Design of Direct Heated Rotary Dryers

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A Major Technical Report

in

The Department

of

Mechanical Engineering

Presented in Partial Fulfillment of the Requirements
for the degree of Master of Engineering at
Concordia University
Montréal, Québec

March 1984

ABSTRACT

DESIGN OF DIRECT HEATED ROTARY DRYERS

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Drying is the term applied to thermal processes for removing undesired moisture from a product. Dryers utilize air to carry away the vaporized water and deliver the necessary heat required for the process.

The model of drying of solid particles (pellets, dust, etc.) presented in this report assumes that the liquid moisture within a solid is carried to its surface through one or more mechanisms, namely, diffusion and capillary motion. It is also assumed that the solid surface is at the wet-bulb temperature of the drying medium and evaporation takes place at the surface only. It is still often assumed at the constant drying rate the surface of the exposed material "behaves" as if it were completely wetted, while at the falling drying rate some of the solid surface is wet and some dry depending on the physical properties of the solid.

The volumetric heat-transfer coefficient and pressure drop in a rotary dryer are examined as a function of the contact area between showering particles and air flow.

The size of a dryer is determined by the application of theoritical formulae and experimental factors. The heat-transfer rate principle is used as the main requirement which must be satisfied in order to establish the overall design of the drying equipment. The validity of this principle and the specific steps involved in the design of a rotary dryer are presented by a numerical example at the end of this report.

TABLE OF CONTENTS

NOMENCLATURE

A	–	cross sectional area of the dryer, m^2
A_m	–	cross sectional area of material retained by a lifter, m^2
A_s	–	cross sectional area of element C as shown in Fig. 24, m^2
c_a	–	specific heat of air, kJ/kg-°C
c_m	–	specific heat of material, kJ/kg-°C
D	–	diameter of dryer, m
D_p	–	equivalent diameter of a particle, m
F	–	drag force between a falling particle and air stream, N
F_a	–	component of F to the direction of air flow, N
F_r	–	Froude number
$F(t)$	–	path of a falling particle, m
G	–	mass velocity of air, kg/hr-m^2
g	–	gravitational acceleration, m/s^2
H	–	thickness of bed load, m
h_c	–	heat transfer coefficient, W/m^2-°C
h_e	–	total heat of evaporation of water at T_w, kJ/kg
k_a	–	thermal conductivity of air, W/m-°C
K_e	–	a constant in case of lifters
k_h	–	a constant in case of heat transfer
k_p	–	a constant in case of pressure drop
L	–	dryer length, m
l_x	–	falling distance of a particle in x direction, m

l_y - falling distance of a particle in y direction, m

$\dot{m}_a$ - mass flow rate of air, kg/hr

n - speed of rotation of dryer, rpm

N_e - effective number of lifters per showering cycle

N_l - number of lifters installed in a dryer

P - pressure drop in a dryer, N/m^2

$\bar{P}_n$ - average number of showering particles

P_{nh} - number of showering particles in case of heat transfer

P_{np} - number of showering particles in case of pressure drop

P_r - Prandtl number

Q_f - heat loss from a surface, W/m^2

Q_t - total heat required, kW

R - radius of dryer, m

R_e - Reynolds number

R_l - radius of a circle depicted by a tip of lifter as shown in Fig. 19

s - specific gravity of material

S - slope of dryer, cm/m

S_e - effective slope of dryer, cm/m

S_c - change in effective slope of dryer, cm/m

T_a - ambient temperature, ^oC

T_b - dry-bulb temperature of drying air, ^oC

T_{gi} - inlet temperature of gases, ^oC

T_{go} - outlet temperature of gases, ^oC

T_{mi} - inlet temperature of material, ^oC

T_{mo}	-	outlet temperature of material, ^oC
T_w	-	wet-bulb temperature of drying air, ^oC
$(\Delta T)_m$	-	overall mean temperature difference, ^oC
t	-	retention time due to Kiln action, min.
t_c	-	time of a completely showering cycle, s
t_f	-	falling time of a particle, s
t_l	-	lifting time of a particle, s
t_r	-	period of rotation of dryer, s
U_a	-	volumetric heat transfer coefficient, W/m^3-^oC
v_a	-	air velocity, m/s
$\dot{v}_a$	-	air flow rate, m^3/min.
v_c	-	velocity of a conveying particle, m/min.
v_h	-	horizontal velocity of a conveying particle, m/min.
v_l	-	lifting velocity of a particle, m/s
$\dot{v}_m$	-	water vapour flow rate, m^3/min.
$\dot{v}_t$	-	total gas flow rate leaving the dryer, m^3/min.
$\bar{v}_p$	-	average falling velocity of a particle, m/s
$\bar{v}_r$	-	average relative velocity of a particle, m/s
V	-	volume of material between two obstructions, m^3
W_m	-	showering load, kg
X	-	hold-up, % of dryer volume
$\frac{\delta W}{\delta t}$	-	drying rate at the constant period, kg water/hr/ kg dry material
α	-	overlap angle of lifters
θ	-	an angle as shown in Fig. 17
μ_a	-	air viscosity, kg/m-s
ρ_a	-	air density, kg/m^3

ρ_m — bulk density of material, kg/m^3

σ — an angle as shown in Fig. 20

ϕ — rotational angle from horizontal plane

ϕ_r' — angle of repose of material

$\dot{\phi}$ — angular velocity of dryer, s^{-1}

INTRODUCTION

Direct heated rotary dryers as shown in Fig. 1 are more widely used in a drying processing plant than any other type of dryer. This is understandable of the wide range of materials which can be dried in them and if they are correctly designed and operated high thermal efficiencies are obtained.

In this report the movement of moisture inside a drying specimen is assumed to occur through various mechanisms including liquid diffusion, capillary flow and surface activated diffusion. The two mechanisms mainly involved during drying are heat-transfer and mass-transfer. Heat is needed to be supplied to the materials in order to vaporize the water, and the resulting vapour is assumed to be carried away by some means, such as an air stream (1).

The volumetric heat-transfer coefficient and the pressure drop in a rotary dryer is analyzed by estimating the contact area between showering particles and air flow. The effective number of the showering particles per unit length is obtained experimentally or by assuming that their exposed surface is equal to the theoritical cross sectional area of the material showered by the lifters.

In a direct heated rotary dryer the heat-transfer coefficient is determined by assuming the heat is transfered mainly by convection from the hot gases to the wet surface of the product. The model of the dryer studied consists of a slightly inclined rotating shell, provided with internal

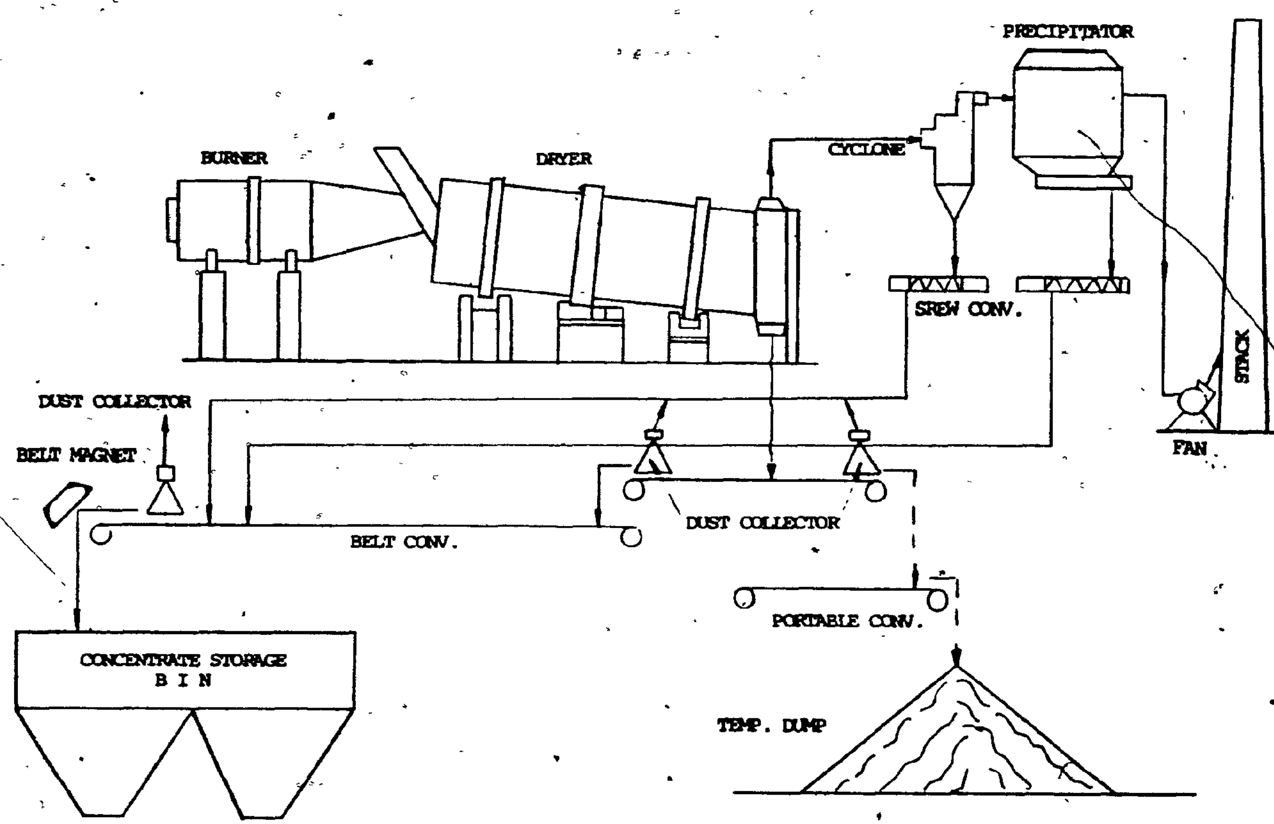


Fig. 1. General arrangemnt of a drying plant

lifters in order to promote agitation of the solids, with feed entering at the high end of the dryer, and hot gases flowing parallel or countercurrent to the material flow. The most important factors influencing dryer design and perfomance are examined from a practical point of view to be optimized under some specified operating conditions.

The capacity of a rotary dryer is determined to be ralated to the lifters shape and arrangement. The percentage of hold-up of the material during showering is used to estimate the depth of the lifters, while their number and arrangement are determined by the physical characteristics of the feedstock.

The length of the time the material stays in the dryer, known as retention time, is defined as the ratio of the material retained in the dryer to the feed rate of the product. The amount of the material held in the dryer between two obstructions is estimated as a function of the geometric configuration of the obstructions and shell diameter, and by neglecting any effect due to dryer slope.

Most of the design work for a direct heated rotary dryer is governed by experience with the product to be processed, and by the application of certain theoritical principles and experimental factors. Although the enclosed data are applicable to more types of thermal dryers, the illustrative example is concerned only with direct heated rotary dryers.

Chapter I

The Mechanism of Drying

1.1 General

The drying of solids is an important operation in certain industrial chemical processes. One can hardly find a process plant where the final solid products or materials technically processed do not undergo a drying operation.

Therefore, for a practical approach to drying problems, certain basic theories and concepts of the mechanism of drying should be understood.

1.2 The drying of bulk solids

When a solid is subjected to thermal drying, there is a complicated interaction (2) between heat-transfer and mass-transfer both on the surface and in the structure of the solid.

Heat-transfer during drying occurs through the flow of heat as a result of convection, conduction or radiation and in some cases as a result of a combination of any of these effects.

Mass-transfer during drying of a wet solid depends on two mechanisms: the internal movement of the moisture as a function of the internal structure and moisture content of the solids, and the external movement of the water vapour from the material surface as a result of temperature, air flow, and area of exposed surface.

1.3 Internal drying mechanism

In spite of the extensive literature studies available, the overall internal drying mechanism has not yet been presented in a single model theory (2).

Among the theories that have won general recognition (3) are the diffusion theory, the capillary theory, and the moving-boundary models. The diffusion theory assumes that the liquid moisture moves through the solid body as a result of a concentration difference. The capillary theory assumes that the flow of liquid moisture through the capillaries is caused by solid-liquid attraction.

In moving-boundary models, the solid is divided into a wet and a dry zone. The wet zone is in the interior and gives very little resistance to moisture transfer. The dry zone is separated from the wet one by an interface at which the evaporation takes place. It is supposed that the moisture moves in the dry zone by vapour diffusion and in the wet zone by capillary motion.

Therefore, the migration of moisture within a solid to its surface will occur through one or more mechanisms, namely, diffusion and capillary flow. These phenomena may occur simultaneously and one or more may be predominant at different stages of drying. The net result, however, will be an outward movement of moisture within the solid.

1.4 External drying mechanism

The mechanism of external evaporation at the solid surface is essentially the diffusion of vapour from the surface of the solid to the surrounding atmosphere through a relatively stationary film of air in contact with its surface. This air film, in addition to presenting a resistance to the vapour flow, itself is an insulant. The thickness of this film rapidly decreases with an increase in the velocity of the drying medium.

The rate of diffusion, and hence evaporation of the moisture, is directly proportional to the exposed area of the solid, inversely proportional to the film thickness, and directly proportional to the difference in the vapour pressure of the moisture at the surface of the solid and the surrounding air. In practice, these conditions are produced through agitation of the solid, the use of fans to promote forced convection, and by controling the supply of fresh air in order to obtain optimum humidity conditions.

It is important to note at this point that, since the layer of air film in contact with the solid during drying remains saturated, the temperature of the solid surface may assume to lie very close to the wet-bulb temperature of the air.

1.5 The periods of drying

The selection of a suitable dryer size therefore, involves the experimental determination of the retention time of the material to be dried as a function of the established operating conditions.

In the case of testing for drying characteristics under forced convection, it is customary to work with a standard bed load. The bed load is the weight of the material left in the rotary drum when both the dryer feed and rotation are stopped.

Empirically it has been established that the bed load should not exceed 16% of the total drum volume (4).

A series of tests is then carried out to determine the rate of drying under different inlet air temperatures, and outlet air velocities. These tests indicate the optimum combination of air temperature and flow to secure the desired dry product in the minimum time.

If now the rate of moisture loss is plotted against time, as shown in Fig. 2, a curve is obtained which more or less is applicable to most solid porous materials. These materials show three distinct stages in the drying-rate curve, namely, section "ab" in which the wet material is warming up; section "bc" in which the rate of drying is assumed to be constant; section "cd" in which the rate of drying falls away by increasing the retention time. Section "bc" is referred to as the period of constant drying rate, while "cd" is referred to as the period of falling rate.

1.6 Constant rate period

It has been often stated that the presence of a constant rate period is explained by the fact that the surface "behaves" as if it were completely wetted (5). The evaporation is taking place from the surface of the solid and so long as this remains surface-wet, is independent of the internal mechanisms within the solid.

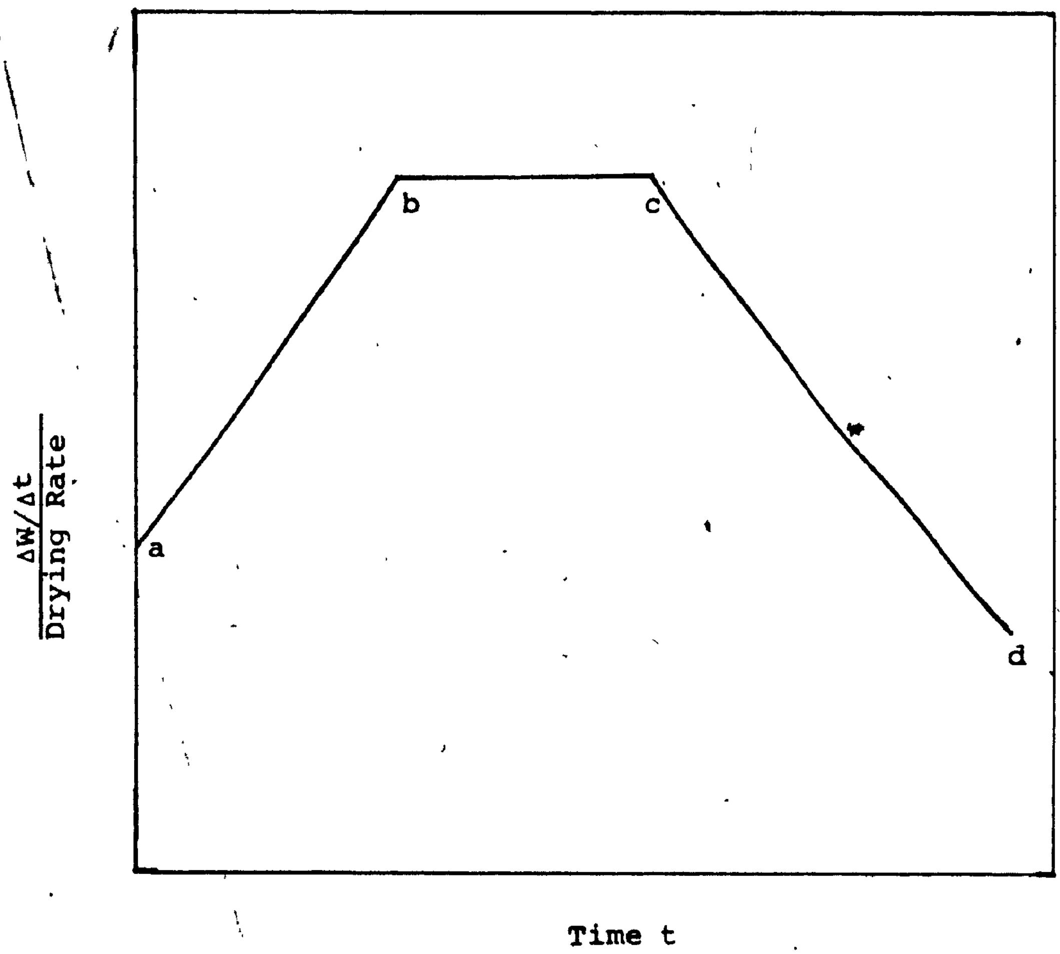


Fig. 2. The periods of drying

The temperature of the air film and of the adjacent solid surface remains substantially constant and is approximately equal to the wet-bulb temperature assuming radiation and conduction effects are negligible. In practice, on an operating convection drying plant, these two effects are unlikely to be wholly absent and result in a higher surface temperature than the wet-bulb temperature and produce a higher constant drying rate.

Summarizing the above, it is evident that the rate of drying during the constant rate period of a capillary porous medium depends on the heat-transfer or mass-transfer coefficient, the area of the solid exposed to the drying medium and the difference in temperature between the drying medium and the wetted surface.

1.7 Falling rate period

In most cases the period of constant rate of drying is followed by a period during which the rate of drying progressively decreases. The trasition from one period to the other takes place at the point of critical moisture content of the solid. Most materials, in a commercial drying scale will not follow exactly the drying curve as indicated in Fig. 2 (6).

While during the constant rate drying period, if it exists, the surface of the exposed solid behaves as if it were completely wetted, at the change to the falling rate period some of the solid surface will be still wet and some dry depending on the physical properties of the feedstock. The rate of evaporation of the less moist surfaces will be lower than that of the completely wetted portions, the net result being a drop in the rate of drying as drying proceeds.

