6-30-1954

# Design of fixed bed absorbers for drying gases

Roger Emery Bibaud
*New Jersey Institute of Technology*

## Recommended Citation

Bibaud, Roger Emery, "Design of fixed bed absorbers for drying gases" (1954). *Theses*. 2243.
https://digitalcommons.njit.edu/theses/2243

# DESIGN OF FIXED BED ADSORBERS FOR DRYING GASES

By

Roger E. Bibaud

Submitted in Partial Fulfilment
of the Requirements
for the Degree of
MASTER OF SCIENCE
in Chemical Engineering
in the
Graduate Division
at the
Newark College of Engineering

June 1, 1954

The author wishes to thank Dr. C. L. Mantell for suggesting the subject of this thesis, and for his patient guidance during its elaboration.

## CONTENTS

## CONTENTS

## CONTENTS

Page

IV - ILLUSTRATIVE PROBLEMS

## LIST OF FIGURES

## LIST OF FIGURES

## LIST OF TABLES

Page

## I - INTRODUCTION

Moisture can be removed from gases by passing them through beds of activated alumina, activated bauxite ("Florite"), or silica gel. These materials are adsorbents, and the moisture is retained on their surfaces. These become saturated with water after a while, and the gas is not dried any more. When the first trace of moisture is noticed in the exit gas stream, the "break point" has been reached. The bed can be reactivated by heating it with a current of hot gas, thereby evaporating the adsorbed moisture and entraining it away. This is the reverse process or "desorption". After cooling, the bed is ready for another cycle of adsorption.

For the continuous drying of a gas, two beds are necessary: while one is adsorbing moisture from the gas, the other is being reactivated. By alternating from one to the other in regular cycles, such as 4, 8, or 12 hours, a continuous supply of dry gas is obtainable.

In a well designed adsorber installation, the time required for reactivation and cooling will be equal to the duration of the adsorption period. This is accomplished by chosing the proper reactivation gas rate and temperature.

## II - SCOPE

It has been the purpose of the author to gather what information is to be found in the literature, to examine it critically, and then assemble it in usable form for design purposes. Some of the articles have been abstracted at the end and should be referred to for the graphs and data they contain. The information presented should enable one to:

1. Chose the adsorbent.
2. Calculate the charge required.
3. Fix the bed and vessel dimensions.
4. Calculate the pressure drop through the bed during adsorption and reactivation.
5. Calculate the maximum flow that the bed can stand.
6. Chose the proper reactivation gas rate.
7. Calculate the time required for reactivation and cooling.
8. Calculate the reactivation heat load.

## III - DESIGN CALCULATIONS

The subject matter of design has been divided into the following parts:

A. PRESSURE DROP.

B. MAXIMUM FLOW RATES.

C. ISOTHERMAL ADSORPTION.

D. ADIABATIC ADSORPTION.

E. REACTIVATION.

F. COOLING.

Under each heading, the various methods found in the literature are given, compared, and analysed. Some original ideas have been presented in parts E and F.

### A. PRESSURE DROP

The pressure drop through the bed must be known in order to be able to specify the discharge pressure of the blower or compressor moving the gas. The following methods have been found in the literature:

1. Amero, Moore, and Capell (2), present a graph of the friction factor "f" as a function of the Reynolds number which is reproduced on page 5. The Reynolds number is based on the average particle diameter. Use is made of the Fanning equation. This method is illustrated in part B "Maximum flow rates", and in section IV "Illustrative problems", Nos. 1 & 2.

2. Brown and Associates (12), give the method of Katz. This method is complicated but very general.

3. Hougen and Watson (13), present a general method based on the Fanning equation.

4. Mantell (14), gives graphs of pressure drop against flow for air through activated alumina and silica gel, but only for atmospheric pressure and temperature.

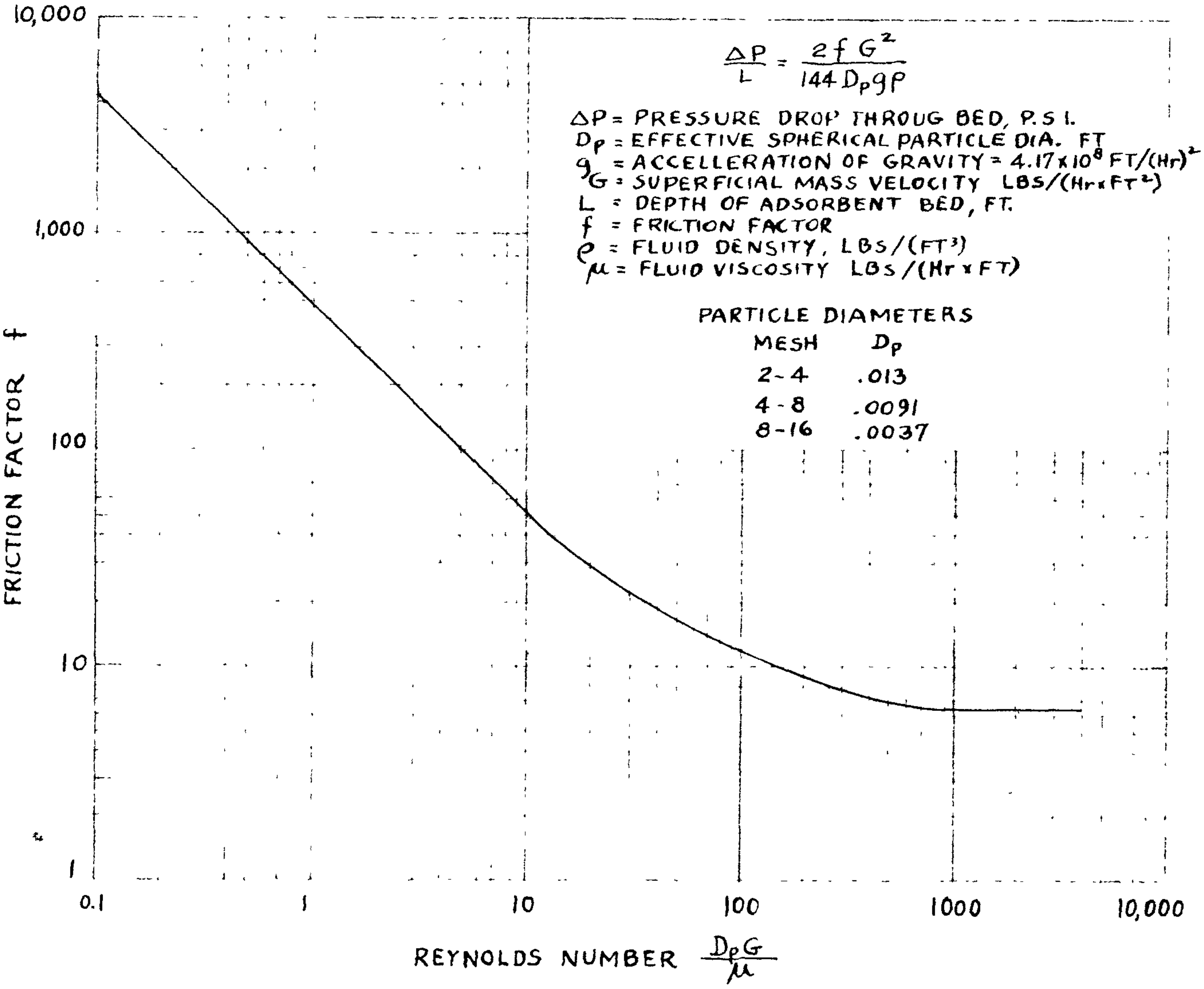


FIG. I PRESSURE DROP THROUGH BEDS OF GRANULAR ADSORBENTS

## B. MAXIMUM FLOW RATES

A gas flowing upward through an adsorbent bed will entrain particles and cause fluidization if the velocity is excessive. It is important to know at what velocity these effects occur. For downward flow, the only disadvantage of too high a velocity is an excessive pressure drop.

### 1. LEVA'S EQUATION

An equation from Leva, Weintraub, and Grummer (17), gives the velocity required for minimum fluidization, and is as follows:

$$G_{mf}^2 = \frac{D_P\ g_c\ \rho_F\ (\rho_S - \rho_F)\ \epsilon_{mf}^3}{2 f\ \lambda^{3-n}\ (1-\epsilon_{mf})^{2-n}}$$

where $G_{mf}$ = Mass velocity required for minimum fluidization, Lbs/(Hr x $Ft^2$), based on cross-sectional area of empty vessel.

$D_p$ = Composite particle diameter, Ft.

$g_c$ = Gravitational constant, $4.18 \times 10^8$ Ft/$(Hr)^2$

$\rho_F$ = Fluid density, Lbs/$Ft^3$

$\rho_S$ = Solid density, Lbs/$Ft^3$

$\epsilon_{mf}$ = Minimum voidage in a bed of solids at which fluidization starts, dimensionless. This is a function of the particle diameter and material, and is read from fig.3

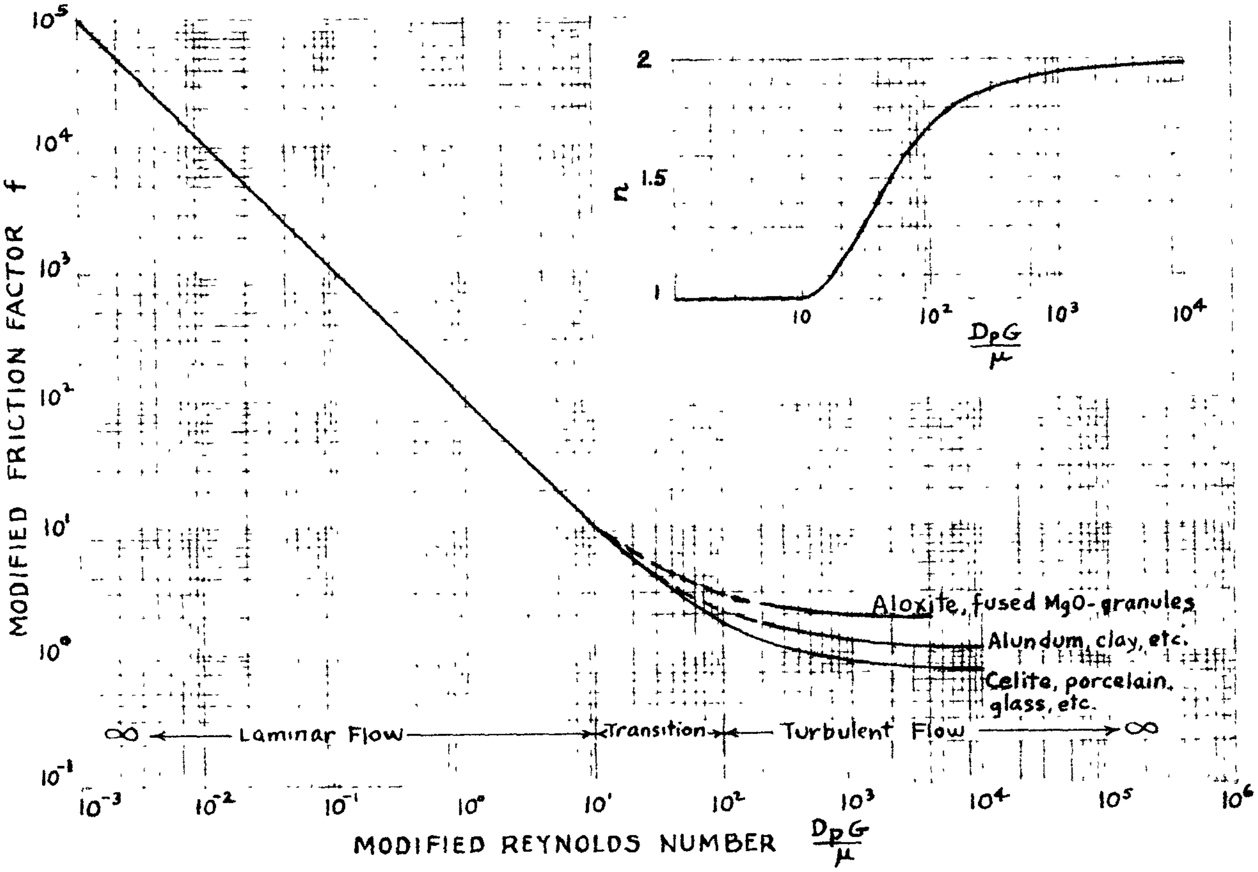


FIG. 2 MODIFIED FRICTION FACTORS VS. MODIFIED REYNOLDS NUMBERS

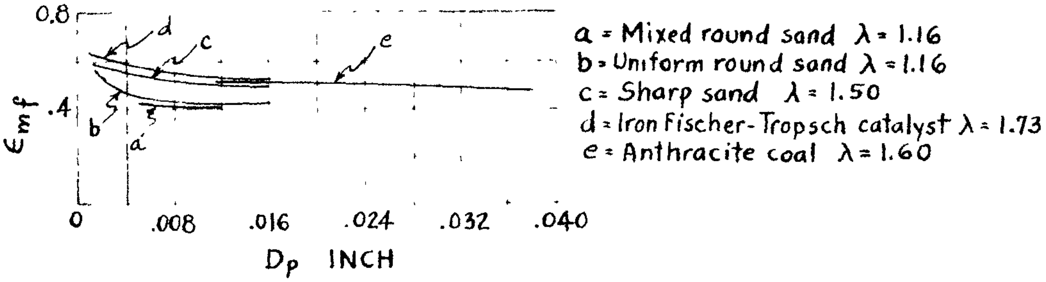


FIG. 3 MINIMUM FLUID VOIDAGE $\epsilon_{mf}$ FOR VARIOUS MATERIALS IN RELATION TO EFFECTIVE PARTICLE DIAMETER $D_p$

$f$ = Modified friction factor, dimensionless, read from fig. 2

$\lambda$ = Particle shape factor, dimensionless, given by: $\lambda = \frac{.205 A}{V^{2/3}}$

A = Surface area of a particle, $Ft^2$.

V = Volume of a particle, $Ft^3$.

n = State of flow factor, dimensionless, read from fig. 2 insert.

$\mu$ = Fluid viscosity, Lbs/(Hr x Ft)

The calculation of the maximum rate at which air could be sent upward through a desiccant bed was undertaken. The air was taken at atmospheric pressure and 68°F, when $\mu$ = .0436 Lbs/(Hr x Ft) and $\rho_F$ = .075 $Lbs/Ft^3$. The desiccant was taken as alumina of various mesh sizes, from 2-4 mesh to 16-20 mesh. The density of the solid, $\rho_s$, was understood to mean the apparent density, which is the average density of the solid and its internal pores. This was taken as 100 $Lbs/Ft^3$ after referring to Mantell (Ref. 14, p.75).

The value of $\lambda$, the shape factor, was taken as 1.6 the same as used for coal by Leva and co-workers. The value of $\epsilon_{mf}$ was taken as constant at 0.5 throughout the range of mesh sizes under consideration. This is in agreement with fig. 3, although the coarser particles have diameters outside the range of this figure.

The results are tabulated below and plotted in fig. 4.

TABLE 1

FLUIDIZATION VELOCITY BY LEVA'S EQUATION

| Mesh | $D_p$ Ft | $\frac{D_pG}{\mu}$ | f | n | $G_{mf}$ $\frac{\text{Lbs}}{\text{HrxFt}^2}$ | v Ft/Sec |
|---|---|---|---|---|---|---|
| 2-4 | .0219 | 725. | 1.3 | 1.935 | 1,450 | 5.44 |
| 4-8 | .01092 | 230. | 1.6 | 1.86 | 920 | 3.40 |
| 8-12 | .00541 | 65,8 | 2.6 | 1.60 | 530 | 1.96 |
| 12-16 | .00383 | 33.8 | 3.7 | 1.35 | 384 | 1.42 |
| 16-20 | .00301 | 19.2 | 5.8 | 1.15 | 278 | 1.03 |

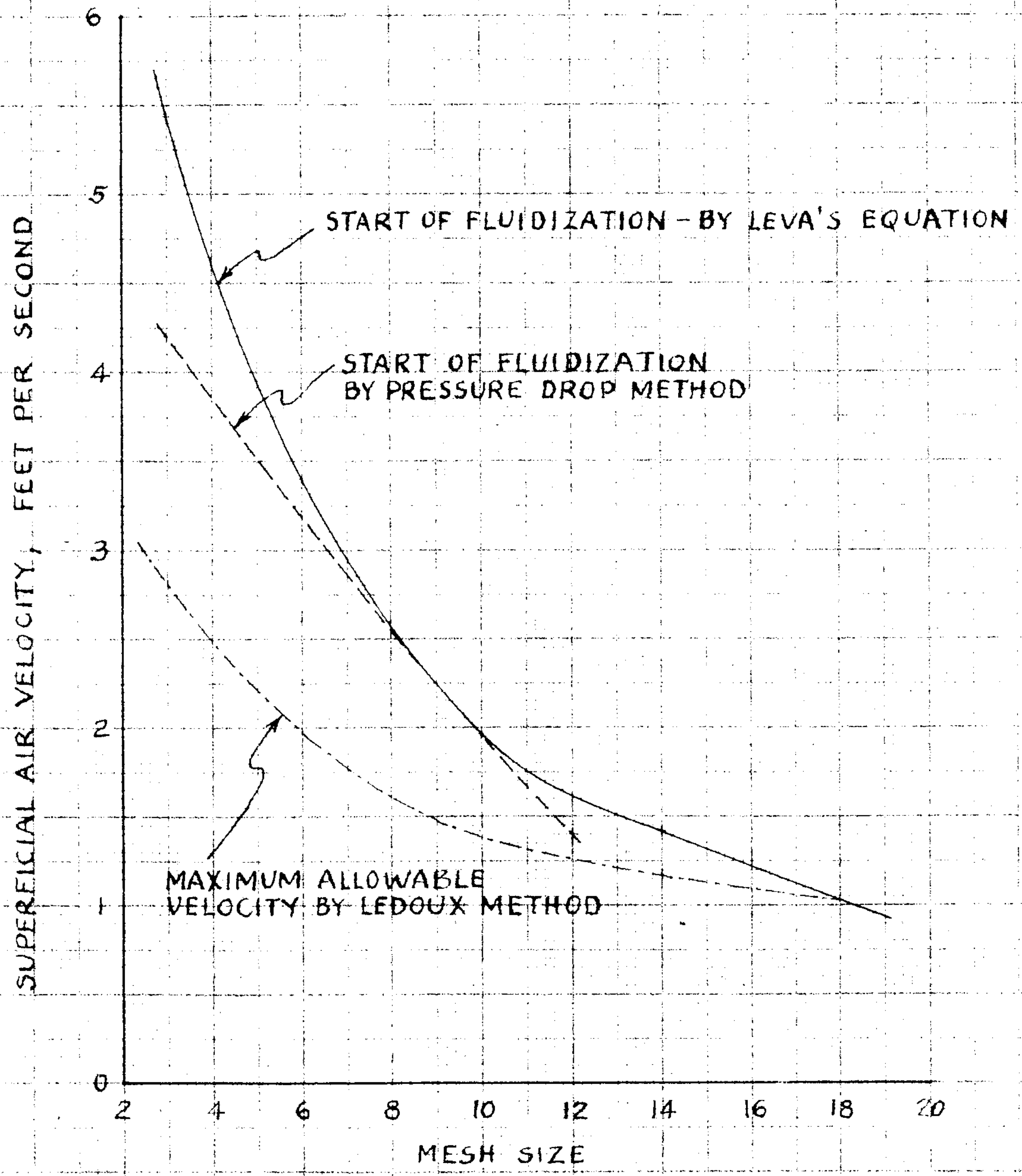


FIG. 4. LIMITING FLOW RATES FOR AIR AT 68°F & 1-ATM. THROUGH BEDS OF ACTIVATED ALUMINA

## 2. PRESSURE DROP METHOD

It is known that fluidization starts when the pressure drop of the fluid through the bed equals the weight of the bed per unit area (See Brown & Associates, ref. 12 p.269). Using fig. 1 for the friction factor, the air velocity required to cause fluidization of alumina was calculated. The method is illustrated in the following calculation of the velocity required to start fluidization of 4-8 mesh alumina.

$$\frac{\Delta P}{L} = \frac{2\ f\ G^2}{D_p\ g\ \rho}$$

$$\frac{\Delta P}{L} = \frac{50}{1} = 50 \text{ Lbs/Ft}^2 \text{ per foot of bed height.}$$

$D_p$ = .0091 from fig. 1

$G$ = $V\rho$, where V is the velocity in Ft/Sec.

