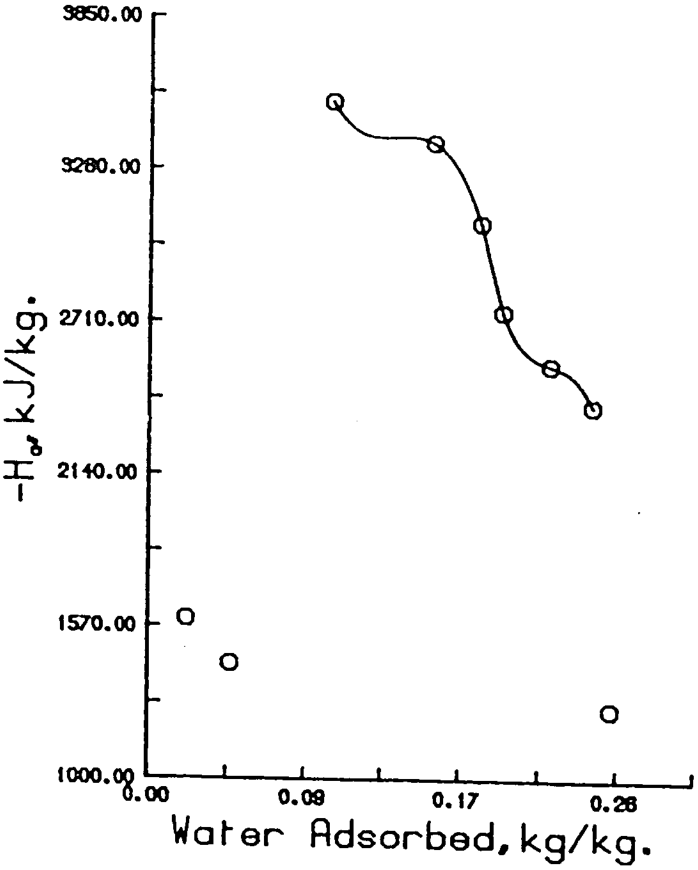


Fig.5.21:Experiment Results:Date 05/03/86.

Adsorption

X_1 = 0.146 kg/kg

T_1 = 34.2 Deg.C

w_1 = 0.035 kg/kg

Q = 39.147l/min(U = 0.393m/s)

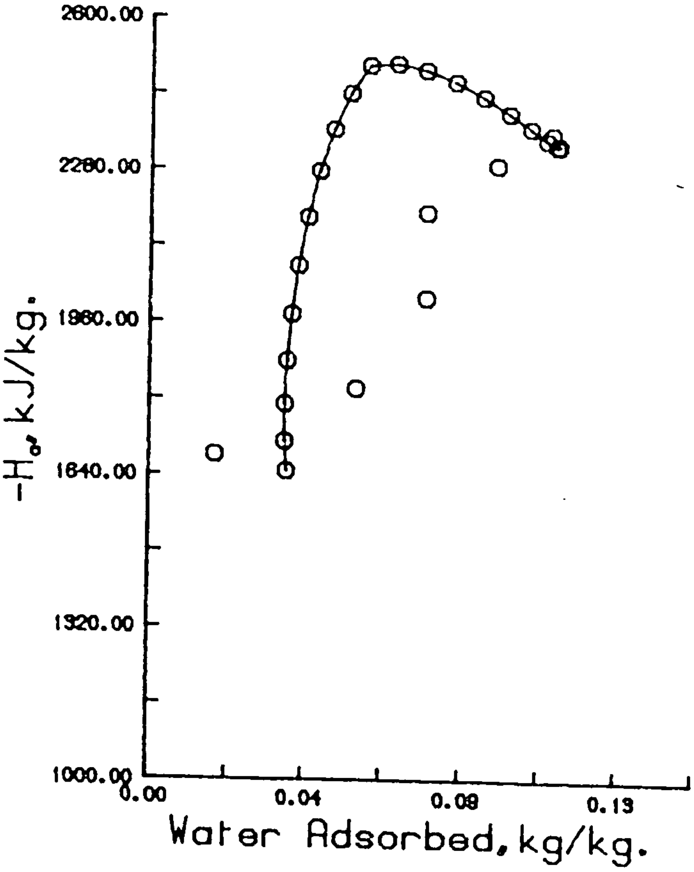


Fig.5.22:Experiment Results:Date 26/03/86.

Adsorption

X_1 = 0.198 kg/kg

T_1 = 47.8 Deg.C

w_1 = 0.077 kg/kg

Q = 45.457l/min(U = 0.456 m/s)

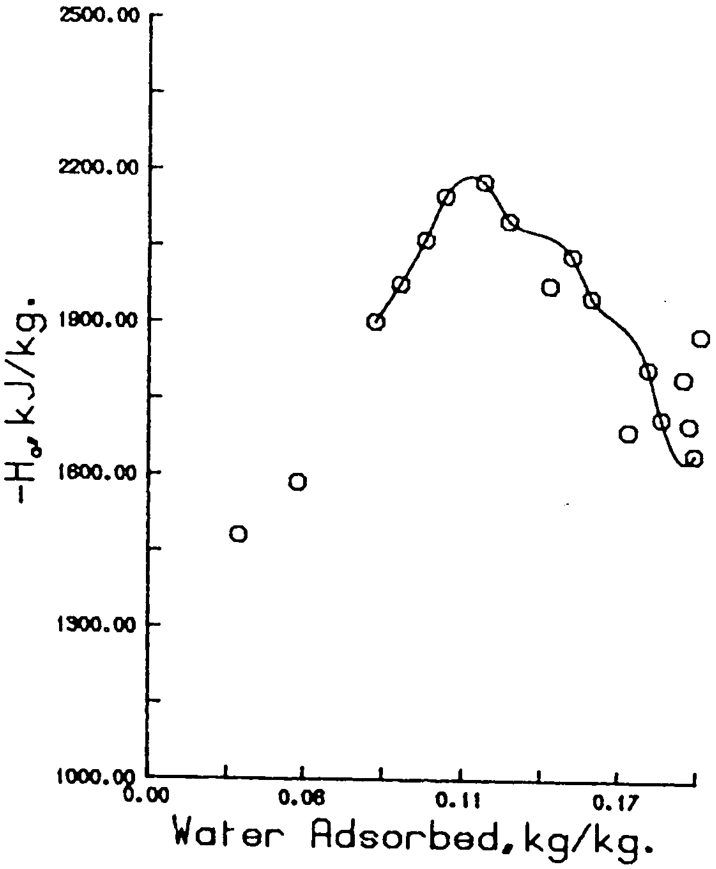


Fig.5.23: Experiment Results: Date 27/03/86.

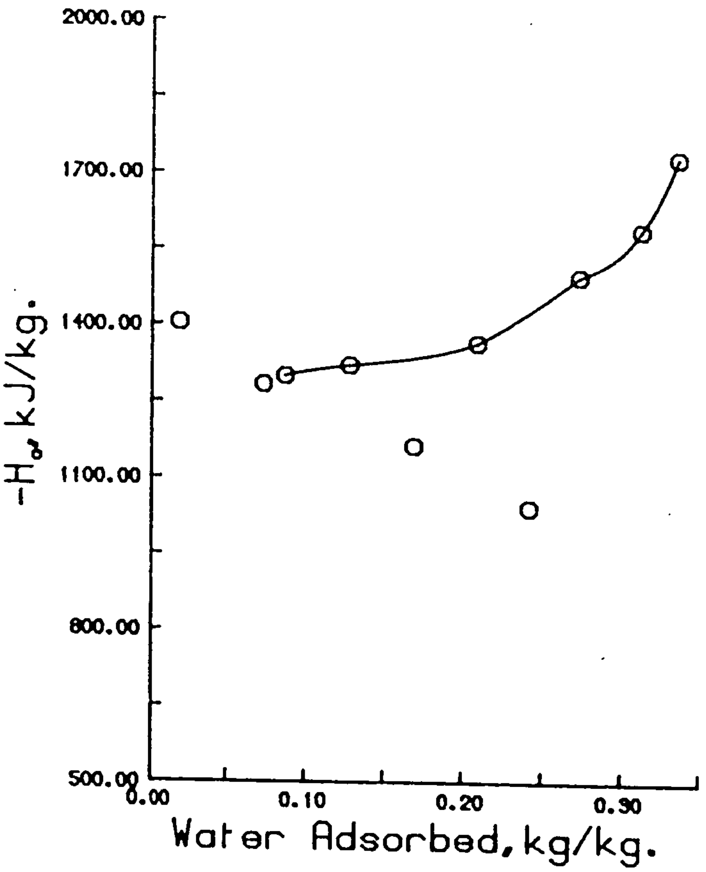
Adsorption

X_1 = 0.173 kg/kg

T_1 = 44.6 Deg.C

w_1 = 0.064 kg/kg

Q = 39.147 l/min (U = 0.393 m/s)



5.2. Estimation of Parameters

The unknown parametrs to be estimated are the Adsorption equilibrium constant, K_A and the Effective diffusivity in the adsorbent particle,De.The Diffusion coefficient in the bulk fluid phase is the limiting value and thus the effective diffusivity in the particle,De is taken to be: Dv = $2.10^{-5} < De < 2.10^{-9}$.The Adsorption equilibrium constant, K_A is then used to deduce the effective heat of Adsorption by solution of equations (2.13) and (2.14).The principle of the estimation is to use experiment temperature profiles to give the total heat generated and use this value to predict theoretical(calculated) temperatures for a set of K_A and De values.The K_A and De set that give minimum error between the calculated temperature profiles and measured ones is taken as the best estimate of these parameters.

In order to make the estimate,the Fluid properties are evaluated at the global mean temperature of the bed of 60°C.See figures 5.1 to 5.10.

Measured data values include:

$Dp = 2.10^{-3}$m:From sieve analysis.

$D_T = 4.597.10^{-2}$m:measred.

Hence,$R=Dp/2=1.10^{-3}$m.

and,$R_T=D_T/2=2.229.10^{-2}$m.

$\varepsilon_b=0.4$:From measured bulk density=1569 $kg/m^3$and true density of 2600 kg/m^3.

Other values from Data books:

$k_s=0.48$W/mk.

$\rho_s=1569kg/m^3$.

$C_s=1000$J/kg.

$k_f=0.024$W/mk.

$\mu_f=2.10^{-5}$kg/sm.

$C_f=1100$J/kgk.

$\rho_f=1.092kg/m^3$.

$Dv=2.06.10^{-5}m^2/s$.

$Sc=\mu_f/\rho_f Dv=0.6$.

$Pr=C_f\mu_f/k_f=0.71$.

Using these values and the measured interstitial air velocity then the following values can be evaluated.

Table 5.1:Some evaluated Results

U [m/s]	Re [-]	Sh [-]	Nu [-]	K_F [m/s]	hp [W/m^{2}k]
0.326	14.2	2.191	5.463	0.023	65.6
0.393	17.2	2.21	5.885	0.023	70.7
0.456	19.2	2.22	6.15	0.023	73.8

Note that

$$Re=UDp\varepsilon_b\cdot\mu_f^{-1}\rho_f$$

The Sherwood number and the Nusselt number are given by equations (2.36) and (2.35) respectively.

$$K_F=ShDv/Dp$$

And

$$hp=Nuk_f/Dp$$

Equation (2.38) gives

$$ke^\circ/k_f=0.707(k_s/k_f)^{1.11}=0.707(0.48/0.024)^{1.11}=19.65$$

Thus,the solid particle effective thermal conductivity,ke° is

$$ke^\circ=19.65\times k_f=19.65\times 0.024=0.472W/mk$$

And with equation (2.37) the Axial thermal dispersion coefficient, α_{ax}

The resulting Adsorption equilibrium constant value,K_A and corresponding De value are taken as the best estimate for the set of readings. This value of K_A,a,and density,ρ_s is used to estimate the heat of Adsorption from the heat generation term,$(-\Delta H_a)\rho_s K_A a$ calculated at the begining.Some results are tabulated in tables 5.2 to 5.4.

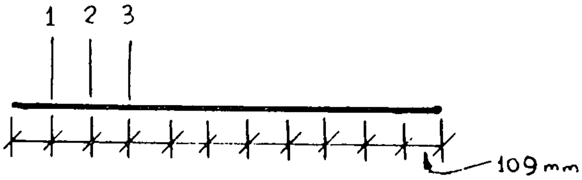
Table 5.2:Results from Parameter Estimation .