Where the initial moisture content of the feedstock is low and the final required one is extremely low, the falling rate period becomes predominant, and the rate of drying varies as the square of the bed load thickness, which indicates the desirability of granulating the feedstock.

1.8 Heat and mass transfer

The rate of heat-transfer in a dryer depends upon the degree of agitation of the solid within the drum and in the case of forced convection dryers, the initial and final temperature and the velocity of the air or gases used to transfer heat.

High air velocities will reduce the thickness of the stationary gas or air film on the surface of the solid and hence increase the heat-transfer and mass-transfer coefficients. In the designing of commercial dryers, it is found to be more practical to consider heat-transfer rates than mass-transfer rates, as the later is a function of the surface temperature of the wet solid which is difficult to determine and cannot, in practice, be assumed to be that of the wet-bulb temperature of the air with an adequate degree of accuracy, due to the effects of conduction and radiation (2).

The heat-transfer coefficient in forced convection dryers where the hot gases movement is parallel with the surface of the wet material, can be expressed (7) in terms of the mass velocity of the heating medium as:

$$h_c = 0.0128G^{.8} \qquad (1)$$

where:

h_c: is the heat-transfer coefficient, $W/m^2\text{-}^oC$

G: is the mass velocity of the air, $kg/hr\text{-}m^2$

In the case of air blown perpendicular to the surface of the solid, the heat-transfer coefficient is greater and has been estimated to be covered by the expression (8)

$$h_c = 0.37G^{.37} \quad (2)$$

Both the above expressions ignore the effects of conduction and radiation. Ignoring the heat required to raise the temperature of the solid, which will be low relative to the total one, a heat balance on the drying operation will yield the expression (9)

$$\frac{\delta W}{\delta t} = h_e(T_b - T_w)/\rho_s H \quad (3)$$

where:

$\frac{\delta W}{\delta t}$: is the drying rate at the constant period, kg water/hr/kg dry material

H: is the thickness of solid bed, m

h_e: is the total heat of evaporation of water at T_w

T_b: is the dry-bulb temperature of the drying air, ^oC

T_w: is the wet-bulb temperature of the drying air, ^oC

ρ_s: is the bulk density of material, kg/m^3

The above expression assumes that the evaporation is taking place from one surface of the material, if evaporation is taking place from both surfaces, as in the case of wire mesh trays, H = 1/2 the total bed thickness.

In case of direct heated rotary dryers, the drying rate during the constant period is more complicated as it is a function of several variables. Not only does it depend on the rate of air flow, air temperature and humidity, but also particle size and the pretreatment given to the wet solid in order to produce a permeable bed.

For the design of rotary dryers, it is necessary to know the value of the volumetric heat-transfer coefficient and pressure drop.

1.9 Volumetric heat-transfer coefficient

Only recently some published data have been available to serve the purpose of studying the heat-transfer mechanism in a rotary dryer based on the following three assumptions (10).

(i) The heat-transfer between particles and air flow occurs only when the particles are showered by the lifters.

(ii) The particles are approximately spherical and free flowing

(iii) The volumetric heat-transfer coefficient U_a, is equal to the product of the effective number of showering particles and the heat-transfer coefficient. The following Equations are obtained from the above assumptions:

$$U_a = h_c \pi D_p (p_{nh}/AL) \quad (4)$$

$$h_c = (k_a/D_p)(2 + 0.6 R_e^{1/2} P_r^{1/3}) \quad (5)$$

where:

U_a: is the volumetric heat-transfer coefficient, $W/m^3\text{-}^oC$

A: is the cross sectional area of dryer, m^2

D_p: is the equivalent diameter of a particle, m

k_a: is the thermal conductivity of air, W/m-^oC

L: is the dryer length, m

P_{nh}: is the effective number of showering particles in case of heat-transfer

P_r: is the Prandtl number

R_e: is the Reynolds number

The Reynolds number is determined from:

$$R_e = D_p \bar{v}_r \rho_a / \mu_a \qquad (6)$$

where:

$\bar{v}_r$: is the average relative velocity of a particle m/s

ρ_a: is the density of air, kg/m^3

μ_a: is the air viscosity, kg/m-s

The average relative velocity $\bar{v}_r$, is given by

$$\bar{v}_r = (\bar{v}_p^2 + v_a^2)^{\frac{1}{2}}$$

where:

$\bar{v}_p$: is the average falling velocity of a particle, m/s

v_a: is the air velocity, m/s

The average falling velocity of a particle $\bar{v}_p$, is approximated by (11)

$$\bar{v}_p = (Dg/2)^{\frac{1}{2}} \qquad (8)$$

where:

D: is the dryer diameter, m

g: is the gravitational acceleration, m/s^2

The average number of showering particles is approximated grafically to be given by (10)

$$\bar{P}_{nh}/L = k_h(X^{1.34}\ F_r^{.41}A/D_p)^e \qquad (9)$$

where:

$\bar{P}_{nh}$: is the average number of showering particles

X: is the hold-up, percentage of dryer volume

F_r: is the Froude number

The Froude number is obtained from

$$F_r = (D\dot{\Phi}/2)Dg \qquad (10)$$

where:

$\dot{\Phi}$: is the angular velocity of dryer, s^{-1}

The effective number of the showering particles, P_{nh}, is proportional to the power e of the average number of showering particles per unit length, $\bar{P}_{nh}/L$.

$$P_{nh} = k_h(\bar{p}_{nh}/L)^e \qquad (11)$$

$$P_{nh} = k_h(\bar{n}_p)^e$$

$$\bar{n}_p = X^{1.34}\ F_r^{.41}A/D_p \qquad (12)$$

Substituting Equation 12 into 4, and rearranging the following is obtained

$$U_aA/h_c\pi D_p^2 = k_h\bar{n}_p \qquad (13)$$

When the left side of Equation 13 is plotted on the ordinate and $\bar{n}_p$ is plotted on the abscissa in a logarithmic chart, the two parameters, in Equation 13, k_h and e, can be determined from the intercept and the slope of the line correlating the data.

1.10 Pressure drop

The pressure drop inside a rotary dryer is analysed and approximated based on the following three assumptions (10).

(i) The pressure drop due to particle presence is caused only by the contact between air and particles showered by the lifters.

(ii) The particles are spherical and free flowing.

(iii) The force unit length that the air flow loses is equal to the product of the drag force, F_a and the effective number of falling particles, P_{nh}/L. Furthermore, it is assumed that P_{np}/L is proportional to the power e of the $\bar{P}_{np}/L$.

The proportionality constant and the exponent must be determined experimentally.

Thus, the following Equations are obtained from the above assumptions:

$$(\Delta P)A/L = k_p F_a (\bar{P}_{np}/L)^e \qquad (14)$$

where:

ΔP: is the pressure drop, N/m^2

F_a: is the component of F to the direction of air flow, N

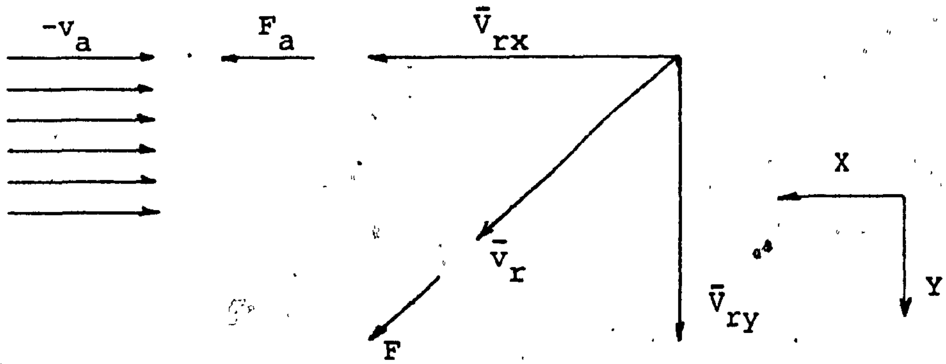
P_{np}: is the effective number of showering particles in case of pressure drop

The drag force component F_a, in the direction of air flow, is determined from Fig. 3

$$F_a = F(v_a/\bar{v}_r) \quad (15)$$

where:

F: is the drag force between a falling particle and air flow, N



$$\bar{v}_r = \bar{v}_{rx}^2 + \bar{v}_{ry}^2$$
$$F_a = F(v_a/v_r)$$

Fig. 3. Explanation of F_a

Figure 3 is derived by assuming that the particles fall perpendicular to the dryer axis having an average falling velocity $\bar{v}_p$, furthermore, is assumed that the air stream in a dryer is acting as the piston flow. Rearranging the above Equations, the following is obtained

$$(\Delta P)A/F_aL = P_{np}/L = k_p(\bar{n}_p)^e \quad (16)$$

The coefficient, k_p, and the exponent, e, in Equation 16 are obtained by plotting $(\Delta P)A/F_aL$ and $\bar{n}_p$ on a logarithmic chart.

Chapter II

Direct-Heated Rotary Dryers

2.1 General

With a few possible exceptions, rotary dryers are more widely used in the process industries than any other type of dryer (12). When the material to be dried can be brought safely into contact with the heated medium, direct-heated rotary dryers are used.

A direct-heated rotary dryer operating at atmospheric pressure mainly consists of a cylindrical shell through which the heated medium flows. The shell rotates through a reduction gear drive arrangement, usually inclined from its horizontal position so that the movement of the material is due to the combined effects of gravity from the higher to the lower end and the action of lifting during showering of the shell.

Direct-heated rotary dryers may be operated with the gas flow parallel to or countercurrent to the material flow. The counter-flow arrangement gives higher overall mean temperatures and consequently higher drying efficiencies than parallel-flow. This may be advantageous when a high product temperature is necessary but is highly undesirable with heat-sensitive materials.

Typical arrangements of parallel-flow and counter-flow dryers are shown in Figs 4 and 5. Fig. 6 shows the general arrangement of a dryer and cooler in an actual installation.

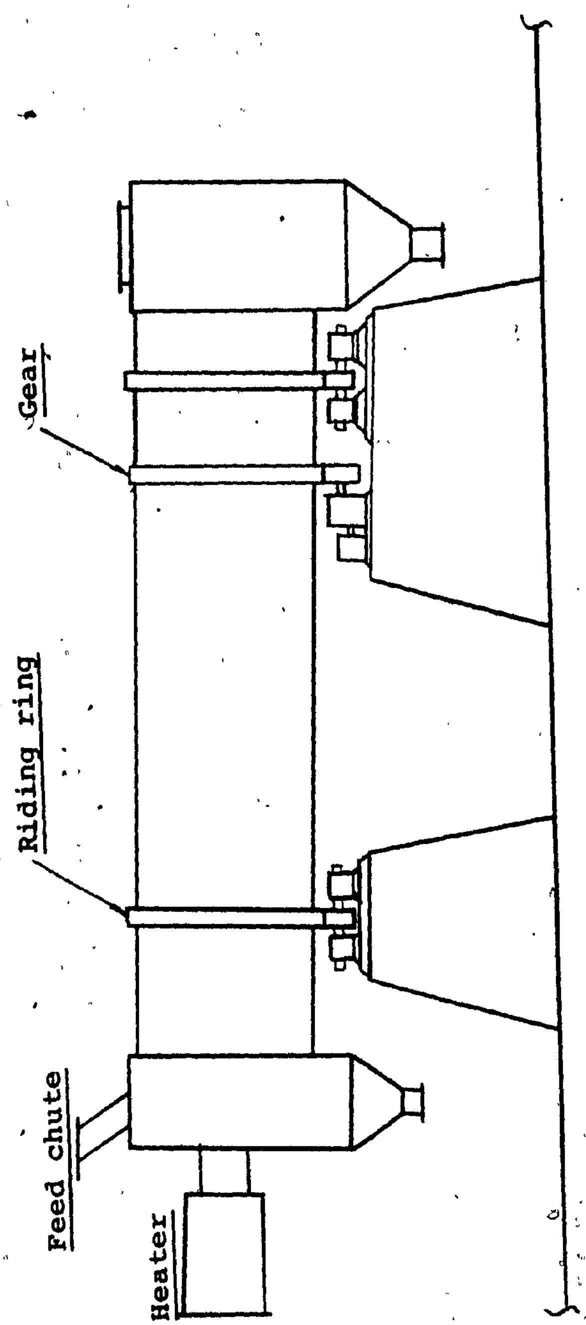


Fig. 4. Direct heated parallel-flow rotary dryer

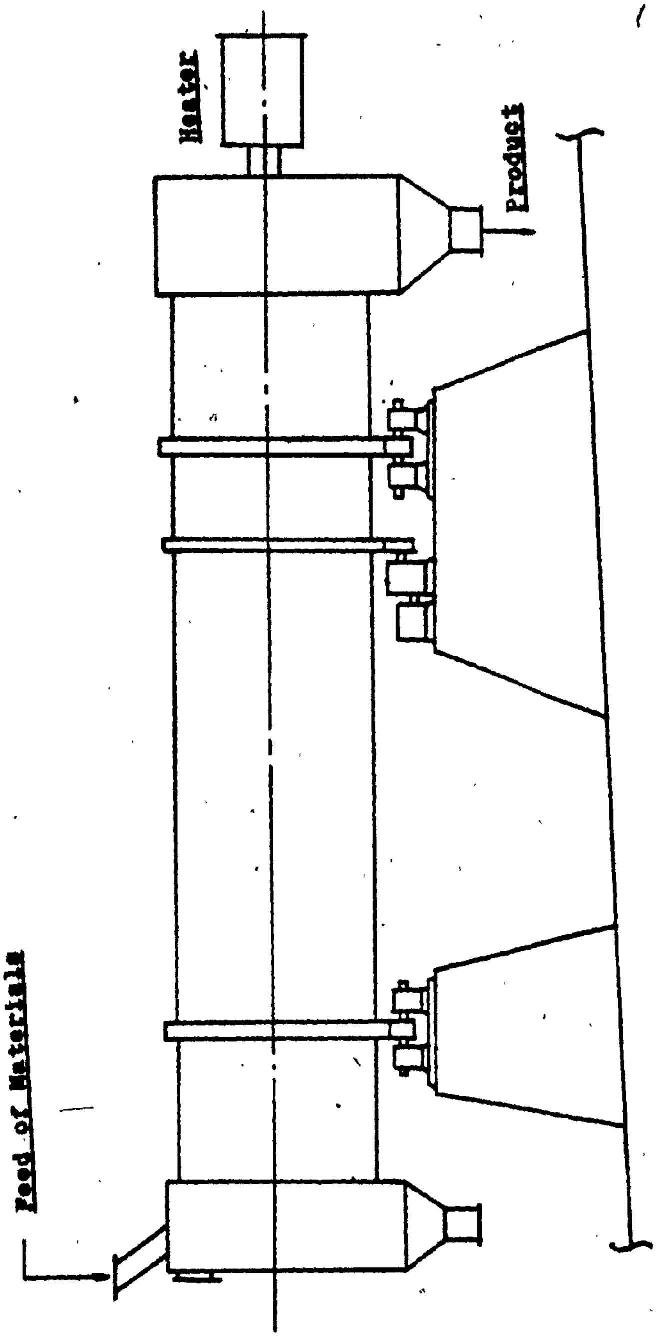


Fig. 5. Direct Heated counter-flow rotary dryer

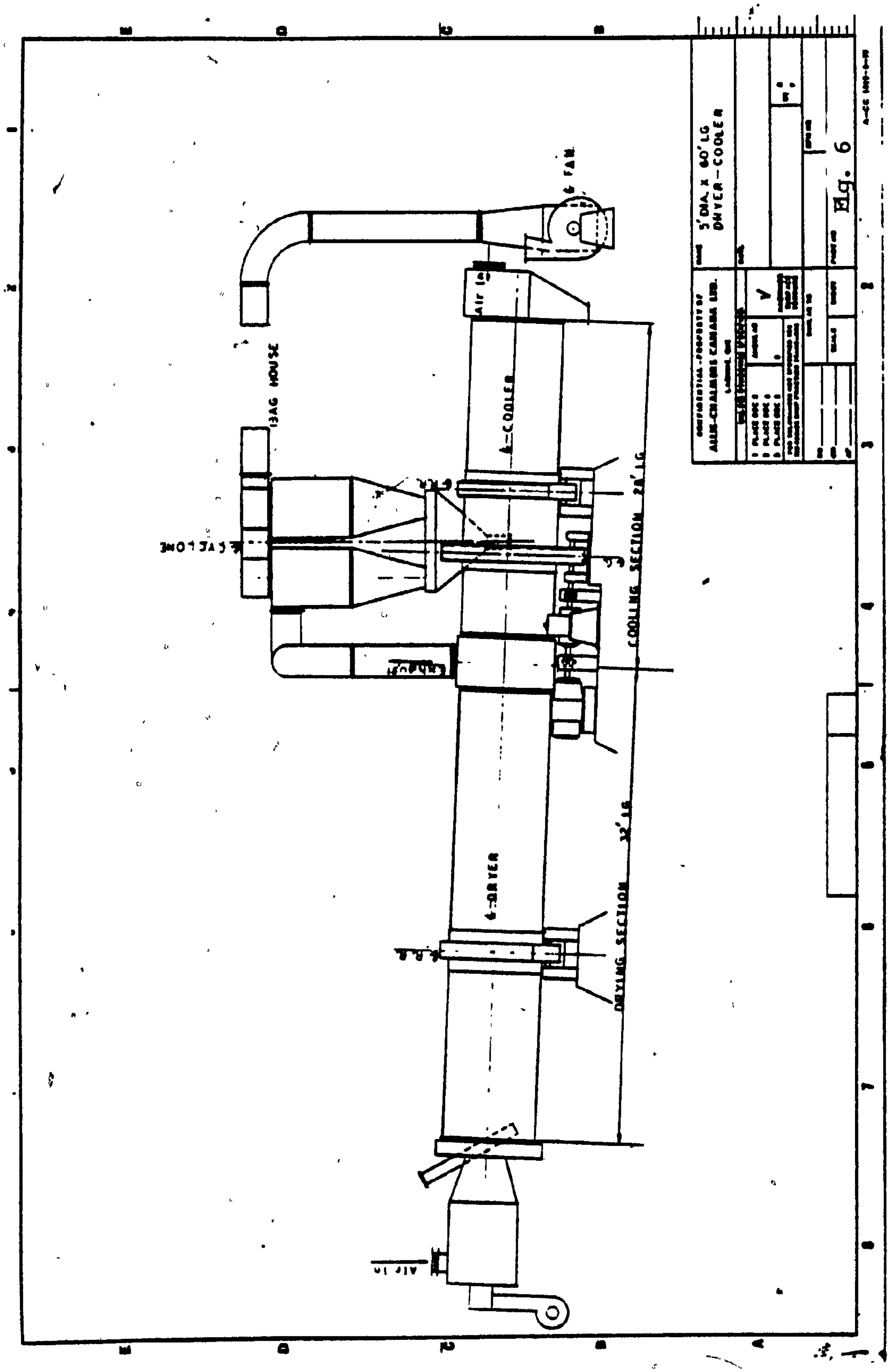

5' DIA. X 60' LG
DRYER-COOLER
FAN
AIR IN
BAG HOUSE
COOLER
CYCLONE
EXHAUST
COOLING SECTION 28' LG
DRYER
DRYING SECTION 32' LG
AIR IN