= .075 V

$\mu$ = .0181 x .000672 = $1.215 \times 10^{-5}$ Lbs/(Hr x Ft)

$$Re = \frac{D_p G}{\mu} = \frac{.0091 \times .075 \times V}{1.215 \times 10^{-5}} = 56.2\ V$$

$$\frac{\Delta P}{L} = 50 = \frac{2\ f\ (.075)^2\ V^2}{.0091\ (32.2)(.075)} = .512\ f\ V^2$$

$$\text{or } V^2 = \frac{97.5}{f}$$

Proceeding by trial and error, values of f are tried in the last equation, and a velocity obtained. The Reynolds number is then calculated for that velocity, and the value of f corresponding is read from fig. 1 It should agree with the value tried.

Try $f = 9.5$

$$V^2 = \frac{97.5}{9.5} = 10.27$$

$V = 3.20$ Ft/Sec.

$Re = 56.2 \times 3.20 = 180$

$f = 9.5$ on fig. 1.

Thus a velocity of 3.20 Ft/Sec. will start fluidization. Other values for different mesh sizes are listed in the table below and plotted in fig. 4.

TABLE 2

FLUIDIZATION VELOCITY

BY PRESSURE DROP METHOD

| Alumina Mesh Size | Velocity Ft/Sec. |
|---|---|
| 2-4 | 4.20 |
| 4-8 | 3.20 |
| 8-16 | 1.40 |

## 3. METHOD OF LEDOUX

Ledoux (18), gives the following formula for calculating the maximum allowable velocity through an adsorbent bed:

$$\frac{G^2}{d_g d_a D g} = .0167 \text{ a dimensionless constant.}$$

where:

$G$ = Maximum allowable mass velocity, Lbs/(Hr x $Ft^2$)

$d_g$ = Fluid density, Lbs/$Ft^3$

$d_a$ = Bulk density of the adsorbent bed, Lbs/$Ft^3$

$D$ = Average particle diameter, Ft.

$g$ = Gravitational constant = $4.17 \times 10^8$ Ft/$Hr^2$

Using the units listed above, the formula reduces to:

$$G = 2,640 \sqrt{d_g d_a D}$$

Results obtained for air at 68°F and 1 atm. and alumina are given in the table below and plotted in fig. 4.

TABLE 3

MAXIMUM ALLOWABLE VELOCITY
BY LEDOUX METHOD

| Alumina Mesh Size | Velocity Ft/Sec. |
|---|---|
| 2-4 | 2.81 |
| 4-8 | 1.98 |
| 8-12 | 1.39 |
| 12-16 | 1.17 |
| 16-20 | 1.04 |

## C. ISOTHERMAL ADSORPTION

Under this heading, the amount of adsorbent to use in an adsorber shall be indicated. The basic figure is the adsorbed water content of the bed at the break point, expressed as a percentage of the weight of the bed in its freshly reactivated condition. It should be noted that adsorbents lose a portion of their adsorptive capacity with use, and a practical figure for design capacity should take that fact into consideration.

In order to have isothermal adsorption, the bed must contain cooling coils to absorb the heat liberated . For high pressures, however, the gas itself serves to carry the heat away, so that conditions can be considered isothermal. This was done in illustrative problem No. 2.

### 1. ACTIVATED ALUMINA

a. Mantell (14), in a table listing the properties of alumina gives the capacity as 12 to 14% water adsorbed at the break point.

b. Aluminum Co. of America (16) gives a capacity of 12% water adsorbed at the break point.

c. Eagleton and Bliss (11) report on the adsorption of water from air of low humidities. They find that in that region, $\leqq$ 3 Lb $H_2O$/Lb air, the capacity is very nearly that corresponding to saturation of the adsorbent under inlet air conditions. Curves are presented giving the partial pressure of water over adsorbents, plotted against water adsorbed. Thus the capacity varies with the moisture content of the inlet gas. They find that in an adsorber the capacity reaches 95% of the equilibrium value corresponding to the moisture in the inlet gas.

Using their equilibrium curve for alumina at 80°F, the following capacities are obtained:

TABLE 4

CAPACITY OF ALUMINA IN LOW HUMIDITY REGION

| | | | |
|---|---|---|---|
| Humidity of incoming air, Lbs $H_2O$/Lb air | .001 | .002 | .003 |
| Partial pressure of $H_2O$ vapor, mm Hg | 1.22 | 2.45 | 3.66 |
| Water content of bed at equilibrium, weight % | 3.6 | 5.0 | 5.8 |
| Capacity of bed, % of reactivated weight | 3.42 | 4.74 | 5.5 |

## 2. SILICA GEL

a. Hougen and Watson (13), present a method for determining the depth of bed required. This method is illustrated in problem No. 2 and is briefly as follows:

The diameter of the bed is chosen and the corresponding mass velocity calculated. The Reynolds number is calculated, and from it, using a formula given for silica gel, the height of a mass transfer unit is calculated. Then, from the inlet moisture content of the gas, the maximum humidity allowable in the outlet stream, and the duration of the adsorption cycle, the total number of transfer units required is read on a graph. Knowing the height of one unit, the bed depth can be calculated.

b. Eagleton and Bliss (11), report on the capacity of adsorbents at low inlet air humidities. According to these authors, if the humidity of the inlet air stream is $\leq$ .003 Lbs $H_2O$/Lb air, 95% of the equilibrium capacity of the bed is reached. Using their equilibrium curve at $80^oF$ for silica gel, the following capacities are obtained.

## TABLE 5

## CAPACITY OF SILICA GEL IN LOW HUMIDITY REGION

| | | | |
|---|---|---|---|
| Humidity of incoming air, Lbs $H_2O$/Lb air | .001 | .002 | .003 |
| Partial pressure of $H_2O$ vapor, mm Hg | 1.22 | 2.45 | 3.66 |
| Water content of bed at equilibrium, weight % | 4.0 | 7.0 | 9.2 |
| Capacity of bed, % of reactivated weight | 3.8 | 6.65 | 8.84 |

As a matter of interest, the equilibrium capacity of silica gel at 80°F obtained from other sources is listed below.

## TABLE 6

## EQUILIBRIUM DATA AT 80°F

## SILICA GEL - MOIST AIR

| | | | |
|---|---|---|---|
| Humidity of air Lbs $H_2O$/Lb air | .001 | .002 | .003 |
| Partial pressure of $H_2O$ vapor, mm Hg | 1.22 | 2.45 | 3.66 |
| Water content of gel, % of reactivated weight<br>Source: | | | |
| Eagleton & Bliss (11) | 4.0 | 7.0 | 9.2 |
| Hubard (10) | 4 | 6.2 | 8 |
| Hougen & Marshall formula (13) | 2.56 | 5.14 | 7.68 |

### 3. FLORITE

This is the trade name for an activated bauxite, and the adsorption capacity for water vapor reported in the literature is as follows:

a. Amero, Moore, and Capell (2), recommend using 5% of the weight of the reactivated bed, as the adsorption capacity for design purposes.

b. Mantell (14), reports on the experimental results of Deschner et al. For new Florite, the amount of water adsorbed up to the break point was 5.61 and 6.25% of the weight of the bed, as obtained in two different tests.

## D. ADIABATIC ADSORPTION

An adsorber that is insulated and that does not contain any means of cooling the bed during adsorption operates adiabatically. It is general practice to cover adsorbers with a layer of insulation to conserve heat during the reactivation period. The bed heats up during adsorption of water vapor, and the dried gas leaves at a higher temperature than it enters.

The capacity of various adsorbents operating under adiabatic conditions as found in the literature is discussed below.

### 1. ACTIVATED ALUMINA

a. Rathmell and Bateman (8), give the results of tests performed on the adiabatic drying of air through activated alumina at atmospheric pressure. Their work is summarized in two graphs which cover the following conditions: (The graphs are reproduced on page 78.)

Humidity of incoming air:

| | | | |
|---|---|---|---|
| .005 | to | .010 | Lbs $H_2O$/Lb air |
| 35% | to | 69.3% | Relative humidity at 68°F |
| 38°F | to | 57°F | Dew point. |

Humidity of outlet air:

.0002 to .0005 Lbs $H_2O$/Lb air

1.40% to 3.49% Relative humidity at 68°F

-25°F to -9°F Dew point.

Contact time: $\frac{1}{2}$ to $2\frac{1}{2}$ Seconds.

These contact times are rather short, and for the longer times currently used it would be conservative practice to use the capacity given at $2\frac{1}{2}$ seconds. The capacity ranges from 1.4 to 10% on the authors' cuves.

b. Derr (19), reports a test on the adiabatic drying of air of rather high moisture content at atmospheric pressure through activated alumina. The data from this test can serve as a basis for design and has been so used for illustrative problem No. 1. Derr's conditions and results were the following:

Humidity of incoming air:

.0178 Lbs $H_2O$/Lb air

95.9% Relative humidity at 75°F

73.8°F Dew point.

Humidity of exit air: Practically nil.

Contact time: 13.9 Seconds

Water adsorbed at break point: 4.75%

Temperature of exit air at break point: 212°F

## 2. SILICA GEL

a. Blanchard (9), reports results of experiments on the adsorption of water vapor from air under atmospheric pressure and adiabatic conditions. The observations are summarized in a graph, reproduced on page 83, which gives the adsorbed water content of the gel at the break point as a function of the inlet air temperature and relative humidity. The temperature of the exit air at the break point can also be read from the graph. The conditions of the tests were the following:

Depth of bed 50 cm or 1.64 feet.
Air velocity 23.5 cm/sec or 0.77 Ft/Sec.

Auxiliary graphs, reproduced on page 84, give the corrections to use for the adsorbent capacity for conditions other than those of the tests.

b. Hubard (10), proposes a method for calculating the adsorbent capacity. The method is also given in Mantell (14), and is the following:

At the end of the adsorption cycle, the gel at the air entrance is very nearly in equilibrium with the incoming air, since the contact has lasted the duration of the adsorbing cycle, ordinarily eight hours. At the exit air end of the bed, the moisture in the air will be the maximum allowable. This humidity corresponds to a certain moisture content in the gel. If it is admitted that equilibrium is attained also at this end of the bed, the moisture content could be read on the author's equilibrium curve provided the temperature is known. This temperature can be calculated by taking a rise of 10°F for each grain of moisture removed from a cubic foot of incoming air.

Knowing the adsorbed water content of the bed at the two ends, the mean content is calculated and used as a basis for calculating the amount of adsorbent required. This method is illustrated in problem No. 3

This method resting on broad simplifying assumptions should be used with caution. Under the high inlet humidity conditions of problem No. 3 ( pages 53-56), it gives an adsorption capacity which appears much too high.

## E. REACTIVATION

It is necessary to know the heat required as well as the time required for reactivation. The higher the temperature of the reactivation gas, the shorter will be the reactivation period. The temperature which must be attained by the adsorbent at the end of the reactivation period is as follows:

| | | | |
|---|---|---|---|
| Alumina | 350 | to | 600°F |
| Florite | 350 | to | 500°F |
| Silica gel | 300 | to | 350°F |

The reactivation must be done countercurrent to the adsorption: if the flow of gas was downward during adsorption, it must be upward during reactivation. The reactivating gas enters the bed at a fixed temperature $t_o$ and leaves at a variable temperature t, cold at first but gradually getting hotter until it attains the desired final temperature $t_f$. The time-temperature curve of the exit reactivation gas always exhibits a plateau, as shown in fig. 5. This plateau

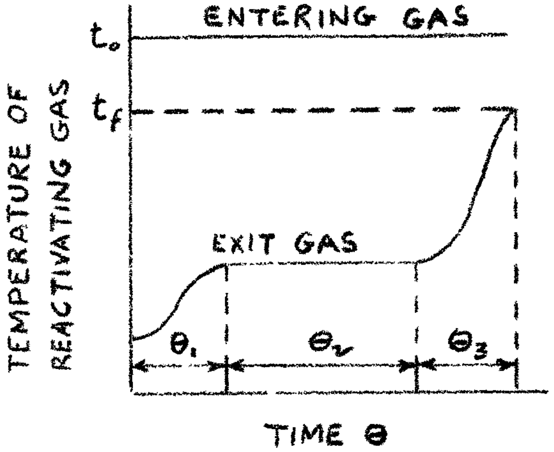


Fig.5 Time-temperature curve during reactivation.

occurs during the evaporation of the adsorbed water.

It is useful to divide the reactivation into three periods: before the plateau, the plateau, after the plateau, and to study each period separately. Since the plateau has to be located at the start, it is necessary to calculate the second period first.

## SECOND PERIOD: THE PLATEAU

The adsorbed water is evaporated at the constant temperature $t_1$. The following sketch, fig. 6, illustrates the arrangement to be considered. Air is used in the example, and for another gas it would be necessary to substitute the proper values of specific heat and molecular weight.

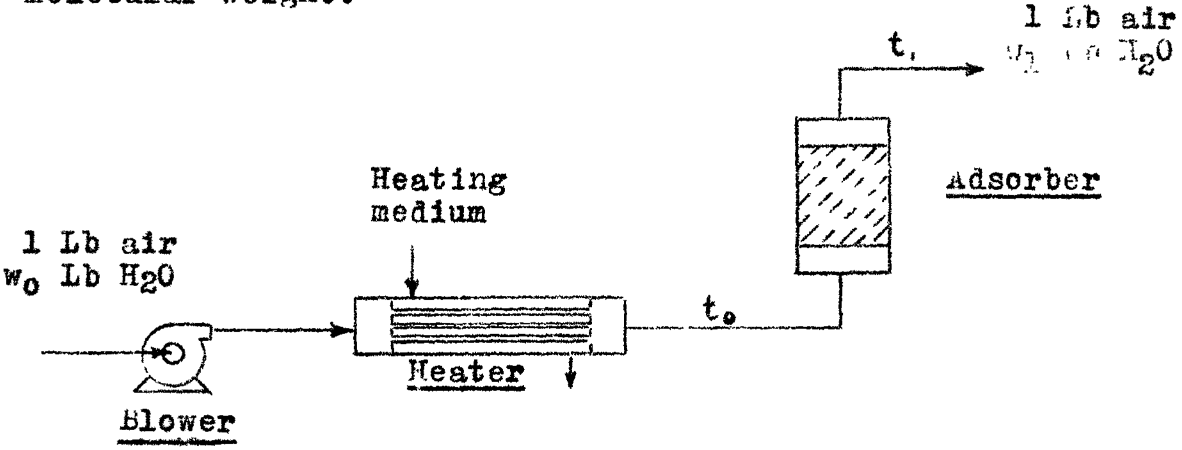


Fig. 6. Reactivation during constant temperature period.

Let $w$ = Humidity of the air, Lbs $H_2O$/Lb air.

$P$ = Vapor pressure of water, mm Hg.

$\lambda$ = Latent heat of vaporization of water, BTU/Lb.

subscript o for entering air.

subscript 1 for air leaving.

The air leaves the apparatus at temperature $t_1$, the plateau temperature. This temperature is obtained by trial and error and checked by heat balance. The given values are $t_o$ and $w_o$. The heat balance is calculated as follows:

Heat required = $q_1 = \lambda_1(w_1 - w_o)$ BTU/Lb air

Heat available = $q_o = (.24 + .45\ w_o)(t_o - t_1)$ BTU/Lb air

Heat balance: $q_o = q_1$

A value of $t_1$ is chosen, and the corresponding values for $P_1$ and $\lambda_1$ are read in a steam table. The outlet humidity $w_1$ is then calculated by the following formula:

$$w_1 = \frac{18\ P_1}{29(760 - P_1)} = \frac{.62\ P_1}{760 - P_1}$$

The heat required $q_1$, and the heat available $q_o$, are calculated and must be equal.

When the value of $t_1$ which satisfies the heat balance has been found, the time required for the second period can be calculated as follows:

Let $W_e$ = Adsorbed water, Lbs.

$A$ = Reactivation gas rate, Lbs/Hr.

$Q$ = Heat to be transferred during the second period, BTU.

$q$ = Heat transfer rate, BTU/Hr

Then $Q = W_e \lambda_1$ BTU

$q = Aq_o$ BTU/Hr

$\theta = Q/q$ Hr = Duration of second period.

## FIRST PERIOD: HEAT DUTY

During this period the bed and vessel are heated from ambiant temperature $t_A$ to the plateau temperature $t_1$. The heat to be transferred is composed of the following parts:

| | |
|---|---|
| 1 ) Heat $W_a$ Lbs of adsorbent | $W_a c_a (t_1 - t_A)$ |
| 1a) Heat $W_e$ Lbs of adsorbed water | $W_e c_e (t_1 - t_A)$ |
| 2 ) Heat $W_s$ Lbs of steel | $W_s c_s (t_1 - t_A)$ |
| 3 ) Heat $W_c$ Lbs of insulation | $W_c c_c (t_1 - t_A)/2$ |
| 4 ) Heat losses through insulation | Negligible |

## THIRD PERIOD: HEAT DUTY

Heating the adsorbent and vessel from the plateau temperature $t_1$ to the final temperature $t_2$ requires the following heat quantities:

1) Heat $W_a$ Lbs of adsorbent $W_a c_a (t_2 - t_1)$

2) Heat $W_s$ Lbs of steel $W_s c_s (t_2 - t_1)$

3) Heat $W_c$ Lbs of insulation $W_c c_c (t_2 - t_1)/2$

4) Heat losses through the insulation:

a) Cylindrical part:

$$q_c = \frac{k\, 2\pi l\, (t_s - t_A)}{2.3 \log_{10}\left(\frac{r_2}{r_1}\right) + \frac{k}{h_t r_2}} \quad \text{BTU/Hr}$$

b) Through the two ends together:

$$q_b = \frac{k\, S\, (t_s - t_A)}{L + \frac{k}{h_t}} \quad \text{BTU/Hr}$$

The following symbols are used:

k = Thermal conductivity of the insulation $\frac{\text{BTU}}{\text{Hr} \times \text{Ft}^2 \times \frac{^\circ\text{F}}{\text{Ft}}}$

l = Length of adsorber, Ft.

$t_s$ = Average temperature of the steel wall during the period.

$t_A$ = Ambiant temperature $^\circ$F

$r_2$ = External radius of the insulation, Ft.

$r_1$ = Internal radius of the insulation, Ft.

$h_t$ = Total heat transfer coefficient, convection and radiation combined, $\frac{\text{BTU}}{\text{Hr} \times \text{Ft}^2 \times {}^\circ\text{F}}$

Take $h_t = 1.5$

S = Surface area of the two ends of the adsorber together, $\text{Ft}^2$

L = Thickness of the insulation, Ft.

## FIRST AND THIRD PERIODS: DURATION

During the first and third periods the temperature of the bed is on the increase and three methods are available to calculate the required time. These methods are:

1. Method of Ledoux.
2. Method of arithmetic mean transfer.
3. Method of logarithmic mean transfer.

In the order named, these methods give progressively longer times of transfer for the third period. The method of Ledoux should give the best answer for the third period. This method is not applicable for the first period because at the end of that period an even temperature throughout the bed has been postulated. Ledoux's method applies only when there is a temperature gradient from one end of the bed to the other at the end of the process. Method 3. should be used for the first period.