Experiment Date:27/03/86/

$De=5.10^{-9} m^2/s$

$(-\Delta H_a \rho_s K_a a) = 4.8.10^{10} J/molm$

$h_0=0.32 W/m^2k$



	Position 1			Position 2			Position 3		
t min	T_F °C	T_{Fc} °C	K_A m^3/kg	T_F °C	T_{Fc} °C	K_A m^3/kg	T_F °C	T_{Fc} °C	K_A m^3/kg
0.7	29.9	36	0.5	22	43.1	0.5	22.8	40.7	0.5
8.1	82.4	42.6	0.5	99.9	44.2	0.5	90	47.2	0.5
16.4	68.6	50.9	0.5	91.9	44.6	0.5	95.6	47.2	0.5
24.7	65.7	49.8	0.5	81.8	45	0.5	89.5	44.6	0.5
32.9	64.1	41.6	0.5	67.6	45.2	0.5	88.3	40.1	0.5
41.3	62.7	36.6	0.5	63.1	43.3	0.5	80	41.2	0.5
49.6	59.5	44.2	0.5	62.1	44.1	0.5	67.5	48	0.5
55.8	58.7	50.3	0.5	60.7	44.4	0.5	65.2	49.3	0.5
64.1	60	50.2	0.5	59.9	45	0.5	65.3	45.2	0.5

From the table,value of $K_A=0.5$.With molecular weight of water equal to 18 kg/kmol,this gives

$$-\Delta H_a=(-\Delta H_a)\rho_s K_A a/(K_A \rho_s a)=4.18.10^{10}/(0.5\times 1569\times 18\times 3000)=1130 \text{ kJ/kg}$$

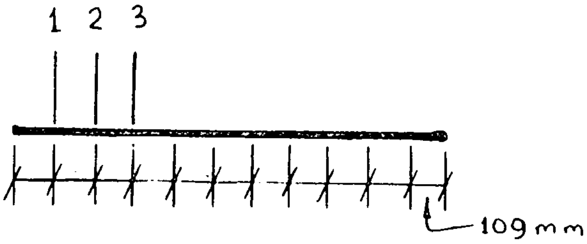
Table 5.3:Results from Parameter Estimation .

Experiment Date:26/03/86/

De=5.10^{-8}m^2/s

$(-\Delta H_a \rho_s K_a a)$ = 6.1.10^{10}J/molm

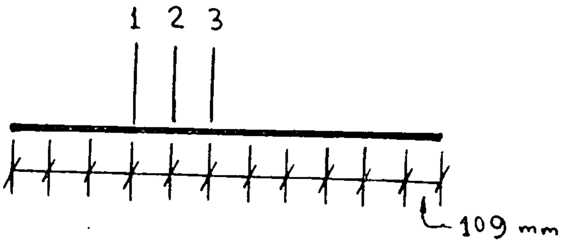
h$_0$=4.8W/m^{2}k



	Position 1			Position 2			Position 3		
t min	T_F °C	T_{Fc} °C	K_A m^3/kg	T_F °C	T_{Fc} °C	K_A m^3/kg	T_F °C	T_{Fc} °C	K_A m^3/kg
0.6	30.3	11.5	0.5	27.4	35.5	0.5	28.6	51	0.5
8	78.7	42.9	0.5	90.3	28.6	0.5	92.7	46.8	0.5
16.3	72.4	76.4	0.5	84.9	45.5	0.5	93.8	43.5	0.5
24.7	70.9	70.6	0.5	78.2	67.3	0.5	87	47.3	0.5
33	67.5	30.6	0.5	73.4	59.7	0.5	81.8	51.2	0.5
41.3	64.4	12.2	0.5	71.5	33.6	0.5	77.5	50.5	0.5
49.6	63.7	50.5	0.5	68.1	30	0.5	73.8	46	0.5
55.8	61.4	74.8	0.5	67.4	43.8	0.5	73.2	43.6	0.5
64.1	60.3	72.7	0.5	64	66.9	0.5	71.8	47	0.5

Similarly,$-\Delta H_a$ = 6.1.10^{10}/(3000×1569×0.5×18)=1450kJ/kg.

Table 5.4:Results from Parameter Estimation .



Experiment Date:28/02/86/

De=5.10^{-8}m^2/s

$(-\Delta H_a \rho_s K_a a)$ = 2.3.10^{11}J/molm

h_0=39.5W/m^{2}k

	Position 1			Position 2			Position 3		
t min	T_F °C	T_{Fc} °C	K_A m^3/kg	T_F °C	T_{Fc} °C	K_A m^3/kg	T_F °C	T_{Fc} °C	K_A m^3/kg
.6	26	30	0.5	27.7	41.5	0.5	27.9	49.5	0.5
8	94.4	40.6	0.5	96.3	39.2	0.5	92.5	42.3	0.5
17.3	92.6	71.7	0.5	97.1	60.7	0.5	99.2	53.8	0.5
23.6	88.6	79.7	0.5	94.8	71.4	0.5	97.6	63.6	0.5
31.8	85	53	0.5	90.9	61.5	0.5	93	63.6	0.5
41	83.1	30.4	0.5	87	40.9	0.5	89.3	48.9	0.5
49.3	81.1	45.6	0.5	84.4	41.5	0.5	86.2	42.8	0.5
56.4	78.2	69.4	0.5	84	58.5	0.5	84.8	52.1	0.5
64.7	76.7	78.2	0.5	82.7	72.1	0.5	83.6	64.9	0.5

Similarly,$-\Delta H_a$ = 2.3.10^{11}/(1569×18+0.5×3000)=5430kJ/kg.

CHAPTER 6

DISCUSSION AND RECOMMENDATIONS

6.1. Experiments Results:General

Results show similar general trends,though complete reproducibility was not achieved as it is not possible to control the bed porosity to be closely similar for different experiments.Figure 6.1 illustrates this problem for feed streams with even identical inlet temperatures and humidities.

6.2. Effect of Fluid Inlet Temperature

It can be seen that the breakthrough time(time for the temperature or concentration at outlet to rise to its maximum value) is longer the lower the Inlet temperature.This is because the bed temperature must be raised by a larger amount to raise its surface vapour pressure to the point at which Adsorption ceases.This is illustrated by figure 6.2.

The cause of sudden drop of outlet humidity of curve A after 75 minutes and curve B after 50 minutes can not be explained.Probably some part of the bed started to dissolve,although this was more noticeable when the bed loading approached a value of 0.5kg/kg.

6.3. Effect of Velocity

The bellows support at the bed inlet was not stable enough to allow velocities higher than 0.456m/s to be used.This was not anticipated in the initial stages of the experiment.Lower velocities,on the other hand,were unsuitable as the experiment time would be too long.The small velocity band of 0.326 to 0.456 m/s might not warrant concrete conclusions as to the effect of velocity.

It seems,and is also logical,that at high fluid velocity the axial particle-to-fluid heat transfer coefficient is higher as depicted by high outlet temperature.Also breakthrough time is shorter for high velocity.See figure 6.3.

In figure 6.3,the curve B for outlet humidity is higher than that of curve a probably due to the fact that curve B-the inlet temperature is higher than that of A.(The slight inlet temperature difference does not mask the comparison as figure 6.2 shows.curve C in figure 6.3 would be higher than that of curve A).

6.4. Effect of Insulation

See figure 6.4.The outlet humidity for the bed without insulation does not rise to a maximum as fast as the one with insulation.More heat is lost and thus the vapour pressure difference between the fluid phase and solid does not fall as fast as in the insulated one.This is undesirable in heat recovery as the purpose is to transfer the heat generated to the gas stream.

6.5. Parameter Estimation

The attempt at Parameter estimation was not successful.The error between calculated and experimental values is high.The value of the Adsorption equilibrium constant,though assumed to be constant was,in reality,expected to show some variation with temperature.The values of heat of Adsorption from parameter estimation of 1130kJ/kg are within the range of those calculated from mass and heat balances,but they are anyhow lower when compared to realistic value of heat of adsorption expected to be in the range of 2260 to 6780kJ/kg.See also under section 5.1.3.

6.6. Regeneration

Few experiments done,but figure 6.5 show that loss of water vapour from the bed is faster the higher the regeneration air temperature.The effect of velocity is not as pronounced as that of temperature,figure 6.6.

6.7. Conclusion

The Adsorption of Water vapour by Magnesium Chloride has been demonstrated to be capable of providing a temperature lift of up to 70 deg.C. The resulting air stream temperature is about 80-100°C,with specific humidity less than 0.07 kg/kg(less than 10%RH).Thus where such a dry hot air can be recirculated to the drying process the method can be useful.

The disadavantages of using Magnesium Chloride as an Adsorbent are solubility and slight corrosion.Solubilty increases with temperature,generally solubility causes loss of bed porosity and increased pressure drops.The formation of solid lumps poses cleaning difficulties.

6.8. Recommendation

Adsorption heat recovery has the potential to recover both the Latent and Sensible heat from moist gas streams.Stable non-soluble adsorbents like Molecular sieves can be used.

For estimating parameters for adsorption of water vapour on Magnesium Chloride,probably a narrow bed can be useful in that the assumption of radial symmetry in concentration becomes more valid.The narrow bed must however be well insulated as the temperature gradient would otherwise be much higher.The mathematics should probably be refined to include the change in voidage.Magnesium chloride particles can lose shape at high water uptake and the bed loss of voidage generally affects the magnitude of the effective surface area available.

Fig.6.1: Experiment Results: Adsorption.

Check Reproduceability

Velocity; U = 0.393 m/s

A: T_1 = 44.6 Deg.C (Date: 13/12/85)

B: T_1 = 44.4 Deg.C (Date: 18/01/86)

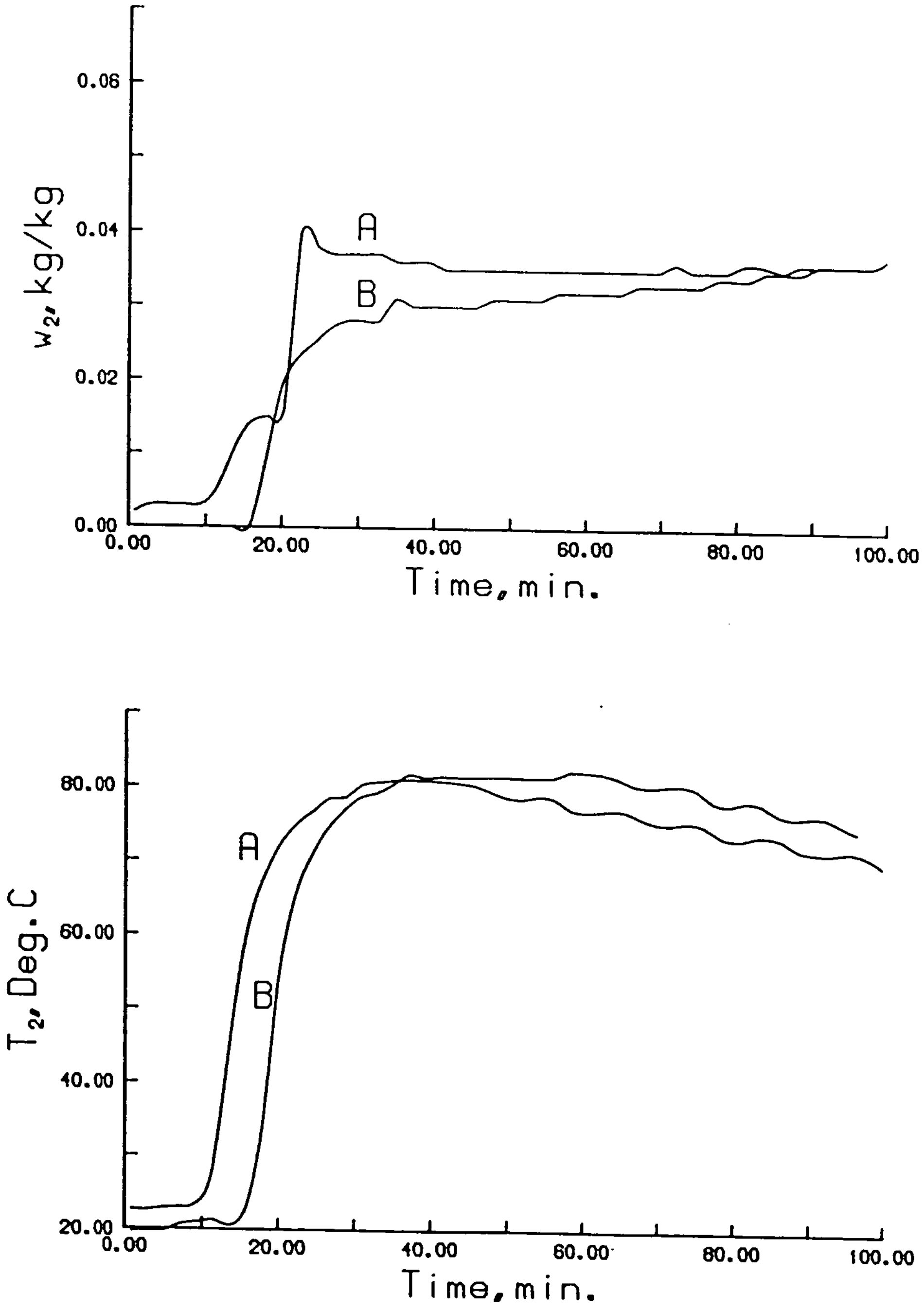


Fig.6.2:Experiment Results:Adsorption.