Fig. 6

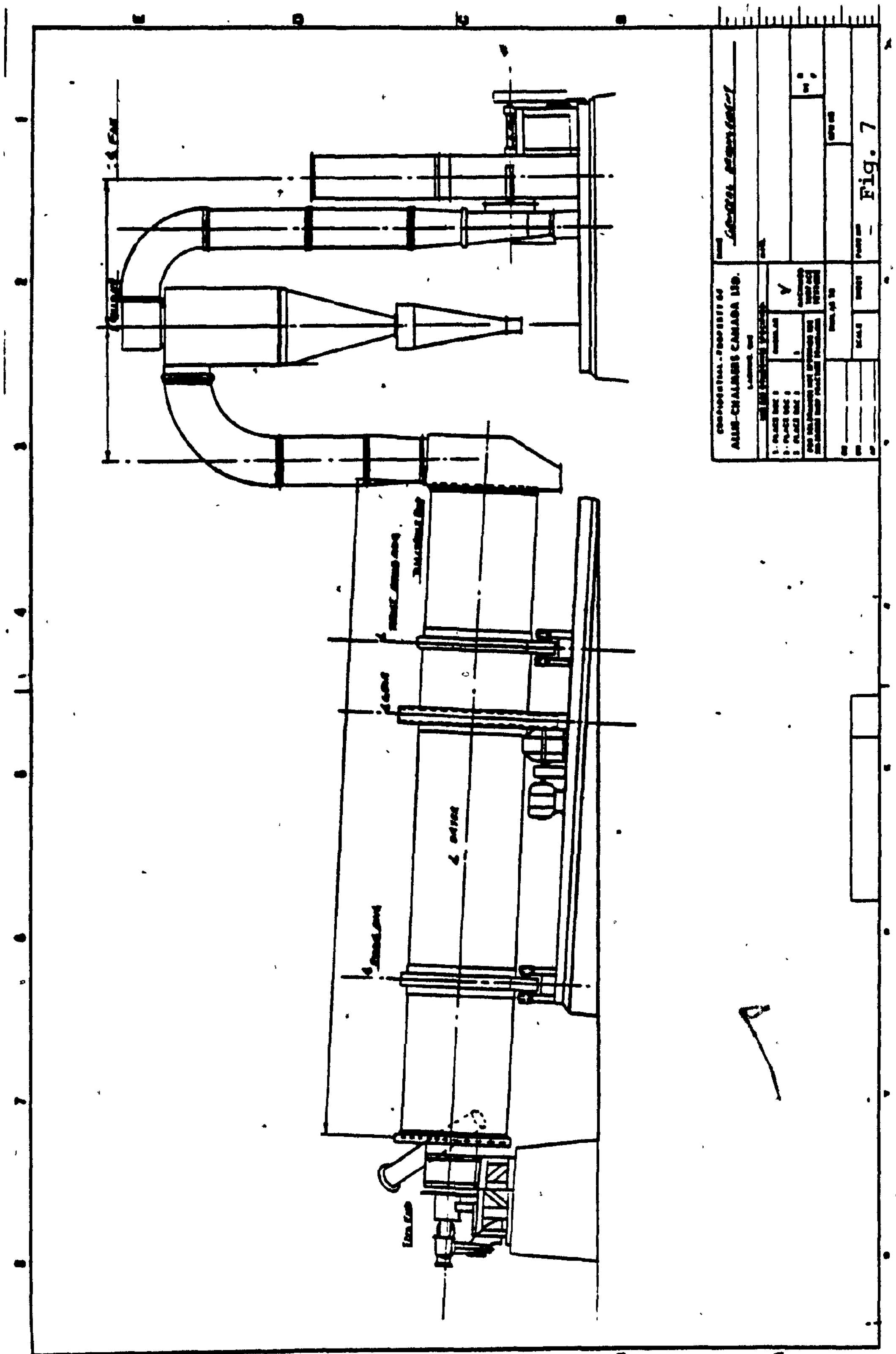


Fig. 7

It can be seen, from Fig. 7 , that a direct-heated rotary dryer essentially consists of a connection for the introduction of the heating medium, a feed connection for wet material, the cylindrical shell provided with machined girth riding rings on suitable roller bearings, a girth gear ring driven by a pinion reduction gear arrangement, an inlet and outlet housing connected to the vapour piping and dust collecting equipment, internals consisting of feed spirals, lifters and seals.

2.2 Design of rotary dryers

Rotary dryers are designed by the application of theoritical formulae and modifying factors determined from operating experience. Occasionally, the necessary factors may be established by pilot tests in case sufficient data are not available.

The most important of the factors influencing dryer design and performance are:

1. Percentage loading
2. Moisture content
3. Air flow rate through the dryer
4. Physical properties of the material
5. Slope of dryer
6. Speed of rotation
7. Dryer length
8. Diameter of the dryer
9. Lifting flights shape and arrangement
10. Retention time

2.2.1 Percentage Loading

The percentage loading of a rotary dryer is being defined as the ratio of hold-up with the dryer to the dryer volume per unit length. Unlifted material within a dryer becomes subject to a rolling effect (kiln action) which must be avoided as it reduces the retention time.

As can be seen in Fig. 8 (13) there is always an optimum loading due to the lifting material beyond which this rolling effect of the material dominates and retention time decreases.

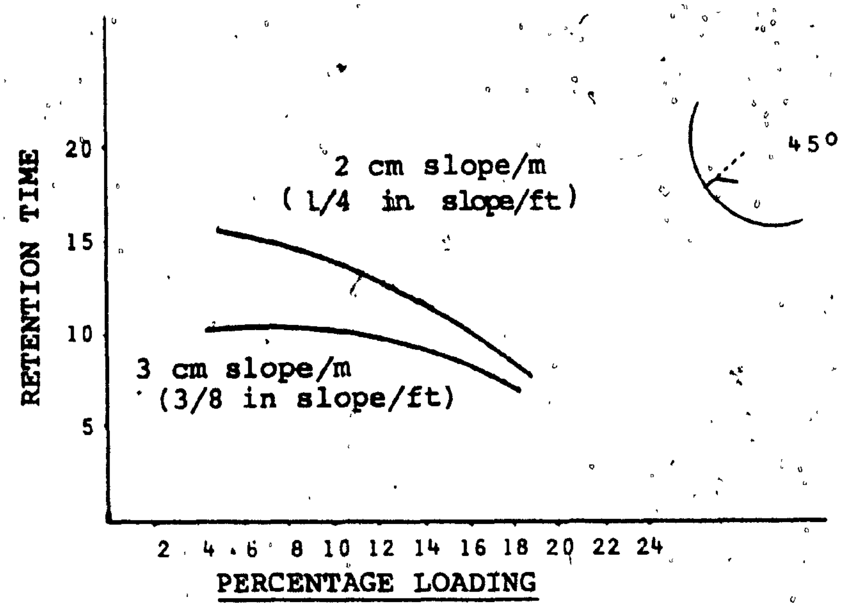


Fig. 8. Effect of percent loading on retention time

Depending upon the slope of the dryer, this loading usually lies between 8% to 12% of the dryer volume per unit length (14).

2.2.2 Moisture content

Although the effect of moisture content on a dryer capacity is generally realised, there are often doubts about the degree of its effect. Fig. 9 shows the direct effect on capacity in tons per hour (TPH) as moisture increases of a selected dryer, with the exhaust air held constant and moisture content, and feed rate of the material in the dryer varied to absorb the supplied heat.

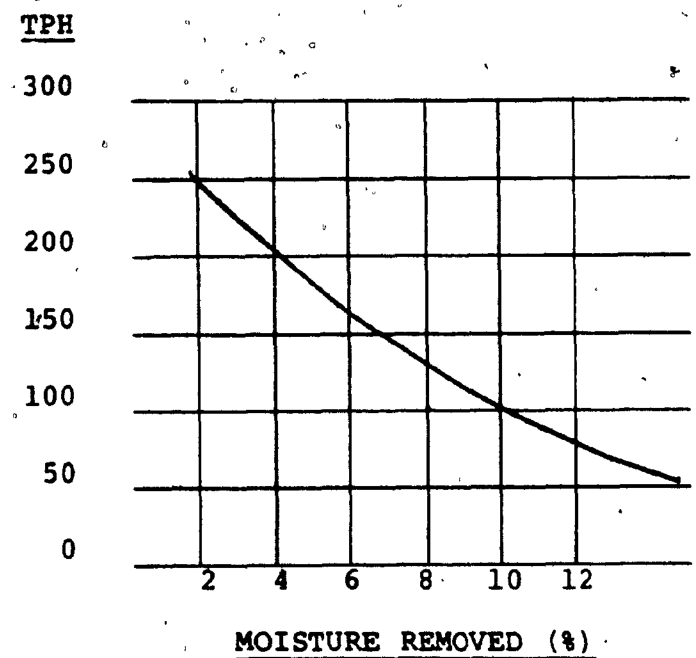


Fig. 9. Dryer capacity vs moisture removed

2.2.3 Air flow rate through a dryer

The velocity of the drying medium in a dryer has an important effect on the retention time and subsequently on the overall design both in parallel-flow and counter-flow arrangements. Air velocity limits depend on the physical characteristics of the material. With materials which are dusty or become dusty during drying air velocities must be at a range where carry-over does not reduce the retention time required for the process. The influence of air velocity can be greater in counter-flow than in parallel-flow as can be seen in Fig. 10 (13). In practice air velocities range from 13.72 m/min. (45.0 ft/min.) for fine material to 640 m/min. (2,100 ft/min.) for coarse heavy material.

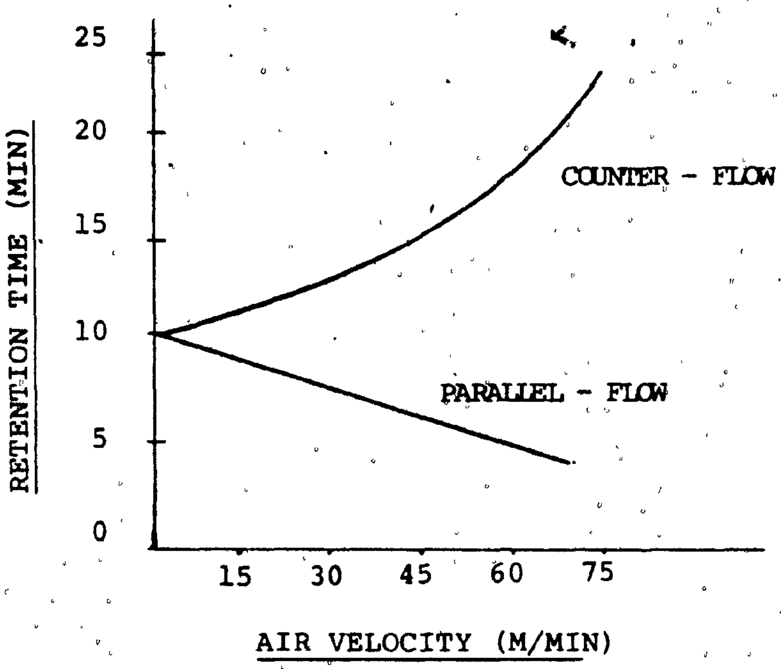


Fig. 10. Effect of air velocity on retention time

2.2.4 Physical properties of the material

Most of the material other than those which are initially free-flowing will undergo considerable change in physical or even chemical properties depending on the drying medium temperature and velocity, and retention time.

The rate of movement of the material inside the dryer will tend to increase as drying proceeds and as break-down of lumps takes place, leading finally to a free-flowing condition.

Some manufactures install chains inside the dryer in order to accelerate drying and flow rate of the material based on the following two assumptions:

(i) Chain used as a means to break-free a sticky material

(ii) Chain used as a means of heat-transfer when processing fines of -200 mesh in the hot end of the dryer where the chain altenatively immersed in the bed of the material, is capable of assisting evaporation of water.

2.2.5 Slope of dryer

The effect of the slope of the dryer shell should be considered separately from the effect of speed of rotation (13). As can be seen in Fig. 11, at a given speed of the shell the retention time is inversely proportional to the slope of the shell.

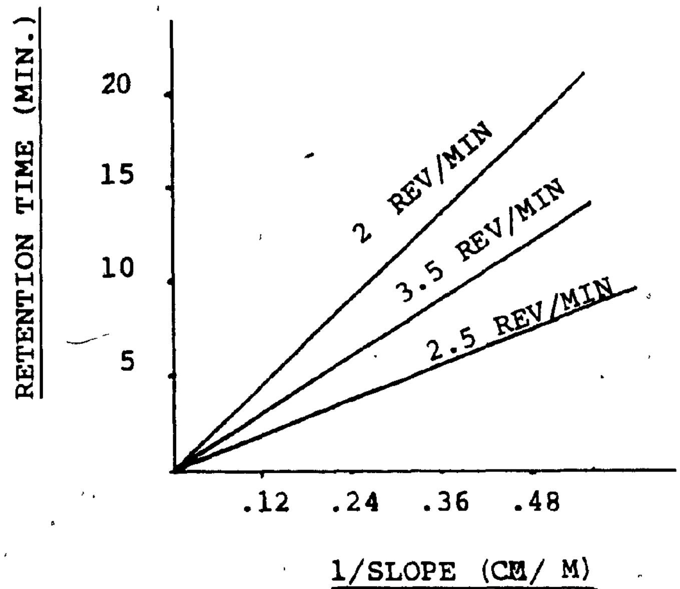


Fig. 11. Effect of dryer slope on retention time

2.2.6 Rate of rotation

It is found generally in practice that the speed of rotation irrespective of lifter shape and spacing is inversely proportional to the retention time. However, the rolling (kiln action) effect is diminished at slow speeds which tend to reduce retention time. Rotational speed (r.p.m.) times dryer diameter (m) usually lies between 9 and 12 (7).

2.2.7 Dryer length

In comparing dryers with the same diameter or cross sectional area and with the same gas velocity, the production capacity may be increased with added length, but on less than a direct ratio.

Some tests performed by Barber-Greene Company (4) showed that with all other factors held constant, increasing the length from 6 m to 9 m (a 50% increase) produced only 20.5%

increase in capacity. In other words the additional length was only partially effective in the capacity of the dryer. The results are shown in Fig. 12 (4).

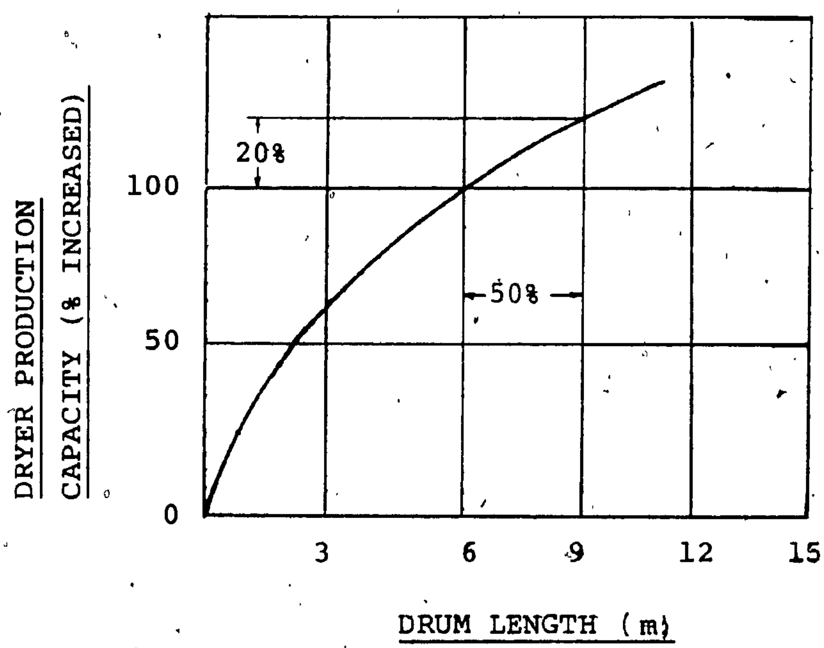


Fig. 12. Effect of dryer length on production capacity

Although production capacity is not proportionally increased as the length of the dryer, the retention time is directly proportional to any change of the latter.

2.2.8 Dryer diameter

Generally it is found that on dryers of the same length with all other factors held constant, production will vary in direct ratio to shell cross sectional area. This means that a dryer with a 50% more cross sectional area will provide a 50% increase in production if the supplied heat and gases are proportionally increased. This effect is shown grafically in Fig. 11 (4).

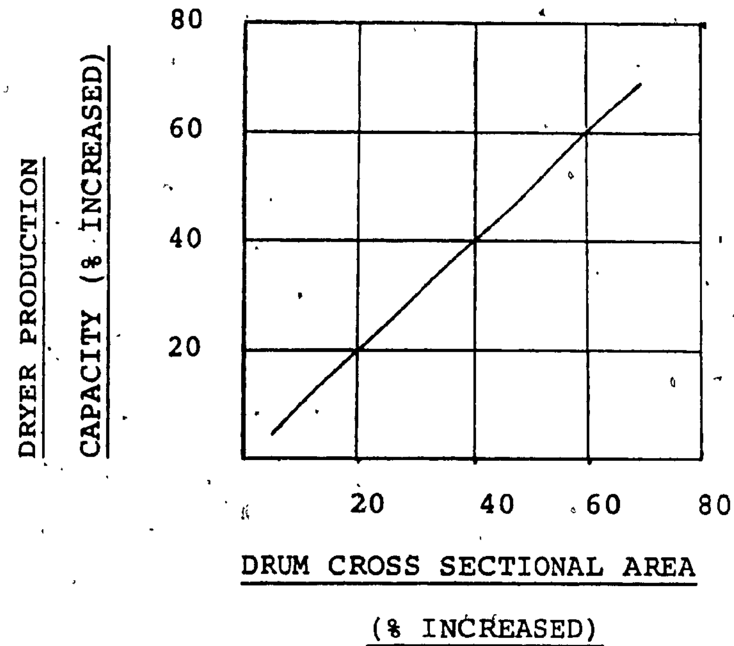


Fig. 13. Production capacity vs shell cross sectional area

2.2.9 Lifting flights shape and arrangement

The efficiency of a direct-heat rotary dryer, apart from the quantity and temperature of the in-going gases, depends to some extend on the exposed surface of the material in contact with the hot gases, and the retention time of the product in the dryer. These parameters will be a function of the number, size and shape of the lifting flights.

The depth and shape of the lifting flights serve two purposes: firstly to produce a curtain veil of material in suspension in the path of the hot gases to assist in heat-transfer; and secondly to retard and control the flow of material through the cylindrical shell from a conveying stand point.

The actual shape of the flights depend on the physical characteristics of the wet feedstock during the course of drying. The shape of straight, single bend, and double bend lifters is shown in Fig. 14.