## 1. METHOD OF LEDOUX

This method is given in reference No. 4 for the cooling of beds but is also applicable to the heating of beds by following the indications below.

The coefficient of heat transfer from the gas to the bed is first calculated by the method of Hougen and Watson, reference No.13, page 985. This will be the coefficient per unit area of the particles, and by multiplying by the surface area per unit volume for the particular adsorbent used, the coefficient per unit volume is obtained.

The following symbols, illustrated in fig. 7 are to be used:

$t_o$ = Temperature of the reactivating gas as it enters the bed.

$t_o'$ = The uniform temperature of the bed at the start of the heating period.

$t'$ = Temperature of the bed, at the reactivating gas exit, after heating time $\theta$

$\theta$ = Heating time in hours since the start of the heating period.

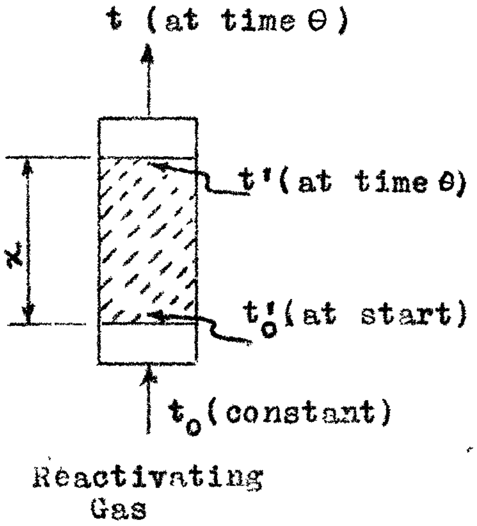


Fig.7. Temperatures during reactivation.

The dimensionless temperature of the bed, T' is defined as follows:

$$T' = \frac{t_o - t'}{t_o - t_o'}$$

Two groups are then formed (dimensionless):

$$X = \frac{h\,x}{c_p\,G} \qquad \text{and} \qquad \Theta = \frac{h\,\theta}{c\,\rho}$$

where:

$h$ = Heat transfer coefficient from gas to bed per unit volume of bed, $\frac{\text{BTU}}{\text{Hr x Ft}^3 \text{x } ^\circ\text{F}}$

$x$ = Bed depth, Ft

$c_p$ = Specific heat of the reactivating gas at constant pressure, $\frac{\text{BTU}}{\text{Lb x } ^\circ\text{F}}$

$G$ = Mass velocity of the reactivating gas $\frac{Lb}{Hr \times Ft^2}$

$c$ = Specific heat of the bed, $\frac{BTU}{Lb \times {}^{o}F}$

$\rho$ = Density of the bed, Lbs/ $Ft^3$

X is first calculated. The corresponding value of $\Theta$ is read on Ledoux's graphs, for the required T', as shown in fig. 8 for X = 20. The heating time is then calculated by:

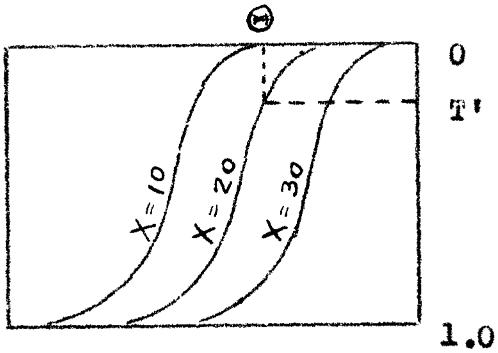


Fig.8. Method of reading Ledoux graphs.

$$\theta = \frac{\Theta c \rho}{h}$$

It is to be noted that the time thus obtained is for the bed only and not for the container. In order to compensate for the heat transferred to the vessel, to the insulation, and lost to the surroundings, it is proposed that the time obtained be corrected for the total duty as follows:

$$\theta_{TOTAL} = \theta_{BED} \times \frac{\text{Total duty}}{\text{Duty for heating bed alone}}$$

## 2. METHOD OF ARITHMETIC MEAN TRANSFER

This method consists in evaluating the heat transfer rate from the gas to the bed at the start and end of the heating period, and taking the arithmetic mean.

The reactivating gas enters the bed at constant temperature $t_o$ and leaves at variable temperature t. The rate of heat transfer at any moment is given by:

$$q = A\ c_p\ (t_o - t)$$

where $A$ = Rate of flow of reactivating gas, Lbs/Hr.

If the exit gas temperature is assumed to be the same as the bed temperature at the exit end, then:

$$q = A\ c_p\ (t_o - t')$$

Now if $t_o'$ = Uniform temperature of the bed at the start.

and $t_f'$ = Desired temperature of the bed at the exit end at the end of the heating period.

The rate of heat transfer at the start is:

$$q_o = A\ c_p\ (t_o - t_o')$$

The rate of heat transfer at the end is:

$$q_f = A\ c_p\ (t_o - t_f')$$

The arithmetic mean rate of heat transfer is:

$$q_{am} = \frac{q_o + q_f}{2}$$

Knowing the total heat to be transferred $Q$, and the mean rate of transfer $q_{am}$, the required time can be calculated:

$$\theta = \frac{Q}{q_{am}}$$

## 3. METHOD OF LOGARITHMIC MEAN TRANSFER

The reactivating gas enters the bed at constant temperature $t_o$, and leaves at variable temperature t. If t' represents the mean temperature of the bed, and if it assumed that the gas leaves also at that temperature, the heat balance is as follows:

Heat lost by the gas:

$$q = \frac{dQ}{d\theta} = A\ c_p\ (t_o - t')\quad \text{BTU/Hr} \qquad (1)$$

where $A$ = Rate of flow of reactivating gas, Lbs/Hr.

The heat gained by the bed is:

$$dQ = W_a\ c_a\ dt'$$

where $W_a$ = Weight of bed, Lbs.

$c_a$ = Specific heat of the bed, $\frac{\text{BTU}}{\text{Lb} \times {}^{o}\text{F}}$

Substituting for dQ in equation (1):

$$q = \frac{W_a\ c_a\ dt'}{d\theta} = A\ c_p\ (t_o - t')$$

from which:

$$d\theta = \frac{W_a\ c_a}{A\ c_p} \cdot \frac{dt'}{(t_o - t')}$$

Integrating between the limits of $t_o'$ and t' for the bed:

$$\theta = \frac{W_a\ c_a}{A\ c_p}\ ln\ \frac{(t_o - t_o')}{(t_o - t')} = \frac{W_a\ c_a}{A\ c_p}\ \ln(1/T')$$

Taking the logarithmic mean rate of heat transfer from the gas to the bed leads to the same result:

$$q_o \quad = \quad A\ c_p\ (t_o - t_o') \quad \text{BTU/Hr at the start}$$

$$q_f \quad = \quad A\ c_p\ (t_o - t') \quad \text{BTU/Hr at the end}$$

The logarithmic mean rate is:

$$q_{lm} \quad = \quad \frac{q_o - q_f}{\ln \frac{q_o}{q_f}} \quad = \quad A\ c_p \frac{t' - t_o'}{\ln \frac{t_o - t_o'}{t_o - t'}} \quad \text{BTU/Hr}$$

The heat transmitted is:

$$Q \quad = \quad W_a\ c_a\ (t' - t_o) \quad \text{BTU}$$

The required heating time is therefore:

$$\theta \quad = \frac{Q}{q_{lm}} \quad = \quad \frac{W_a\ c_a}{A\ \ c_p}\ \ln \frac{t_o - t'}{t_o - t_o'} \quad = \quad \frac{W_a\ c_a}{A\ \ c_p} \ln(1/T')$$

## F. COOLING

After the reactivation, the bed must be cooled from temperature $t_0'$ to temperature $t'$, a few degrees above the temperature of the coolant gas, $t_0$. The heat to be removed is composed of three parts:

| | |
|---|---|
| 1) Cool $W_a$ Lbs of adsorbent | $W_a c_a (t_0' - t')$ |
| 2) Cool $W_s$ Lbs of steel | $W_s c_s (t_0' - t')$ |
| 3) Cool $W_c$ Lbs of insulation | $W_c c_c (t_0' - t')/2$ |

The cooling time can be obtained by Ledoux's method.* The coefficient of heat transfer is obtained by using the method shown in Hougen and Watson, reference No. 13, page 985. This coefficient is then transformed to volume basis by multiplying it by the number of square feet of surface area in a cubic foot of adsorbent. For this value, see the same reference page 1085.

The cooling time so calculated is for cooling the bed alone. In order to compensate for the cooling of the vessel and insulation, the following formula is proposed:

$$\Theta_{\text{TOTAL}} = \Theta_{\text{BED}} \times \frac{\text{Total heat}}{\text{Heat removed from bed alone}}$$

---

*See reference No. 4 abstracted on pages 62-64

## IV - ILLUSTRATIVE PROBLEMS

### - PROBLEM NO. 1 -

It is desired to dry 1000 SCFM of air, measured dry at 60°F and 1 atm. The air is at atmospheric pressure and 80°F and has a relative humidity of 70%. The dried air must have a dew point below -60°F. Using 2-4 mesh alumina and an 8 hour period for adsorption, design an adsorber to operate adiabatically. For reactivation hot air is available at 400°F. Find the adsorbent charge, the vessel dimensions, the reactivation air flow, the pressure drop during adsorption and during reactivation, and the reactivation heat load.

### PRELIMINARY CALCULATIONS

DRY AIR FLOW:

By weight $\frac{1000 \times 492 \times 29 \times 60}{520 \times 359} = 4{,}600$ Lbs/Hr.

By volume $\frac{1000 \times 540}{60 \times 520} = 17.30$ CFS (80°F, 1 atm)

WATER TO BE ADSORBED:

Inlet moisture................ .0154 Lbs $H_2O$/Lb dry air

Maximum exit moisture......... .00002 Lbs $H_2O$/Lb dry air
(At end of adsorbing cycle)

Water to be adsorbed 4,600 x .0154 = 70.8 Lbs/Hr

## SOLUTION

**BASIS:**

Adsorbent: 2 to 4 mesh activated alumina

Conditions: Adiabatic

Adsorbing cycle: 8 Hours

Reactivating and cooling cycle: 8 Hours

## ADSORBENT CHARGE

**BASIS:**

Adiabatic adsorption experiments of Derr, ref. No.[19]

Break point obtained: .0476 Lbs $H_2O$/Lb alumina.

Inlet moisture: .0178 Lbs $H_2O$/Lb air.

Inlet air temperature: 75°F.

Pressure: 1 atmosphere.

Our conditions are nearly the same except for our inlet moisture which is lesser: .0154 Lbs $H_2O$ per Lb. of air. Under adiabatic conditions and at high humidities, the capacity of an adsorbent increases with a decrease in inlet moisture. The break point should then be about .050 Lbs $H_2O$/Lb alumina for our conditions.

Water to be adsorbed per cycle 70.8 x 8 = 566 Lbs.

Required adsorbent charge 566/.050 = 11,320 Lbs

Plus 20% excess = 2,264

13,584 Lbs.

Say 13,600 Lbs.

## ADSORBER

### DIMENSIONS:

Basis: Ratio of height to diameter to lie between
2 and 5 (Amero, reference No. 2)

Volume of adsorbent: 13,600/50 = 272 $Ft^3$

Diameter: 5'-0"

Cross-sectional area: 19.62 $Ft^2$
(This cross-sectional area must be chosen in regards to pressure drop during adsorption and reactivation, and to maximum allowable velocity during reactivation. These have been calculated at the end of the problem.)

Height of bed: 272/19.62 = 13.88 Ft

Height of adsorber: 20'-0"

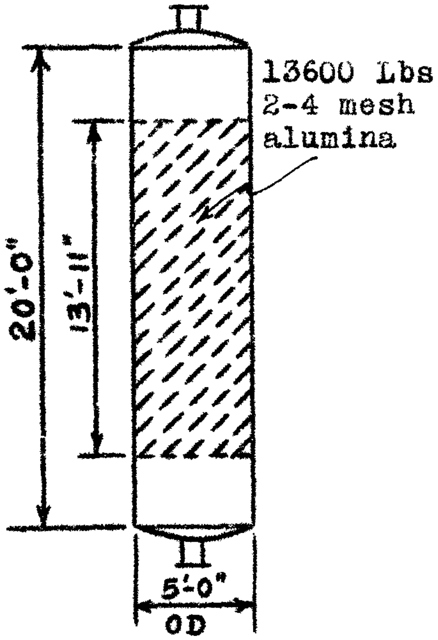


Fig. 9. Adsorber for problem 1.

### WEIGHT OF STEEL:

Basis: 1/4" Wall thickness

Cylinder: 5 x $\pi$ x 20 = 314 $Ft^2$

Ends: 2 x 19.6 = 39

353

Weight: 353 x 10.2 = 3,600 Lbs.

### WEIGHT OF INSULATION:

Baldwin-Hill Co, rockwool felt.

Density: 8 $Lbs/Ft^3$

Thermal conductivity: .025 BTU/(Hr x Ft x °F)

Specific heat: .24 BTU/(Lb x °F)

Thickness: 2"

$$\text{Cylinder: } 20 \times \frac{\pi}{4}\left[(5.33)^2 - (5.00)^2\right] = 53.4\ Ft^3$$

$$\text{Ends: } 2 \times \frac{2}{12} \times \frac{\pi}{4}\,(5.33)^2 = \underline{7.44}$$

60.8

Weight: 60.8 x 8 = 486 Lbs.

# REACTIVATION

## BASIS:

Reactivating fluid: Air at atmospheric pressure and 400°F.

Rate of flow: 6500 Lbs/Hr

This rate is arrived at by trial and error to give a duration within 8 hours for reactivating and cooling.

## DETERMINATION OF THE PLATEAU:

Given $t_o = 400°F$

$w_o = .0154$ Lbs $H_2O$/Lb air

Try $t_1 = 121°F$ (The plateau)

Then $P_1 = 89.8$ mm Hg

$\lambda_1 = 1{,}024$ BTU/Lb

$$w_1 = \frac{.62\ P_1}{760 - P_1} = \frac{.62 \times 89.8}{760 - 89.8} = .0831 \text{ Lbs } H_2O\text{/Lb air}$$

Heat required $q_1 = \lambda_1(w_1 - w_o) = 1024(.0831 - .0154) = 693$ BTU/Lb air

Heat available
$$q_2 = (.24 + .45w_o)(t_o - t_1)$$
$$= \left[.24 + (.45)(.0154)\right](400 - 121)$$
$$= 688 \text{ BTU/Lb dry air}$$

The plateau is 121°F to the nearest degree.

## HEAT DUTY:

**First period**: Heating adsorber from 80°F to to 121°F.

| | | |
|---|---|---|
| 1 ) Alumina | 13,600 (.25)(121 - 80) | = 139,300 BTU |
| 1a) Adsorbed water | 566 ( 1 ) (121 - 80) | = 23,200 |
| 2 ) Steel | 3,600(.113)(121 - 80) | = 16,700 |
| 3) Insulation | 486 (.24)(121 - 80)/2 | = 2,390 |
| 4 ) Losses | Negligible | |
| | | 181,590 BTU |

**Second period**: Evaporation of water at 121°F.

Heat duty = 566 x 1024 = 580,000 BTU

**Third period**: Heating adsorber from 121°F to 350°F

| | | | |
|---|---|---|---|
| 1) Alumina | 13,600 (.25)(350 - 121) | = | 778,000 BTU |
| 2) Steel | 3,600(.113)(350 - 121) | = | 93,100 |
| 3) Insulation | 486 (.24)(350 - 121)/2 | = | 13,300 |
| 4) Losses (see below) | 2.5 x 7,900 | = | 19,700 |
| | | | 904,100 BTU |

Losses: Ambiant temperature 80°F

Mean temperature of steel $\frac{350 + 121}{2} = 236^\circ F$

$$q_c = \frac{.025 \times 2 \times \pi \times 20\ (236 - 80)}{2.3 \log \frac{2.667}{2.50} + \frac{.025}{1.5 \times 2.667}} = 6{,}910 \text{ BTU/Hr}$$

$$q_b = \frac{.025 \times \frac{\pi}{4}(5.33)^2 \times 2(236-80)}{\frac{2}{12} + \frac{.025}{1.5}} = 972$$

7,882

Say 7,900 BTU/Hr

Estimating 2.5 hours for the third period:

Losses = 2.5 x 7,900 = 19,700 BTU

## DURATION OF FIRST PERIOD

Method of logarithmic mean transfer.

Heat transfer rate at start:

$$q_o = A\ c_p\ (t_o - t_o') = 6500 \times .24\ (400-80) = 499,000 \text{ BTU/Hr}$$

Heat transfer rate at end:

$$q_f = A\ c_p\ (t_o - t') = 6500 \times .24\ (400-121) = 435,000 \text{ BTU/Hr}$$

Mean transfer rate:

$$q_{lm} = \frac{499,000 - 435,000}{2.3 \log \frac{499,000}{435,000}} = 467,000 \text{ BTU/Hr}$$

Duration:

$$\theta = \frac{181,600}{467,000} = 0.388 \text{ Hour.}$$

## DURATION OF SECOND PERIOD

Heat transfer rate:

$$q = 6500 \times .24\ (400 - 121) = 435,000 \text{ BTU/Hr}$$

Duration:

$$\theta = \frac{580,000}{435,000} = 1.33 \text{ Hours}$$

## DURATION OF THIRD PERIOD

Method of Ledoux.

Calculation of heat transfer coefficient by method of Hougen and Watson.

$$G = \frac{6500}{19.62} = 332 \text{ Lbs/(Hr} \times \text{Ft}^2)$$

Viscosity of air for the range $80^\circ$-$400^\circ$F $\frac{.018 + .025}{2} = .0215$ cp.

$$\mu = .0215 \times 2.42 = .052 \text{ Lb/(Hr} \times \text{Ft)}$$

$D = .022$ Ft for 2-4 mesh material (Ref. 13, p. 1085)

$$Re = \frac{D\ G}{\mu} = \frac{.022 \times 332}{.052} = 140$$

$$j_h = \frac{1.95}{(Re)^{.51}} = \frac{1.95}{(140)^{.51}} = .157$$

$$Pr = \frac{c_p \mu}{k} = .74 \text{ for air}$$

$$h_G = \frac{j_h\ G\ c_p}{(Pr)^{2/3}} = \frac{.157 \times 332 \times .24}{(.74)^{2/3}} = 15.3 \text{ BTU/(Hr}\times\text{Ft}^2\times{}^\circ\text{F)}$$

$$h = 15.3 \times 117 = 1790 \text{ BTU/(Hr} \times \text{Ft}^3 \times {}^\circ\text{F)}$$

$$X = \frac{h\ x}{c_p\ G} = \frac{1790 \times 13.9}{.24 \times 332} = 312$$

$$T' = \frac{t_o - t'}{t_o - t_o'} = \frac{400 - 350}{400 - 121} = .179$$

$$\Theta = \frac{h\ \theta}{c\ \rho} = \frac{1790\ \theta}{.25 \times 50} = 143\ \theta$$

$$\Theta = 332 \text{ from Ledoux's graphs}$$

$$\theta = \frac{332}{143} = 2.32 \text{ Hours for bed alone}$$

$$\theta_{CORR.} = 2.32 \times \frac{904,100}{778,000} = 2,69 \text{ Hours for total adsorber.}$$

## REACTIVATION SUMMARY

| | HEAT DUTY BTU | DURATION HOURS |
|---|---|---|
| First period........ | 181,600 | 0.39 |
| Second period....... | 580,000 | 1.33 |
| Third period........ | 904,100 | 2.69 |
| | 1,665,700 | 4.41 |

## COOLING

The bed and shell are to be cooled from 350°F to 85°F using a stream of air at 80°F. The rate of flow is to be the same as for the reactivation.