Effect of Inlet Temperature.(U=0.393m/s)

A: T_1 = 54.4 Deg.C

B: T_1 = 48 Deg.C

C: T_1 = 44.4 Deg.C

D: T_1 = 34.2 Deg.C

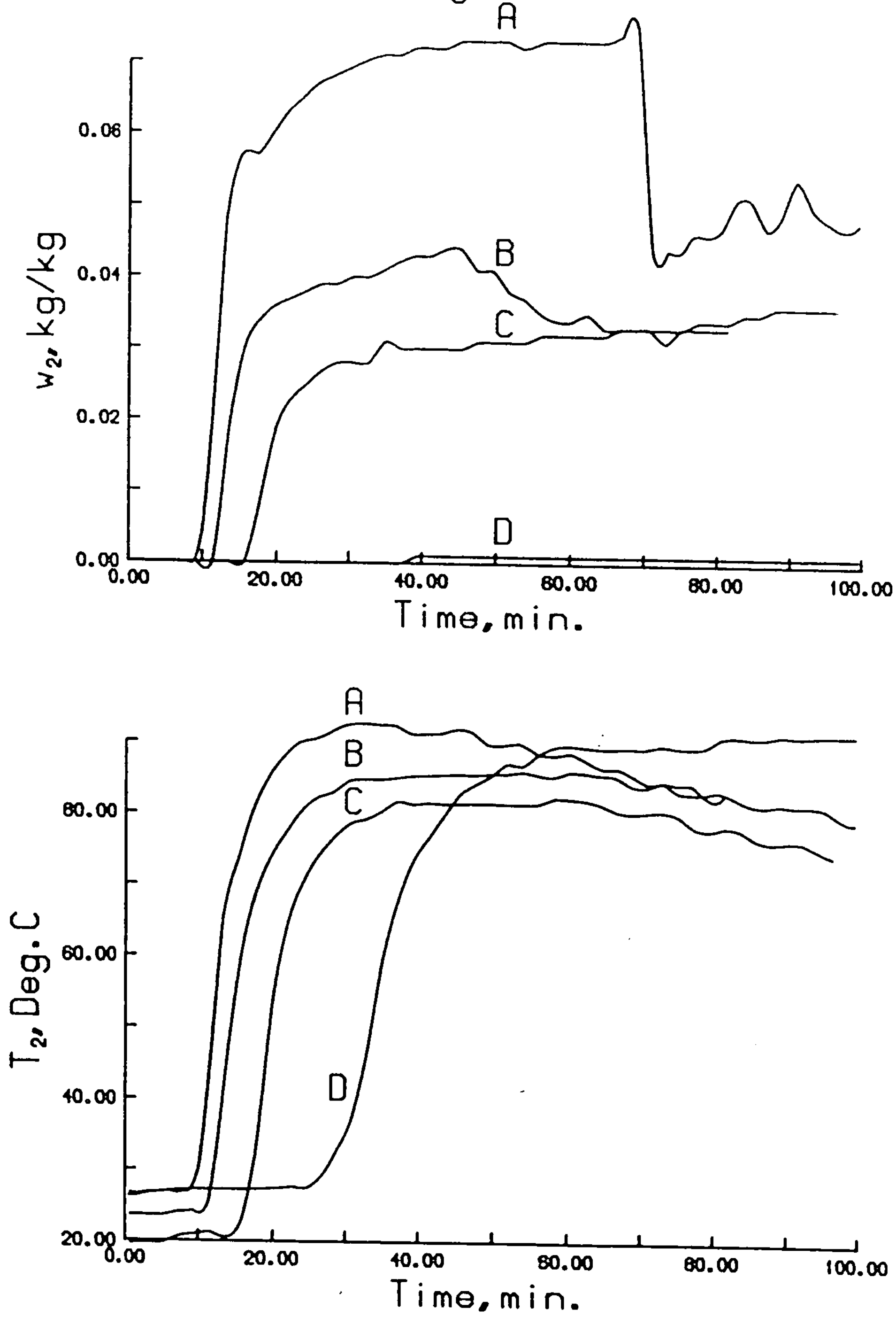


Fig.6.3:Experiment results:Adsorption

Effect of Velocity

A: U = 0.456 m/s; T_1 = 47.8 Deg.C

B: U = 0.393 m/s; T_1 = 52.3 Deg.C

C: U = 0.326 m/s; T_1 = 52 Deg.C

Date:A:-26/03/86;B:-26/02/86;C:-28/11/85

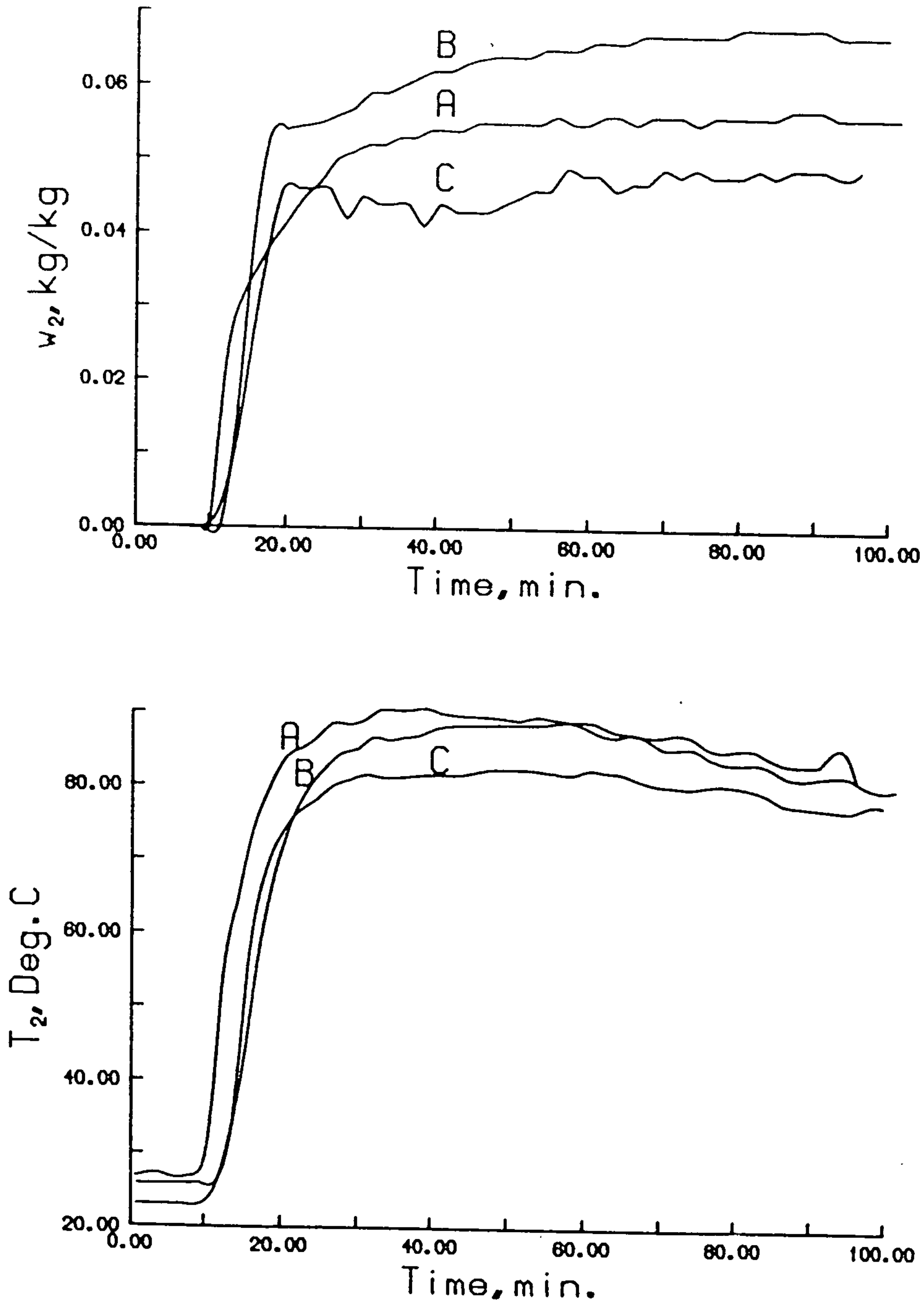


Fig.6.4: Experiment Results: Adsorption.

Effect of Insulation

Velocity; U = 0.393 m/s

A: T_1=44.4 Deg.C (Date: 18/01/86)

B: T_1=44.6 Deg.C (Date: 23/03/86)

B: Bed without Insulation.

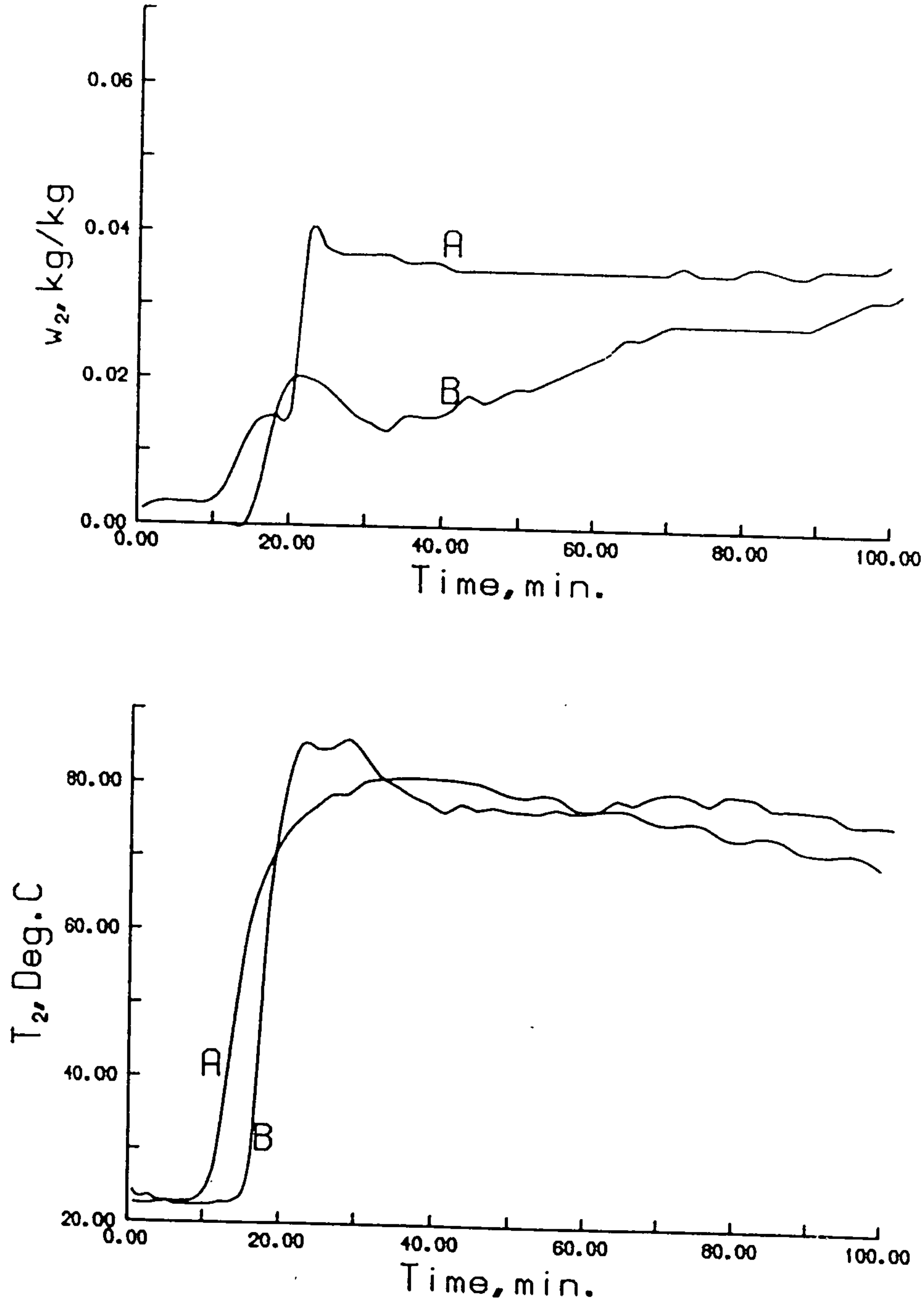


Fig. 6.5: Experiment Results:Regeneration
Effect of Air Regeneration Temperature
Air flow :A:0.594m/s;B:0.452m/s
A:-Air Regeneration Temp.=164 Deg.C
B:-Air Regeneration Temp.=144 Deg.C