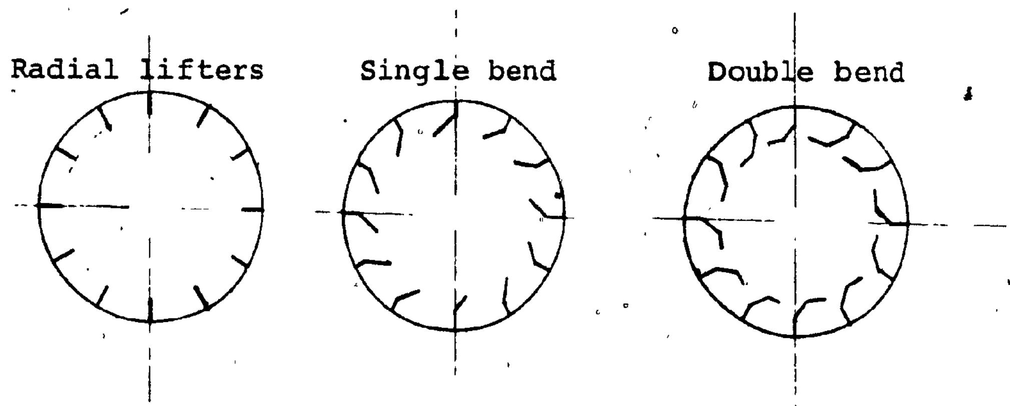


Fig. 14. Lifting flights shapes

Some principles on the use of each type are:

(i) where long retention times are nacessary straight lifters should be used. These materials obtain no benefits from the better showering pattern of the single or double bend lifters because time is the controlling factor.

(ii) if the material to be dried is sticky and not free flowing, it is better to use single bend lifters rather than double bend ones.

(iii) for free flowing material double bend lifters are used

(iv) some manufactures use another type of lifters, namely sawtooth after their shape as shown in Fig. 15. This type performs best on relatively free flowing materials where long retention times are not required.

(v) it is found that the drying performance can be improved in particular cases by using combinations of lifter shapes on the same unit. For example, straight or single bend lifters could be used at the feed end where the product is relatively wet and sticky, whereas double bend lifters could be used toward the discharge end where the product is sufficiently dry to be free flowing.

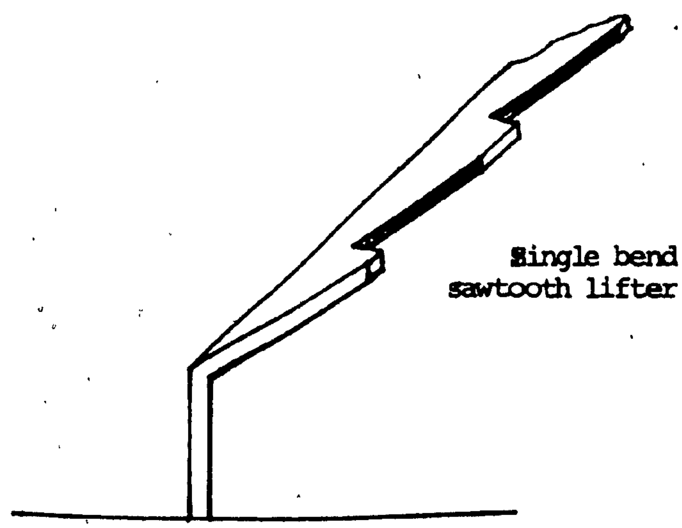


Fig. 15. The shape of a sawtooth lifting flight

Lifters may be installed as continuous pieces along the length of the dryer or may be staggered in order to improve showering of the material. Their number should usually be between 0.6 and 1.2 times the diameter of the dryer measured in meters, while their depth should be between 1/12 to 1/8 the dryer diameter.

Before discussing the parameters required to be determined to arrive at a reasonable shape and lifter design, let us clear some common and erroneous impressions.

In a conventionally designed dryer, a particle spends only a fraction of its time in the showering curtain, usually not over 3 to 5% of the time, while it spends the rest of it in a layer on the shell (4). A particular lifter shape gives a constant showering curtain of materials exposed to the drying medium, within normal operating ranges.

From some tests (4), it appears that in a properly designed dryer too much showering of the material will interfere with combustion more than it will assist in increased heat-transfer.

This was discovered during testing of lifter shapes that gave very efficient veils in the cross sectional area of the shell but proved to restrict maximum production capacity because of problems of combustion. There is a limitation as to how much fuel can be burned with a specified exhaust gas volume, as the volume includes the product of combustion, the moisture carry-out, and excess air. Combustion can only be increased by the presence of excess air in order to supply the oxygen required to atomize the additional fuel particles which are under sufficiently high temperature that will support combustion. These additional fuel particles may be cooled off by a too heavy showering curtain of materials at the critical combustion point, and the unburned particles will then leave the stack as "black smoke" or be deposited on the material.

The production capacity was increased by reducing the veil through rearranged lifter design. However, there is also a point where too limited a veil will restrict heat-transfer to the point that it will reduce production capacity.

2.2.9.1 Design

This section will present the basic design philosophy which can be used to size lifters for a particular job.

An optimum design condition for the lifters is established through some experimental and theoretical parameters. Their values will be seen to be a function of the physical characteristics of the product and geometry of the lifters.

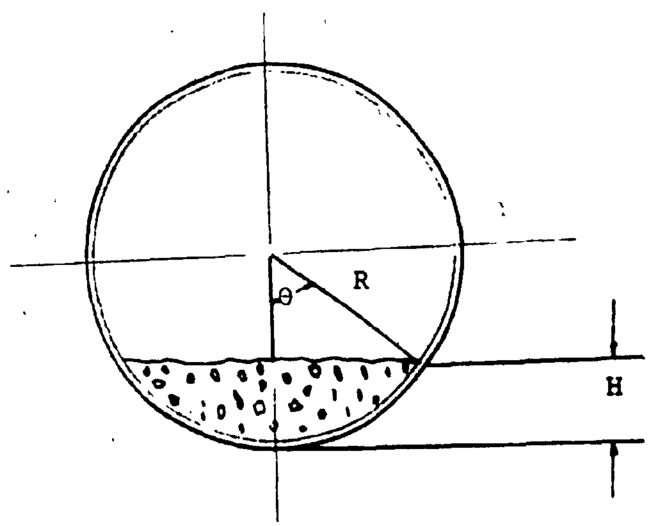


Fig. 16. Cross sectional view of bed load in a dryer

$$H = R - R\cos\theta$$

$$H/R = 1 - \cos\theta \quad (17)$$

where:

H: is the depth of bed load, m

R: is the radius of dryer, m

θ: is an angle as shown in Fig. 17, degrees.

The height of the lifters is assumed to be equal, approximately, to the depth of the bed load as shown in Fig. 16, for a particular percentage of loaded area is determined from Fig. 17, by assuming all the material rest on the shell of the dryer.

The physical size and shape of each lifter and the angle of repose of the product determine the amount of the material showered by each lifter as it goes through its showering cycle.

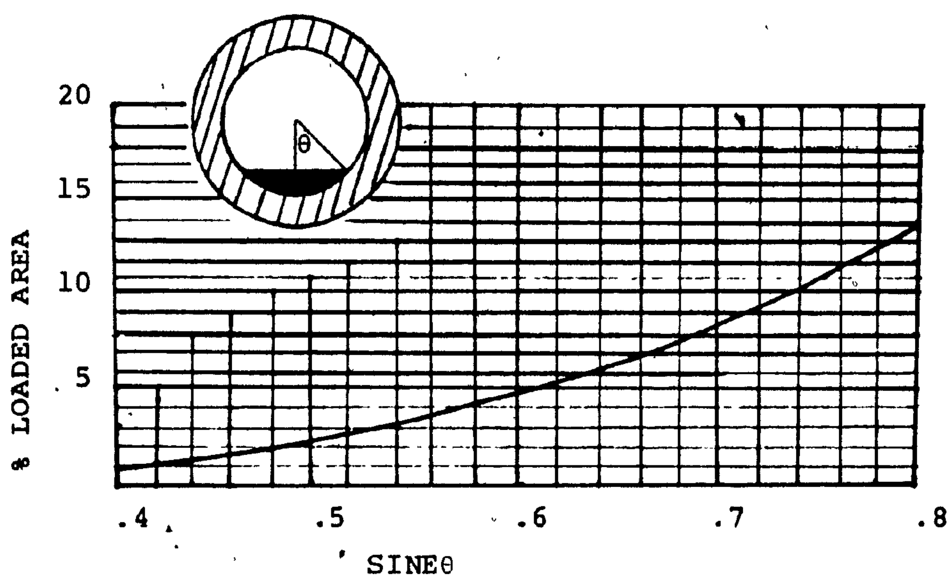


Fig. 17. Percent of loaded area vs sine of angle θ

The number of lifters per meter of dryer diameter can be determined graphically in such a way that overlap of the lifters will not occur. In other words, overlap will not be a problem, if angle α, as shown in Fig. 18, multiplied by the number of lifters is not greater than 360°.

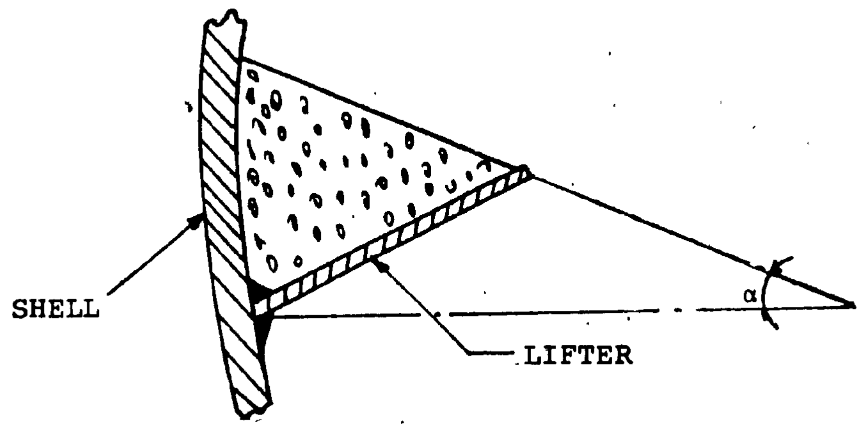


Fig. 18. Cross sectional area of the material held-up by a lifter

Once, the number of rows, shape and size of lifters is established, the showering load must be estimated and compares with already existing limits. Generally, the showering load can be calculated by estimating the effective number of lifting and falling particles per showering cycle.

The behavior of particles over the cross sectional area of a dryer is shown schematically in Fig. 19 (10). The solid line (a_4a_1) indicates an apparent falling locus and the lines $a_1\dot{a}_1$, $a_2\dot{a}_2$ and $a_3\dot{a}_3$ indicate true falling loci.

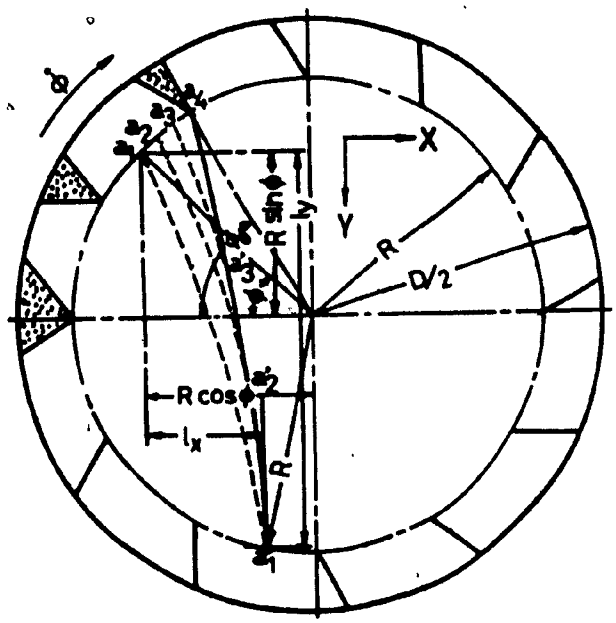


Fig. 19. Motion of a particle over the cross section of a rotary dryer

The average product particle picked up by the lifter falls a distance described by the following Equation (15).

$$F(t) = (R_1\cos\phi - l_x)^2 + (l_y - R_1\sin\phi)^2 - R_1^2 \qquad (18)$$

where:

l_x: is the falling distance in the x direction, m

l_y: is the falling distance in the y direction, m

R_1: is the radius of a circle depicted by a tip of lifter, m

Equation 18 was found to have an approximate value which is in good agreement with its practical use (15):

$$F(t) = D\sin\phi \qquad (19)$$

where:

ϕ: is the rotational angle from horizontal line

From the theory of kinematics (11), the falling path of a particle under the acceleration of gravity, starting with zero velocity is given by

$$F(t) = g\ t_f^2/2 \tag{20}$$

where:

t_f: is the falling time, s

Equating 19 to 20, and solving for t_f yields

$$t_f = (2D\ \sin\phi/g)^{\frac{1}{2}} \tag{21}$$

The lifting time is estimated from the following two Equations:

$$v_l = 2D\phi/t_l \tag{22}$$

where:

t_l: is the lifting time, s

v_l: is the lifting velocity, m/s

and

$$v_l = n\pi D/60 \tag{23}$$

where:

n: is the speed of rotation, rpm

Equating 22 to 23, and solving for t_l yields

$$t_l = 120\ \phi/n\pi \tag{24}$$

The total time required for a complete showering cycle is the sum of the falling and lifting time.

$$t_c = t_f + t_l \tag{25}$$

The number of lifters used per showering cycle is related to the number of lifters installed in a dryer by the following Equation (16)

$$N_e = K_e N_l \tag{26}$$

where:

K_e: is a proportionality constant

N_e: is the effective number of lifters per showering cycle

N_l: is the number of lifters installed in a dryer

The proportionality constant is determined from

$$K_e = t_c/t_r \tag{27}$$

where:

t_r: is the period of rotation of the shell, s

The percentage of the cross sectional area of the dryer covered by showering is

$$X = 100N_e(A_m L/AL) \tag{28}$$

where:

A_m: is the cross sectional area of material retained by a lifter, m^2

X: is the hold-up, % of dryer volume

The other method of estimating the showering load was discussed in section 1.9 and is based on the average number of showering particles per unit length of dryer.

2.2.10 Retention time

The length of the time the material stays in the dryer, known as retention time, is affected by a number of factors and is determined experimentally for each particular application.

Experimental work (17) has resulted in arriving at an empirical Equation from which the retention time can be approximately calculated taking into acount the effect of the previously mentioned variables:

$$t = 3.094\sqrt{\phi_r}\,L/(nDS) \times \text{Factor} \qquad (29)$$

where:

t: is the retention time, minutes

S: slope of the dryer, cm/m

ϕ_r: is the angle of repose of material, degrees

Equation 29 simply assumes that if there is more than enough material in the dryer to fill the lifters, the extra material must progress through the shell by tumbling along the lower portion (kiln action) of the shell.

In this section, the above Factor is determined in relation to the obsrtuctions installed inside a dryer in order to increase the retention time of the material. The behavior of the material between two obstructions (annular rings) is shown in Fig. 20. The volume of the product is estimated from the basic assumption that the material will progress to the lower obstruction following an upward path.

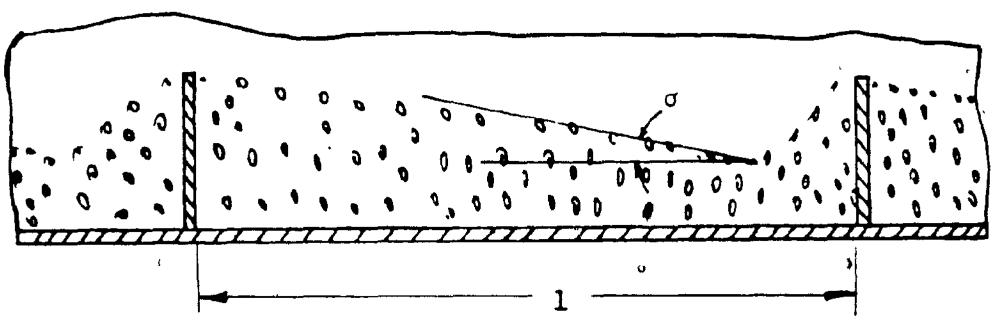


Fig. 20. Motion of particles between two obstructions

The volume of the solids is determined by neglecting the effect due to the slope of the dryer, and using three different geometric elements to represent the cross sectional area of the material as shown in Fig. 21.

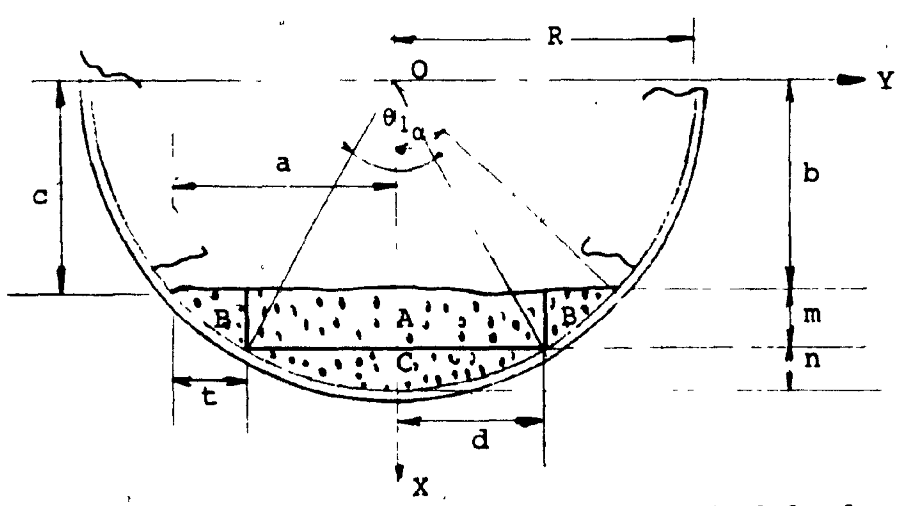


Fig. 21. Geometric presentation of the bed load

2.2.10.1 Calculation of volume

1. Element A

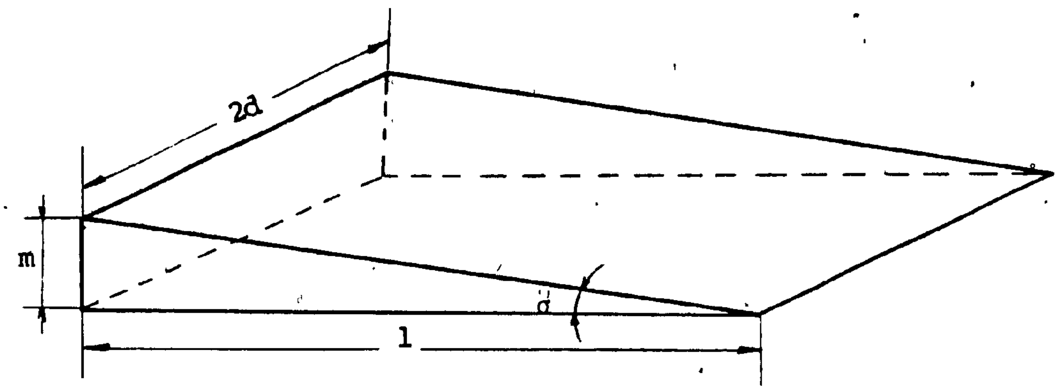


Fig. 22. Presentation of element "A"