**HEAT DUTY:**

| | | | |
|---|---|---|---|
| 1) Alumina | 13,600 | $(.25)(350 - 85) =$ | 900,000 BTU |
| 2) Steel | 3,600 | $(.113)(350 - 85) =$ | 108,000 |
| 3) Insulation | 486 | $(.24)(350 - 85)/2 =$ | 15,400 |
| | | | 1,023,400 BTU |

**DURATION:** Method of Ledoux

$$X = \frac{h\ x}{c_p\ G} = \frac{1790 \times 13.9}{.24 \times 332} = 312$$

$$T' = \frac{t' - t_o}{t_o' - t_o} = \frac{85 - 80}{350 - 80} = .0185$$

$$\Theta = \frac{h\ \theta}{c\ \rho} = \frac{1790\ \theta}{.25 \times 50} = 143\ \theta$$

$\Theta$ = 319 from Ledoux's graph.

$\theta = \frac{319}{143} = 2.23$ Hours for bed alone.

$\theta_{CORR.} = 2.23 \times \frac{1,023,400}{900,000} = 2.54$ Hours for complete adsorber.

### SUMMARY - REACTIVATION PLUS COOLING

| | DURATION HOURS |
|---|---|
| Reactivation | 4.41 |
| Cooling | 2.54 |
| Total | 6.95 |
| Safety margin | 1.05 |
| Cycle | 8.00 |

## PRESSURE DROP

Allen's method given in reference No. 2

**ADSORBING CYCLE:**

Basis: Air temperature 80°F

$$\rho = \frac{29 \times 492}{359 \times 540} = .0736 \text{ Lbs/Ft}^3$$

$$\mu = .018 \times 2.42 = .0435 \text{ Lb/(Hr. x Ft)}$$

$$G = \frac{4600}{19.62} = 234 \text{ Lbs/(Hr x Ft}^2)$$

$D$ = .013 Ft (Effective spherical particle diameter given by Allen for 2-4 mesh)

$$\frac{D\,G}{\mu} = \frac{.013 \times 234}{.0435} = 70$$

$f$ = 14 on Allen chart (Figure 1 on page 5.)

$$\Delta P = \frac{2\,f\,L\,G^2}{D\,g\,\rho\,144} = \frac{2 \times 14 \times 13.9\ (234)^2}{.013 \times 4.17 \times 10^8 \times .0736 \times 144}$$

$$= 0.36 \text{ Lb/In}^2$$

**REACTIVATING CYCLE:**

Basis: Air temperature 400°F

$$\rho = \frac{29 \times 492}{359 \times 860} = .0462 \text{ Lb/Ft}^3$$

$$\mu = .025 \times 2.42 = .0605 \text{ Lb/(Hr x Ft)}$$

$$G = \frac{6500}{19.62} = 332 \text{ Lbs/(Hr x Ft}^2)$$

$$D = .013 \text{ Ft}$$

$$\frac{D\,G}{\mu} = \frac{.013 \times 332}{.0462} = 71.3$$

$$f = 14$$

$$\Delta P = \frac{2 \times 14 \times 13.9 \times (332)^2}{.013 \times 4.17 \times 10^8 \times .0462 \times 144}$$

$$= 1.19 \text{ Lbs/In}^2$$

## MAXIMUM MASS VELOCITY

Basis: Reactivation period

Method of Ledoux.

$$G_{max} = 2{,}640 \sqrt{d_g\, d_a\, D}$$
$$= 2{,}640 \sqrt{(.0462)(50)(.022)}$$
$$= 594 \text{ Lbs/(Hr x Ft}^2\text{)}$$

The actual mass velocity is 332 Lbs/(Hr x Ft$^2$) or 56% of the maximum allowable.

---

## -PROBLEM NO. 2-

It is desired to dry 1000 SCFM of air, measured dry at 60°F and 1 atm. The air is at a pressure of 1000 PSIA and 80°F and is saturated with water. The dried air must have a dew point below -60°F measured at atmospheric pressure. Using 2-4 mesh silica gel and an 8 hour adsorption period, design an adsorber. At the high pressure isothermal conditions can be assumed during adsorption. For reactivation hot air at 1 atm. and 400°F is available. Find the adsorbent charge, the vessel dimensions, the reactivation air flow, the pressure drop during adsorption and reactivation, and the reactivation heat load.

## PRELIMINARY CALCULATIONS

### DRY AIR FLOW:

By weight $\frac{1000 \times 492 \times 29 \times 60}{520 \times 359} = 4{,}600$ Lbs/Hr.

By volume $\frac{1000 \times 540 \times 14.7}{60 \times 520 \times 1000} = 0.255$ CFS

### WATER TO BE ADSORBED:

Inlet moisture............ .000316 Lbs $H_2O$/Lb dry air.

Maximum exit moisture .... .0000213 Lbs $H_2O$/Lb dry air.
(At end of adsorbing cycle)

Water to be adsorbed 4,600 x .000316 = 1.45 Lbs/Hr.

## SOLUTION

Adsorbent: Silica gel, 2 to 4 mesh.

Conditions: Isothermal.

Adsorbing cycle: 8 Hours.

Reactivating and cooling cycle: 8 Hours.

At high pressure conditions are very nearly isothermal during adsorption without the use of cooling coils.

## MAXIMUM MASS VELOCITY

Basis: Adsorption period

Method of Ledoux

$$G_{max} = 2{,}640 \sqrt{d_g\, d_a\, D}$$

$$d_g = \frac{29 \times 1000 \times 492}{359 \times 14.7 \times 540} = 5.00 \text{ Lbs/Ft}^3$$

$$G_{max} = 2{,}640 \sqrt{(5.00)(39)(.022)}$$

$$= 5{,}460 \text{ Lbs/(Hr x Ft}^2)$$

## ADSORBENT CHARGE

Method of Hougen and Watson, reference No. 13.

Try a column of 18" inside diameter.

Inside cross-sectional area 1.76 $Ft^2$

$G = \frac{4600}{1.76} = 2615$ Lbs/(Hr x $Ft^2$) or 48% of maximum allowable

$D_p = .022$ Ft (Particle diameter)

$\mu = .018 \times 2.42 \times 1.1 = .0479$ Lb/(Hr x Ft)

(The 1.1 is a pressure correction factor)

$\frac{D_p G}{\mu} = \frac{.022 \times 2615}{.0479} = 1,200$

$\left(\frac{D_p G}{\mu}\right)^{-.51} = (1200)^{-.51} = .0269$

For silica gel:

$a = .703\ a_v \left(\frac{D_p G}{\mu}\right)^{-.51}$

$= .703 \times 117 \times .0269 = 2.21$ Transfer units per foot

$b = \frac{.789\ G\ p_s\ a_v}{\pi \rho_s} \left(\frac{D_p G}{\mu}\right)^{-.51}$

$\pi = 1000/14.7 = 68$ atm.

$b = \frac{.789 \times 2615 \times .0345 \times 117 \times .0269}{68 \times 39}$

$= .0845$ per Hour

At the break point:

$y/y_o = .0000213/.000316 = .0675$

Bed depth, Z:

Try $Z = 2.0$ Ft.

$aZ = 2.21 \times 2.0 = 4.42$

Referring to fig 216a, page 1087 of Hougen & Watson:

$b\tau = .68$

$\tau = .68/.0845 = 8.05$ Hours

A bed two feet thick will thus reach the break through point in 8,05 hours. A depth of three feet will be used to give a safety margin of about 50%.

Volume of the adsorbent: 3 x 1.76 = 5.28 $Ft^3$

Weight of the adsorbent: 5.28 x 39 = 206 Lbs.

## ADSORBER

An adsorber 18" ID x 6'-0" long shall be used.

Wall thickness per ASME code:

$$t = \frac{1000 \times 9}{10,000 - 600} = .948"$$

Use 1" wall thickness.

WEIGHT OF STEEL

$$\text{Cylinder} \quad \frac{19 \times \pi \times 6}{12} = 29.8 \text{ Ft}^2$$

$$\text{Ends} \quad 2 \times \left(\frac{20}{12}\right)^2 \frac{\pi}{4} = \frac{4.4}{34.2}$$

Weight of steel = 34.2 x 40 = 1370 Lbs.

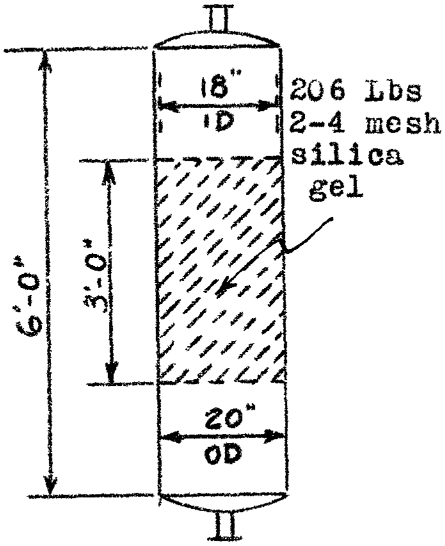


Fig. 10. Adsorber for problem No.2

WEIGHT OF INSULATION

Baldwin-Hill Rockwool felt.

Density: 8 $Lbs/Ft^3$

Thermal conductivity: .025 BTU/(Hr x Ft x $^oF$)

Specific heat: .24 BTU/(Lb x $^oF$)

Thickness: 2"

$$\text{Cylinder:} \quad 6 \times \frac{\pi}{4}\left[(2)^2 - (1.667)^2\right] = 5.80 \text{ Ft}^3$$

$$\text{Ends:} \quad 2 \times \frac{2}{12} \times \frac{\pi}{4}(2)^2 = \frac{1.05}{6.85}$$

Weight: 6.85 x 8 = 55 Lbs.

## REACTIVATION

### BASIS:

Reactivating fluid: Air at atmospheric pressure and 400$^{\circ}$F.

Rate of flow: 400 Lbs air/Hr.

This rate of flow is obtained by trial and error so that the reactivation and cooling can be finished within 8 hours.

### PLATEAU:

The plateau will occur at 121$^{\circ}$F as in problem No. 1.

### HEAT DUTIES:

**First period:** Heat adsorber from 80$^{\circ}$F to 121$^{\circ}$F

| | | | | |
|---|---|---|---|---|
| 1 ) | Silica gel | 206 (.22)(121 - 80) | = | 1,860 BTU |
| 1a) | Adsorbed water | 11.6(1) (121 - 80) | = | 476 |
| 2 ) | Steel | 1370(.113)(121 - 80) | = | 6,350 |
| 3 ) | Insulation | 55 (.24)(121 - 80)/2 | = | 271 |
| 4) | Losses | Negligible | | |
| | | | | 8,957 BTU |

**Second period:** Evaporation of the adsorbed water at 121$^{\circ}$F.

Duty = 11.6 x 1024 = 11,900 BTU

**Third period:** Heating the adsorber from 121$^{\circ}$F to 400$^{\circ}$F.

| | | | | |
|---|---|---|---|---|
| 1) | Silica gel | 206 (.22)(350 - 121) | = | 10,400 BTU |
| 2) | Steel | 1370(.113)(350 - 121) | = | 35,400 |
| 3) | Insulation | 55 (.24)(350 - 121)/2 | = | 1,510 |
| 4) | Losses | 874 x 4 | = | 3,500 |
| | | | | 50,810 BTU |

Losses: Ambiant temperature $80^{o}F$

Mean temperature of steel shell $\frac{350 + 121}{2} = 236^{o}F$

$$q_c = \frac{.025 \times 2 \times \pi \times 6 \ (236 - 80)}{2.3 \log \frac{1.000}{0.833} + \frac{.025}{1.5 \times 1.00}} = 740 \text{ BTU/Hr}$$

$$q_b = \frac{.025 \times \frac{\pi}{4} \ (2)^2 \times 2 \ (236-80)}{\frac{2}{12} + \frac{.025}{1.5}} = \underline{134}$$

$$874 \text{ BTU/Hr}$$

Estimating 4 hours for the third period:

Losses $= 4 \times 874 = 3{,}500$ BTU

## DURATION OF FIRST PERIOD

Method of logarithmic mean transfer rate.

Transfer rate at start:

$$q_o = A \ c_p \ (t_o - t_o') = 400 \times .24 \ (400 - 80) = 30{,}700 \text{ BTU/Hr}$$

Transfer rate at end:

$$q_f = A \ c_p \ (t_o - t') = 400 \times .24 \ (400 - 121) = 26{,}800 \text{ BTU/Hr}$$

Mean transfer rate:

$$q_{lm} = \frac{30{,}700 - 26{,}800}{2.3 \log \frac{30{,}700}{26{,}800}} = 28{,}700 \text{ BTU/Hr}$$

Duration:

$$\theta = \frac{8{,}957}{28{,}700} = 0.312 \text{ Hour}$$

## DURATION OF SECOND PERIOD

Transfer rate:

$$q = 400 \times .24 \ (400 - 121) = 26{,}800 \text{ BTU/Hr}$$

Duration:

$$\theta = \frac{11{,}900}{26{,}800} = 0.444 \text{ Hour}$$

## DURATION OF THIRD PERIOD

### 1. Method of Ledoux

$G = 400/1.76 = 228$ Lbs/(Hr x Ft$^2$)

Viscosity of air between 80°F and 400°F $\frac{.018 + .025}{2} = .0215$ cp.

$\mu = .0215 \times 2.42 = .052$ Lb/(Hr x Ft)

$D = .022$ Ft for 2-4 mesh adsorbent (Ref. 13 p. 1085)

$$Re = \underline{D\ G} = \frac{.022 \times 228}{.052} = 96.4$$

$$j_h = \frac{1.95}{(Re)^{.51}} = \frac{1.95}{(96.4)^{.51}} = 0.189$$

$$Pr = \frac{c_p \mu}{k} = 0.74 \text{ for air}$$

$$h_G = \frac{j_h\ G\ c_p}{(Pr)^{2/3}} = \frac{0.189 \times 228 \times .24}{(.74)^{2/3}} = 12.6 \text{ BTU/HrxFt}^2\text{x}^\circ\text{F)}$$

$$h = 12.6 \times 117 = 1470 \text{ BTU/(Hr x Ft}^3 \text{ x }^\circ\text{F)}$$

$$X = \frac{h\ x}{c_p\ G} = \frac{1470\ (3)}{.24\ (228)} = 80.6$$

$$T' = \frac{t_o - t'}{t_o - t'_o} = \frac{400 - 350}{400 - 121} = .179$$

$$\Theta = \frac{h\,\theta}{c\,\rho} = \frac{1470\ \theta}{.22 \times 39} = 171\,\theta$$

$\Theta$ = 93 on Ledoux's graph

$\theta = 93/171 = 0.544$ Hour for bed alone.

$\theta_{CORR.} = 0.544 \times \frac{50,810}{10,400} = 2.66$ Hours for complete adsorber.

### REACTIVATION SUMMARY

| | HEAT DUTY BTU | DURATION HOURS |
|---|---|---|
| First period | 8,960 | 0.312 |
| Second period | 11,900 | 0.444 |
| Third period | 50,810 | 2.66 |
| | 71,670 | 3.42 |

## COOLING

**HEAT TO BE REMOVED:**

The adsorbent and shell will be cooled from 350°F to 85°F with air at 80°F. The flow rate is to be the same as used during reactivation, namely 400 Lbs/Hr.

| | | | |
|---|---|---|---|
| 1) Silica gel | 206 (.22)(350 - 85) | = | 12,000 BTU |
| 2) Steel | 1370(.113)(350 - 85) | = | 41,000 |
| 3) Insulation | 55 (.24)(350 - 85)/2 | = | 1,750 |
| | | | 54,750 |

**DURATION:** Method of Ledoux.

$$X = \frac{h\,x}{c_p\,G} = \frac{1470\ (3)}{.24\ (228)} = 80.6$$

$$T' = \frac{t' - t_o}{t'_o - t_o} = \frac{85 - 80}{350 - 80} = .0185$$

$$\Theta = \frac{h\,\theta}{c\,\rho} = \frac{1470\ \theta}{.22 \times 39} = 171\ \theta$$

$\Theta$ = 115 according to Ledoux's chart.

$\theta$ = 115/171 = .673 Hour for bed alone.

$$\theta_{CORR.} = .673 \times \frac{54,750}{12,000} = 3.06$$ Hours for complete adsorber.

### SUMMARY OF REACTIVATION PLUS COOLING

| | DURATION IN HOURS |
|---|---|
| Reactivation | 3.42 |
| Cooling | 3.06 |
| | 6.48 |
| Safety margin | 1.52 |
| Cycle | 8.00 |

# PRESSURE DROPS

## ADSORBING CYCLE:

Basis: Air at 80°F and 1000 PSIA

$\rho$ = 5.00 Lbs/Ft$^3$

$\mu$ = .0479 Lb/(Hr x Ft)

G = 2615 Lbs/(Hr x Ft$^2$)

D = .013 Ft (Effective spherical particle diameter for 2-4 mesh material)

$$\frac{D\ G}{\mu} = \frac{.013 \times 2615}{.0479} = 709$$

f = 6.6 according to fig. 1

$$\Delta P = \frac{2\ f\ L\ G^2}{D\ g\ \ 144} = \frac{2 \times 6.6 \times 3\ (2615)^2}{.013 \times 4.17 \times 10^8 \times 5.00 \times 144}$$

$$= .069 \text{ PSI}$$

## REACTIVATING CYCLE:

Basis: Air at 400°F and 1 atmosphere.

$$\rho = \frac{29 \times 492}{359 \times 860} = .0462 \text{ Lbs/Ft}^3$$

$\mu$ = .025 x 2.42 = .0605 Lb/(Hr x Ft)

G = 400/1.76 = 228 Lbs/(Hr x Ft$^2$)

D = .013 Ft

$$\frac{D\ G}{\mu} = \frac{.013 \times 228}{.0605} = 49.0$$

f = 17

$$\Delta P = \frac{2 \times 17 \times 3\ (228)^2}{.013 \times 4.17 \times 10^8 \times .0462 \times 144}$$

$$= 0.15 \text{ PSI}$$

## MAXIMUM FLOW RATE

Basis: Reactivation period

Method of Ledoux

$$G_{max} = 2{,}640 \sqrt{d_g\ d_a\ D}$$

$$= 2{,}640 \sqrt{(.0462)(39)(.022)}$$

$$= 525 \text{ Lbs}/(\text{Hr} \times \text{Ft}^2)$$

The actual mass velocity is 228 Lbs/(Hr x $Ft^2$) or 43% of the maximum allowable.

---

## - PROBLEM NO. 3 -

Adiabatic drying.

Comparison of silica gel with alumina.

Comparison of Blanchard's method with Hubard's.

It is desired to dry 546 CFH of air at atmospheric pressure, at 75°F and 95.9% relative humidity. There must be no trace of moisture in the exit air. For an adiabatic drier using:

a) alumina

b) silica gel

calculate the adsorbent charge required for a 7.1 hour adsorption period. For silica gel use the methods of:

a) Blanchard (9)

b) Hubard (10)

**CONDITIONS:**

Air flow: 546 CFH

Pressure: Atmospheric

Temperature: 75°F (23.9°C)

Humidity of entering air:

9 Grains per cubic foot

.0178 Lbs $H_2O$ per Lb of air

95.9% relative humidity

21.15 mm $H_2O$ vapor pressure

73.8°F (23.2°C) Dew point

Running time to break point: 7.1 Hours

Water adsorbed: 7.1 x 546 x 9 / 7000 = 4.98 Lbs.

**SOLUTIONS**

**a) Alumina.** Using Derr's data (19).

Adsorbent charge: 105 Lbs.