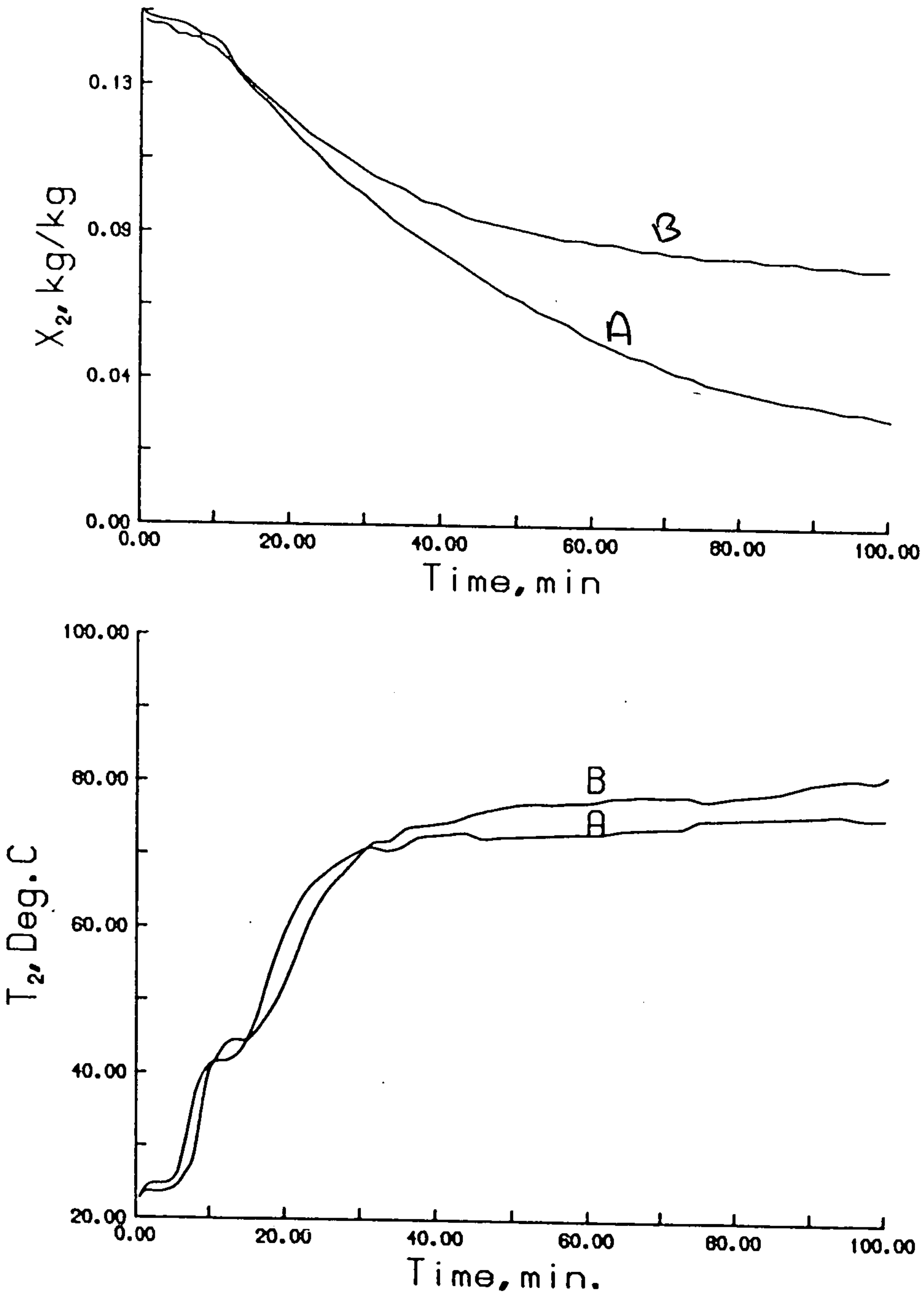


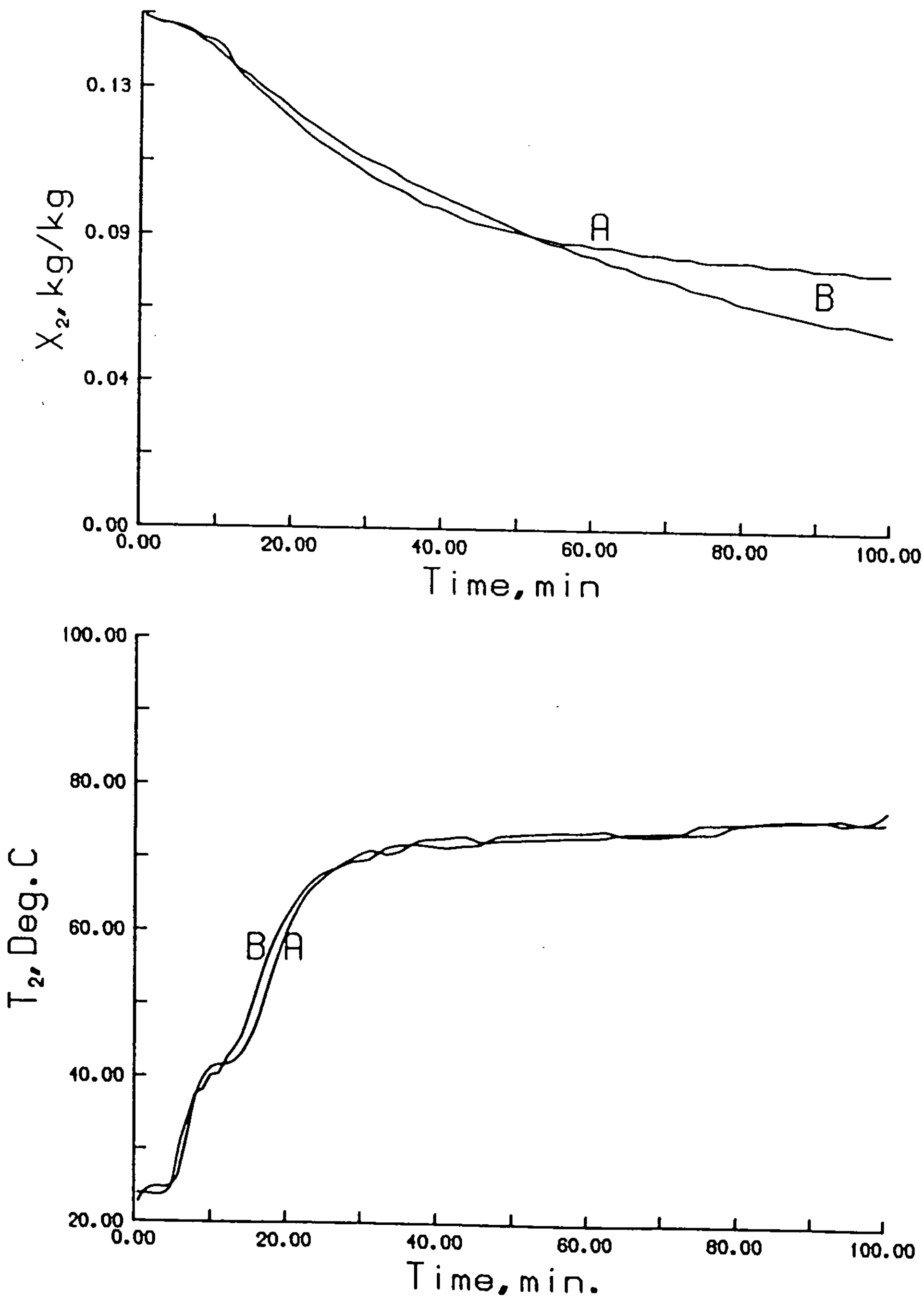
Fig.6.6: Experiment Results:Regeneration

Effect of Regeneration Air Velocity

Air Regeneration Temp. =144 Deg.C

A:- U = 0.594 m/s

B:- U = 0.452 m/s



6.9. Example:Design of a Magnesium Chloride Adsorber for Heat Recovery

Experimental results suggest:

1. Inlet humidity:Up to 0.15 kg/kg possible.
2. Inlet (feed)temperature 30 to 60 °C.
3. Restrict final bed loading to about 0.5 to 0.6 kg/kg.No advantage in attaining higher bed loading as heat of adsorption falls for higher bed loading.
4. Cycle time:Restrict to not more than 60-90 minutes.Logical practical approach is to let the process run until the temperature starts to fall or the adsorbent material start to dissolve whichever comes first.
5. Equipment:Pressure drop must be considered.If a centrifugal fan is used,this limits the pressure drop to about 250-500mmWater.In practice linear gas velocities are restricted to 0.25-0.5 m/s.Thus the bed cross section area is selected to give this range of velocity.Bed depths of 0.3-1m are common.Again this would depend on the pressure drop across the unit.(See also page 67 /16/.)
6. Amount of Adsorbent:calculate from knowledge of point 1 and points 3 through 5.

Example

Moist Air flow $Q = 1\ m^3/s$.

Feed condition = 50°C and 50%RH.

Adsorbent particle size,$d=2.10^{-3}m$.

Bed voidage,$\varepsilon = 0.4$.

Fluid viscosity,$\mu=2.10^{-5}kg/sm$.

Fluid density,$\rho=1.092kg/m^3$.

At 50°C and 50%RH,humidity,$\omega=0.042kg/kg$.

Velocity range :$0.25<U<0.5m/s$:Take $U = 0.5\ m/s$.

Therefore bed cross section area,$A = Q/U= 1/0.5=2m^2$.

Hence bed diameter,$D=(A\times4/\pi)^{1/2}=(2\times4/\pi)^{1/2}=1.6m$.

Thus true air velocity,U

$$U = Q\times4/(\pi D^2)=1\times4/(\pi\times1.6^2)=0.498\text{m/s}.$$

Thus take velocity,U=0.5m/s.

Pressure drop estimated by the Ergun's empirical correlation

$$\Delta P/l=150(1-\varepsilon)^2\mu U/\varepsilon^3d^2+1.75(1-\varepsilon)\rho U^2/\varepsilon^3d$$

Thus the pressure drop per unit length of bed is

$$\Delta P/l=150(1-.4)^2\times2.10^{-5}\times.5/(.4^3\times2.10^{-3})$$
$$+1.75(1-.4)\times1.092\times.5^2/(.4^3\times2.10^{-3})$$

ie,$\Delta P/l$=5720 N/m^{2}m.This is equivalent to 583 mm Water.

Pressure drop limit is 250-500mm Water if Centrifugal fans used.Thus if a value of 500mmWater is taken,then

Bed depth,h=0.8m.

Hence Adsorbent weight,$M_b=\pi D^2h(1-\varepsilon)\rho_s/4$

Where,ρ_s is the density of the adsorbent;equal to 1569kg/m^3.

ie,$M_b=1569\times\pi\times1.6^2\times0.8\times0.6/4=1515$kg.

Under actual conditions,the adsorption process would be left to run until either the outlet temperature started to fall below accepted level or until the bed started to lose porosity due to the adsorbent material dissolving, whichever comes first.

In the experiment,mean change in bed loading ,ie $X_{final}-X_{initial}$, was about 0.25kg/kg.Thus taking this value ,the amount of water adsorbed,M_w is

$M_w=\Delta X\times M_b=0.25\times1515=380$kg.

$M_w=Q\rho\omega t$;where t is the cycle time.

Thus the cycle time,$t = M_w/Q\rho\omega = 380/(1\times1.092\times0.042) =$ 8285sec(2.3hours).(Note that in the experiment,air was saturated,at 50°C humidity,ω = 0.087kg/kg,this would give a cycle time of 4000sec or 67 minutes(1.1hours).

Summary:

Air flow = 1 m^3/s(3.9t/h).

Inlet conditions = 50 °C,50%RH.

Water vapour duty = 0.2t/h.

Bed diameter = 1.6m.

Bed depth = 0.8m.

Adsorbent:Magnesium Chloride.

Adsorbent weight = 1.5 t.

Cycle time up to 2.3 hours.