The volume of the element A is given by

$$V_a = mld \tag{30}$$

2. Element B

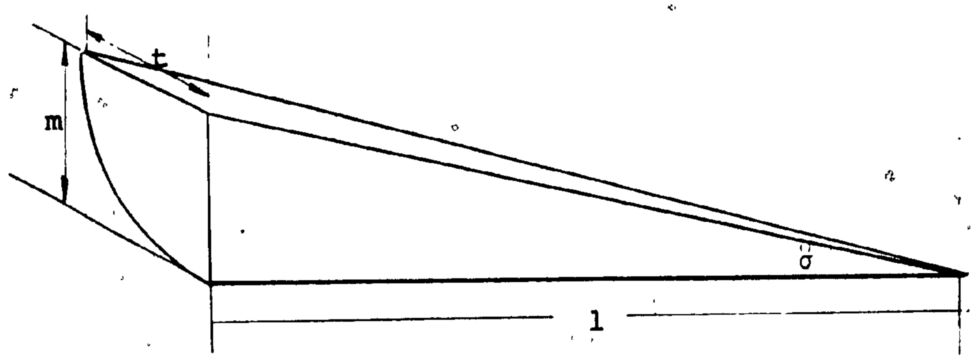


Fig. 23. Presentation of element "B"

The volume of the element B can be expressed as the volume of a pyramid with base 1/2 tc and height l

$$V_b = 1/6\,(tml) \tag{31}$$

3. Element C

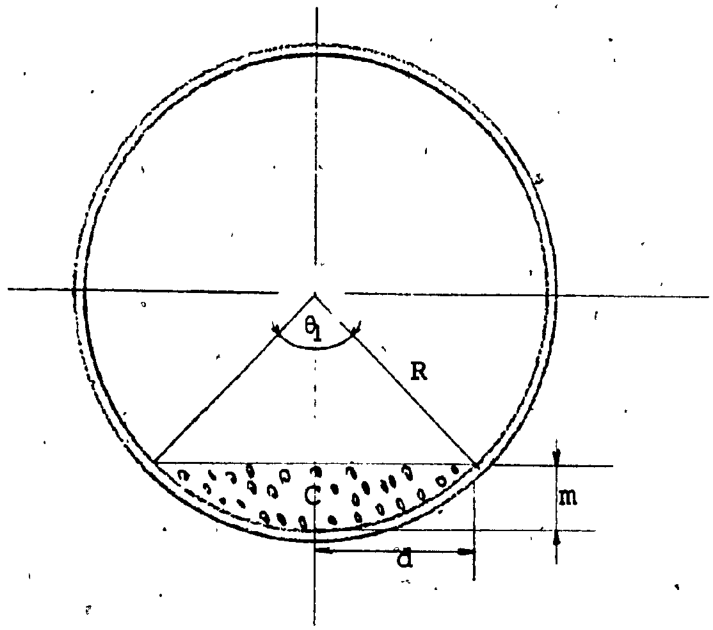


Fig. 24. Presentation of cross sectional area of element "B"

The cross sectional area of the circular segment shown in Fig. 24 is given by

$$A_s = (1/2)\ R^2(\theta_1 - \sin\theta_1) \qquad (32)$$

where

$$\theta_1 = 2\theta = \tan^{-1}\ d/c \qquad (33)$$

The volume of element C is

$$V_c = A_s l \qquad (34)$$

The volume of the material between the two obstructions is equal to:

$$V = V_a + 2V_b + V_c \qquad (35)$$

The dimentions shown in Fig. 21 can be determined by trigonometry from the calculated inside radius of the dryer and the percentage of the loaded area.

$$a = R \sin\alpha \tag{36}$$

$$b = R \cos\alpha \tag{37}$$

$$c = R \cos\Theta \tag{38}$$

$$d = R \sin\Theta \tag{39}$$

$$m = c - b \tag{40}$$

$$n = R - c \tag{41}$$

$$t = a - d \tag{42}$$

where angle α can be directly read from Fig. 17.

The depth of the obstructions is established through a trial an error procedure until the value of the retention time in Equation 29 is approximately equal to the retention time specified for this drying operation. The percentage of the loaded area due to the presence of the obstacle is calculated and angle Θ is determined again from Fig. 17.

Finally, the Factor can be defined as the ratio of the volume of the material as calculated in this section to the volume due to bed load.

2.3 Sizing of direct-heated rotary dryers

2.3.1 General

The specific steps to determine the size of a rotary dryer under certain operating conditions are outlined in their normal sequence, in which they occur, in order to establish the parameters of the drying process.

2.3.2 Heat balance

It is assumed that the drying of solids in a dryer is taking place in three stages.

(i) Heating the solids to the wet-bulb temperature of the drying medium.

(ii) Drying the material substantially at this temperature.

(iii) Heating up the material to its discharge temperature and evaporating some of the moisture remaining at the end of stage (ii).

Direct-heating rotary dryers suffer considerable heat losses both from the combustion chamber and from the dryer shell surface unless adequate insulation is provided to minimize this effect. This would mean the difference between a heat loss of 15,770 to 18,930 W/m^2 (5,000 to 6,000 Btu/hr-ft^2) when insulated and 790 to 950 W/m^2 (250 to 300 Btu/hr-ft^2) when adequately insulated.

Major heat losses are also those in the exhaust gases. Their use in the heat recovering system to whatever extent is permissible, will assist to increase the inlet temperature of the combustion and tempering air in the process.

The overall heat-transfer operation can be covered by the expression

$$Q_t = U_a AL(\Delta T)_m \tag{43}$$

where:

Q_t: is the total heat required, kW

$(\Delta T)_m$: is the overall temperature difference, ^oC

Determination of the temperature difference at each stage of drying is difficult, so that an overall treatment of the heat-transfer mechanism covered by the above expression is more practicable.

Furthermore, where the product is high in moisture content, $(\Delta T)_m$ can be considered to approximate to the logarithmic mean temperature, which is defined to be:

1. For parallel-flow dryers

$$(\Delta T)_m = \frac{(T_{gi} - T_{mi}) - (T_{go} - T_{mo})}{\ln \dfrac{(T_{gi} - T_{mi})}{(T_{go} - T_{mo})}} \qquad (44)$$

2. For counter-flow dryers

$$(\Delta T)_m = \frac{(T_{gi} - T_{mo}) - (T_{go} - T_{mi})}{\ln \dfrac{(T_{gi} - T_{mo})}{(T_{go} - T_{mi})}} \qquad (45)$$

The logarithmic mean temperature difference can be determined from Chart 3 (16).

2.3.3 Gas flow rate

The volume of air per minute required to transfer the heat is determined from the following Equations

$$\dot{m}_a = Q_t/c_a(T_{gi} - T_a) \tag{46}$$

$$\dot{v}_a = \frac{\dot{m}_a}{60} \times \frac{359}{29} \times \frac{(273 + T_{go})}{(273 + 0)} \times 0.06243 \tag{47}$$

where:

- c_a: specific heat of air, kJ/kg-^{o}C
- $\dot{m}_a$: mass flow rate of air, kg/hr
- T_a: ambient temperature, ^{o}C
- T_{gi}: inlet gas temperature, ^{o}C
- T_{go}: outlet gas temperature, ^{o}C, for Equ. 47 use ^{o}F
- T_{mi}: inlet material temperature, ^{o}C
- T_{mo}: outlet material temperature, ^{o}C
- $\dot{v}_a$: air flow rate, m^3/min.

The total volume of the gases leaving the dryer is equal to the sum of the air and water vapour volume.

$$\dot{v}_m = \frac{\text{kg/hr evaporated}}{60} \times \text{sp. vol. vapour} \tag{48}$$

$$\dot{v}_t = \dot{v}_a + \dot{v}_m \tag{49}$$

where:

- $\dot{v}$: water vapour flow rate, m^3/min.
- $\dot{v}_t$: total amount of gases leaving the dryer, m^3/min

2.3.4 <u>Design velocities</u>

A particle can be conveyed by the aerodynamic effect of the gas stream. A relationship was developed between conveyed material velocities and equivalent diameter of particles as a function of the bulk weight density (16).

In a horizontal pipe

$$v_h = 6000\ sD_p^{0.4}/(s + 1) \tag{50}$$

where:

D_p: equivalent diameter of a particle, use inches

s: specific gravity of the conveyed material

v_h: velocity of conveyed particles, m/min.

The calculated velocity is corrected at the design gas temperature in terms of density ratio.

$$v_c = v_h \times \frac{1.2}{\rho_a} \tag{51}$$

where:

v_c: corrected gas velocity in terms of density ratio, m/min.

The formula assumes that the gas velocity will be equal to the velocity of the picked-up particles at the discharge end of the dryer, and all fines of the calculated size will be lifted and conveyed. The conveyed load of the material is usually expressed in grains per cubic meter of the exhaust gases.

The effect of gas velocity on the showering load is expressed as:

$$S_e = S + S_c. \tag{52}$$

where:

S: the slope of dryer, cm/m

S_c: the change in the slope as a result of gas velocity cm/m

S_e: the effective slope, cm/m

The variable S_c has a positive value in parallel-flow dryer, and a negative in a counter-flow.

2.3.5 Dryer diameter

The diameter of the dryer is related to the velocity of the gases by the following Equation

$$D = 2 \left(\frac{\dot{V}_t}{v_c \pi} \right)^{\frac{1}{2}} \tag{53}$$

It can be determined directly from the above expression as long as the velocity of the gases is known or is already established for this application.

2.3.6 Dryer length

The length of a dryer operating in either parallel-flow or counter-flow involves the calculation of the length corresponding to the overall heat-transfer process.

$$L = \frac{Q_t}{A(\Delta T)_m U_a} \tag{54}$$

Actually, the calculated length of the dryer may be increased one to six times to meet the recommended value of the retention time specified under the given set of operating conditions.

2.3.7 Dew point

The exhaust gas temperature has a minimum range beyond which the water in the outcoming gases will condense on the drying products in a parallel-flow dryer. Experimentally it was found that the dew point of the exhaust gases should be at least 10 to 20 ^{o}C higher than the final product temperature in order to avoid condensation on the outgoing product.

Chapter III

Design Data

3.1 General

Most of the enclosed data are applicable to more types of thermal dryers but the worked example below, is concerned specifically with direct-heated rotary dryers. In this system granulated material is exposed to a drying medium of hot gas stream. Solids and gas come in contact in a rotating drum, where a direct-fired air heater provides the make-up gas for heating and absorption of the evaporated water.

3.2 The problem

The client specifies the drying of a material, its feed rate, initial and final moisture contents, and most of the time its physical size and characteristics. More often than not, the feed and also the air at inlet to the air heater are at ambient temperature, taken 16 ^{O}C (60 ^{O}F). In order to select the correct size of equipment it is the object of the enclosed design procedure to give values to:

(i) the flow rate of gases entering and leaving the dryer

(ii) the rate of fuel consumption

(iii) the percentage of loaded of the cross sectional area per unit length

(iv) retention time

(v) the dryer efficiency, dew point and moisture content of the exhaust gases.

(vi) the dust load in exhaust gas

(vii) the horsepower requirements

The following example illustrates the basic techniques of sizing a dryer.

3.3 Design example

3.3.1 Capacity

It is required to dry 30,000 kg/hr of granular material from 14% to 3% of moisture. The specific heat of the material is 0.84 kJ/kg-^{O}C (0.2 Btu/lb$_m$-^{O}F), and its bulk density is 1,760 kg/m^3 (110 lb$_m$/ft^3) wet and 1,440 kg/m^3 (90 lb$_m$/ft^3) dry. The screen analysis of the material on a percentage basis was recorder as:

% of material	mesh size	
11.8	10	+100
46.2	-100	+140
29.8	-140	+200
8.7	-200	+270
3.5	-270	

3.3.2 Design discussion

The effectiveness of any form of dryer varies with the nature and size of the feedstock and before the design can proceed, it is necessary to know the safety range of temperature of the drying medium. This can only be obtained by experience with similar materials, or by conducting pilot plant tests. For present purposes it is assumed the material is capable of being heated by gas, in a parallel-flow dryer, at 980 to 1,090 °C (1,800 to 2,000 °F) and it has been decided that an exhaust gas temperature of 149 °C (300 °F) will produce satisfactory conditions in the discharge with a material temperature of 100 °C (212 °F).

The true duty of a dryer is to evaporate a given rate of water but to this must be added the heat losses due to the nature of the process and imperfections of the equipment.

The final design is illustrated in Fig. 25. Although it has been determined by an indirect method, its final arrangement is presented at this point so the overall design concept is easily understood.

3.3.4 Mass balance

Dry solids in feed = 30,000(1 - 0.14)

$$\dot{W}_m = 25,800 \text{ kg/hr } (46,470 \text{ lb/hr})$$

Water rate in feed = 30,000 x 0.14

$$\dot{W}_w = 4,200 \text{ kg/hr } (9,250 \text{ lb/hr})$$

Let $\dot{W}$ in kg/hr be the water rate in the product, then

$$0.03 = \frac{\dot{W}}{\dot{W} + 25,800}$$

thus

$$\dot{W} = 0.03 \times 25,800/0.97$$

$$\dot{W} = 800 \text{ kg/hr } (1,760 \text{ lb/hr})$$

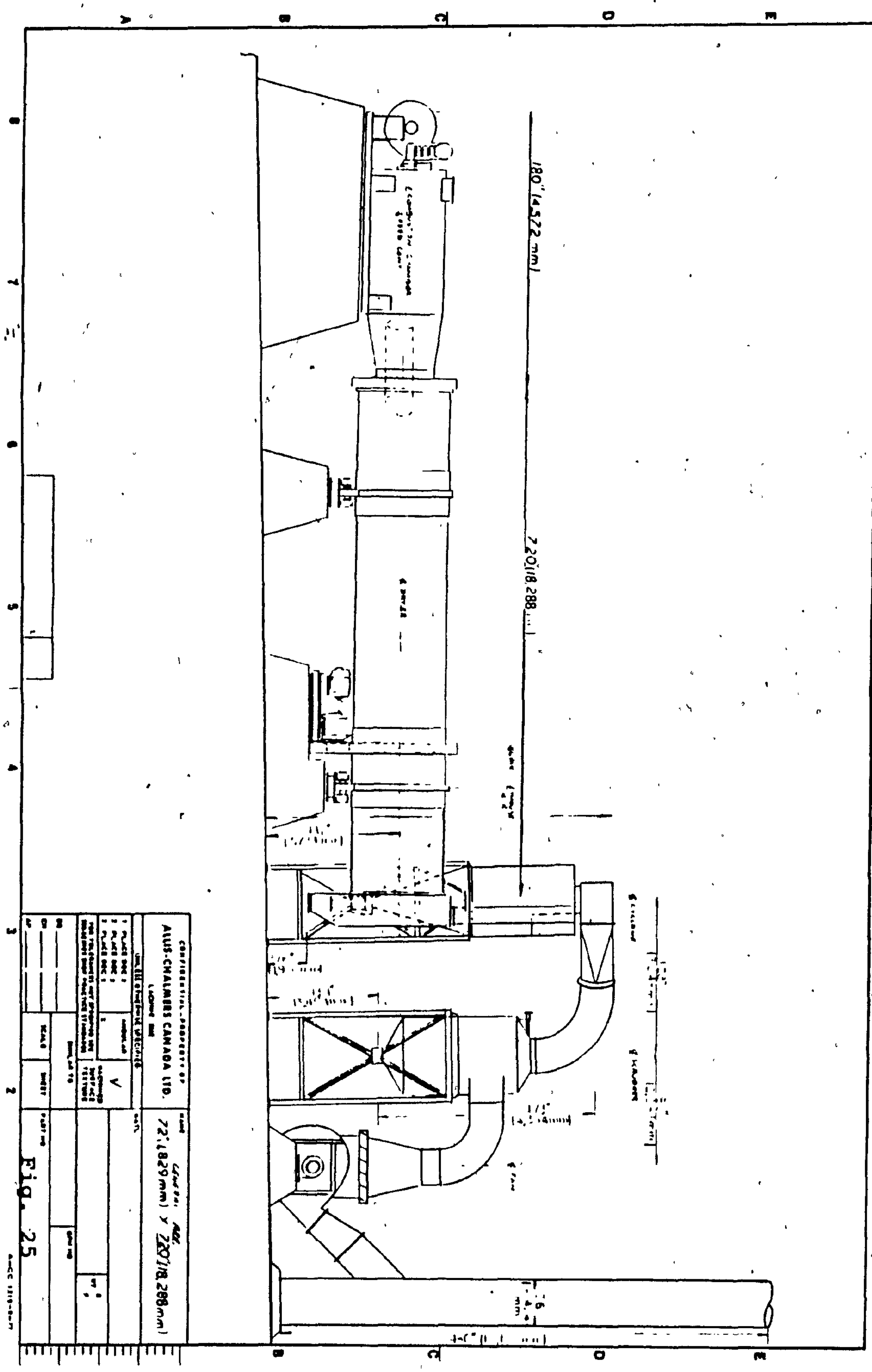


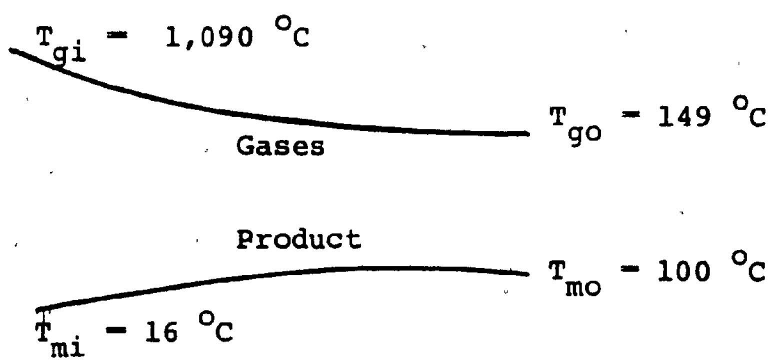
Fig. 25

The amount of the water evaporated is then

$$\dot{W}_e = 4,200 - 800 = 3,400 \text{ kg/hr } (7,500 \text{ lb/hr})$$

3.3.4 Heat balance

For a parallel-flow rotary dryer



Heat requirements

(A) - Heat to raise the temperature of the feedstock

$$Q_a = \dot{W}_m \times c_m (T_{mi} - T_{mo})$$

$$Q_a = \frac{25,800}{3,600} \times 0.84 \; (100 - 16)$$

$$Q_a = 506 \text{ kW } (1,726,550 \text{ Btu/hr})$$

(B) - Heat to residual moisture

From the thermodynamic tables of water and steam, the enthalpy of water at 16 °C (60 °F) is

$$h_w = 65.3 \text{ kJ/kg } (28.07 \text{ Btu/lb}_m)$$

and the enthalpy of water at 100 °C (212 °F) is

$$H_w = 419 \text{ kJ/kg } (180.16 \text{ Btu/lb}_m)$$

then

$$Q_b = \dot{W} (H_w - h_w)$$

$$Q_b = \frac{800}{3,600} (419 - 65.3) = 78.6 \text{ kW } (268,190 \text{ Btu/hr})$$