Bed dimensions: 12" Dia. x 32"

Bed volume : 2.09 Cu.Ft.

Average adsorbed water content of bed at break point:

4.98 x 100 / 105 = 4.75%

Maximum bed temperatures:

245°F at 12" after 2.5 Hours operation

213°F at 30" after 7.1 Hours operation

Superficial air velocity : .152 ÷ .785 = .193 FPS

**b) Silica gel. Method of Blanchard.** (Using graphs pages 83-84)

Water adsorbed by bed at break point: 6.8%

Adsorbent charge: 4.98 / .068 = 73 Lbs.

Bed volume: 73 / 44 = 1.66 Cu.Ft.

Bed dimensions: 13.5" Dia. x 20"

Superficial velocity: .152 / 1.0 = .152 FPS or 4.6 Cm/Sec

Correction to adsorbed water: 6.8 x 1.07 = 7.3%

Corrected figures:

Adsorbent charge: 4.98 / .073 = 68 Lbs.

Bed volume: 68 / 44 = 1.55 Cu.Ft.

Bed dimensions: 13" Dia. x 20"

Superficial velocity: .152 / .92 = .165 FPS or 5.0 Cm/Sec

Maximum bed temperature: 169°F (76°C)

**c) Silica gel. Method of Hubard.** (Described on pages 21-22)

Bed entrance: Gel is in equilibrium with incoming air at 75°F and 95.9% relative humidity (73.8°F dew point or .83" Hg). Hubard's graph indicates an adsorbed water content above 35%. (The point is beyond the range of the graph.)

Bed outlet: Gel is dry.

Average adsorbed water content: 35/2 = 17.5%

Adsorbent charge: 4.98 / .175 = 18.5 Lbs.

Maximum bed temperature: 75 + (9x10) = 165°F

## TABLE 7

## SUMMARY

SOLUTIONS TO PROBLEM 3.

| METHOD | DERR | BLANCHARD | HUBARD |
|---|---|---|---|
| ADSORBENT | ALUMINA | SILICA | SILICA |
| WATER ADSORBED AT BREAK POINT % | 4.75 | 7.3 | 17.5 |
| **ADSORBENT** CHARGE LBS | 105 | 68 | 19 |
| BED VOLUME CU.FT. | 2.09 | 1.55 | -- |
| BED DIMENSIONS | 12"øx32" | 13"øx20" | -- |
| SUPERFICIAL VELOCITY FPS | .193 | .165 | -- |
| MAXIMUM TEMPERATURE OF BED °F | 245 | 169 | 165 |

## V.- REFERENCES

1. Hougen, O.A., and Marshall, W.R., Jr.
Chem. Eng. Progress 43, 197-208 (1947)
"Adsorption from a fluid stream flowing through
a stationary granular bed".

2. Amero, R.C., Moore, J.W., and Capell, R.G.
Chem. Eng. Progress 43, 349-370 (1947)
"Design and use of adsorptive drying units".

3. Chem. Eng. 59, 322 (Jan. 1952)
"Drying of air in fixed beds: Can calculations be made?".

4. Ledoux, E.
Ind. Eng. Chem. 40, 1970-77 (1948)
"Dynamic cooling of adsorbent beds".

5. Othmer, D.F., and Josefowitz, S.
Ind. Eng. Chem. 40, 723-5 (1948)

6. Riley, M.L.
World Oil 130, No.1, 184-6 (Jan. 1950)
"Operating and design features of adsorption type
dehydrators".

7. Nutter, I.E., and Van Vliet, C.D.
Petroleum Refiner 30, No. 5, 98-102 (May 1951)
"Panoma plant achieves low maintenance-operation costs".

8. Rathmell, B.L., and Bateman, P.J.
J. Inst. Heating & Ventilating Engrs. 19, 471-522 (Feb.'52)
"Air drying by solid granular adsorbents".

9. Blanchard, L.
Proceedings 11th Cong. Pure & Applied Chem. London
Vol. 5, pp 993-1001 (1947)
"Application du gel de silice à la dessiccation
industrielle des gaz".

10. Hubard, S.S.
Ind. Eng. Chem. 46, 356-8 (Feb. 1954)
"Equilibrium data for silica gel and water vapor".

11. Eagleton, L.C., and Bliss, H.
Chem. Eng. Progress 49, 543-8 (Oct. 1953)
"Drying of air in fixed beds".

12. Brown, G.G. and associates.
"Unit operations". (1950)
John Wiley & Sons, Inc. New York.

13. Hougen, O.A., and Watson, K.M.
"Chemical process principles. Part three.
Kinetics and catalysis". (1943)
John Wiley & Sons, Inc. New York.

14. Mantell, C.L.
"Adsorption". Second edition. (1951)
McGraw-Hill Book Co., New York.

15. Ledoux, E.
"Adsorption des gaz et des vapeurs.
Applications industrielles".
Librairie Polytechnique Ch. Béranger, Paris (1948)

16. "Activated alumina".
Aluminum Co. of America, Pittsburgh. (1949)

17. Leva, M., Weintraub, M., Grummer, M., and Pollchick, M.
Ind. Eng. Chem. 41, 1206-1212 (1949)
"Fluidization of an anthracite coal".

18. Ledoux, E.
Chem. Eng. 55 No. 3 pp 118-119 (March 1948)
"Avoiding destructive velocity through adsorbent beds".

19. Derr, R.B.
Ind. Eng. Chem. 30, 384-388 (April 1938)
"Drying air and commercial gases with activated alumina".

## VI - LITERATURE ABSTRACTS

### ABSTRACT FROM REFERENCE NO. 2

Amero, R.C., Moore, J.W., and Capell, R.G.
Chem. Eng. Progress 43, 349-370 (1947)
"Design and use of adsorptive drying units."

Units described use "Florite" desiccant.

| | | |
|---|---|---|
| Analysis: | $Al_2O_3$ ............ | 60 - 70% |
| | $SiO_2$ ............ | 5 - 11 |
| | $Fe_2O_3$............ | 10 - 20 |
| | $TiO_2$ ............ | 1 - 3 |
| | Ignition Loss.... | 4 - 6 |

The capacity of the desiccant as weight per cent moisture adsorbed between regenerations is determined. The amount of moisture to be adsorbed per cycle is determined. The weight of desiccant required is calculated and its volume determined. From considerations of flow rate and allowable pressure drop, the tower diameter is established. The calculated design is then compared with units in table No. 6 to see if it is reasonable.

Table No. 6 is a list of 11 Florite drying units built for drying gaseous and liquid hydrocarbons. It gives location, quantity of gas or liquid, pressure, height and diameter of towers, number of towers, and total weight of Florite in the units.

Suggested design bases are the following:

1. Desiccant capacity: 5% moisture
2. Length of drying cycle: 8 or 12 or 24 hours
3. Dimensions of tower
   Ratio of height to diameter: 2 to 5 for complete drying
   1 or less for air conditioning
   (to minimize pressure drop)
4. Pressure drop: Use Allen chart for f vs Re.
5. Regeneration: Table No. 8 discusses factors involved.

## ABSTRACT FROM REFERENCE NO. 3

Chem. Eng. 59, 322 (Jan. 1952)
"Drying of air in a fixed bed: Can calculations be made?".

A method of calculating the moisture content of effluent gas from adsorbers is presented. It was checked against experimental runs conducted at Yale by Eagleton and Bliss. The adsorption is considered taking place in a zone of constant width which moves up the bed in the direction of gas flow. Two resistances are used: one through the gas film and the other through the solid film. Mass transfer through the solid film is given by:

$$dq/dt = k_s S \, (q_i - q)$$

Typical calculation:

A dryer is fed with air at 95°F having a 30°F dew point. The dew point of the outlet air is to be minus 25°F or less. Determine when this maximum dew point will be reached. The dryer is 12" in diameter and filled with 8 to 14 mesh alumina to a depth of 4 feet. The air flow rate is 150 lbs/hr.

Solution:

$G = 150/\pi r^2 = 191$ lbs/(hr. x sq. ft.)

Experimental data:

For alumina and Florite $k_g S = 9.3\, G^{.55}$

For silica gel $k_g S = 6.3\, G^{.55}$

For $k_s S$ an average value of 7.3 can be used

$a = .0480$ lbs. $H_2O$/lb solid @ $C_0 = .00345$ lbs. $H_2O$/lb air & pp = 4.20 mm Hg

$\alpha = .022$ lbs. $H_2O$/lb solid

$$k_gS = 9.3\ (191)^{.55} = 167.5$$

$$r = -k_gS/k_sS = -167.5/7.3 = -23.0$$

$$\frac{c_d}{c_o} = \frac{\alpha}{a} - rc_o$$

$c_o$ = .00345 corresponding to 30°F (-1.11°C) inlet air dewpoint

$$\frac{c_d}{c_o} = \frac{.022}{.048}\quad (23.0)(.00345) = .456$$

Inlet air vapor pressure is 4.20 mm Hg.

Outlet air vapor pressure is 0.328 mm Hg.

$$c/c_o = .328/4.20 = .078$$

This is less than $c_d/c_o$, therefore the following equation is used:

$$\ln \frac{c_d/c_o}{c/c_o} = -\ \frac{c_ok_gSy}{aV} + \frac{k_gSx}{V} + 2 - \frac{C_o}{C_D}$$

The bed weight is $4\pi(1)^2(51.2)/4 = 161$ lbs.

$$\ln \frac{.456}{.078} = \frac{-(.00345)(167.5)\ y}{(.048)(150)} + \frac{(167.5)(161)}{150}\quad 2\quad -1/.456$$

$$1.768 = -.0802\ y + 179.8 + 2\quad -2.19$$

$$y = 2220 \text{ lbs. of air}$$

$$t = 2220/150 = 14.8 \text{ hours.}$$

Note: See reference No. 11 for symbols and their units.

Mathematical errors which appeared in the original article have been corrected in this abstract.

## ABSTRACT FROM REFERENCE NO. 4.

Edward Ledoux
Ind. Eng. Chem. 40,1970-1977 (1948)
"Dynamic cooling of adsorbent beds".

A graphical method is presented for the determination of the cooling curve of a bed.

$\frac{dt}{dx}$ = Rate of heating of the gas per unit distance

$\frac{-dt'}{d\theta}$ = Rate of cooling of the bed per unit time

$c_p G \frac{dt}{dx}$ = Heat picked up by the gas, BTU/(cu.ft.x hr.)

$-cd.\frac{dt'}{d\theta}$ = Heat lost by adsorbent bed

$h(t'-t)$ = Heat transferred from bed to gas stream

The last three expressions being equal:

$$c_p G.\ \frac{dt}{dx} = h(t'-t) = -cd.\frac{dt'}{d\theta} \quad \text{............}(1)$$

Although h, $c_p$, c, are functions of temperature, the ratios $h/c_p$ and h/c are nearly constant with temperature.

$$\text{Let } X = \frac{hx}{c_p\ G} \qquad \Theta = \frac{h\theta}{cd}$$

$$T = \frac{t-t_o}{t'-t_o} \qquad T' = \frac{t'-t_o}{t'_o-t_o}$$

Then substitution in (1) gives:

$$\frac{dT}{dX} = (T'-T) = \frac{-dT'}{d\Theta} \quad \text{..............}(2)$$

All variables in equation(2) are dimensionless. The solution to equation (2) is given in three graphs similar to the one shown at the right and covering the range shown.

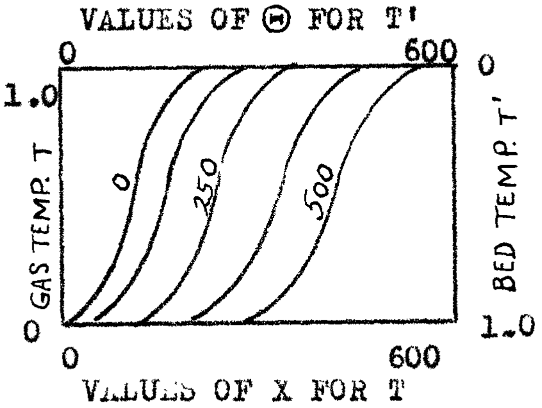


Fig.11. Range of Ledoux graphs.

The following example illustrates the method. A bed of adsorbent 2.92 feet deep is initially at 400°F and is to be cooled with air at 75°F. The air rate of flow will be 4.5 lbs/(minxsq.ft.) The coefficient of heat transfer is given by the expression:

$$h = 10\ G^{0.7} \quad \text{BTU/(min. x }^{o}\text{F x Ft}^{3}\text{ of bed)}$$

The specific heat of the bed is .22 and that of the air is .24. How long will it take to cool the bed down to 75°F?

Solution:

$$h = 10\ G^{0.7} = 10\ (4.5)^{0.7} = 29.6$$

$$X = \frac{hx}{c_p G} = \frac{(29.6)(2.92)}{(.24)(4.5)} = 80$$

$$\Theta = \frac{he}{cd} = \frac{(29.6)\ e}{(.22)(55)} = 2.45\ e$$

Use the author's fig. 3 which covers this range. Read the T' and scales. The curves are then constant for X. For X = 80, T' is practically zero at $\Theta$ = 115. Therefore, the time required to cool the bed to 75°F will be:

$$e = \Theta/2.45 = 115/2.45 = 47 \text{ minutes.}$$

## SYMBOLS

$G$ = Mass velocity of the gas.

$c$ = Specific heat of the solid.

$c_p$ = Specific heat of the gas.

$d$ = Apparent density of the bed.

$h$ = Coefficient of heat transfer for the bed per unit volume.

$t$ = Temperature of the gas.

$t'$ = Temperature of the bed.

$t_o$ = Temperature of the gas at inlet to bed.

$t_o'$ = Temperature of the solid at the start at the gas inlet.

$\theta$ = Time.

## ABSTRACT FROM REFERENCE NO. 5.

Othmer, D.F., and Josefowitz, S.
Ind. Eng. Chem. 40, 723-725 (1948)
"Correlating adsorption data".

It has been noted by Berényi that $dF/dc$ does not vary much with temperature at some distance below the critical point. $F$ is the free energy and $c$ the concentration of adsorbate adsorbed on the solid. The free energy change in isothermal adsorption is expressed by:

$$\Delta F = RT \ln (P/P_0) \quad \text{or} \quad \ln (P_0/P) = -\Delta F/RT$$

where $P$ = equilibrium pressure.

$P_0$ = vapor pressure.

This expression is accurate if the gas phase obeys the ideal gas laws, and the adsorbed phase is incompressible. It can be used to calculate the adsorption isotherm at any temperature if the isotherm at one temperature is known. For example at 80°C the vapor pressure of pure benzene is 759 mm, and the equilibrium pressure of .15 gram of benzene adsorbed on 1 gram of carbon is 4.15 mm. What is the equilibrium pressure for the same adsorbate concentration at 120°C when the vapor pressure is 2233 mm?

Solution:

$$\text{At } 80^\circ\text{C or } 353^\circ\text{K} \quad 2.3 \log \left(\frac{759}{4.15}\right) = \frac{-\Delta F}{(1.987)(353)}$$

$$-\Delta F = 3660$$

$$\text{At } 120^\circ\text{C or } 393^\circ\text{K} \quad 2.3 \log \left(\frac{2233}{P}\right) = \frac{3660}{(1.987)(393)}$$

$$P = 20.8 \text{ mm}$$

The experimentally determined value is 19 mm.

## ABSTRACT FROM REFERENCE NO. 6.

Max L. Riley
World Oil 130, No.1, 184-186 (Jan. 1950)
"Operating and design features of adsorption type dehydrators".

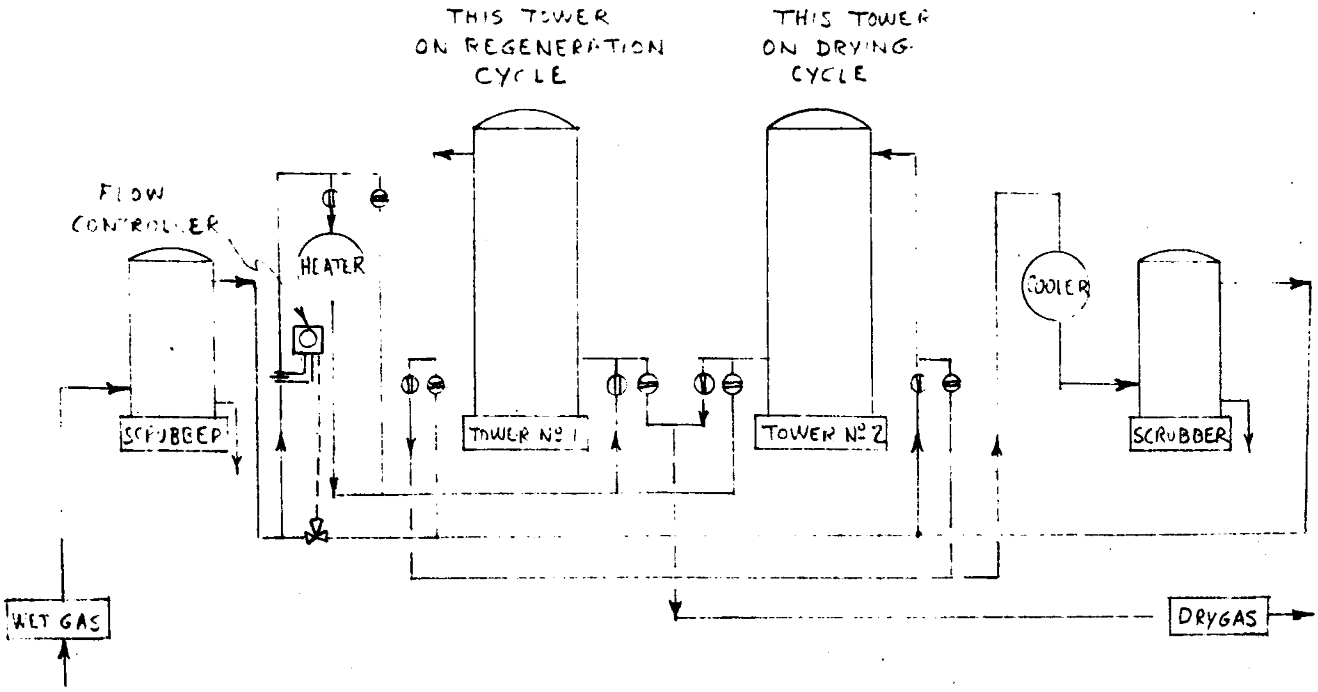
Adsorption drying is used for natural gas to prevent the formation of hydrates in pipe lines. It is also used in high pressure gasoline plants to remove moisture from condensate gas. In practice a tower is switched either on a definite time cycle or when the outlet gas shows too much moisture. Using aluminum oxide type desiccants, when the dew point reaches 5 to 10°F the tower is put on regeneration.

### Typical System:

A typical flow diagram for a natural gas drying plant is shown on the next page. During the drying cycle the gas flows downward in the tower, whereas during regeneration it flows upward. For regeneration the gas is heated to 350°F to 400°F by means of a steam heated exchanger before being introduced into the tower. The regeneration gas stream imposes an additional load on the drying tower and should be kept to a minimum. It is only a small part (10%) of the total gas flow. If cooling water is not available, the dried gas stream can be used to pick up the heat from the regeneration stream in an exchanger. Such a practice will result in the dried gas stream being heated about 20°F.