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LOW GRADE HEAT RECOVERY

A

ADSOBERNT:MAGNESIUM CHLORIDE (UNHYDROUS)

DATE:13/01/86

EXPERIMENT NO........: 1

TIME (MIN)	FLOW (BITS)	TEMPERATURE (DEGC)									
		1	2	3	4	5	6	7	8	9	10
.804	0	36.6	60.1	21.9	23.4	13.5	23.9	24	23.9	24	23.
2.929	670.6	39	79.3	24.1	29.3	13.7	24.1	24.1	23.9	24	2[illegible].
5.066	671.2	36.7	88.7	25.8	78.3	12.6	25.9	23.6	24	24.2	23.
7.195	666.9	42.7	92	27.8	90.4	12.6	72.7	42.9	24.6	24.1	24.
9.315	666.9	54.6	92	28.8	93.9	14.9	87.2	78.6	24.4	33.1	24.
11.416	671.5	57.7	90.4	30.5	94	16.3	91.5	86.3	49.8	77.7	25.
13.538	669.3	63.9	89.7	31	94	16.9	92.2	89.1	80.8	89	62.7
15.724	670.7	80.5	87.9	31.2	93.8	14.7	93.7	90	88.3	91.9	83.6
17.837	669.7	87.5	86.1	32.6	93.6	15.2	94	92	90.8	92.1	88.5
19.93	672.1	91.1	85.6	33.6	94.4	16.7	94.1	92.1	92.2	92.5	90.2
22.054	671.2	96	84.7	33.7	94.5	17.4	94.6	92.5	92.5	93	92.3
24.147	670	97.5	84	34.1	93.8	17.4	94.6	92.8	92.9	93.6	93
26.262	667.6	99.9	83	35.4	92.7	17.6	94.6	92.9	93	94.2	92.5
28.377	669.4	101.9	82	35.6	93.1	17.5	94.6	93	93.1	94.3	92.7
30.503	671.2	102.8	81	35.2	91.3	17.4	93.5	92.9	93	94	92.6
32.609	672.9	102.4	79.6	35.3	90.8	17.2	92.8	92.6	92.9	93.2	92.6

34.736	664.1	98.7	79.1	35.8	89.5	17.6	92.5	92.5	92.9	93.1	92.6
38.969	657.1	91.1	77.3	35.4	87.9	17.8	92.7	93	92.8	93	92.7
41.117	667.5	55	76.1	35.8	87.3	18	91.4	92.9	93	93.1	92.9
43.243	671.3	77.3	75.8	36.1	86.4	18.1	91.6	91.7	93.2	93.2	93.2
45.338	666.4	86.3	75.2	36.2	85.7	18.8	90.5	91.4	93.5	93.9	93.2
47.466	672.5	86.6	73.8	35.3	84.8	19	89.6	91.6	93.9	93.7	93.8
49.562	673	85.8	73.9	35.1	83.7	18.3	89.5	90.3	93.7	93.4	93.9
51.69	675.2	85.8	72.2	35	83.8	18.4	87.8	89.6	93.6	92.1	93.8
53.798	671.8	85.4	72.3	34.6	82	18.4	88	89.8	93.3	91.7	93.6
55.915	667.8	82.9	71.6	34	81.7	18	86	87.8	91.7	91.6	93.1
58.023	672.2	75.6	70.3	33.7	81	18.1	85.7	87.5	91.4	91.5	92.2
60.141	673.8	78.6	69.9	34.8	79.8	18.6	84.8	87.4	91.4	90.4	91.8
62.249	670.2	77.7	69.6	34.7	79.9	19.3	83.8	85.8	91.8	89.6	91.5
64.388	671.7	77.3	70.4	34.7	79.7	19	83	86	91.2	90	91.7
66.495	678.8	74.2	70.2	34.1	78.5	19.6	81.8	84.6	89.9	89.4	91.8
68.591	679	76.5	69.6	33.3	78	18.3	81.5	83.9	89.8	87.9	91.2
70.687	677.5	75.9	68.4	33.3	78.2	18.8	80.1	83.7	90	88.1	90.1
72.793	672.5	82.3	69	33.5	78.5	18.5	80.3	82.3	88.8	87.9	90.2
74.898	675.9	74.4	68.2	33.4	78.3	19.4	78.5	82.6	88.2	86.5	90.4
77.014	675	62.7	66.9	33.4	78.7	20.4	78.6	81	88.5	86.6	89.4

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79.107	681	56.8	67	33.3	77.9	21.3	77.3	80.6	87.4	85.9	88.
81.285	685.5	46.9	66.7	34	76.7	22.7	76.5	80.4	86.3	84.5	88.

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ABSORPTION HEAT RECOVERY (LOW GRADE HEAT RECOVERY)

ADSORBERNT:MAGNESIUM CHLORIDE (UNHYDROUS)

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DATE:13/01/86

AMBIENT TEMPERATURE 25 DEG C

WATER BATH TEMP. 55 DEG C

ROTAMETER SCALE 10 CM

(FLOW APPROX.COSTANT) 39.147 L/MIN

INITIAL BED LOADING .156 KG/KG)

INITIAL BED WEIGHT 1120.3 G

(RESULTS BASED ON MEASURED OUTLET HUMIDITY)

	TIME (MIN)	FLOW (KG)	TIN (C)	WIN (G/G)	TOUT (C)	WOUT (G/G)	TBED (C)	X (G/G)	HL (KJ)	HADSO KJ/KG
1	.804	.051	43.9	.061	23.6	0	31.7	.159		
2	2.929	.188	45.6	.067	23.6	0	35	.168		
3	5.066	.325	46.1	.069	23.6	0	41.6	.177	2	−270
4	7.195	.462	46.8	.072	24.1	0	51.7	.187		
5	9.315	.598	47	.073	24.3	0	60.2	.197		
6	11.416	.733	47.2	.073	25.6	0	70.2	.206	8	−910
7	13.538	.869	47.1	.073	42.9	.018	82.6	.214		
8	15.724	1.01	47.2	.073	59.8	.03	89.5	.219		
9	17.837	1.146	47.3	.074	69.1	.034	92.2	.225	15	−2815
10	19.93	1.281	47.6	.075	74.3	.036	93.3	.229		
11	22.054	1.418	48.6	.079	77.7	.037	94.8	.235		
12	24.147	1.554	48.6	.079	80.6	.038	95.2	.242	16	−2250
13	26.262	1.691	48.3	.078	82.3	.039	95.7	.247		
14	28.377	1.828	48.2	.078	83	.039	96	.254		
15	30.503	1.966	48	.077	84.6	.04	95.7	.258	16	−2083
16	32.609	2.102	47.8	.076	84.8	.04	95.3	.265		

17	34.736	2.24	47.7	.076	84.8	.041	94.6	.269		
18	38.969	2.513	47.7	.076	85.3	.043	93.5	.271	21	-2341
19	41.117	2.652	47.9	.076	85.4	.043	89.2	.27		
20	43.243	2.79	48	.077	85.5	.044	91.6	.271		
21	45.338	2.926	48	.077	85.6	.044	92.4	.282	15	-2043
22	47.466	3.064	48.2	.078	85.5	.041	92.1	.282		
23	49.562	3.2	48.9	.081	85.7	.041	91.7	.284		
24	51.69	3.338	49	.081	85.7	.038	91	.288	15	-1984
25	53.798	3.474	48.9	.081	86	.037	90.7	.292		
26	55.915	3.611	48.5	.079	85.6	.035	89.6	.297		
27	58.023	3.747	48.5	.079	85.3	.034	89.2	.298	15	-1543
28	60.141	3.884	48.5	.079	86	.034	88.3	.295		
29	62.249	4.02	48.5	.079	85.9	.035	87.8	.306		
30	64.388	4.158	48.5	.079	65.6	.033	87.7	.303	14	-1516
31	66.495	4.294	48.5	.079	85.4	.033	86.7	.301		
32	68.591	4.43	48.5	.079	64.2	.033	86.2	.3		
33	70.687	4.566	48.6	.079	83.9	.033	85.8	.3		
34	72.793	4.702	48.8	.08	84.7	.031	86.4	.297		
35	74.898	4.838	48.9	.081	84.3	.033	85	.296		
36	77.014	4.975	48.9	.081	83.1	.033	83.2	.295		
37	79.107	5.111	48.9	.081	82.5	.033	81.9	.293		
38	81.285	5.253	48.9	.081	82.8	.033	80.4	.292		

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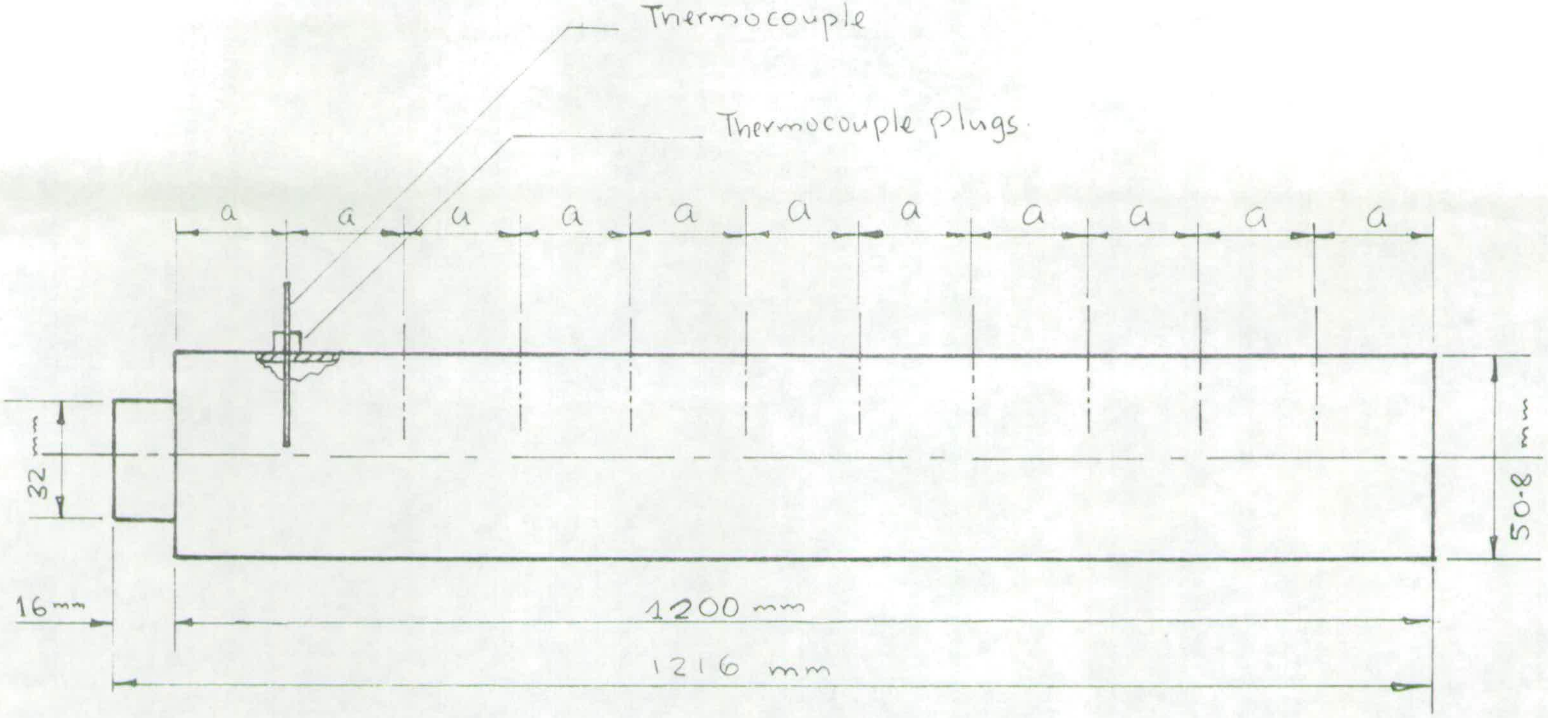

a = 109·1 mm. 'a'

thickness of tube = 2·4 mm

Number of thermocouples = 10.

Fig 3·6a: Sketch of Adsorbent bed showing thermocouple Locations.