<u>(C) - Heat</u> to elevate excess water to boiling point

The enthalpy of water at 100 °C (212 °F) is 419 kJ/kg

then

$$Q_c = \dot{W}_e (H_w - h_w)$$

$$Q_c = \frac{3,400}{3,600} (419 - 65.3) = 334.05 \text{ kW } (1,139,800 \text{ Btu/hr})$$

<u>(D) - Heat</u> to evaporate water at 100 °C (212 °F)

The latent heat of evaporation at 100 °C is 2,256.68 kJ/kg (970.2 Btu/lb_m)

$$Q_d = \dot{W}_e \times 2,256.68$$

$$Q_d = \frac{3,400}{3,600} \times 2,256.68 = 2,131.2 \text{ kW } (7,271,900 \text{ Btu/hr})$$

<u>(E) - Heat</u> loss in superheating water at 149 °C (300 °F)

From the tables of the thermodynamic properties of water and steam at atmospheric pressure the enthalpies are:

$$h_s = 2,675.83 \text{ kJ/kg } (1,150.4 \text{ Btu/lb}_m)$$

$$H_s = 2,774.68 \text{ kJ/kg } (1,192.9 \text{ Btu/lb}_m)$$

then

$$Q_e = \dot{W}_e (H_s - h_s)$$

$$Q_e = \frac{3,400}{3,600} (2,774.68 - 2,675.83)$$

$$Q_e = 93.4 \text{ kW } (318,690 \text{ Btu/hr})$$

(F) - Heat loss from dryer

The heat loss from the dryer can be estimated from Chart 1 (16) by entering the value of the variables as being presented in this Chart. Assume a temperature difference between ambient air and dryer shell surface of 66 °C (150 °F), and wind velocity of 3.05 m/s (10 ft/s), then the heat loss per square meter of dryer surface is 2,208 W/m^2 (700 Btu/hr-ft^2).

$$Q_f = U_d \times \pi \times D \times L$$

$$Q_f = 2,208 \times \pi \times 1.83 \times 18.3$$

$$Q_f = 232.3 \text{ kW } (792,630 \text{ Btu/hr})$$

(G) - Heat loss from combustion chamber

The heat loss per square meter of combustion chamber surface is estimated as above, with U_d = 6,940 W/m^2 (2,200 Btu/hr-ft^2) at ΔT = 177 °C (350 °F) and wind velocity of 3.05 m/s (10 ft/s).

$$Q_g = 6,940 \times \pi \times 2.6 \times 3.05$$

$$Q_g = 173 \text{ kW } (590,290 \text{ Btu/hr})$$

The overall heat as calculated in this section is

$$Q_1 = Q_a + Q_b + Q_c + Q_d + Q_e + Q_f + Q_g$$

$$Q_1 = 3{,}548 \text{ kW } (12{,}106{,}130 \text{ Btu/hr})$$

Air required to transfer heat and heat losses

$$\dot{m}_a = Q_1/c_a(T_{gi} - T_a)$$

$$\dot{m}_a = 3{,}548{,}000/1.005\times10^3\ (1{,}090 - 16)$$

$$\dot{m}_a = 3.29 \text{ kg/s} = 11{,}838 \text{ kg/hr } (26{,}044 \text{ lb}_m\text{/hr})$$

(B) - Heat loss in exhaust gases

$$Q_b = \dot{m}_a c_a (T_{go} - T_a)$$

$$Q_b = 3.29 \times 1.005\ (149 - 16)$$

$$Q_b = 440 \text{ kW } (1{,}501{,}324 \text{ Btu/hr})$$

(C) - Heat loss in moisture in exhaust gases

Assume 70% relative humidity and 16 $^{\circ}$C (60 $^{\circ}$F) ambient temperature from the Psychrometric Chart

$$\text{Moisture content} = 0.0075\ \frac{\text{lb}_m \text{ of moisture}}{\text{lb}_m \text{ of dry air}} \times \dot{m}_a$$

$$= 0.0075 \times 11{,}838 = 88.78 \text{ kg/hr}$$

$$= (195 \text{ lb}_m\text{/hr})$$

then

$$Q_c = \frac{88.78}{3{,}600}\ (2{,}774.68 - 65.3)$$

$$Q_c = 66.8 \text{ kW } (227{,}928 \text{ Btu/hr})$$

The overall heat as calculated in this section is

$$Q_2 = Q_b + Q_c = 506.8 \text{ kW } (1{,}729{,}000 \text{ Btu/hr})$$

Heat loss in burning fuel

From the fuel data Table 1 (16), the gross heating value (GHV), and the net heating value (NHV) of the natural gas are:

$$\text{GHV} = 46,857 \text{ kJ/kg } (20,145 \text{ Btu/lb}_m)$$

$$\text{NHV} = 42,272 \text{ kJ/kg } (18,174 \text{ Btu/lb}_m)$$

$$\text{Availability of fuel} = 42,272/46,857 = 90.215\%$$

The gross heat requirements are

$$Q_t = (Q_1 + Q_2)/0.90215$$

$$Q_t = 4,055.35/0.90215 = 4,495.2 \text{ kW } (15,338,000 \text{ Btu/hr})$$

The heat loss in burning fuel is

$$(4,495.2 - 4,055.35) = 439.85 \text{ kW } (1,500,813 \text{ Btu/hr})$$

The water in burning fuel is

$$\dot{W}_b = 439.85/(2,774.68 - 65.3)$$

$$= 0.162 \text{ kg/s} = 584.4 \text{ kg/hr } (1,285 \text{ lb}_m/\text{hr})$$

Volume of gases leaving dryer

The air quantity calculated previously does not take into account the gas quantity required in heat losses.

$$\text{Total air} = Q_t/c_a(T_{gi} - T_a)$$

$$= 4,495.2/1.005(1,090 - 16) = 4.16 \text{ kg/s}$$

$$= 14,993 \text{ kg/hr } (32,984 \text{ lb}_m/\text{hr})$$

Water evaporated

(i)	moisture in material	3,400
(ii)	moisture in air	88.29
(iii)	moisture in burning fuel	584.4
	Total	4,072.7 kg/hr
		(8,960 lb_m/hr)

Gas quantities

$$\text{Air} = \frac{14,993}{60} \times 0.06243 \times \frac{359}{29} \times \frac{(273 + 149)}{(273 + 0)}$$

The conversion factor of one ft^3/lb_m is equal to 0.06243 m^3/kg

Air = 298.52 m^3/min. (10,542 CFM)

$$\text{Water} = \frac{4,072.7}{60} \times 0.06243 \times \frac{359}{18} \times \frac{(273 + 149)}{(273 + 0)}$$

Water = 130.6 m^3/min. (4,612 CFM)

Total = 429 m^3/min. (15,154 CFM)

Density of gases leaving dryer

$$\rho_a = (14,993 + 4,072.7)/429 \times 60$$

$$\rho_a = 0.74 \text{ kg/m}^3 \; (0.046 \text{ lb}_m/\text{ft}^3)$$

$$\text{Humidity} = 4,072.7/14,993 = 0.272 \frac{\text{kg water}}{\text{kg dry air}}$$

3.3.5 Velocity of gases

Since the dust load leaving a dryer is proportional to the cost of the dust collecting equipment, it was found to be more reasonable to determine the gas velocity in terms of the amount of the particles leaving the dryer.

Some useful data

MESH SIZE	MICRON
10	1650
20	830
35	420
48	300
65	220
100	150
150	110
200	74
325	44

One micron = 0.001 = 0.0001 cm = 0.00004 in.

0.454 kg of dust (1 lb) = 7,000 grains

Dust loads are usually expressed in grains/m^3 (grains/ft^3)

From Table 2 (16)

$$s = 1.44 \text{ (Dry sand)}$$

From the screen analysis of the material, it is assumed D_p = 200 mesh.

Then,

$$D_p = 74 \text{ micron} = 0.0074 \text{ cm } (0.00292 \text{ in.})$$

The conveyed velocity is

$$v_h = 6{,}000 \times 1.44 \times 0.305 \times 0.00292^{0.4}/(1.44 + 1)$$
$$= 104.6 \text{ m/min. } (343 \text{ ft/min.})$$

Correcting v_h, at the design temperature in terms of density ratio.

$$v_c = 104.6 \times \frac{0.075}{0.046} = 170.5 \text{ m/min. (560 ft/min.)}$$

Dust load

The particle analysis is given on a volume basis of one cubic meter of material.

$$\rho_m = 1{,}440 \text{ kg/m}^3 \text{ (90 lb}_m\text{/ft}^3\text{)}$$

Volume of material = (25,800 + 800)/1,440

= 18.5 m^3/hr (652 ft^3/hr)

Volume of conveyed material = 18.5 x 0.122

= 2.26 m^3/hr (79.54 ft^3/hr)

Weight of conveyed material = 2.26 x 1,440 = 3,254 kg/hr

= (7,159 lb_m/hr)

$$\text{Dust load} = \frac{3{,}254 \times 7{,}000}{0.454 \times 60} \times \frac{1}{429} = 1{,}950 \text{ grains/m}^3$$

= (55.2 grains/ft^3)

3.3.6 Dryer diameter

The diameter of a dryer is related to the volume of the outgoing gases by

$$D = 2(\dot{v}_t/v_c\pi)^{\frac{1}{2}},$$

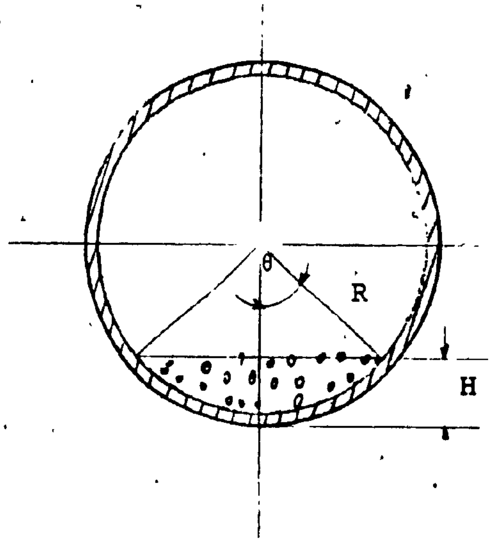
$$D = 2(429/170.5 \times \pi)^{\frac{1}{2}} = 1.83 \text{ m (6 ft)}$$

3.3.7 Design of lifters

Assume the percentage of the loaded area of the dryer is 12%, then from Fig. 17 (16).

$\sin\theta = 0.76$

$\theta = 50^{\circ}$

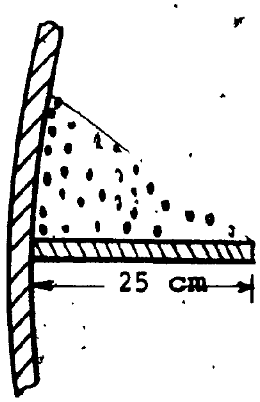


$H = R\,(1 - \cos\theta)$

$= 0.92(1 - \cos 50) = 0.32$ m (1 ft)

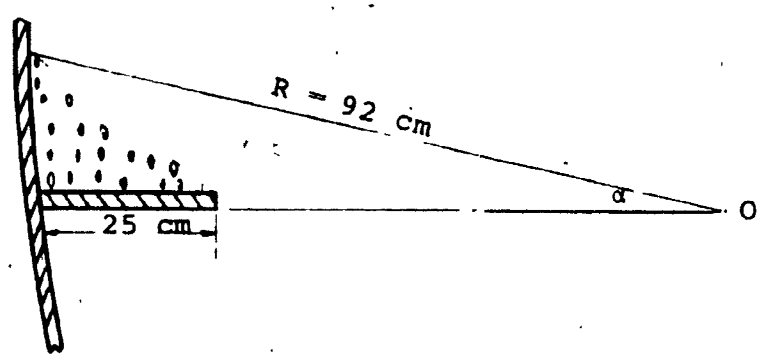
Therfore, a lifter depth of 25 cm (10 in.) will be adequate.

The angle of repose of material is $\phi_r = 32^{\circ}$, from Table 3 (16). The cross sectional area of the material retained by each lifter is determined as follows



$$A_m = 0.5 \times 25^2 \times \tan 32 = 195 \text{ cm}^2 \ (0.21 \text{ ft}^2)$$

Number of lifters



$$\tan \alpha = \frac{25 \times \tan 32}{R}$$

$$= 25 \times 0.625/92 = 0.17$$

$$\alpha = 10^o$$

$$N_1 = 360/10 = 36$$

For fabrication purposes 24 lifters have been used.

The falling time of a particle is

$$t_f = (2D \sin \phi/g)^{\frac{1}{2}}$$

$$= (2 \times 1.83 \times 0.53/9.81) = 0.445 \text{ s}$$

The speed of rotation times the dryer diameter in meters lies between 9 and 12.

$$n \times D = 12$$

$$n = 12/1.83 = 6.5 \text{ rpm}$$

<u>The lifting time</u>

$$t_1 = 120 \times \phi/n\pi$$

with

$$\phi = (32/180) \times \pi = 0.56 \text{ radians}$$

$$t_1 = 120 \times 0.56/6.5 \times \pi = 3.29 \text{ s}$$

<u>The showering cycle time</u>

$$t_c = t_f + t_1 = 3.735 \text{ s}$$

<u>Number of lifters</u> used per showering cycle

$$N_e = K_e N_1$$

with

$$K_e = t_c/t_r$$

$$t_r = 60/n = 60/6.5 = 9.23 \text{ s}$$

and

$$K_e = 3.375/9.23 = 0.405$$

$$N_e = 0.405 \times 24 = 9.72$$

<u>The showering load</u> per unit length of dryer

$$W_m = N_e \times A_m \times \rho_m$$

$$\rho_m = (1{,}760 + 1{,}440)/2 = 1{,}600 \text{ kg/m}^3$$

$$W_m = 9.72 \times 0.0195 \times 1{,}600 = 303 \text{ kg/m (204 lb/ft)}$$

Dryer length

$$L = Q_t/U_a A(\Delta T)_m$$

with

$$A = \frac{\pi}{4} \times D^2 = \frac{\pi}{4} \times 3.35 = 2.63 \text{ m}^2 \ (28.3 \text{ ft}^2)$$

$$(\Delta T)_m = \frac{(1{,}090 - 16) - (149 - 100)}{\ln \frac{(1{,}090 - 16)}{(149 - 100)}} = 332 \ ^{o}C \ (626 \ ^{o}F)$$

The volumetric heat-transfer coefficient

$$U_a = h_c \pi \ D_p^2 (P_{nh}/AL)$$

with

$$h_c = \frac{k_a}{D_p} (2 + 0.6 \ R_e^{1/2} \ P_r^{1/3})$$

$$R_e = D_p \bar{v}_r \ \rho_a / \mu_a$$

$$\bar{v}_r = (\bar{v}_p^2 + u^2)^{\frac{1}{2}}$$

and

$$\bar{v}_p = (Dg/2)^{\frac{1}{2}}$$

$$= (1.83 \times 9.81/2)^{\frac{1}{2}} = 3 \text{ m/s} \ (9.84 \text{ ft/s})$$

$$u = v_c$$

$$= 170.5/60 = 2.84 \text{ m/s} \ (9.32 \text{ ft/s})$$

$$\bar{v}_r = (3^2 + 2.84^2)^{\frac{1}{2}} = 4.13 \text{ m/s} \ (13.55 \text{ ft/s})$$

The average particle diameter is determined from the screen analysis as follows

$$D_p = 0.118 \times 0.042 + 0.452 \times 0.0118 + 0.298 \times 0.0103$$

$$+ 0.087 \times 0.00742 + 0.035 \times 0.00612$$

$$D_p = 0.0142 \text{ cm} = 1.42 \times 10^{-4} \text{ m } (4.7 \times 10^{-4} \text{ ft})$$

At $\rho_a = 0.74$ kg/m^3 the gases have

$$c_a = 1.0258 \text{ kJ/kg-}^{\circ}\text{C}$$

$$k_a = 0.0389 \text{ W/m-}^{\circ}\text{C}$$

$$\mu_a = 2.566 \times 10^{-5} \text{ kg/m-s}$$

$$P_r = 0.681$$

thus

$$R_e = 1.42 \times 10^{-4} \times 4.11 \times 0.74/2.566 \times 10^{-5} = 17$$

and

$$h_c = \frac{0.0389}{1.42} \times 10^4 \, (2 + 0.6 \times 17^{1/2} \times 0.681^{1/3})$$

$$= 1{,}144 \text{ W/m}^2\text{-}^{\circ}\text{C } (201 \text{ Btu/hr-ft}^2\text{-}^{\circ}\text{F})$$

The term $\pi D_p^2(P_{nh})$ may be assumed to be equal to the showering area of the material retained by the lifters, and AL is the volume of unit length of the dryer.

$$\pi D_p^2(P_{nh}) = N_e A_m$$

$$= 9.72 \times 0.0195 = 0.1895 \text{ m}^2 \, (2.04 \text{ ft}^2)$$

$$AL = 2.63 \text{ m}^2 \, (28.3 \text{ ft}^2)$$

$$U_a = 1,144 \times 3.3 \times \frac{0.1895}{2.63} = 275 \text{ W/m}^3\text{-}^oC$$

$$= (15 \text{ Btu/hr-ft}^3\text{-}^oF)$$

$$L = 4,495,200/275 \times 2.63 \times 332$$

$$L = 18.3 \text{ m (60 ft)}$$

3.3.8 Bed load calculations

(A) - Showering load

$$W_m = 303 \times 18.3 = 5,545 \text{ kg (12,220 lb)}$$

(B) - Effective slope

As a first trial assume the slope of the dryer to be 4.17 cm/m (0.5 in/ft). The effect of gas velocity on the effective slope was determined experimentally (16) to be covered by the following expression

$$S_c = 5.2 \text{ AU/W}$$

with

$$W = W_m \times t_f/t_c$$

$$= 5,545 \times 0.445/3.735 = 660 \text{ kg (1,455 lb)}$$

and

$$U = \frac{v_a \rho_a L}{\text{Divisor}}$$

with

$$\text{Divisor} = 5,000 \log \frac{4,950}{v_c - 50} = 4,935$$

$$U = 560 \times 0.046 \times 60/4,935 = 0.313$$

$$S_c = 5.2 \times 28.3 \times 0.313/1,455 = 0.032 \text{ m/m}$$

For parallel-flow

$$S_e = S/100 + S_c = 4.17/100 + 0.032 = 0.0737 \text{ m/m}$$

(C) - Showering output per minute is equal to the showering load per meter of dryer length times the advance rate of the showering material.

$$\text{Advance rate} = \frac{D \sin\phi}{t_c} \times S_e \times 60$$

$$= \frac{1.83 \times 0.53}{3.735} \times 0.0737 \times 60$$

$$= 1.15 \text{ m/min. } (3.77 \text{ ft/min.})$$

Showering output = 303 x 1.15 = 348 kg/min. (767 lb/min.)