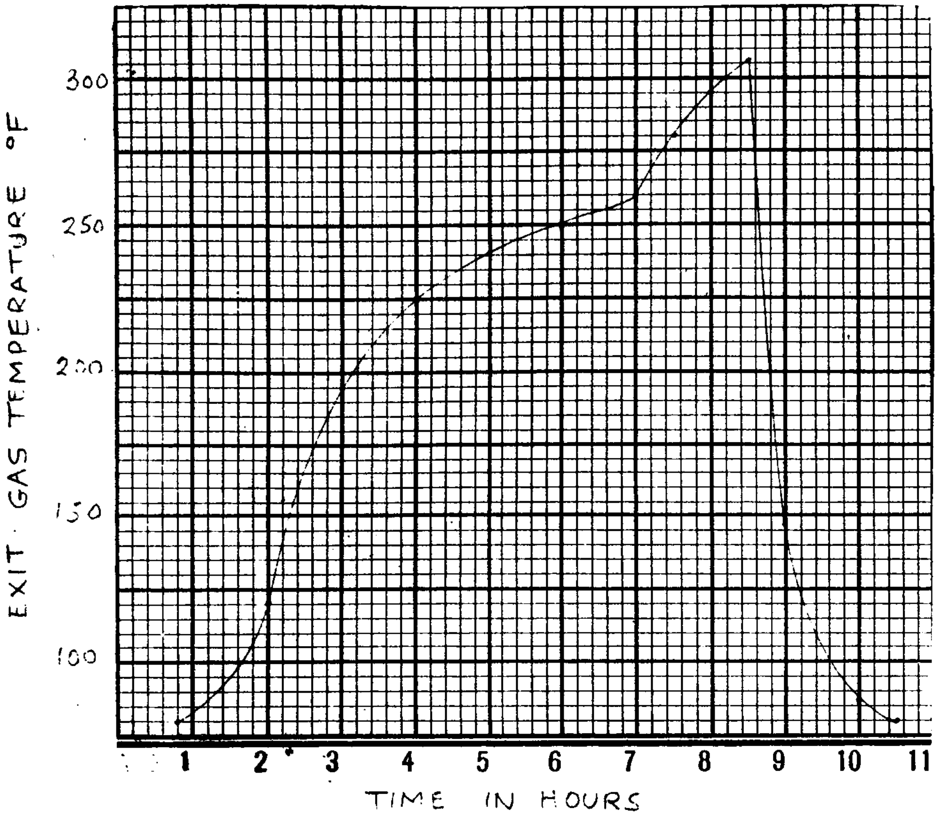
### Precooling of the regenerated tower:

Precooling of the regenerated tower is done by continuing the regeneration gas stream but by making it by-pass the heater.



TYPICAL FLOW DIAGRAM OF NATURAL GAS DRYING PLANT

**FIG. 12**



TYPICAL REGENERATION CYCLE

CONDITIONS: GAS PRESSURE 900 PSIG
ENTERING GAS TEMP 365°F
GAS SP. G. 0.60

**FIG. 13**

## Adsorption capacity of bauxite.

The adsorption capacity of bauxite varies with the temperature as shown in table 8. Optimum conditions consist of high pressure and low temperature. However around 80°F considerable hydrocarbons get adsorbed along with the water.

TABLE 8
ADSORPTION CAPACITY OF BAUXITE.

| Gas Temp. °F | Adsorption Cap. %$H_2O$ by wt. |
|---|---|
| 60 | 7.35 |
| 65 | 6.67 |
| 70 | 6.00 |
| 80 | 5.00 |
| 90 | 4.00 |
| 100 | 3.00 |
| 120 | 1.90 |
| 140 | 1.10 |

Table 9 shows the analysis of liquid taken from the separator following the regeneration cooler. This table is for the drying of a gas at 900 PSIG and 80°F containing 1000 gpm of propane plus fractions.

TABLE 9
ANALYSIS OF ADSORBED HYDROCARBONS.

| Hydrocarbon | Mol % |
|---|---|
| Methane | 10.70 |
| Ethane | 7.96 |
| Propane | 7.29 |
| I-Butane | 2.54 |
| N-Butane | 5.68 |
| I-Pentane | 4.46 |
| N-Pentane | 3.95 |
| Hexanes plus | 57.42 |

## Basic design features:

1. Pressure drop
2. Desiccant quantity
3. Accessibility to desiccant for replacement.

## Design basis:

Velocity for 4-8 mesh 25 to 40 feet per minute

Capacity of "Florite" 5%

Cycles per day affect only the height of tower.

Minimum cycle time 6 hours required for regeneration and precooling.

**Example.**

It is required to dry 20,000 MCF/Day of gas, under the following conditions:

| | |
|---|---|
| Input pressure | 1500 psi |
| Separator temperature | $80^{\circ}F$ |
| Moisture in saturated gas | 2.95 gallons / MMCF |

A. Desiccant required.

$$\frac{2.95 \times 8.33 \times 20}{.05} = 9830 \text{ lbs.}$$

At 50 lbs per cu. ft. 196.6 cu. ft.

For each tower on an 8-hour cycle:

$$.333 \times 9830 = 3275 \text{ lbs. or } 65.5 \text{ cu. ft.}$$

B. Tower size.

Allowable velocity 25 feet per minute.

Gas in at a specific gravity of .700

Flow is 20,000 Std. MCF/Day or 13,889 CFM (Std.)

Supercompressibility factor for 1500 psi and $80^{\circ}F$ is found to be .760

$$Q = \frac{13{,}889 \times 15 \times 540 \times .760}{1500 \times 520} = 109.6 \text{ CFM}$$

$$A = 109.6 / 25 = 4.38 \text{ sq. ft.}$$

Diameter = 2.36 feet

C. Height of bed.

$$2.36 \times 2.36 \times .785 \times L = 65.5$$

$$L = 15 \text{ feet}$$

$$\text{Ratio } H/D = 15/2.36 = 6.35$$

Note: Increasing the tower diameter to the next standard size would make the ratio H/D fall within the desired range.

## ABSTRACT FROM REFERENCE NO. 7

I. Earl Nutter and C.D. Van Vliet
Petroleum Refiner 30, No. 5, 98-102 (May 1951)
"Panoma plant achieves low maintenance-operation costs".

Equipment in a natural gasoline plant of the Panoma Corporation near Hooker, Oklahoma, is described. The gas dehydration plant is of the dry desiccant type and consists of two towers, one of which dries gas while the other is being regenerated. On the drying cycle, gas enters the bottom of the tower tangentially and is rid of liquid droplets. The bottom serves as a separator for entrained liquid. The gas leaves the separator compartment and passes up a large central pipe within thetower to about the middle. There it enters a distributing compartment which divides the stream into two parts: one continuing upward and the other deflected downward. Each stream passes through an adsorbent section and is rejoined with the other at the exit to be fed to the "residue header".

Regeneration is accomplished by passing 10% of the total wet gas inlet stream through steam heated exchangers and then counterflow through the two adsorbent sections of the tower. Heating is continued until the temperature of the beds reaches 350°F. Gas leaving is cooled through a water cooled exchanger after which it is allowed to flow to the residue header and mix with the dried gas. The mixture is within the dew point requirements.

A large by-pass line is arranged around the dehydration plant so that gas may be sent to the residue header directly without being dried. This is done purposely so as to lengthen the drying cycle of the adsorber. The dew point of the mixture of dried and wet gas is continually tested by an instrument which controls the amount of wet gas by-passing the drier. As the adsorbent bed becomes saturated less and less wet gas is allowed to by-pass it, until finally the by-pass line is closed. At that moment the drying tower is put on regeneration. In this manner the drying cycle is lengthened about 25% over the conventional method of operation.

## ABSTRACT FROM REFERENCE NO. 8.

Rathmell, B.L., and Bateman, P.J.
J. Inst. Heating & Ventilating Engrs. 19, 471-522 (Feb. 1952)
"Air drying by solid granular adsorbents."

Tests were made in a pilot plant on the drying of air for use in wind tunnels. Uncooled beds of silica and alumina were used. For drying ordinary atmospheric air uncooled beds are uneconomical but may be combined with a refrigerated pre-cooler. The maximum permissible humidity in wind tunnels is .0005 Lbs $H_2O$/Lb air. In the operation of a wind tunnel a portion is continually abstracted at .0005 humidity, dried to .0002 humidity, and returned to the tunnel.

### Inlet humidity and bed capacity.

In uncooled beds, the higher the inlet humidity, Lbs $H_2O$/Lb air, the lower is the bed capacity. This is due to the rise in temperature which offsets the increase in capacity obtainable because of the higher partial pressure of the water.

### Inlet humidity and temperature rise.

The base temperature of the bed is the dry bulb temperature of the incoming gas. The heat liberated and therefore the temperature rise is very nearly proportional to the inlet humidity when complete drying is accomplished.

Air pressure.

In wind tunnels where the pressures used may go up to only 4 atmospheres the effect of pressure is negligible. But for high pressures such as used for gas liquefaction the increase in gas density impedes the diffusion of $H_2O$ molecules and has to be included in the calculations.

Isothermal compression of a gas at constant humidity, Lbs $H_2O$/Lb. air, increases the partial pressure of the water vapor and consequently greater adsorption results since the temperature rise is the same.

## PILOT PLANT EQUIPMENT AND OPERATION

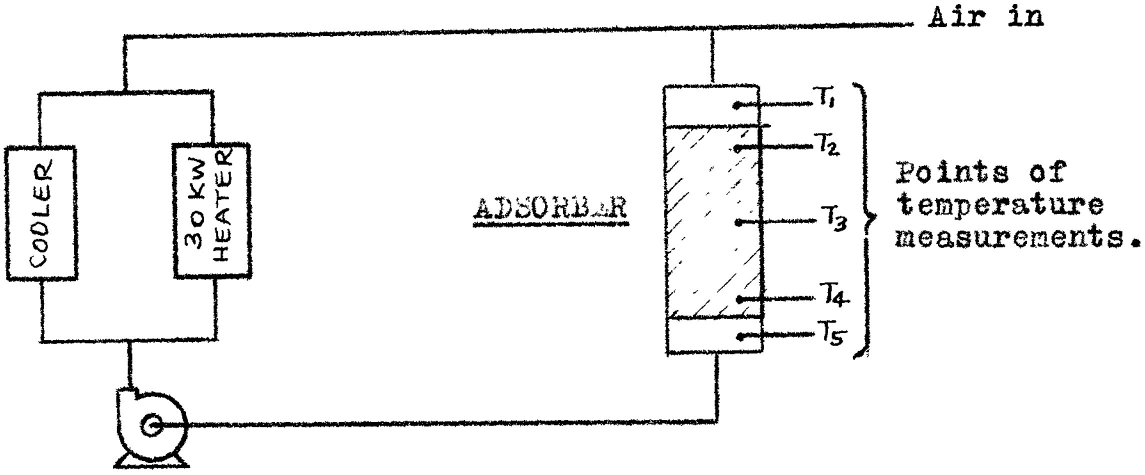


Fig.14. Arrangement of equipment for adiabatic adsorption tests by Rathmell and Bateman.

Bed: Square cross-section 2'-6" on the side.
Maximum depth of 6 feet.

Casing: Covered with 2" of insulation.

Regeneration: Circulate 300°C air through the bed until its temperature reaches 240°C.

Cooling: After regeneration the bed was cooled with air recirculated in a closed circuit through a water cooled exchanger.

Adsorption: Adiabatic.

## TABLE 10

## ADSORBENTS USED AND RANGE OF TESTS OF RATHMELL & BATEMAN

| Series of Tests | Adsorbent | Grade Mesh | Depth of Bed Inches | Wt. of re-activated Adsorbent Lbs | No. of Tests | Contact Time Seconds | Range of Inlet Humidity $\lambda_i$x100 |
|---|---|---|---|---|---|---|---|
| 1 st | Alumina | 2-4 | 25 | 534 | 56 | 2.5<br>1.7<br>1.25<br>.83<br>.42 | .35<br>to<br>1.2 |
| 2nd | Silica | 6-10 | 25 | 520 | 27 | 2.5<br>1.25<br>.83 | .58<br>to<br>1.45 |
| 3 rd | Silica | 6-10 | 12 | 254 | 23 | 1.2<br>.8<br>.4 | .8<br>to<br>1.13 |
| 4 th | Alumina | 4-8 | 25 | 585 | 13 | 1.25 | .35<br>to<br>.96 |
| 5 th | Alumina | 4-8 | 21 | 494 | 18 | 1.35 | .32<br>to<br>.72 |
| 6 th | Silica | 6-10 | 12 | 254 | 8 | 1.35 | .28<br>to<br>.61 |

### NOTES

The units of $\lambda_i$ , the inlet humidity, are Lbs $H_2O$/Lb. air

First Series: The maximum pressure drop was 18.5" water.

Second Series: The pressure drop at 0.5 second contact time was 105" water.

Third Series: The bed resistance was the same for the first series.

Fifth Series: The bed resistance was the same as for the first and third series.

Sixth Series: These tests were undertaken to extend the humidity range of the second and third series.

## RESULTS

Typical results are shown in figures 15 and 16.

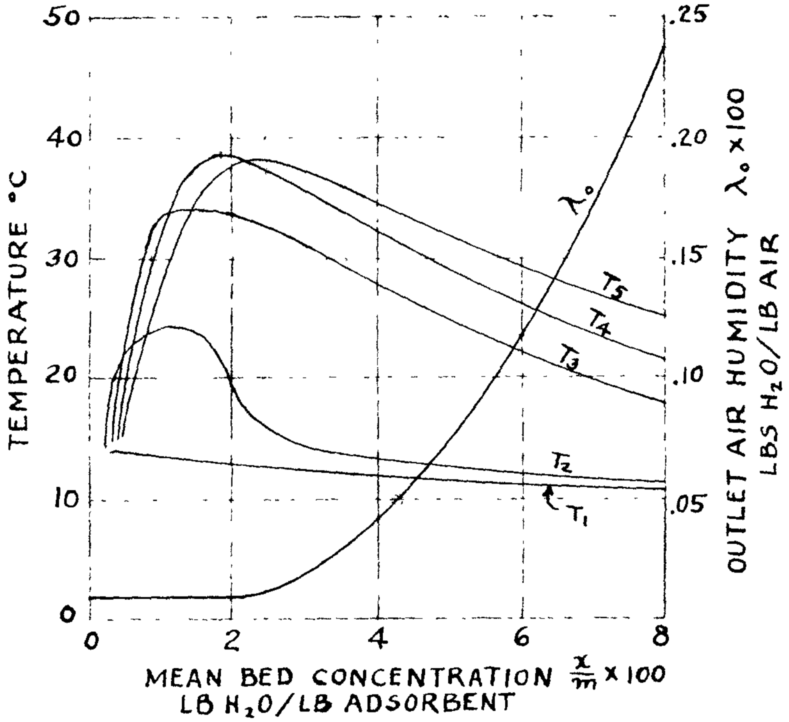


FIG. 15. BED TEMPERATURE AND OUTLET AIR HUMIDITY VARIATIONS DURING A DRYING CYCLE.

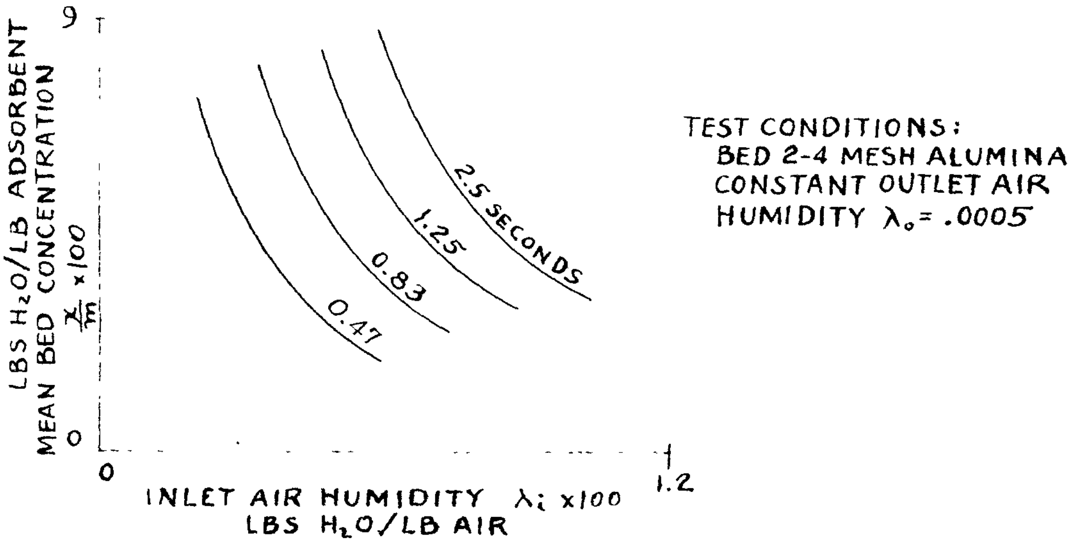


FIG. 16. RELATION BETWEEN INLET AIR HUMIDITY AND BED CONCENTRATION FOR VARIOUS CONTACT TIMES.

### Mean bed humidity.

The mean bed humidity x/m expressed as pounds of water adsorbed per pound of adsorbent is given by:

$$\frac{x}{m} = \frac{lA}{m} \cdot \frac{V}{l}\int_0^{\tau} (\lambda_i - \lambda_o)\,\rho_A \, d\tau$$

### Maximum bed temperature.

The following equations apply for the range of inlet humidity $\lambda_i$ = .003 to .015 Lbs $H_2O$/Lb. air.

For alumina $T = 3{,}500\,\lambda_i$

For silica $T = 2{,}950\,\lambda_i - 3.5$

where T = Maximum bed temperature rise above the dry bulb temperature of the incoming gas. Degrees centigrade.

### Temperature gradient perpendicular to direction of flow.

Variations of 1/2 to 1 $\frac{1}{2}$ °C only were observed.

### Break point related to peak temperature.

In very fast flows the outlet humidity reached the break point before the peak temperature of the bed was reached. In slower flows the peak bed temperature was reached much earlier in the cycle.

### Depth of bed and capacity.

Deeper beds are more efficient but cause higher pressure drops. For the same break point a deep bed will have a higher capacity expressed as pounds of water adsorbed per pound of adsorbent, than a shallow one. Furthermore, a deep bed with less contact time may have more capacity than a shallow bed with a longer contact time.

**Grain size and capacity.** The smaller grain sizes have the higher capacity.

## USE OF RESULTS IN DESIGN

The test results have been summarized in figures 17 and 18 for use in design. The curves are exact for the following conditions:

1. Drying of air at atmospheric pressure and temperature. Air density of .077 Lbs/Cu.Ft.
2. Desiccant is 2-4 mesh alumina.
3. Drying is adiabatic.
4. Depth of bed is 25" or 2.1 feet.