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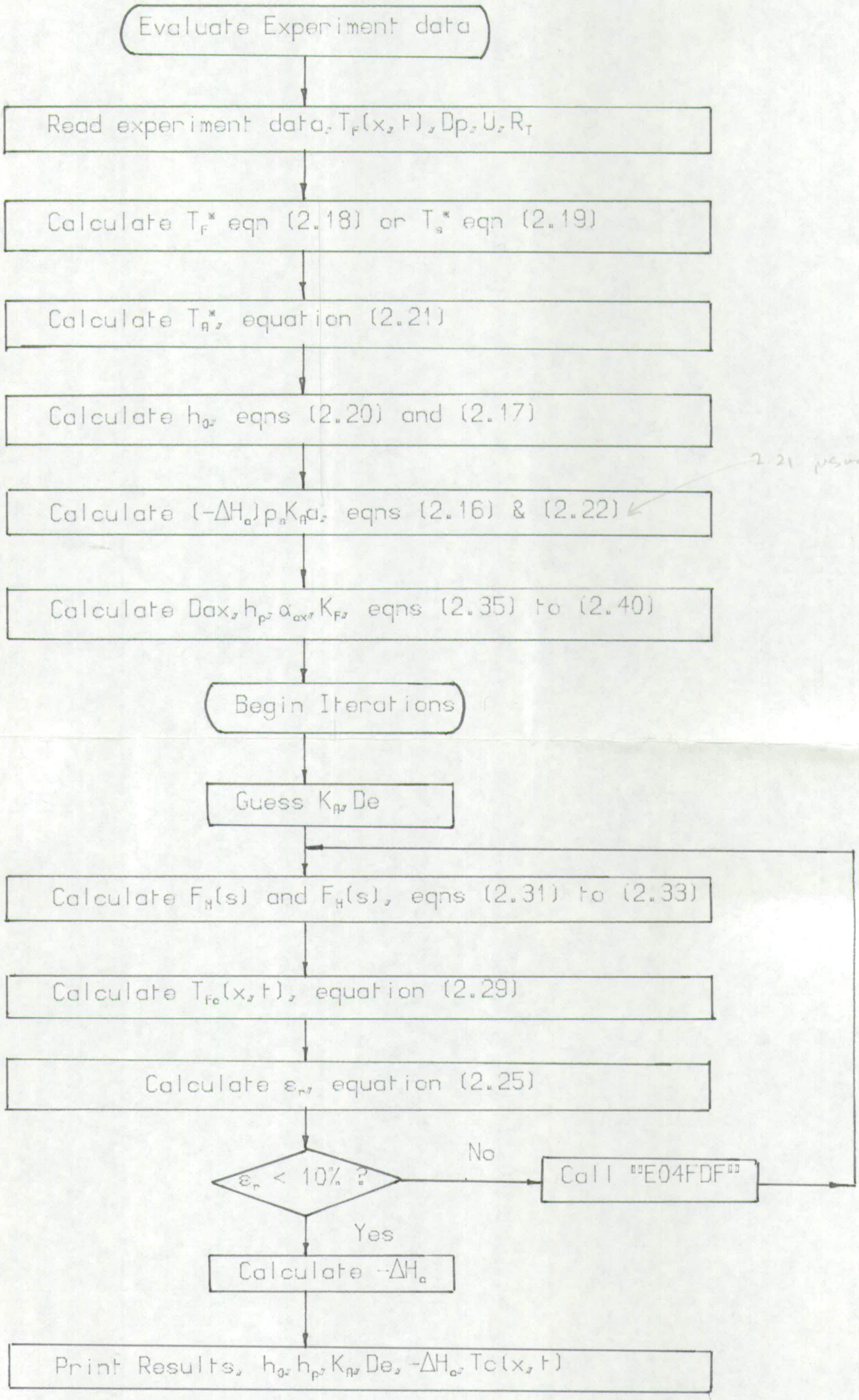
Fig. 2.5a: Algorithm for Parameter Estimation Solution



2.21 presumably

Note: K_A and De values are varied in the "NAG" "E04FDF" subroutine. The "NAG" "E04FDF" is an algorithm in fortran language for finding anconstrained minimum of a sum of squares of M non-linear functions in N variables. In this case 2 variables, De and K_A.

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Fig. A1: Bed Temperature vs Bed Axial Distance

Parameter: time

Experiment Date: 26/03/86: U= 0.456 m/s: Inlet Temp.= 47.8 DegC

Note: Faulty temp. measurement not plotted. (mark ↓)

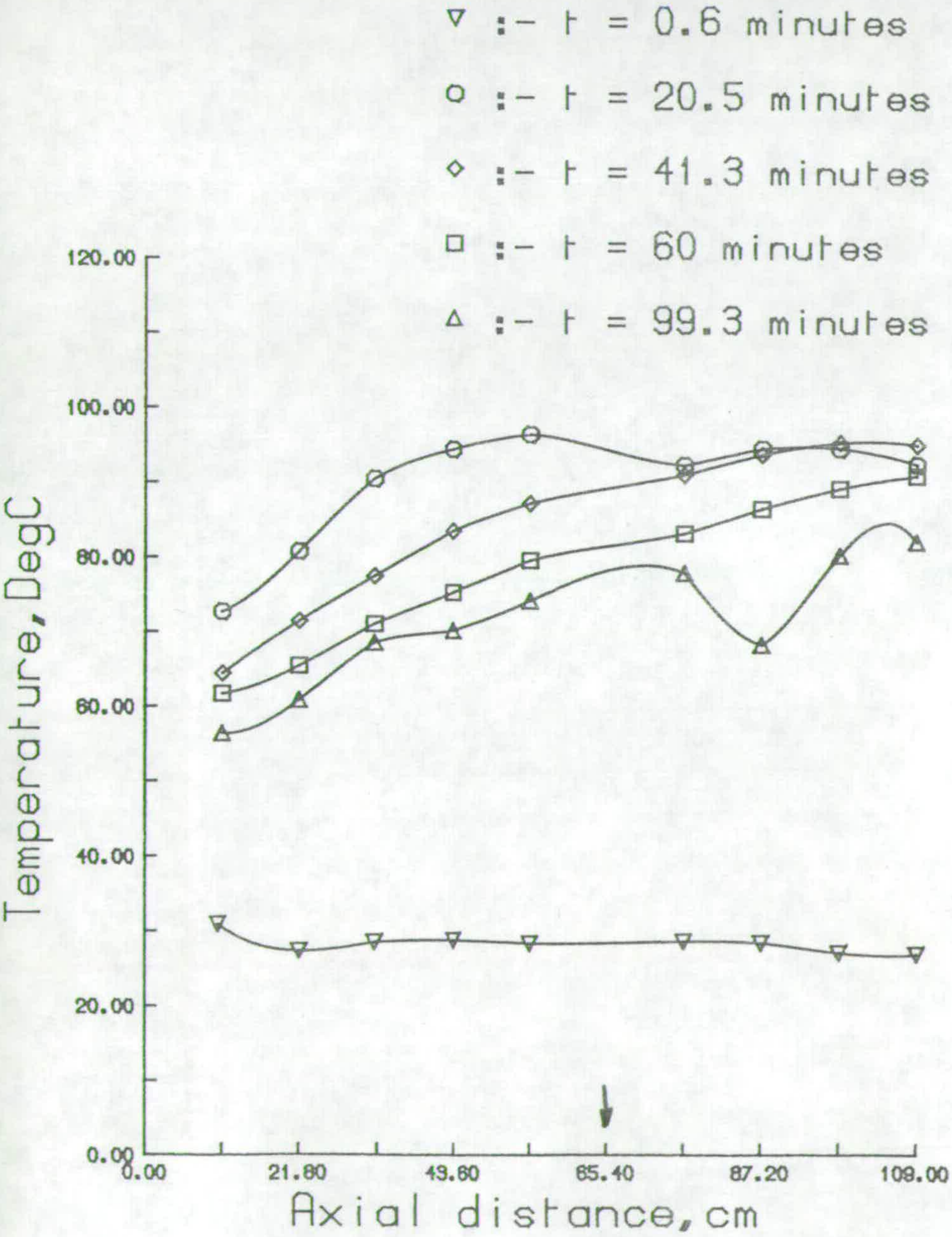

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Fig.A2: Bed Temperature vs Bed Axial Distance

Parameter: time

Experiment Date:5/03/86: U= 0.393 m/s: Inlet Temp.= 34.2 DegC

Note: Faulty temp. measurement not plotted.(mark↓)

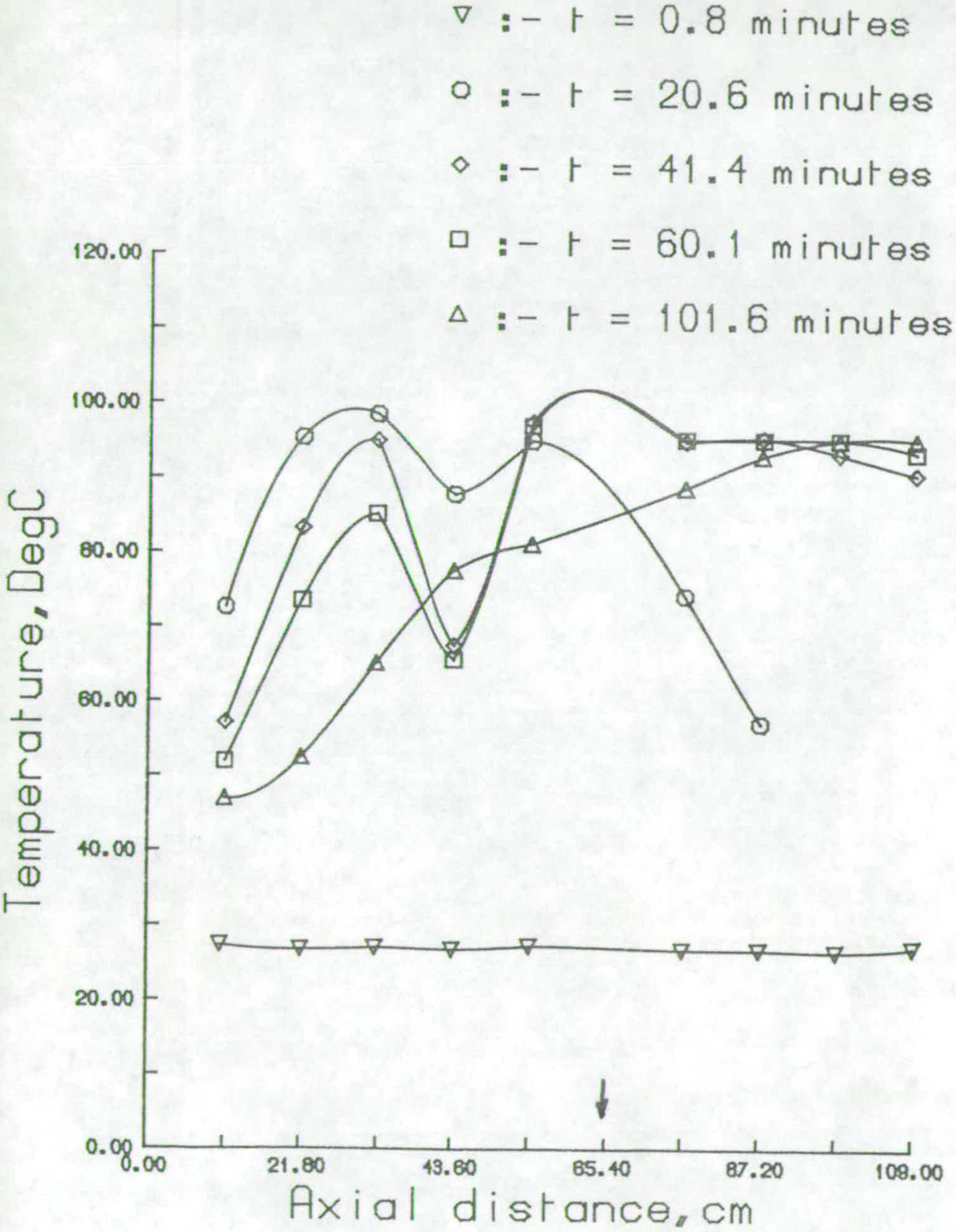

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Fig.A3: Bed Temperature vs Bed Axial Distance

Parameter: time

Experiment Date:18/01/86: U= 0.393 m/s: Inlet Temp.= 44.4 Deg(

Note: Faulty temp. measurement not plotted.(marked ↓)

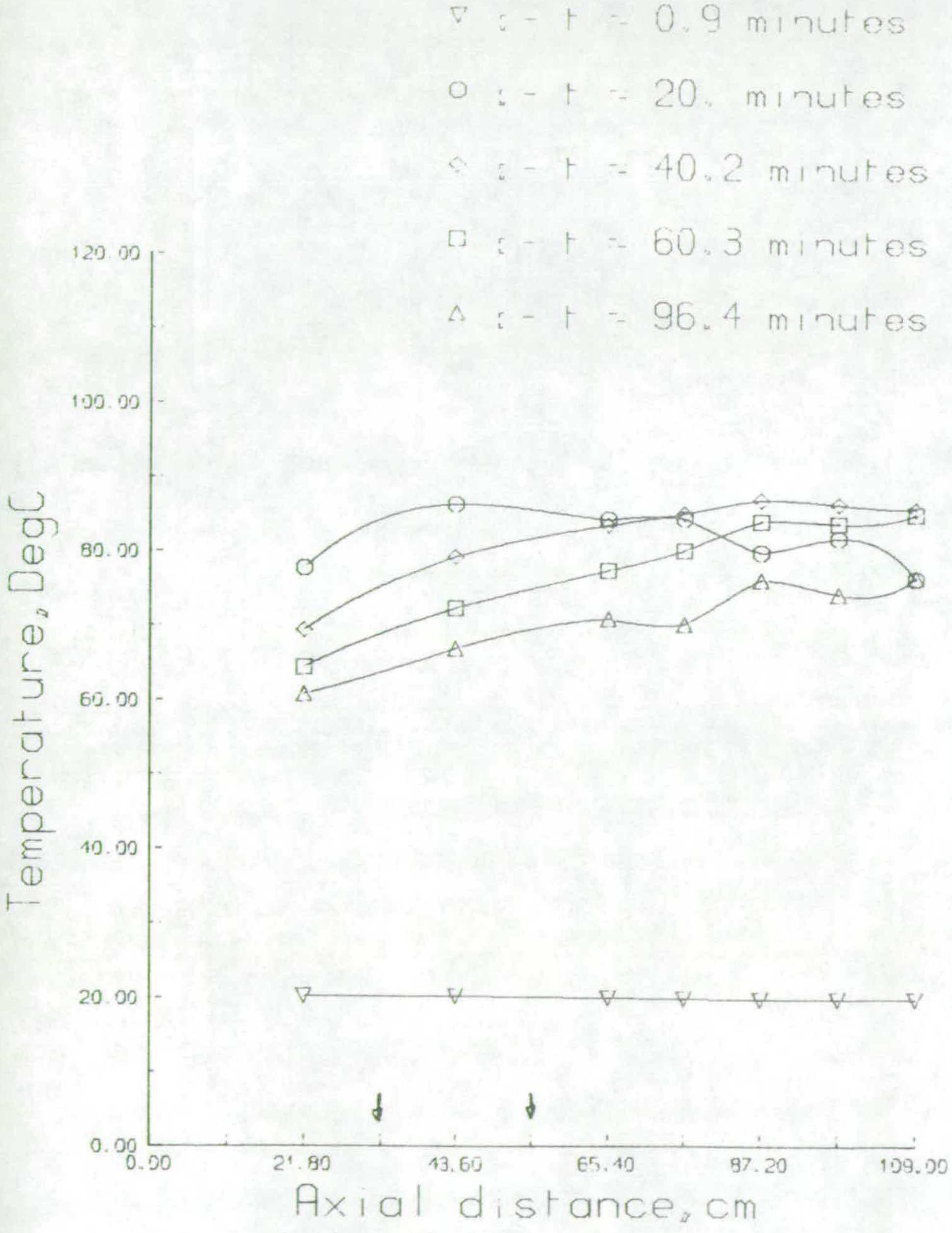

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Fig.A4: Bed Temperature vs Bed Axial Distance