(D) - Kiln action load

1. Retention time

$$t = \frac{3.094(32)^{\frac{1}{2}} \times 18.3}{4.17 \times 6.5 \times 1.83} = 6.5 \text{ min.}$$

2. Kiln action output

Mean input load = (30,000 + 26,600)/2 = 28,300 kg/hr

= (62,390 lb/hr)

Kiln action output = mean input load - showering output

= 28,300 - 20,880 = 7,420 kg/hr

= (16,360 lb/hr)

3. Kiln action load

$$\text{Kiln action load} = \frac{t}{60} \times \text{Kiln action output}$$

$$= 0.1083 \times 7420 = 804 \text{ kg } (1,772 \text{ lb})$$

4. Mean retention time is taken as the ratio of the bed load to the mean throughput

Total bed load = 5,545 + 804 = 6,349 kg (13,992 lb)

$$t_m = \frac{6,349}{28,300} \times 60 = 13.46 \text{ min.}$$

5. Percentage of shell loaded

$$X = \frac{\text{bed load}}{AL} \times \frac{1}{\rho_m} \times 100$$

$$= \frac{6,349}{1.83 \times 18.3} \times \frac{1}{1,600} \times 100 = 11.85\%$$

Both retention time and the percentage loaded of the shell are in good agreement with previously experimental data.

3.3.9 Horsepower calculations

1. Showering horsepower

$$SHP = \frac{\text{showering load} \times B}{33,000 \times E}$$

with

$$B = \frac{D \sin\phi}{t_c} = \frac{1.83 \times 0.53}{3.735} \times 60 = 15.58 \text{ m/min.}$$

$$= (51.11 \text{ ft/min.})$$

$E = 0.9$

$$SHP = \frac{12,220 \times 51.11}{33,000 \times 0.9} = 21 \text{ hp}$$

2. Kiln action horsepower

$$KHP = \frac{\text{Kiln action load} \times F \times \sin\phi_o}{33,000 \times 0.9}$$

with

$\phi_o = 18^{\circ}$ (angle of conveying from Table 3)

$F = 2\pi nR = 2\pi \times 6.5 \times 3 = 123$ ft/min.

$$KHP = \frac{1,772 \times 123 \times 0.31}{33,000 \times 0.9} = 2.3 \text{ hp}$$

3. Friction horsepower

$$FHP = 0.0000092 \times W_r \times D_r \times n \times F_f$$

with

W_r = 24,500 kg (54,000 lb) (total rotating weight)

D_r = 2,134 mm (84 in) (diameter of riding ring)

F_f = 0.018 for oil lubricated bearings

= 0.06 for grease lubricated bearings

$$FHP = 54,000 \times 84 \times 6.5 \times 0.018 \times 0.0000092 = 5 \text{ hp}$$

Total = 28.3 hp

3.4 Auxiliary equipment

1. Cyclone

Conventional types of centrifugal separators are used to reclaim the fines.

The three Charts 8, 9, and 10 (16) which are included offer a simplified method for selecting the right size cyclone for a particular application, taking into account the air flow rate and temperature, the particle size and density of the dust to be collected, the altitude at the customer's plant site, and the desired collection efficiency and permissible pressure drop.

A. Design conditions

1. 429 m^3/min. (15,150 CFM) at 149 °C (300 °F) and zero elevation.
2. Dust analysis: 1.5 specific gravity with 15% less than 10 Microns.
3. 85% - 90% collection efficiency required.

B. Find

1. Cyclone size
2. Cyclone pressure drop at 21 °C (70 °F)
3. Cyclone pressure drop at 149 °C (300 °F)
4. Dust load leaving cyclone

C. Procedure

Step 1 - Find size, velocity and equivalent pressure drop at standard conditions using Charts 8 and

9. Using Chart 10, find collection efficiency. If below 85% - 90% collection efficiency, a branch of smaller cyclones will be required.

Step 2 - On Chart 8, it is seen that a size 169 single cyclone will handle 429 m^3/min. (15,150 CFM) at an inlet velocity of 884 m/min. (2,900 ft/min.)

Step 3 - Using Chart 9, at an inlet velocity of 884 m/min. (2,900 ft/min.) rise vertically to intersect with 149 °C (300 °F) curve, move horizontally left to zero elevation line and read 8 cm W.C. (3.15 in W.C.). This is the static pressure drop at operating conditions (S.P.D.). Again at 884 m/min. (2,900 ft/min.) line, move vertically to intersect 21 °C (70 °F) curve and move horizontally to the left and read 11 cm W.C. (4.33 in W.C.) on zero elevation line. This is the static pressure drop at standard conditions.

Step 4 - On Chart 10 rise from the temperature scale at 149 °C (300 °F) to intersect the 1.5 specific gravity curve, move horizontally to line "A". Connect point on line "A" with size 169 on line "B". Where line "A - B" intersects line "C", connect with 15% point line "D" and read corrected % - 10 micron line "E". We read 55% which is transfered to scale "F" to intersect 11 cm

(4.33 in) and drop to read collection efficiency of 85%

D. Summary

Cyclone: single

size 169

capacity: 429 m^3/min. (15,150 CFM) at 149 °C (300 °F)

velocity: 884 m/min. (2,900 ft/min.)

S.P.D.: 8 cm (3.15 in) W.C. at 149 °C (300 °F)

S.P.D.: 11 cm (4.33 in) W.C. at 21 °C (70 °F)

efficiency: 85%

dust load leaving cyclone:

$$1{,}950(1 - 0.85) = 293 \text{ grains/m}^3$$
$$= (8.33 \text{ grains/ft}^3)$$

2. Wet scrubber

If additional efficiency of collection is required, other secondary devices must be provided, such as wet scrubbers.

The use of wet scrubbers, represents an inexpensive way to achieve high efficiency gas cleaning required by today's air pollution control. An effective scrubber cleans industrial exhaust gases to a 1.8 grains/m^3 (0.05 grains/ft^3) or less.

A. Design conditions

1. 429 m^3/min. (15,150 CFM) at 149 ^oC (300 ^oF)
2. Humidity 0.272 kg water/kg dry air
3. Dust load 293 grains/m^3 (8.33 grains/ft^3)
4. 99% collection efficiency required

B. Find:

1. Scrubber pressure drop at operating temperature
2. Outlet m^3/min. (CFM) and gas temperature
3. Scrubber size
4. Pressure drop at 21 ^oC (70 ^oF)
5. Water rate
6. Scrubber pressure drop
7. Evaporation rate of water

C. Procedure

Step 1 - The dust load involved coincides to that designed as "B" in Table 6 (16). From Chart 11 (16) an efficiency of 99% for curve B requires a pressure drop of at least 23 cm W.C. (9 in W.C.).

Step 2 - From Chart 12 (16), F_R = 0.875. Outlet gas flow rate = 429 x 0.875 = 375 m^3/min. (13,256 CFM). Outlet gas temperature 73 ^oC (163 ^oF).

Step 3 - From Table 7 (16) the smaller scrubber size capable of holding 375 m^3/min. (13,256 CFM) is a D-70.

Step 4 - For a dry fan, F_t from Table 8 (16) is 1.43 at zero elevation. The pressure drop is therefore (23)x(1.43) = 32.89 cm W.C. (12.87 in W.C.). For a wet fan the outlet gas density at 73 °C (163 °F) is 0.847 kg/m³ (0.053 lb_m/ft^3). The pressure drop is therefore, (23)x(1.2)/0.847 = 32.58 cm W.C. (12.83 in W.C.).

Step 5 - We have three possible water requirements, depending on the piping system we use in Fig. 26 (16).

$$GPM = \frac{G \times CFM(inlet)}{F_c}$$

For piping system 1:

$$\text{Water requirements} = \frac{(8)(15,150)}{1,000} = 121 \quad \text{GPM}$$

For piping system 2:

$$\text{Water requirements} = \frac{(3)(15,150)}{3,070} = 14.8 \quad \text{GPM}$$

For piping system 3:

$$\text{Water requirements} = \frac{(3)(15,150)}{58,500} = 0.8 \quad \text{GPM}$$

Step 6 - From Chart 14 (16) water lost by evaporation is 0.289 gals/1,000CFM (inlet)

$$\text{Evaporation} = \frac{0.289 \times 15,150}{1,000} = 4.4 \quad \text{GPM}$$

D. Summary

Final selection is therefore a D-70 Allis Chalmers scrubber, with a pressure drop at operating conditions of 23 cm (9 in) W. C.. Pressure drop at 73 ^{o}C (163 ^{o}F) is 32 cm (12.7 in) W.C.. Collection efficiency 99%.
Outlet gas flow rate 375 m^3/min. (13,256 CFM). Outlet gas temperature 73 ^{o}C (163 ^{o}F). Outlet gas density 0.847 kg/m^3 (0.053 lb_m/ft^3). Dust load leaving scrubber = 293(1 - 0.99) = 2.93 grains/m^3 (0.0833 grains/ft^3). Water requirements are as follows, plus 4.4 GPM lost by evaporation.

Piping system	GPM
1. Once through	121
2. Recycle to 5% slurry	14.8
3. Recycle and thicken to 50% sludge	0.8

3. I.D. Fan selection

On the basis of the established volume of gases leaving the drying equipment (CFM), pressure drop at operating conditions, and pressure drop at ambient air temperature the fan may be selected from the fan manufacture's Charts in accordance with his instructions or usual practice.

The fan was selected as shown in Fig. 25, in the wet side of the scrubber having in mind that the wheel of the fan must be resistant to corrosion, abrasive wear is minimized and the fan operation is more efficient because it is handling a smaller quantity of denser air.

The sizing of the fan will be made according to the following specifications:

1. <u>Fan capacity</u>

Rating = 1.2 x 375 = 450 m^3/min. (16,000 CFM)

Density of gases = $\frac{429}{375}$ x 0.74 = 0.847 kg/m^3

= (0.053 lb_m/ft^3)

Operating temperature = 73 °C (163 °F)

2. <u>Static pressure drop</u>

(i)	across combustion chamber	=	0.64 cm W.C.
(ii)	across dryer	=	1.27
(iii)	across vapour piping	=	8.89
(iv)	across syclone	=	8.0
(v)	across scrubber	=	32.26
	<u>Total</u>	=	51.06 cm W.C.
		=	(20.1 in W.C.)

The static pressure drop through the dryer can be estimated as has been shown in section 1.10, while in the vapour piping was calculated with the help of a computer program.

TABLE 1

FUEL DATA

Type of Fuel	NHV Btu/Lb.	GHV Btu/Lb.	Weight Lbs./Cu. Ft. or Lbs./Gallon	Lbs. Air Per Lb. Fuel	Lbs. Com. Gas Per Lb. Fuel
Natural Gas 970 Btu/Cu.Ft.	18174	20145	0.0481	14.508	15.508
Natural Gas 1100 Btu/Cu.Ft.	20750	22970	0.0478	16.549	17.549
#2 Fuel Oil	18389	19638	7.089	14.433	15.433
#4 Fuel Oil	18181	19353	7.518	14.181	15.181
#6 Fuel Oil (Bunker C)	17370	18345	8.23	13.503	14.501
Commercial Propane	19950	21669	4.24	15.649	16.649
Commercial Butane	19667	21312	4.84	15.4391	16.4391

TABLE 2

PHYSICAL PROPERTIES OF SOLID MATERIALS

Material	Specific Gravity	Lbs. per Cu. Ft.
Asbestos	2.0-2.8	125-175
Ashes	—	43
Asphalt	—	69-94
Asphaltum	1.4	87.3
Balsa	0.11	6.9
Barytes	4.50	281
Basalt	2.72	171
Brick, Common	1.79	112
Brick, Fire	2.40	150
Brick, Hard	2.00	125
Brick, Pressed	2.16	135
Brick, Soft	1.80	112
Brickwork in Com.	1.79	112
Brickwork in Mort.	1.76	110
Cardboard	—	43
Cement, Portland	1.30	94
Cement, Slag	1.9-2.3	130
Chalk	2.77	173
Charcoal	0.35	22.5
Clay	2.16	135
Coal, Bitum., Broken	?	50
Coal, Anthr., Broken	1.50	93.5
Coke, Loose	0.43	26.8
Cork, Granul.	0.07	6.0
Cork, Pressed	0.23	14.0
Corundum	3.90	24.9
Diamond	3.01-3.53	188-220
Dolomite	2.90	181
Earth, Dry, Loose	1.2	75
Earth, Dry, Packed	1.5	93
Earth, Moist, Loose	1.3	81
Earth, Moist, Packed	1.6	100
Emery	4.0	250
Feldspar	2.5	159
Flint	2.6	164
Galena	—	460-470
Glass, Plate	2.76	172
Glass, Window	2.52	157
Glue	—	79
Granite	2.62	167
Graphite	1.9-2.3	126
Gravel, Dry, Loose	1.4-1.7	90-105
Gravel, Dry, Packed	1.6-1.9	100-120
Gravel, Wet	1.9	120
Gunpowder, Black	1.0	62.4
Gypsum	2.28	144
Hornblende	—	187.0
Ice	0.92	57.4

Material	Specific Gravity	Lbs. per Cu. Ft.
Leather, Dry	—	54.0
Lime	0.85	53
Limestone-solid	2.95	184
Linoleum	—	74
Magnesia (Carbonated)	2.40	150
Magnesite	3.00	187
Marble	2.72	170
Mansonry, Dress	2.56	160
Mansonry, Dry, Rubble	2.40	150
Mica	2.93	183
Mortar	1.52	94.8
Mud, Average	1.54	115
Oak	.60-.90	38.56
Paper	0.7-1.15	43.72
Paraffin	0.87	54
Peat	1.33	83
Pitch	1.15	71.8
Plaster-of-Paris	1.5	10.3
Plumbago	2.27	143
Porcelain	2.38	149
Pressed Wood Pulp	—	12
Pumice Stone	0.92	57
Quartz	2.65	165
Rock Salt	—	135
Rosin	1.10	68.6
Rubber, Hard	—	74
Rubber, White	0.93	58
Salt	1.18	73.5
Sand, Dry	1.44	89.7
Sand, Wet	1.76	110
Sandstone	2.40	150
Silica, Fused	—	138
Slag	—	125-240
Slate	2.80	175
Snow, Compact	0.80	50
Soapstone	2.73	174
Stone, Crushed	1.6	100
Sugar	1.6	100
Sulphur	2.0	125
Talc	2.6	169
Tallow	0.94	58.7
Tar	1.00	67.5
Terra Cotta	1.90	119
Tile	1.83	114
Trap Rock	2.79	185
Wax, Bees	0.97	60.5
Wood	0.3-0.90	26-56

TABLE 3

WEIGHTS, AND ANGLES OF VARIOUS MATERIALS

Material	A	B	C
Alumina, Sized or Briquette	65	22°	10°
Aluminum Hydrate, Ground	13.5	34°	24°
Aluminum Sulfate, Granular	54	32°	15°
Ash Black, Ground	105	27°	15°
Ash Fly, Powdered	45	42°	30°
Ashes, Wet	47	50°	38°
Ashes, Dry	38	40°	27°
Bauxite, Ground Dried	68	35°	23°
Beauxite, Mine Run	85	31°	17°
Beans, Soy - Cake	45	32°	18°
Beans, Soy - Meal	40	27°	14°
Beans, Soy - Crushed	34	35°	22°
Beans, Soy - Whole	47	22°	7°
Beans, Soy - Split	44	25°	10°
Buckwheat	34.5	25°	13°
Barley	39	48°	35°
Carbon, Coke, Crushed, Sized	30	28°	13°
Cement, Clinker	88	33°	20°
Cement, Portland	95	39°	28°
Charcoal, Wood, Pulp, Granular	26.5	35°	25°
Chips, Wood	22	36°	25°
Chromide Acid, Flake	75	25°	13°
Cinders, Blast Furnace	57	35°	23°
Clay, Dry in Lump Loose	—	35°	21°
Clay, Ground	—	35°	22°
Clay, Gray, Granular	—	35°	20°
Coal, Anth., Broken, Loose	54	22°	8°
Coal, Anth., Chestnut	46	22°	8°
Coal, Bituminus, Minus ¼", Dry	42	29°	15°
Coal, Bituminus, Minus ¼", Wet	50	40°	25°
Coal, Bituminus Sized, Wet or Dry	45	27°	14°
Copra, Medium Size Pieces	33	20°	9°
Copra, Meal, Ground	40	39°	25°
Copra, Expeller Cake Ground	32	30°	16°
Copra, Expeller Cake Chopped	29	20°	8°
Copper Sulfate, Ground	75	31°	17°
Clover Seed (60 lbs per Bu.)	48	28°	15°
Cocoanut, Shredded	25	27°	15°
Coffee Beans, Green	42	25°	10°

NOTE:

A = Weight, lb_m/ft^3

B = Angle of Repose

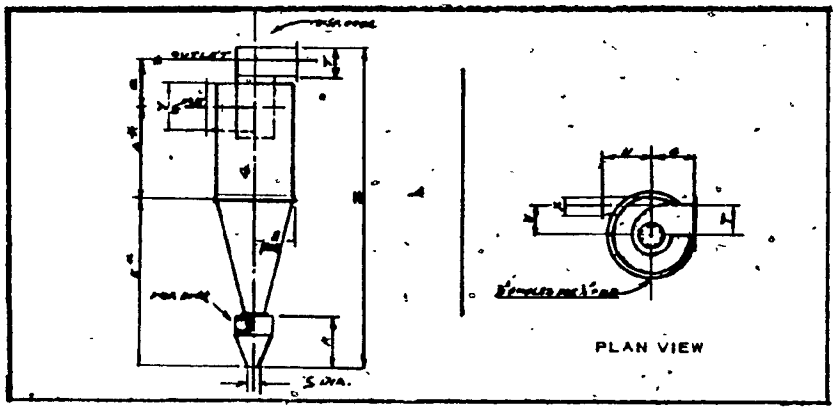
C = Maximum Belt Conveying Angle

Material	A	B	C
Coffee Steel Cut	28	23°	10°
Corn Shelled (56 Lbs per Bu.)	45	21°	7°
Cornmeal (50 Lbs per Bu.)	40	35°	22°
Cotton Seed	25	29°	19°
Cotton Seed Meal	33	35°	22°
Earth, Fullers, Raw	42	35°	21°
Earth, Common Loam Dry Loose	76	35°	20°
Feldspar, Crushed	100	32°	17°
Glue (Pellet)	45	25°	11°
Gravel, Sharp	—	40°	27°
Gravel, Round	—	30°	15°
Green Stone, Trap, Loose Piles	107	35°	21°
Gypsum	142	45°	33°
Gypsum in Regular Lumps	82	30°	15°
Gypsum Ground	56	40°	27°
Iron Oxide Pigment	25	40°	27°
Iron Ore Limonite	237	40°	28°
Kaolin, Green Crushed	64	35°	19°
Kaolin, Pulverized	22	45°	32°
Lead, #70 Red	230	40°	31°
Lead, Silicate Granulated	230	30°	15°
Lead, Sulphate, Basic Pulverized	184	45°	32°
Lime, Briquette	60	26°	15°
Lime, Burned Pulverized	27	43°	29°
Lime, Fine	45	40°	26°
Lime, Mason	17	40°	27°
Limestone, Pulverized	85	47°	34°
Limestone, Mixed Sized	105	35°	21°
Limestone, Coarse Sized	98	25°	12°
Mica, Ground	13.5	36°	28°
Molybdenumite Ore, Powdered	107	40°	25°
Manganese	460	39°	24°
Nitrate of Soda	68	24°	10°
Oats, (32 Lbs per Bu.)	26	21°	8°
Phosphate, Dicalcium, Granular	60	30°	17°
Phosphate, Super Ground	51	45°	30°
Phosphate, Tri-Sodium Granular	60	26°	13°
Phosphate, Tri-Sodium Pulverized	50	40°	29°
Phosphate, Florida	93	27°	14°
Phithalic Anhydride, Flakey	42	24°	10°
Rice	50	20°	8°
Rock, Phosphate, Pulverized	60	40°	28°
Rubber, Scrap	23	35°	22°
Salt, Cake	76	36°	21°
Salt, Granulated	81	31°	16°
Salt Rock, Crushed	75	25°	11°
Sand, Mine Run	95	35°	21°
Sand, Coarse Sized	95	30°	16°
Sand, Fine	95	32°	18°