The authors state that the curves also apply to 2-4 mesh silica gel. For other grain sizes of alumina or silica gel a correction factor is given in figure 19. For other bed depths, the authors suggest the following relation:

$$\frac{x}{m} - \left(\frac{x}{m}\right)_{2.1} = \frac{l - 2.1}{30}$$

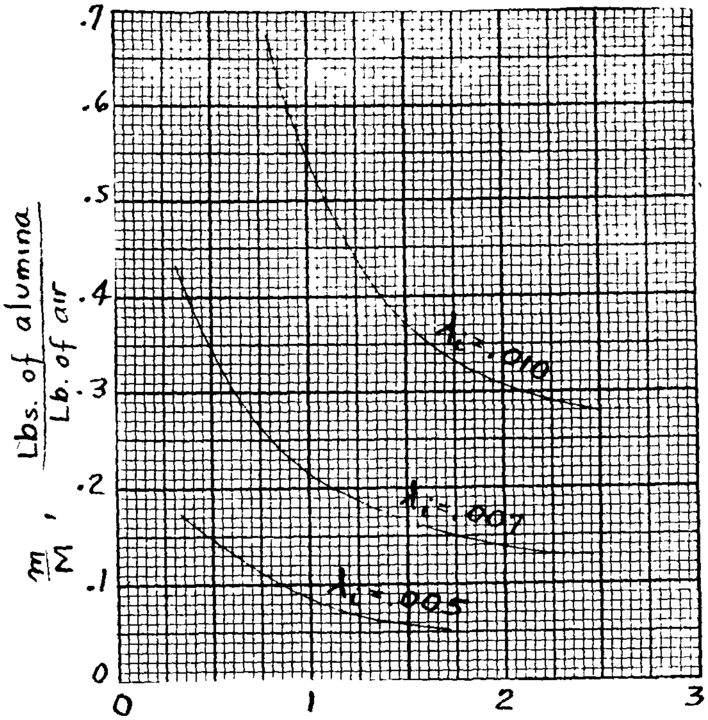
The curves of figures 17 and 18 show the amount of desiccant required per pound of air, m/M, plotted against contact time, t, for various values of inlet air humidity. The contact time is given by the following equation:

$$t = \frac{m}{\rho_g} \cdot \frac{\rho_a \tau}{M}$$

or $$\frac{m}{M} = \frac{t \rho_g}{\tau \rho_a} = t.K$$

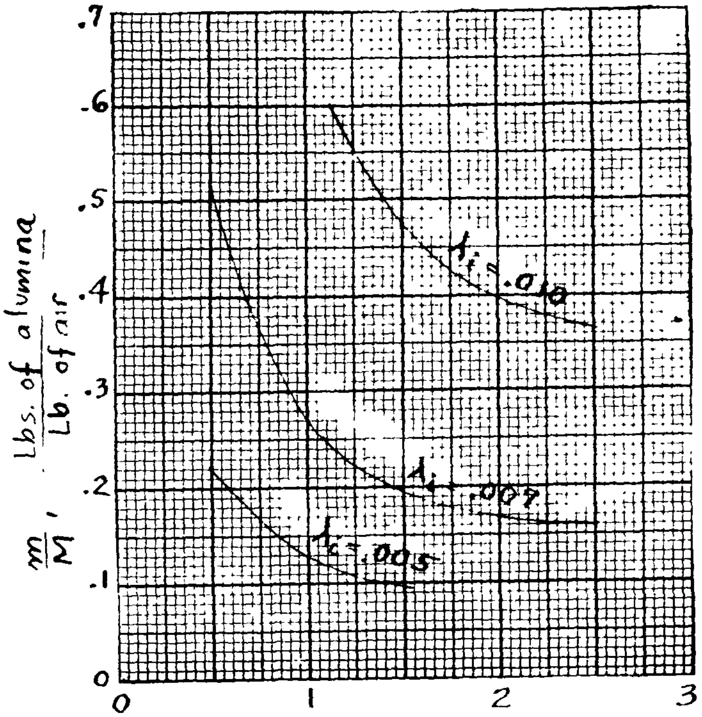
where $$K = \frac{\rho_g}{\tau \rho_a}$$

# ADIABATIC ADSORPTION CAPACITY OF 2-4 MESH ALUMINA IN BED 25" DEEP



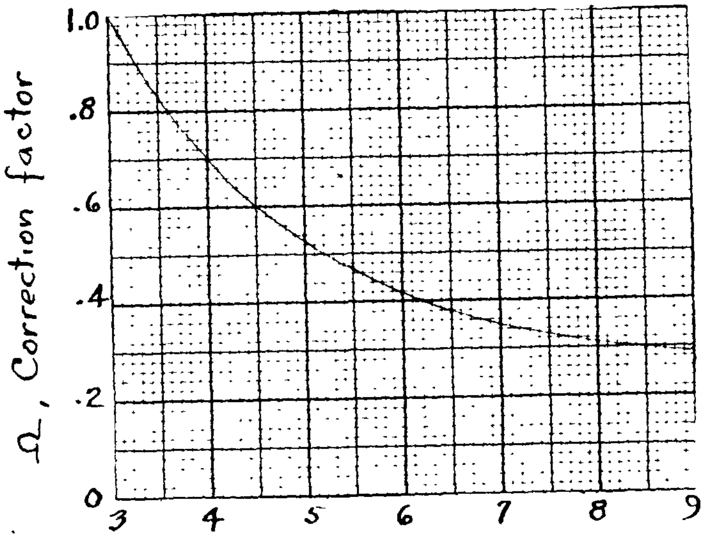
t, contact time, seconds

Fig. 17 Outlet air humidity = .0005



t, contact time, seconds

Fig. 18 Outlet air humidity = .0002



Mean mesh size of grains

Fig. 19 Correction for grain size

## EXAMPLE NO. 1

Using a 25" bed of 2-4 mesh alumina, how much alumina is required to dry 10 Lbs/Sec of air from an inlet humidity of .007 to a maximum outlet humidity of .0002 Lbs $H_2O$/Lb. of air. The air density is .077 Lbs/Cu. ft. and the bulk density of the bed is 40 Lbs/Cu.ft. Conditions are adiabatic, and the drying cycle is 2 hours.

Solution: $$K = \frac{\rho_g}{\rho_a \tau} = \frac{40}{.077 \times 2 \times 3600} = .0722$$

$$\frac{m}{M} = Kt = .0722\ t$$

This is the equation of a straight line going through the origin. This line, when drawn on figure 18, is seen to intersect the .007 humidity curve at t = 2.2 seconds.

$$\frac{m}{M} = .0722 \times 2.2 = .159$$

$$M = 10 \times 3600 \times 2 = 72,000$$

$m$ = .159 x 72,000 = 11,500 Lbs alumina required.

## EXAMPLE NO. 2

Using a 15" bed of 4 - 8 mesh alumina, how much alumina is required to dry 10 Lbs/Sec of air from an inlet humidity of .006 to a maximum outlet humidity of .0002 Lbs $H_2O$/Lb. air. The air density is .077 Lbs/Cu.ft. Conditions are adiabatic and the drying cycle is 2 hours.

Solution: $$K = \frac{\rho_g}{\rho_a z} = \frac{40}{.077 \times 2 \times 3600} = .0722$$

$$\frac{m}{M} = Kt = .0722\ t$$

This line intersects the .005 humidity line at t = 1.35 and the $\overset{.007}{\wedge}$ humidity line at t = 2.2 on figure 18.

Interpolating for .006 inlet humidity t = 1.77

$$\frac{m}{M} = .0722 \times 1.77 = .128$$

$$M = 10 \times 3600 \times 2 = 72{,}000 \text{ Lbs. air}$$

$$m = .128 \times 72{,}000 = 9{,}200 \text{ Lbs. of alumina}$$
2-4 mesh, 25" bed.

The grain size correction for 4-8 mesh is read from figure 19 to be .42.

$$m = .42 \times 9{,}200 = 3{,}870 \text{ Lbs. of alumina}$$
4-8 mesh, 25" bed

$$x = M\lambda_i = 72{,}000 \times .006 = 432 \text{ Lbs. } H_2O$$

$$\left(\frac{x}{m}\right)_{2.1} = \frac{432}{3{,}870} = .1118$$

$$\frac{\ell - 2.1}{30} = \frac{1.25 - 2.1}{30} = -.0283$$

$$\frac{x}{m} = \left(\frac{x}{m}\right)_{2.1} + \frac{\ell - 2.1}{30} = .1118 - .0283 = .0835$$

$$m = \frac{432}{.0835} = 5{,}180 \text{ lbs. of alumina}$$
4-8 mesh, 15" bed.

## ABSTRACT FROM REFERENCE NO. 9

Blanchard, Louis.
Proceedings 11th Cong. Pure & Applied Chem. London.
Vol. 5 pp 993-1001 (1947)
"Application du gel de silice à la dessiccation industrielle des gaz".
(Applications of silica gel to the industrial drying of gases.)

### General Considerations.

The physical properties of silica gel are not definite like those of a crystalline material. The microstructure is variable and depends on the method of preparation. For the adsorption of water vapor use is made of micro-porous gels of .65-.75 apparent specific gravity or ultramicroporous gels of .80 apparent specific gravity. This property alone is not enough to define the gel as two gels of the same apparent specific gravity can have different adsorptive power. X-ray diffraction patterns are helpful in the study of structure.

### Isothermal vs Adiabatic Adsorption.

Figure 20 shows how the moisture content of the gel at the break point varies from isothermal to adiabatic operation.

### Dynamic Adiabatic Air Drying.

A drying column was set up in which the course of the temperature and moisture content of both air and adsorbent at various heights in the columns could be followed. Results in a form useful for design, are shown in figure 21. The tests were made with a bed depth of 50 cm (20") and a superficial air velocity of 23.5 cm/sec (.77 ft/sec).

For other bed depths and superficial velocities figures 22 and 23 give the corresponding change in the moisture content of the bed at the break point.

Dynamic Adsorption of Various Gases.

The same moisture content of the bed at the break point has been observed for air as for other gases and condensible vapors. In the latter case the vapor is first adsorbed and then gradually replaced by water vapor.

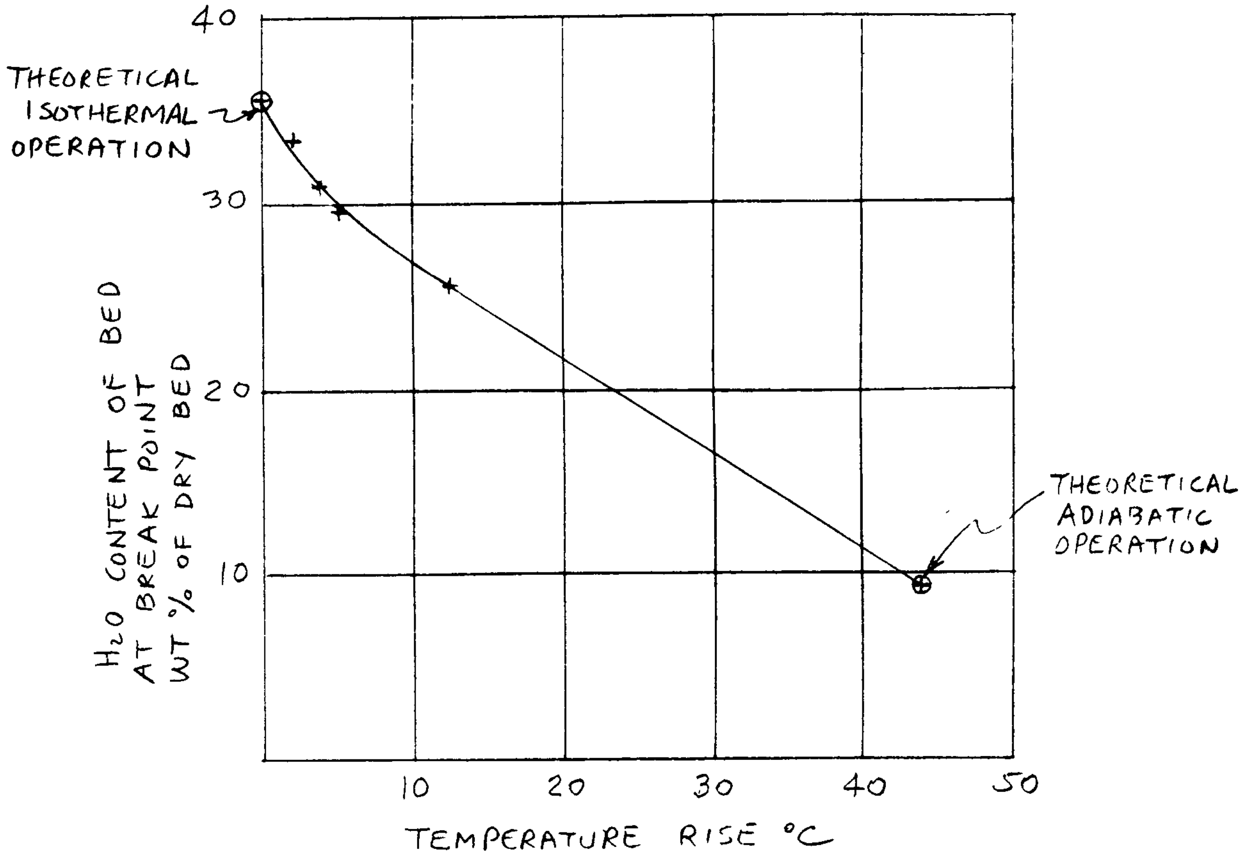


Fig.20 Moisture content of bed at break point related to method of operation.

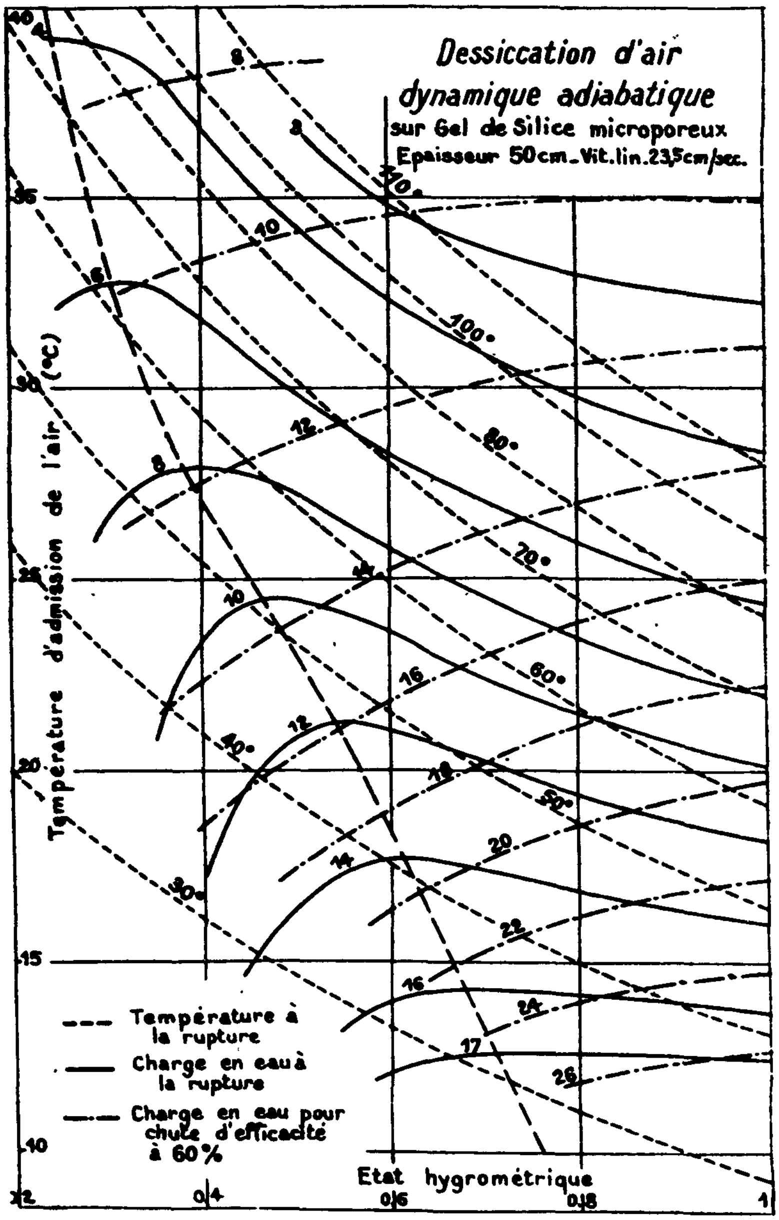


Figure 21 Adiabatic air drying.

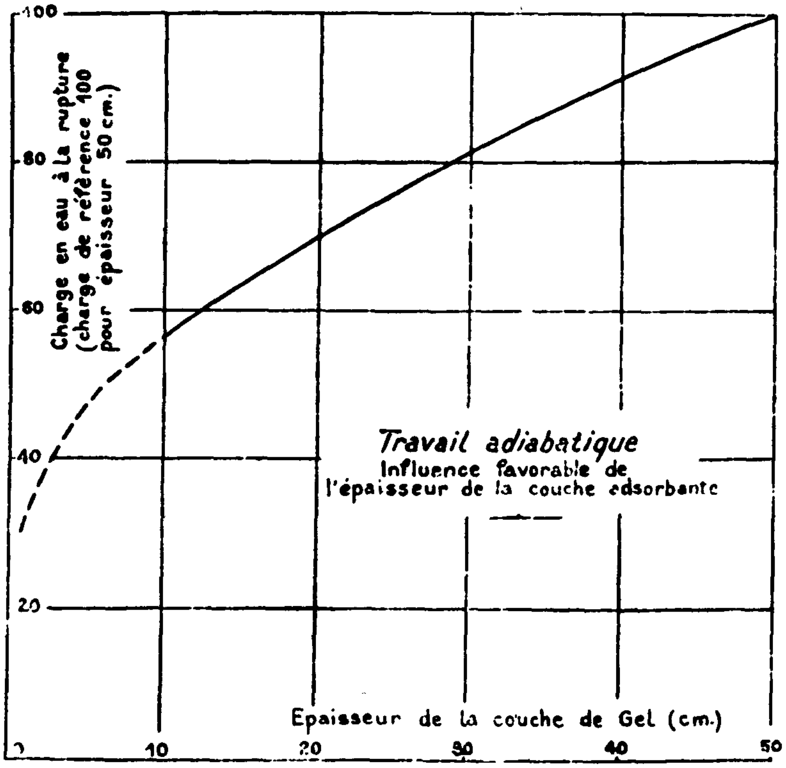


Figure 22 Influence of bed depth on adsorption capacity.

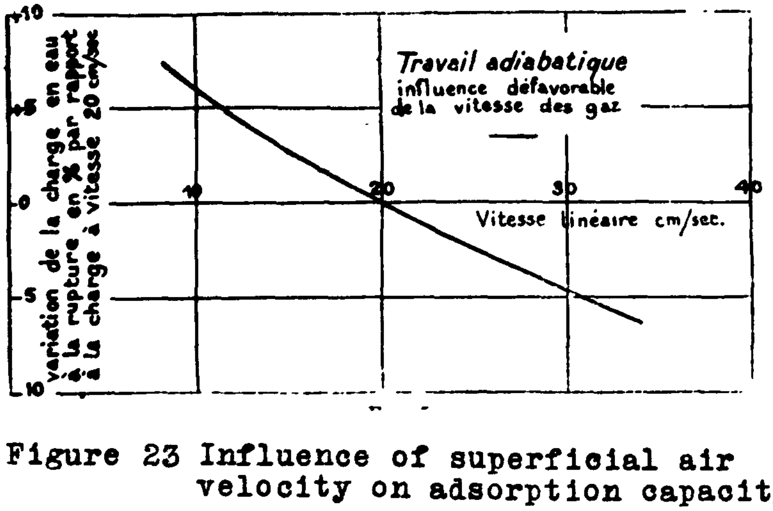


Figure 23 Influence of superficial air velocity on adsorption capacity.

## ABSTRACT FROM REFERENCE NO. 10.

S.S. Hubard
Ind. Eng. Chem. 46, 356-358 (Feb. 1954)
"Equilibrium data for silica gel and water vapor".

Two graphs are presented. One, isobaric, gives the water adsorbed as a function of temperature for various water vapor pressures. The other, isothermal, gives the partial pressure of water as a function of amount adsorbed, for various temperatures.

A method is given for calculating the adsorbent charge in an air drier. Two cases are considered. The first is for the production of completely dried air. The silica gel at the entrance is considered in equilibrium with the incoming air so that its water content can be read from the graphs. At the exit and the gel remains dry up to the break point. Thus the average moisture content of the bed is half that calculated for the inlet end.

In the second case, moisture is allowed to be present in the exit air up to a fixed maximum. First the maximum temperature reached by the bed is calculated by taking a rise of 10°F for each grain of water removed per cubic foot of air feed. This temperature is attained from layer to layer in the bed toward the exit end. At the break point the exit end of the bed will have reached this temperature. Taking as a base of calculation that the gel at the exit end is in equilibrium with the exit air at that temperature, its water content is also read from the graphs. The average moisture content of the bed is taken as the average of the inlet and exit ends.