Parameter: time

Experiment Date:26/02/86: U= 0.393 m/s: Inlet Temp.= 52.3 DegC

Note: Where faulty temp. measurement not plotted. (marked ↓)

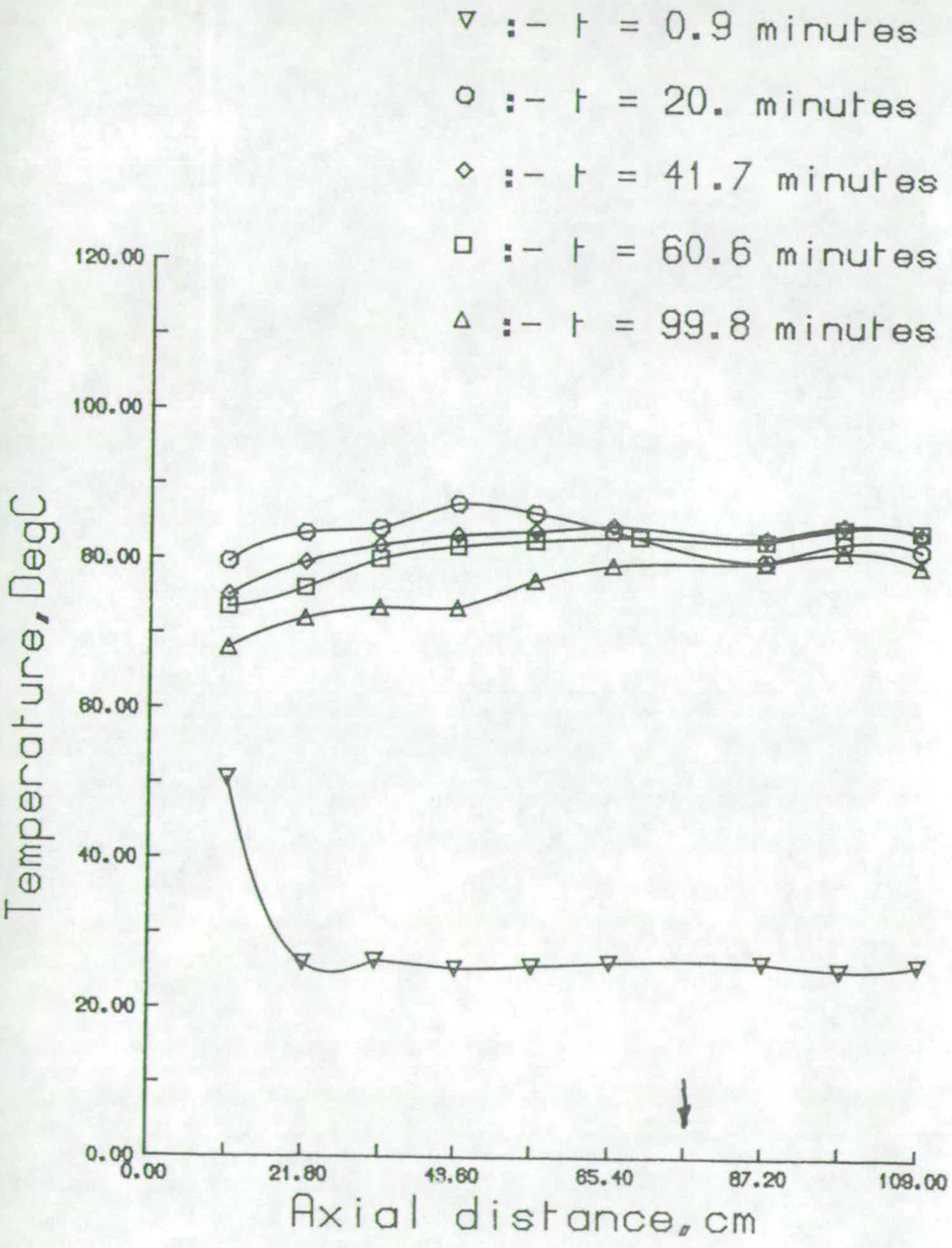

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Fig.A5: Bed Temperature vs Bed Axial Distance

Parameter: time

Experiment Date:28/02/86: U= 0.393 m/s: Inlet Temp.= 54.4 DegC

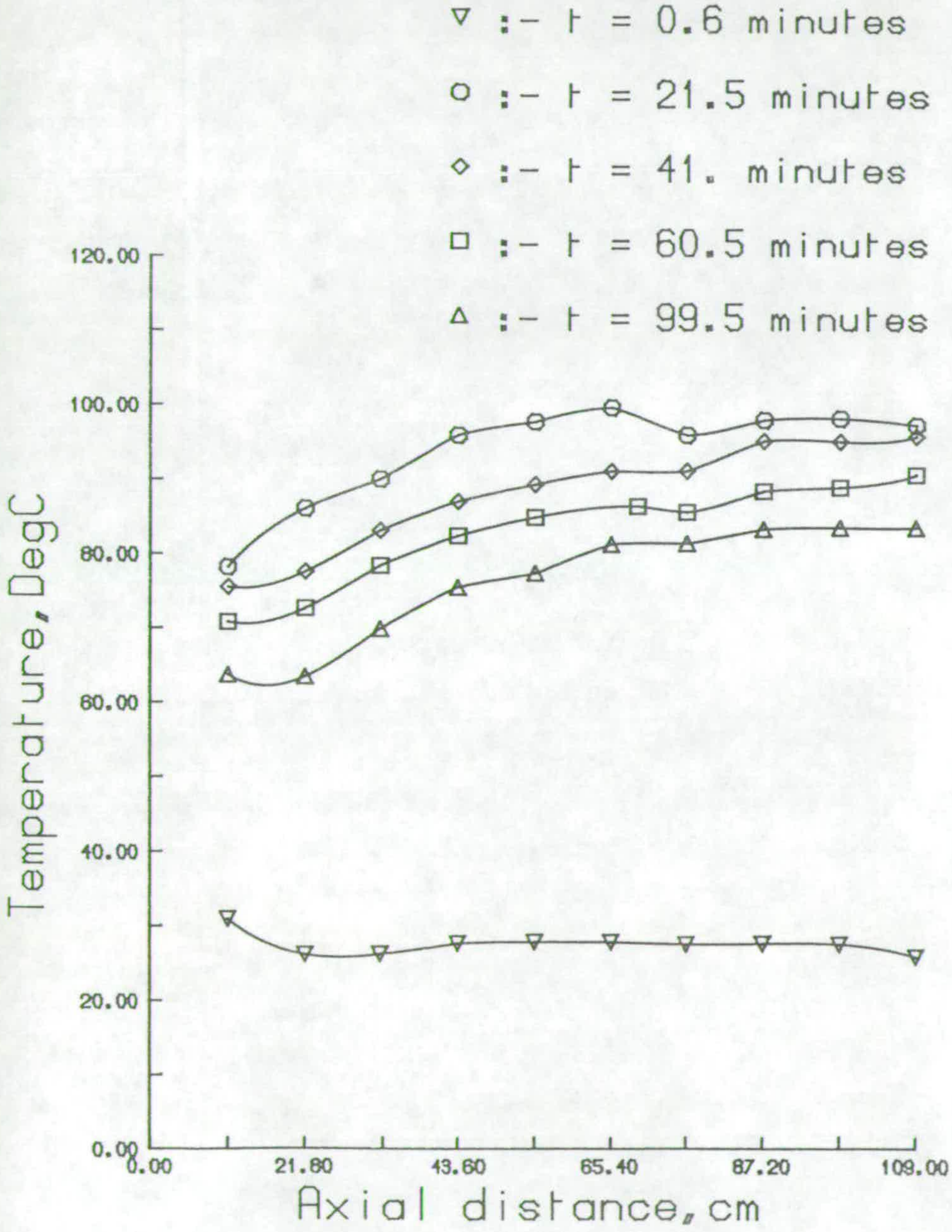

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Fig. A6: Bed Temperature vs Bed Axial Distance

Parameter: time

Experiment Date: 27/03/86: U= 0.393 m/s: Inlet Temp.= 44.6 DegC

Note: Faulty temp. measurement not plotted.(marked ↓)

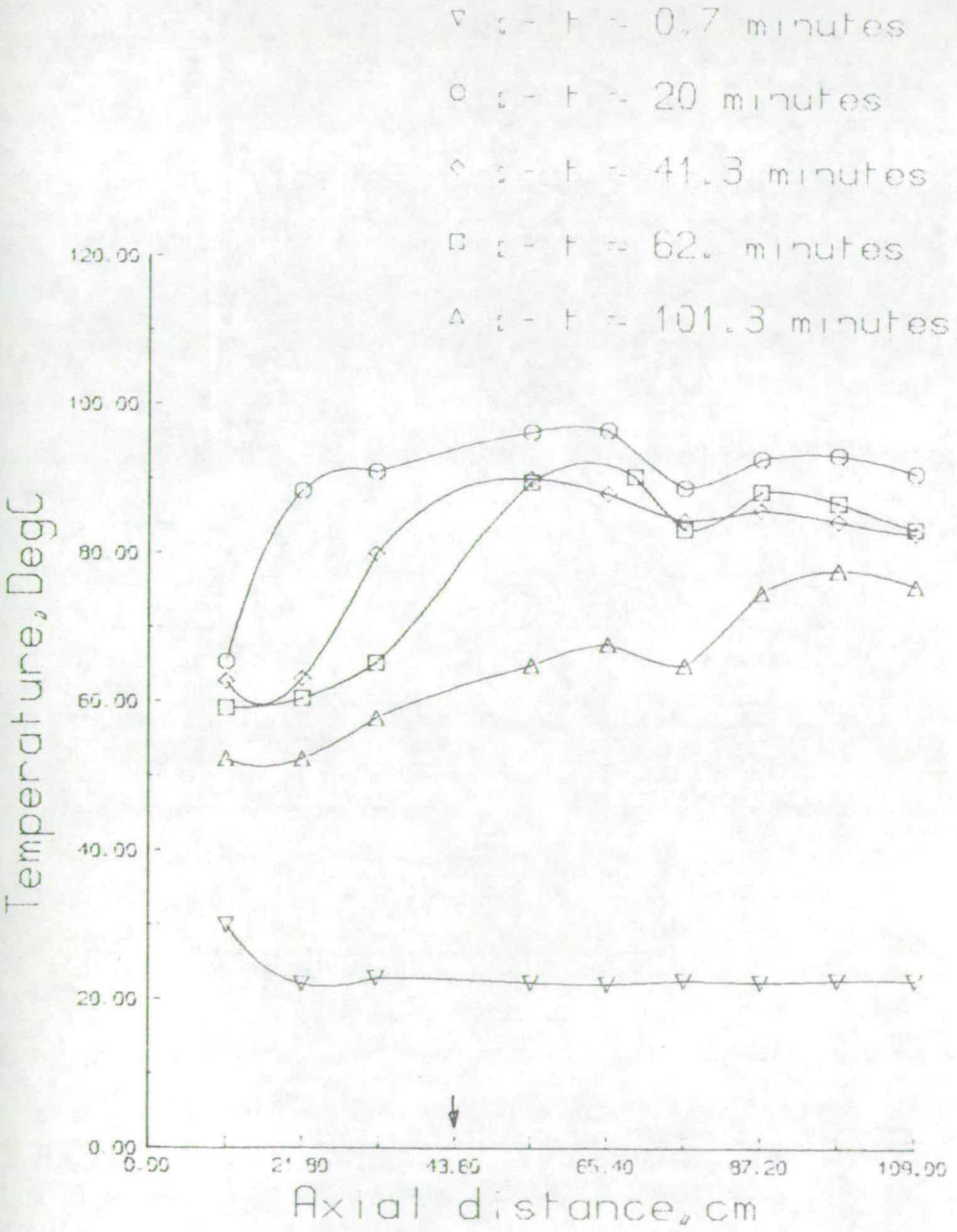

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Fig. A7: Bed Temperature vs Bed Axial Distance