EXAMPLE.

Calculate the silica gel charge required for drying 100 CFM of air at 80°F and 68% relative humidity (water vapor pressure 0.7" Hg, dew point 68°F) in an 8 hour adsorption cycle. Maximum humidity in outlet air to be that corresponding to 18°F dewpoint (0.1" Hg), which corresponds to the removal of 6.5 grains of moisture per cubic foot of air feed.

At the end of the adsorption cycle, the silica gel at the entrance will contain 32.6% water as read from the graphs. The gel at the exit end will attain the temperature of 80 plus 10 x 6.5 = 145°F. At that temperature and for an 18°F dewpoint, the gel will contain 1.6% adsorbed water. The average moisture content of the gel is then (32.6 + 1.6)/2 = 17.1% Water to be adsorbed in 8 hours is 100 x 60 x 8 x 6.5 / 7000 = 43.9 Lbs. Silica gel required is 43.9/.171 = 283 Lbs. Use 10% more to compensate for loss of capacity with use.

## ABSTRACT FROM REFERENCE NO. 11.

L.C. Eagleton and H. Bliss
Ch.E. Progress 49, 543-548 (Oct.1953)
"Drying of air in fixed beds."

Experiments were performed on the drying of airr in fixed beds. The column diameter was 0.628" ID and the height of the bed varied from 0.16 to 1.75 feet. Conditions studied were the following:

Adsorbents: Alumina, silica gel, "Florite".
Granulation: .056" to .079" diameter
.0675" aver ag dia. or 10 mesh.
Air rate: 33 to 520 Lbs/(Hr x $Ft^2$)
Moisture in inlet air: .001 to .01 Lbs $H_2O$/Lb air.
Air temperature: 80°F, 95°F, 110°F.
Operating conditions: Isothermal.

The experiments were continued until the exit air had the same humidity as the inlet air. The authors calculated adsorption band widths defined as the weight of gas in the bed having humidities within arbitrarily chosen limits, such as $c/c_0$ from 0.1 to 0.8 They found that the band width (measured in mass units) varied with the air flow rate, the initial humidity $c_0$, and the adsorbent used, but was independent of bed height.

Equilibrium isotherms between $c_i$ and $q_i$ were simplified and represented by straight lines intercepting the $q_i$ axis at $\alpha$ as shown in the figure on the next page.

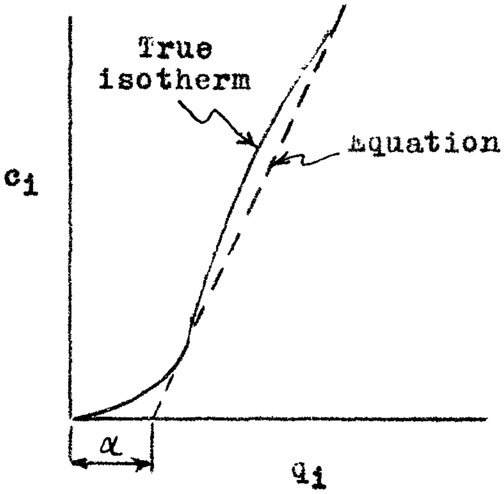


Fig. 24. Equilibrium isotherm representation.

The values of $\alpha$ which should be independent of grain size are as follows:

TABLE 11

Values of $\alpha$

| Temperature | 80°F | 95°F | 110°F |
|---|---|---|---|
| Alumina | .025 | .022 | .014 |
| Florite | .020 | | |
| Silica | .20 | | |

The equation of an isotherm is:

$$q_i = \frac{(a - \alpha)\, c_i}{c_o} \quad \ldots\ldots\ldots (1)$$

Water diffuses through two films in series, a gas film and a solid film, as expressed by the following two equations:

$$\left(\frac{\partial q}{\partial t}\right)_x = k_g S\,(c - c_i) \quad \ldots\ldots\ldots (2)$$

$$\left(\frac{\partial q}{\partial t}\right)_x = k_s S\,(q_i - q) \quad \ldots\ldots\ldots (3)$$

These equations lead to the following solutions:

If $c_D > c$:

$$\mathrm{Ln}\left(\frac{c_D/c_o}{c/c_o}\right) = -\frac{c_o k_g S y}{aV} + \frac{k_g S x}{V} + 2 - c_o/c_D \quad \ldots (4)$$

If $c_D < c$:

$$\mathrm{Ln}\left[\frac{1-(c_D/c_o)}{1-(c/c_o)}\right] = \left[\frac{c_D c_o}{1-(c_D/c_o)}\right]\left[\frac{c_o k_g S y}{aV} - \frac{k_g S x}{V} - 2 \quad c_o/c_D\right] \quad \ldots (5)$$

In these equations:

$$c_D = \frac{\alpha}{\frac{a}{c_o} - r} \qquad r = - \frac{k_g S}{k_s S}$$

$k_g S$ is obtained from equation (4) by plotting ln $(c/c_o)$ against y for low values of $c/c_o$ and measuring the slope. With this value of $k_g S$, the slope of a plot of ln $(1-c/c_o)$ against y (eq.5) gives $c_D$, thence r and $k_s S$.

Equations (4) and (5) are valid only for values of inlet humidities below .003 Lbs $H_2O$/Lb air.

The values obtained for $k_g S'$ were as follows:

Alumina and Florite $k_g S' = 9.3\ G^{.55}$

Silica gel $k_g S' = 6.3\ G^{.55}$

For all three $k_s S' = 7.3$

To calculate the adsorbent charge required in a drier for inlet humidities below .003 Lbs $H_2O$/Lb air it can be assumed that equilibrium is attained between the incoming air and 95% of the adsorbent in the bed.

## NOTATION

a = Capacity of solid in equilibrium with gas of concentration $c_o$, Lbs $H_2O$/Lb solid.

c = Concentration of water in air, Lbs $H_2O$/Lb air.

$c_D$ = Concentration in air at point of discontinuity, Lbs $H_2O$/Lb air.

$c_i$ = Concentration in air at gas-solid interface, Lbs $H_2O$/Lb air.

$c_o$ = Inlet concentration, Lbs $H_2O$/Lb air.

G = Air flow rate based on free bed cross-section, Lbs/(Hr x $Ft^2$)

$k_g$ = Gas film transfer coefficient, $\dfrac{\text{Lbs adsorbed water}}{(\text{Hr} \times \text{Ft}^2) \times \dfrac{\text{Lbs } H_2O}{\text{Lb air}}}$

$k_s$ = Solid film transfer coefficient, $\dfrac{\text{Lbs adsorbed water}}{(\text{Hr} \times \text{Ft}^2) \times \dfrac{\text{Lbs } H_2O}{\text{Lb solid}}}$

q = Average concentration of adsorbate in solid particles, Lbs $H_2O$/Lb solid.

$q_i$ = Concentration in solid at gas-solid interface, Lbs $H_2O$/Lb solid.

r = $-k_gS/k_sS$

S = Surface area of particles, $Ft^2$/Lb solid.

S' = Surface area for activated alumina, $Ft^2$/Lb solid. Used with $k_g$ and $k_s$ as follows:

$k_gS = k_gS'$ for activated alumina.

$k_sS = k_sS'$ for activated alumina.

$k_gS \times \dfrac{S \text{ for alumina}}{S \text{ for other adsorbent}} = k_gS'$ for other adsorbent.

$k_sS \times \dfrac{S \text{ for alumina}}{S \text{ for other adsorbent}} = k_sS'$ for other adsorbent.

t = Time in hours.

V = Air flow rate, Lbs/Hr.

x = Weight of bed, Lbs.

y = Vt - mx, Lbs air downstream.

$\alpha$ = Constant from table 11.

m = Bed voidage expressed as Lbs air/Lb adsorbent.

## VII - CONCLUSIONS

After having searched the literature thoroughly, the author did not find any integrated method of design that covers all points encountered in the design of an adsorber. The contribution that has been made here is the piecing together of all partial information into a comprehensive method that one can follow through to design an adsorber.

The subject least treated in the literature is the reactivation heat duty and duration. In fact only Mantell (14) gives a method of estimating the reactivation time. However, it was felt that a more detailed method should be evolved that would cover all cases. The three elements: adsorbent charge, adsorbed water, and amount of metal, which determine the heat load do not have equal importance in all cases. By examining the contribution of each element separately and establishing its relative importance better judgement can be exercised in evaluating the duration of the reactivation period.

Ledoux (4) gives a method for estimating the cooling time but does not take the shell into account, nor does he give a way of estimating the heat transfer coefficient. The author has proposed a correction to the cooling time calculated by Ledoux's method to account for the presence of the metal shell. For the heat transfer coefficient, the author proposes using the Hougen and Watson method (13).

Hougen and Marshall (1) give a method for determining the charge of adsorbent in a drier, but it applies only for silica gel under isothermal conditions. Amero, Moore, and Capell (2) give design information for gas driers using activated bauxite but do not give any details on the computation of the reactivation and cooling time which are major factors in adsorber design.

It was felt that a complete review of the literature was needed in order to extract from it what it contains, and piece together all information into a complete correlated method of design. Where certain items were found missing, the author did his best to supply a logical and reasonable solution.

The method proposed consists of the following steps:

1. Determine the amount of moisture to be adsorbed per hour.
2. Determine from the gas-moisture ratio, the nature of the adsorption.
3. Chose the adsorbent and the time cycle.

4. From the moisture to be adsorbed, the time cycle, and the nature of the adsorption, calculate the charge of adsorbent.
5. Calculate the maximum allowable mass velocity by Ledoux's method (page 13), under adsorption and reactivation conditions.
6. Chose a bed diameter that satisfies the following two conditions:
   a) Keep the mass velocity below a specified fraction of the allowable maximum.
   b) Keep the bed height to diameter ratio between 2 and 5.
7. Set the vessel dimensions and calculate the weight of metal and insulation.
8. Calculate the reactivation heat load, separating it into the three periods suggested by the author.
9. By trial and error determine the reactivation gas rate to complete the reactivation within the allotted time.
10. Determine the cooling load.
11. Determine the cooling time. If the bed alone accounts for over 50% of the load, use the Ledoux method (pages 34, 62-64). If the bed alone accounts for less than 50% of the load, use the log mean rate method as developed by the author (page 32).
12. Calculate the pressure drop during adsorption and reactivation using fig.1 on page 5, taken from Amero, Moore, and Capell (2).

In order to briefly illustrate the procedure to be followed, a final numerical example will be given.

## PROBLEM NO. 4

Design an adsorber to dry 5000 SCFM of $CO_2$, measured dry at 60°F and 1-atm. The gas is at 300 PSIA and 80°F and saturated with water. It must be dried to negligible moisture content. Reactivation is to be accomplished with hot air at 1-atm. and 400°F.

Solution. The flow is first converted to Lb-Moles/Hr and Lbs/Hr basis:

$$CO_2 \text{ flow} = \frac{5000 \times 60 \times 492 \times 14.7}{359 \times 540 \times 300} = 37.3 \text{ Lb-Moles/Hr.}$$

$$\approx 37.3 \times 44 = 1640 \text{ Lbs/Hr.}$$

The moisture content is then calculated from the vapor pressure of water at 80°F, namely 0.507 PSIA:

$$H_2O \text{ flow} = \frac{37.3 \times .507}{300 - .507} = .0631 \text{ Lb-Moles/Hr.}$$

$$\approx .0631 \times 18 = 1.14 \text{ Lbs/Hr.}$$

A test is then made to determine the nature of the adsorption (assuming no cooling coils used), whether isothermal or adiabatic. The heat liberated during adsorption can be taken as the latent heat of water or roughly 1000 BTU/Lb:

$$\text{Heat liberated} = 1.14 \times 1000 = 1140 \text{ BTU/Hr.}$$

The test is then this: if all the heat goes into the dried gas, how much will its temperature increase? The specific heat of $CO_2$ being 0.21 BTU/(Lb x °F):

$$\Delta t = \frac{1140}{1640 \times .21} = 3.3^{\circ}F$$

This being such a small rise, the adsorption can be considered isothermal.

The adsorbent to be used is next chosen, and can be activated bauxite, activated alumina, or silica gel. The amount required in the adsorber will be greatest with bauxite, and least with silica gel. The choice is a matter of economics. The time cycle must also be chosen: 4, 8, 12 or 24 hours, and is a matter of management policy.

Suppose alumina of 1/4" to 8 mesh is chosen along with a 12-hour cycle. The amount of water to be adsorbed per cycle is then:

Water to be adsorbed = 12 x 1.14 = 13.7 Lbs per cycle.

The amount of adsorbent required to the break point at a 12% adsorption capacity (see p. 14) is:

$$\text{Alumina required} = \frac{13.7}{.12} = \begin{array}{rl} 114 & \text{Lbs} \\ \underline{57} & \text{plus } 50\% \text{ excess} \\ 171 & \text{Lbs} \end{array}$$

A 50% excess is used to compensate for loss of capacity with use and to cover design uncertainties. The volume of the bed is then: 171/50 = 34.2 $Ft^3$.

The bed should have a ratio of height to diameter in the range of 2 to 5. The diameter must be chosen large enough to keep the velocity below the maximum allowable during both adsorption and reactivation. Because of its simplicity the method of Ledoux is preferred in determining the maximum allowable velocity. Ledoux's formula is:

$$G_{max} = 2640 \sqrt{d_g d_a D}$$

The average particle diameter D for 1/4" to 8 mesh material is:

$$D = \frac{.25 + .093}{2 \times 12} = .0143 \text{ Ft.}$$

During adsorption:

$$d_g = \frac{44 \times 492 \times 300}{359 \times 540 \times 14.7} = 2.28 \text{ Lbs/Ft}^3$$

$$G_{max} = 2640 \sqrt{2.28 \times 50 \times .0143} = 3370 \text{ Lbs/(Hr} \times \text{Ft}^2)$$

During reactivation:

$$d_g = \frac{29 \times 492}{359 \times 860} = .0462 \text{ Lbs/Ft}^3$$

$$G_{max} = 2640 \sqrt{.0462 \times 50 \times .0143} = 480 \text{ Lbs/(Hr} \times \text{Ft}^2)$$

So far only the flow during adsorption is known, namely 1640 Lbs/Hr of $CO_2$, and based on that figure, the minimum flow area is 1640/3370 = 0.486 $Ft^2$, which corresponds to a diameter of 9-1/2". It would be advisable to stay at 50% or less of the maximum velocity. This would be obtained in a 14" OD x 1/4" wall shell having a 0.995 $Ft^2$ flow area. In such a shell the velocity during adsorption would be:

$$G = 1640/.995 = 1650 \text{ Lbs/(Hr}\times\text{Ft}^2) \text{ or } 49\% \text{ of maximum.}$$

The bed depth would be 34.2/.995 = 3.44 Ft. Allowing about a foot of free space at each end will give a shell length of 5'-6". In the proposed adsorber the bed has a height to diameter ratio of 3.44x12/13.5 = 3.06 which is within the 2 to 5 range.

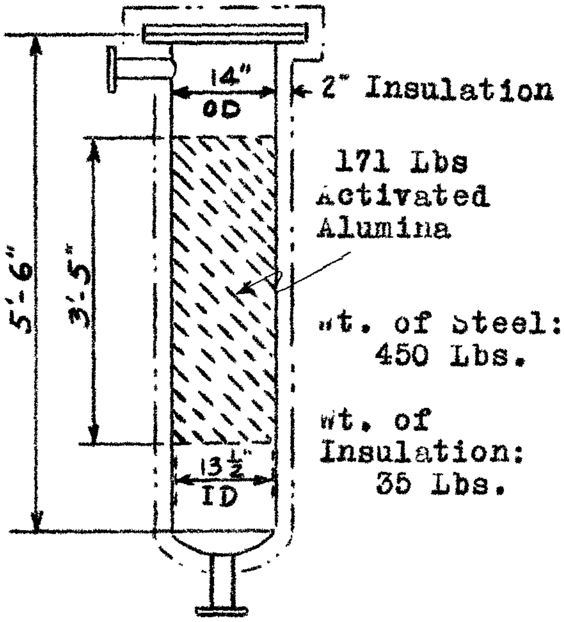


Fig. 25. $CO_2$ Drier.

A tentative design as shown in fig. 25 has been arrived at. It now remains to determine the reactivation air rate to complete the reactivation and cooling within 12 hours and to check if the rate is below the maximum allowable. This air rate is found by trial and error.

First the plateau temperature is located as explained in the text (pages 24-26), and is found to be 121°F. The reactivation is then divided into three periods and the corresponding heat duties calculated. The results are:

| | |
|---|---|
| 1. Heat adsorber from ambient to 121°F | Duty = 4,570 BTU |
| 2. Evaporate water at 121°F | Duty = 14,000 BTU |
| 3. Heat adsorber from 121°F to 350°F | Duty = 25,800 BTU |

Try 250 Lbs/Hr as a reactivation air rate, equivalent to a mass velocity:

Reactivation G = 250/.995 = 252 Lbs/(Hr x $Ft^2$)

or 52% of maximum allowable.

With this air rate, the duration of each period is calculated.

<u>First period</u>. Method: Log mean transfer rate.

$$q_o = 250\ (.24)(400 - 80) = 19{,}200 \text{ BTU/Hr.}$$

$$q_f = 250\ (.24)(400 - 121) = 16{,}700 \text{ BTU/Hr}$$

$$q_{lm} = \frac{19{,}200 - 16{,}700}{2.3 \text{ Log } \frac{19{,}200}{16{,}700}} = 17{,}200 \text{ BTU/Hr}$$

Duration = 4,570/17,200 = 0.266 Hr.

<u>Second period</u>.

Duration = 14,000/16,700 = 0.839 Hr.

<u>Third period</u>.

If heating the bed were the greater part of the heat load, the Ledoux method would be used for the third period. However, in the present case, the bed accounts for only 9,800 BTU out of a total of 25,800 BTU. The log mean transfer rate method is indicated because it applies more correctly to the heating of a heat conductive body such as the adsorber shell.

$$q_o = 250\ (.24)(400 - 121) = 16{,}700\ \text{BTU/Hr}$$

$$q_f = 250\ (.24)(400 - 350) = 3{,}000\ \text{BTU/Hr}$$

$$q_{lm} = \frac{16{,}700 - 3{,}000}{2.3 \text{ Log } \frac{16{,}700}{3{,}000}} = 7{,}980\ \text{BTU/Hr}$$

Duration = 25,800/7,980 = 3.24 Hrs.

The reactivation will then take:

$$0.266 + 0.839 + 3.24 = 4.35\ \text{Hrs.}$$

Cooling.

The cooling time is also preferably calculated by the log mean transfer rate method rather than the Ledoux method because the greater part of the cooling duty is for the vessel. The duty to cool the adsorber from 350°F to 80°F is 26,400 BTU of which 11,600 is for the bed alone. Using the same air flow as for the reactivation and taking 70°F as the air temperature:

$$q_o = 250\ (.24)(350 - 70) = 16{,}800\ \text{BTU/Hr}$$

$$q_f = 250\ (.24)(80 - 70) = 600\ \text{BTU/Hr}$$

$$q_{lm} = \frac{16{,}800 - 600}{2.3 \text{ Log } \frac{16{,}800}{600}} = 4{,}860\ \text{BTU/Hr}$$

Duration = 26,400/4,860 = 5.44 Hrs.

The total time required for reactivation and cooling is 4.35 + 5.44 = 9.79 Hrs which is within the 12 hours available. To complete the design information the pressure drop is calculated using fig.1, and is found to be 0.11 PSI during adsorption and 0.35 PSI during reactivation. The design shown in fig. 25 should thus be satisfactory.