Parameter: time

Experiment Date: 13/01/86: U= 0.393 m/s: Inlet Temp. = 48 DegC

Note: Faulty temp. measurement not plotted. (mark ↓)

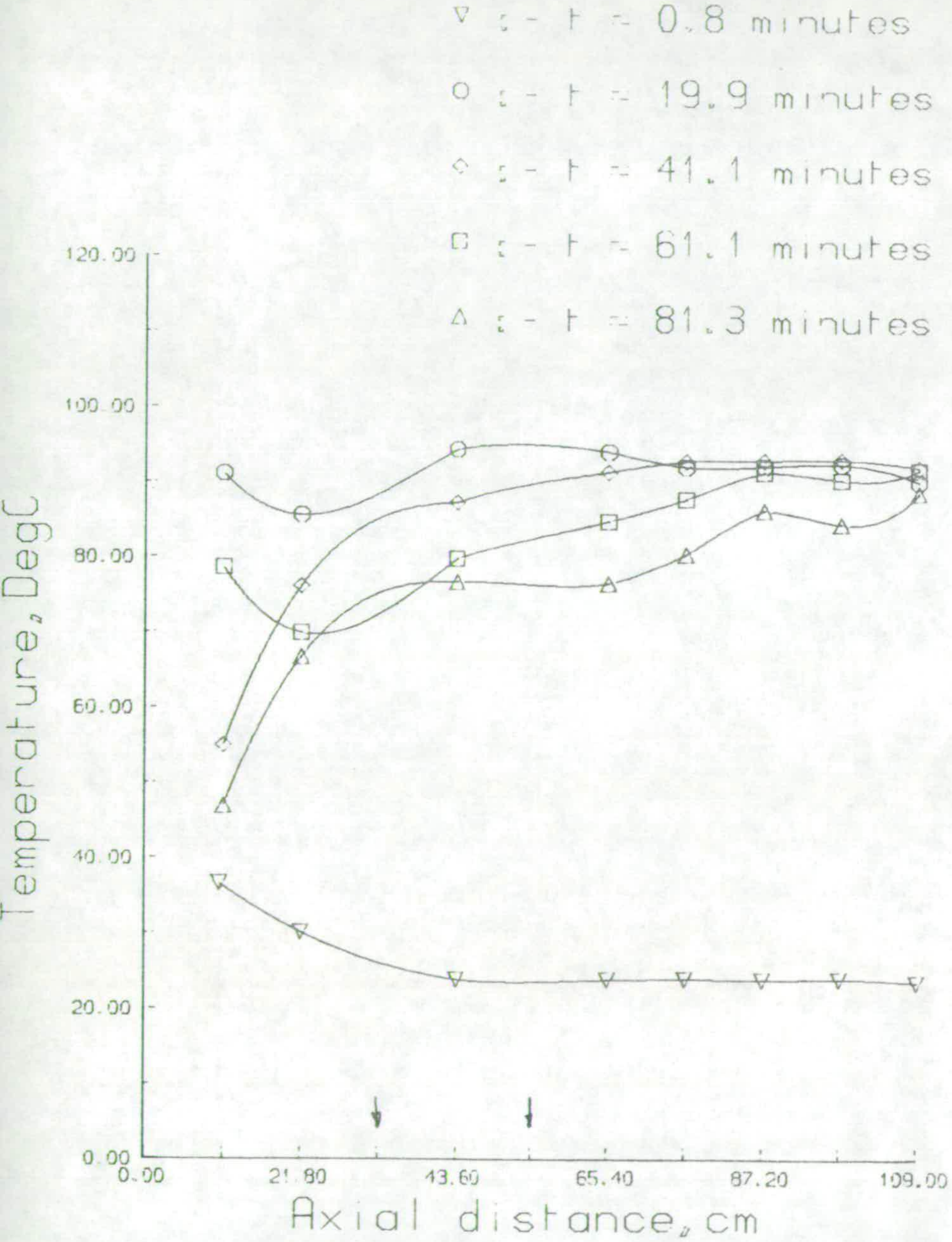

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Fig.A8: Bed Temperature vs Bed Axial Distance

Parameter: time

Experiment Date:28/11/85: U= 0.393 m/s: Inlet Temp.= 52 DegC

Note: Faulty temp. measurement not plotted.(marked ↓)

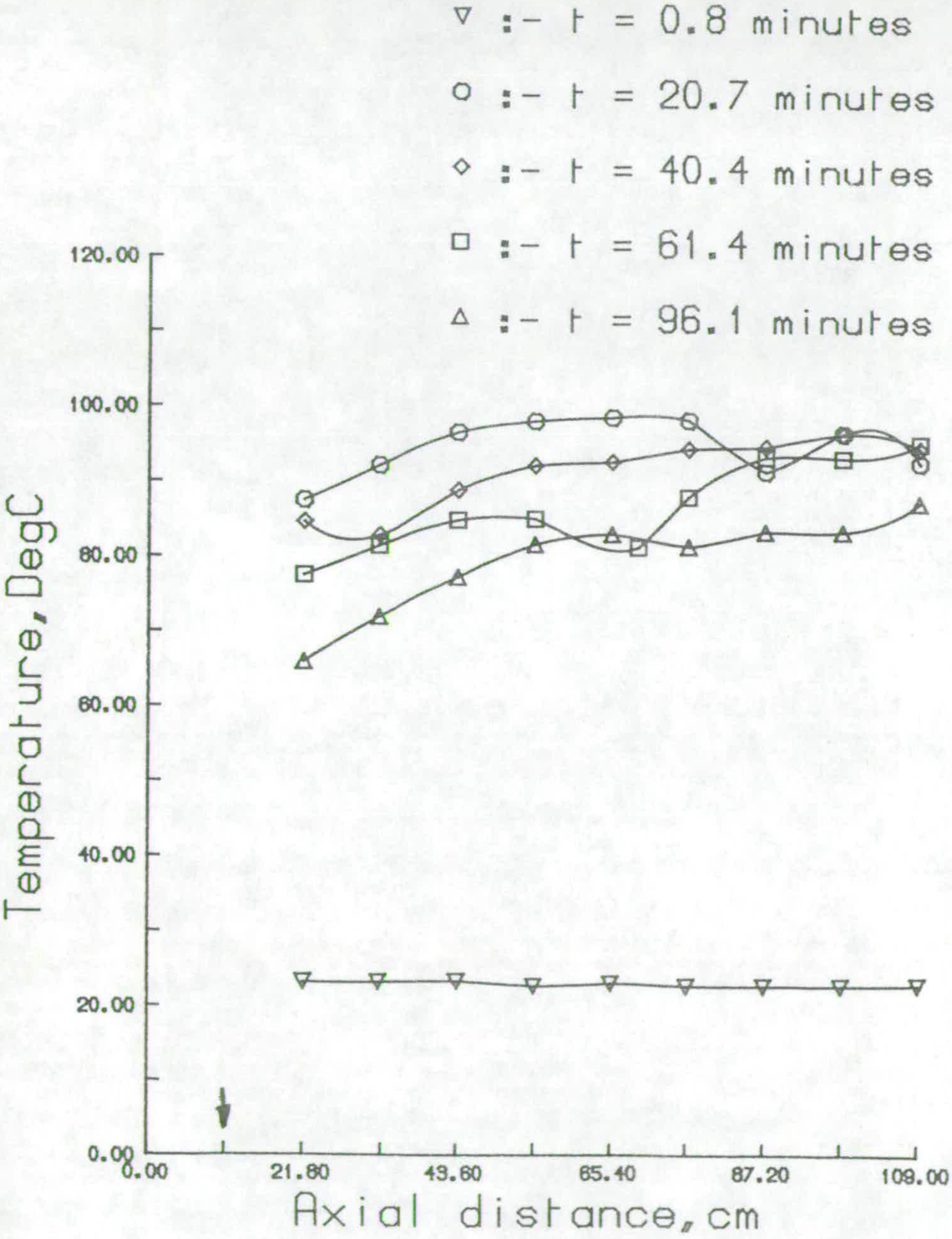

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Fig.A9: Bed Temperature vs Bed Axial Distance

Parameter: time

Experiment Date:03/12/85: U= 0.393 m/s: Inlet Temp.= 44.6 DegC

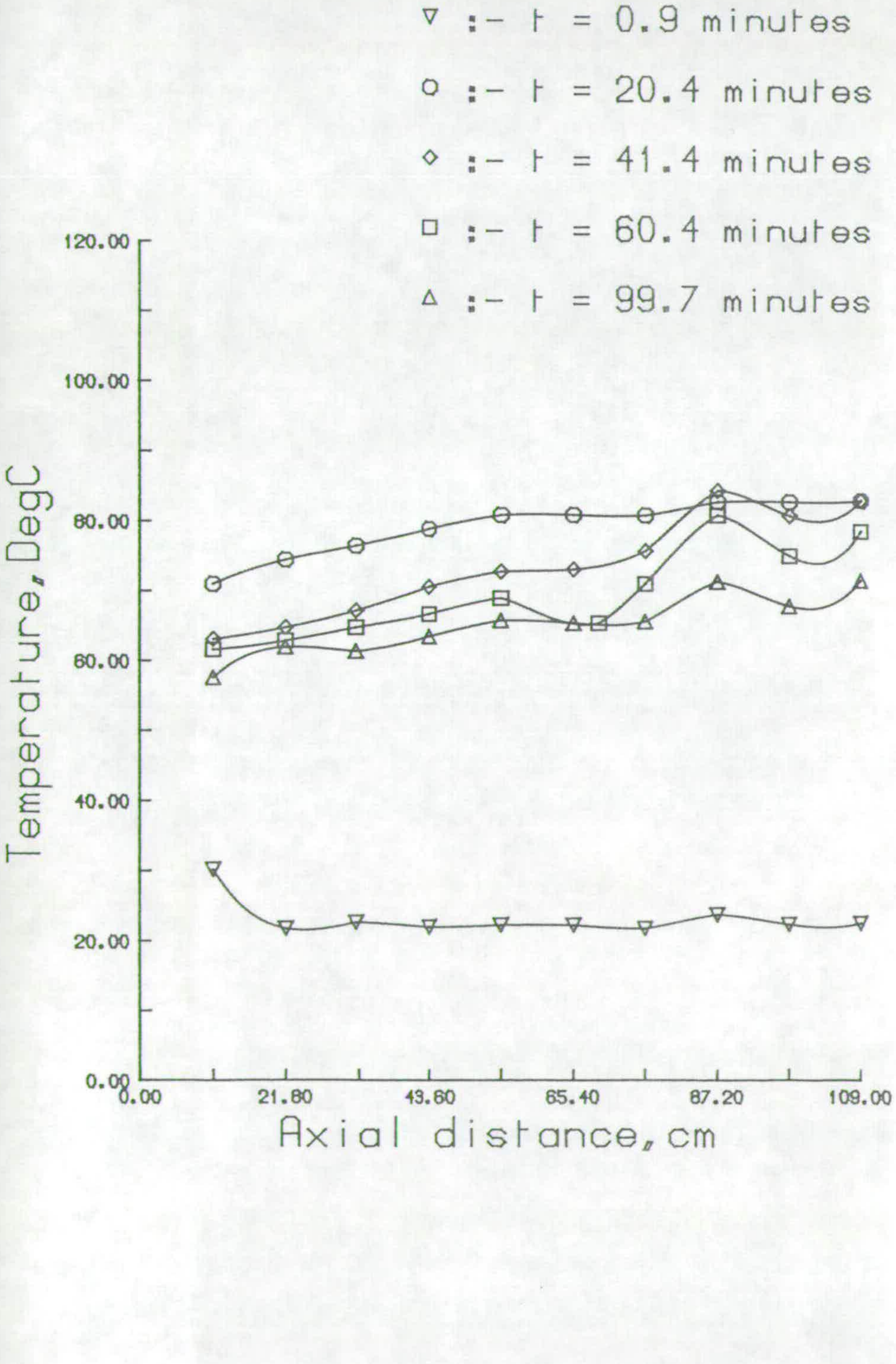

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Fig.A10: Bed Temperature vs Bed Axial Distance

Parameter: time

Experiment Date:05/12/85: U= 0.393 m/s: Inlet Temp.= 45.5 DegC

Note: Faulty temp. measurement not plotted. (marked ↓)