Material	A	B	C
Sand, Core	65	39°	27°
Slag, Furnace Granulated	122	25°	13°
Slag, Birmingham	82	25°	13°
Slate, Fine Ground	82	35°	22°
Slate, Granules Flakey	87	28°	15°
Soap Chips	10	30°	18°
Soda Ash Light	30	37°	25°
Soda Ash Dence	66	32°	19°
Soda Ash Briquette	50	22°	10°
Soda, Bicarbonate	43	42°	27°
Sodium Nitrate Granular	68	24°	11°
Sodium Sulfate	88	31°	18°
Starch Tablet Granular Crystals	40	24°	12°
Sulpha, Pulverized	50	45°	30°
Sulpha, Coarse	76	32°	20°
Sawdust, Drip	20	36°	22°
Sawdust, Ground	20	45°	31°
Shale	85	39°	26°
Wheat (60 Lbs per Bu.)	48	23°	10°
Zinc Ore Roasted Granular	110	38°	27°

TABLE 4

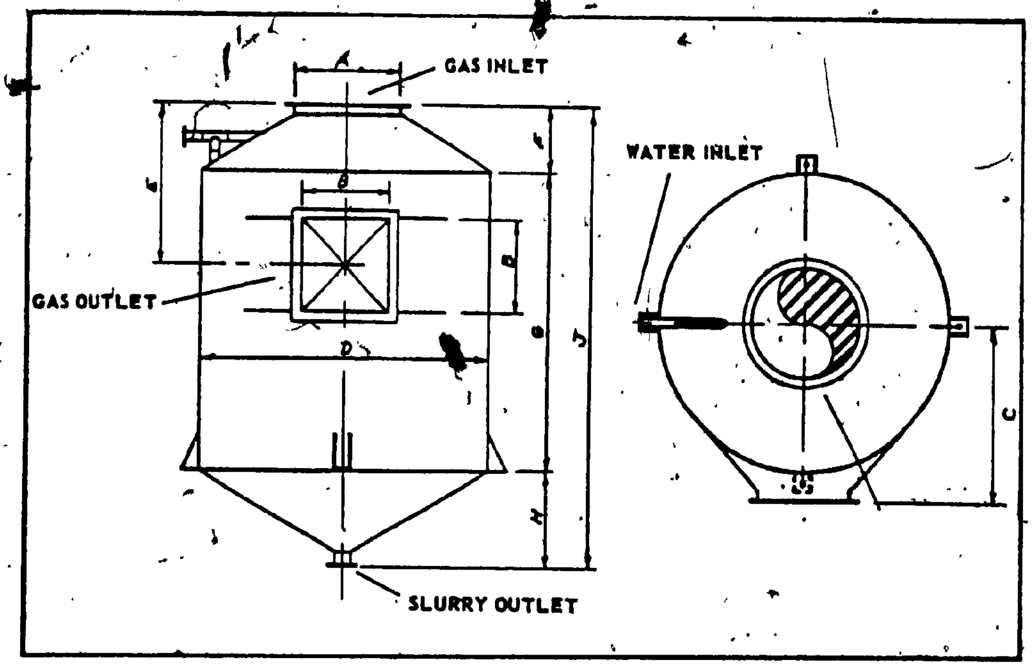
SINGLE MODEL "L" CYCLONE



Size	A *	E	G	H	K	Q	R	S	Outlet		V	Inlet		Z
									T	U		X	Y	
118	22 3/8	10 3/8	10 1/2	11	3'-2	14 1/8	10 1/2	4	9		6 3/4	4 1/2	11 1/2	6'-7
120	25 1/4	11 3/8	11	12	3'-5	15 1/4	10 1/2	6	10		7 1/2	5	12 1/2	7'-2 1/2
122	27 5/8	12 3/8	11 1/2	13	3'-9	16 3/8	11 1/2	6	11		8 1/4	5 1/2	13 3/4	7'-10 1/2
124	30	13 3/8	12	14	4'-1 1/2	17 1/2	13	6	12		9	6	15	8'-7
126	32 7/8	14 3/8	12 1/2	15	4'-6 1/2	18 5/8	15	6	13		9 3/4	6 1/2	16 1/4	9'-4 1/2
129	36 7/16	15 7/8	13 1/4	16 1/2	5'-0 3/4	20 5/16	16 3/4	6	14 1/2		10 7/8	7 1/4	18 1/8	10'-4 3/4
132	40	17 3/8	14	18	5'-7 1/2	22	19	6	16		12	8	20	11'-5 1/2
135	44 1/16	18 7/8	14 3/4	19 1/2	6'-2 1/4	23 11/16	21 1/4	6	17 1/2		13 1/8	8 3/4	21 7/8	12'-6 3/4
139	48 13/16	21 1/4	15 3/4	21 1/2	6'-9 1/4	25 15/16	22 1/4	8	19 1/2		14 5/8	9 3/4	24 3/8	13'-9 3/4
143	54 1/16	23 7/8	16 1/4	23 1/2	7'-6 3/4	28 3/16	25 3/4	8	21 1/2		16 1/8	10 3/4	26 7/8	15'-3 3/4
147	58 13/16	25 1/4	17 1/4	25 1/2	8'-3 1/4	30 7/16	28 1/4	8	23 1/2		17 5/8	11 3/4	29 3/8	16'-8 3/4
152	65 1/4	27 3/4	19	28	9'-2 1/2	33 1/4	32	8	26		19 1/2	13	32 1/2	18'-6

TABLE 5

MODEL D SCRUBBER



DIMENSIONS									
SIZE	40	50	60	70	80	90	100	110	120
A	15½	19½	23½	27	31	35	43	46½	50½
B	18	22½	27	31½	36	40½	45	49½	54
C	25½	31	37	43	48½	54½	60½	66	72
D	40	50"	60	70	80	90	100	110	120
E	29	34¾	40½	46¾	53	58¾	64½	70¾	77
F	9	11	12½	14½	16½	18	19½	21½	23½
G	64½	79½	94½	110	125½	141	156½	172	187½
H	12½	15½	18	21	24	26½	29½	32½	35
J	86	106	125	145½	166	185½	205½	226	246

TABLE 6

PARTICULATE CLASSIFICATIONS

CURVE	
A	Coarse dust - mechanically generated: Approximate particle size distribution: 20% less than 10 microns. Typical sources: Conveyor points, crushers, screens, baggers.
B	Fine dust - mechanically generated: Particle size distribution: 90% plus less than 10 microns. Typical sources: Fines passed by high efficiency cyclones, recovering effluent from dryers, coolers, airswet mills, coal dryers, etc.
C	Ultra-fine dust - mechanically generated: Particle size distribution: all less than 5 microns. This material is the result of particle size degeneration due to repeated mechanical reworking. Typical source: regenerated lime kilns, and catalyst kilns.
D	Fume. Particle size distribution: all submicron. This material is formed by the condensation and solidification of gaseous components. Typical sources: TVA ammoniators (ammonium chloride), carbon black furnaces, cupolas and secondary melting furnaces.

TABLE 7

CFM CAPACITIES

SIZE	MAXIMUM OUTLET CFM	SIZE	MAXIMUM OUTLET CFM
40	4,400	110	33,000
50	7,000	120	40,000
60	10,000	130	46,000
70	13,000	140	54,000
80	17,500	150	62,000
90	22,000	160	70,000
100	27,000	170	80,000

TABLE 8

DENSITY FACTORS

TEMP. °F	ELEVATION IN FEET							
	0	1000	2000	3000	4000	5000	6000	7000
-60	.76	.78	.81	.84	.87	.91	.94	.98
-40	.79	.82	.85	.88	.92	.95	.99	1.03
-20	.83	.86	.89	.93	.96	1.00	1.04	1.08
0	.87	.90	.93	.97	1.00	1.04	1.08	1.12
20	.91	.94	.97	1.01	1.05	1.09	1.13	1.17
40	.94	.98	1.01	1.05	1.09	1.13	1.18	1.22
60	.98	1.02	1.06	1.09	1.14	1.18	1.22	1.27
70	1.00	1.04	1.08	1.12	1.16	1.20	1.25	1.30
80	1.02	1.06	1.10	1.14	1.18	1.22	1.27	1.32
100	1.06	1.10	1.14	1.18	1.22	1.27	1.32	1.37
120	1.09	1.13	1.18	1.22	1.27	1.32	1.36	1.42
140	1.13	1.17	1.22	1.26	1.31	1.36	1.41	1.47
160	1.17	1.21	1.26	1.31	1.35	1.41	1.46	1.52
180	1.21	1.25	1.30	1.35	1.40	1.45	1.51	1.57
200	1.25	1.29	1.34	1.39	1.44	1.50	1.55	1.61
220	1.28	1.33	1.38	1.43	1.49	1.54	1.60	1.66
240	1.32	1.37	1.42	1.47	1.53	1.59	1.65	1.71
260	1.36	1.41	1.46	1.52	1.57	1.63	1.69	1.76
280	1.40	1.45	1.50	1.56	1.62	1.68	1.74	1.81
300	1.43	1.49	1.54	1.60	1.66	1.72	1.79	1.86
320	1.47	1.53	1.58	1.64	1.70	1.77	1.84	1.91
340	1.51	1.56	1.62	1.68	1.75	1.81	1.88	1.96
360	1.55	1.60	1.66	1.73	1.79	1.86	1.93	2.00
380	1.59	1.64	1.70	1.77	1.84	1.91	1.98	2.05
400	1.62	1.68	1.75	1.81	1.88	1.95	2.02	2.10
420	1.66	1.72	1.79	1.85	1.92	2.00	2.07	2.15
440	1.70	1.76	1.83	1.89	1.97	2.04	2.12	2.20
460	1.74	1.84	1.87	1.94	2.01	2.09	2.17	2.25
480	1.77	1.84	1.91	1.98	2.05	2.13	2.21	2.30
500	1.81	1.88	1.95	2.02	2.10	2.18	2.26	2.35
520	1.85	1.92	1.99	2.06	2.14	2.22	2.31	2.40
540	1.89	1.96	2.03	2.11	2.19	2.27	2.35	2.45
560	1.92	2.00	2.07	2.15	2.23	2.31	2.40	2.49
580	1.96	2.03	2.11	2.19	2.27	2.36	2.45	2.54

CHART 1

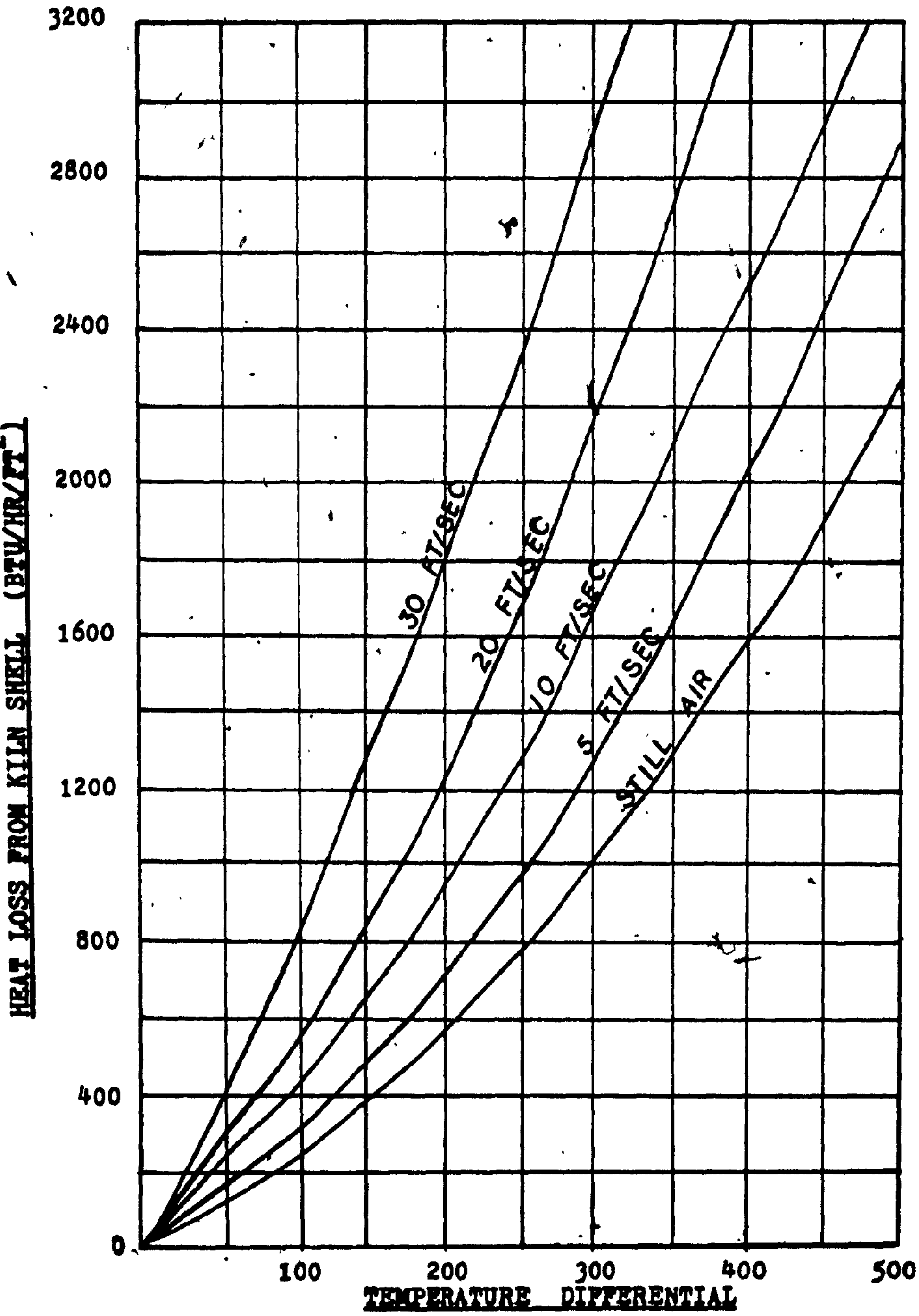

3200
2800
2400
2000
1600
1200
800
400
0
100
200
300
400
500
HEAT LOSS FROM KILN SHELL (BTU/HR/FT^2)
TEMPERATURE DIFFERENTIAL
30 FT/SEC
20 FT/SEC
10 FT/SEC
5 FT/SEC
STILL AIR

CHART 2

APPROXIMATE SPECIFIC HEATS OF GASES

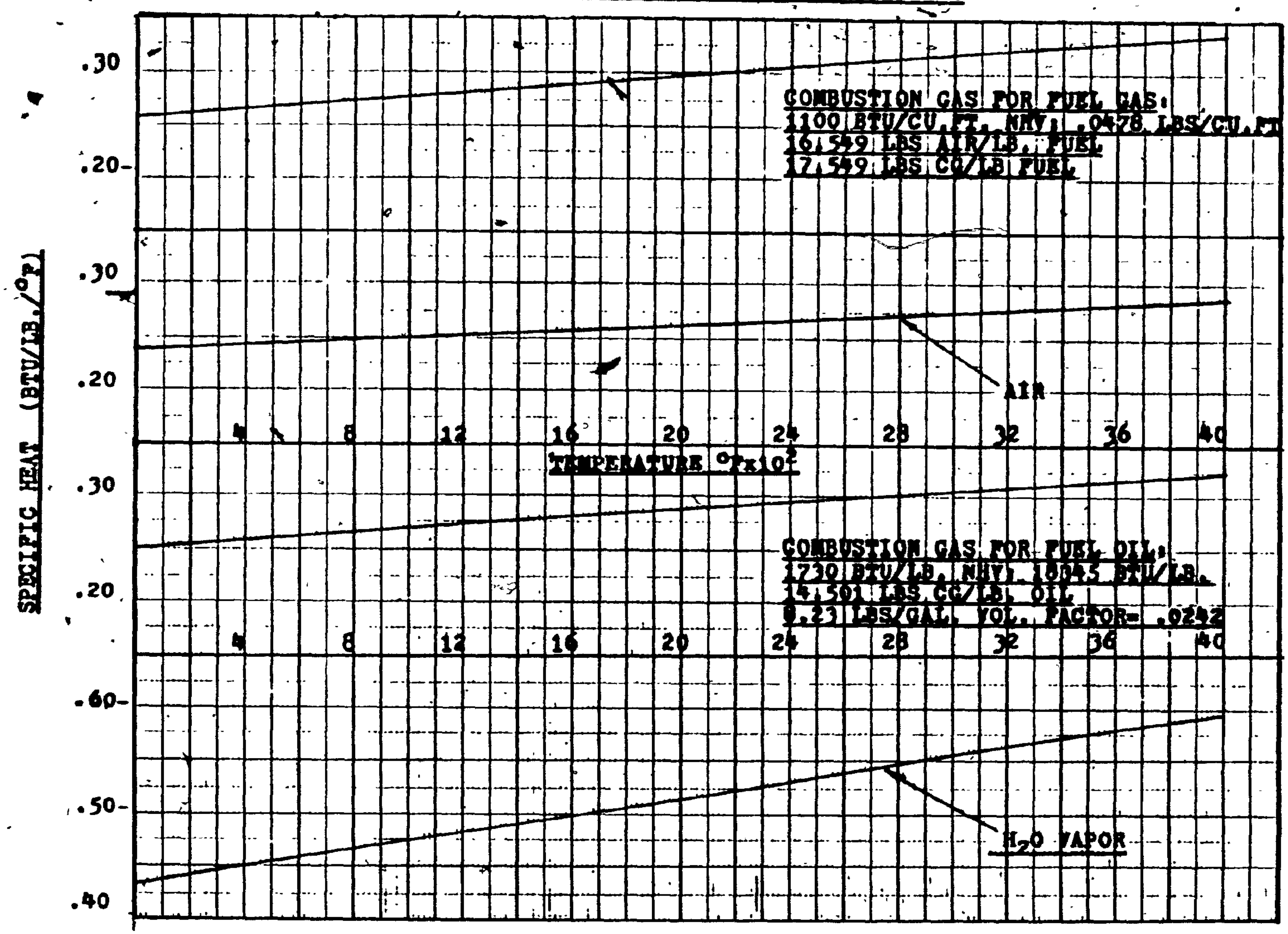


CHART 3

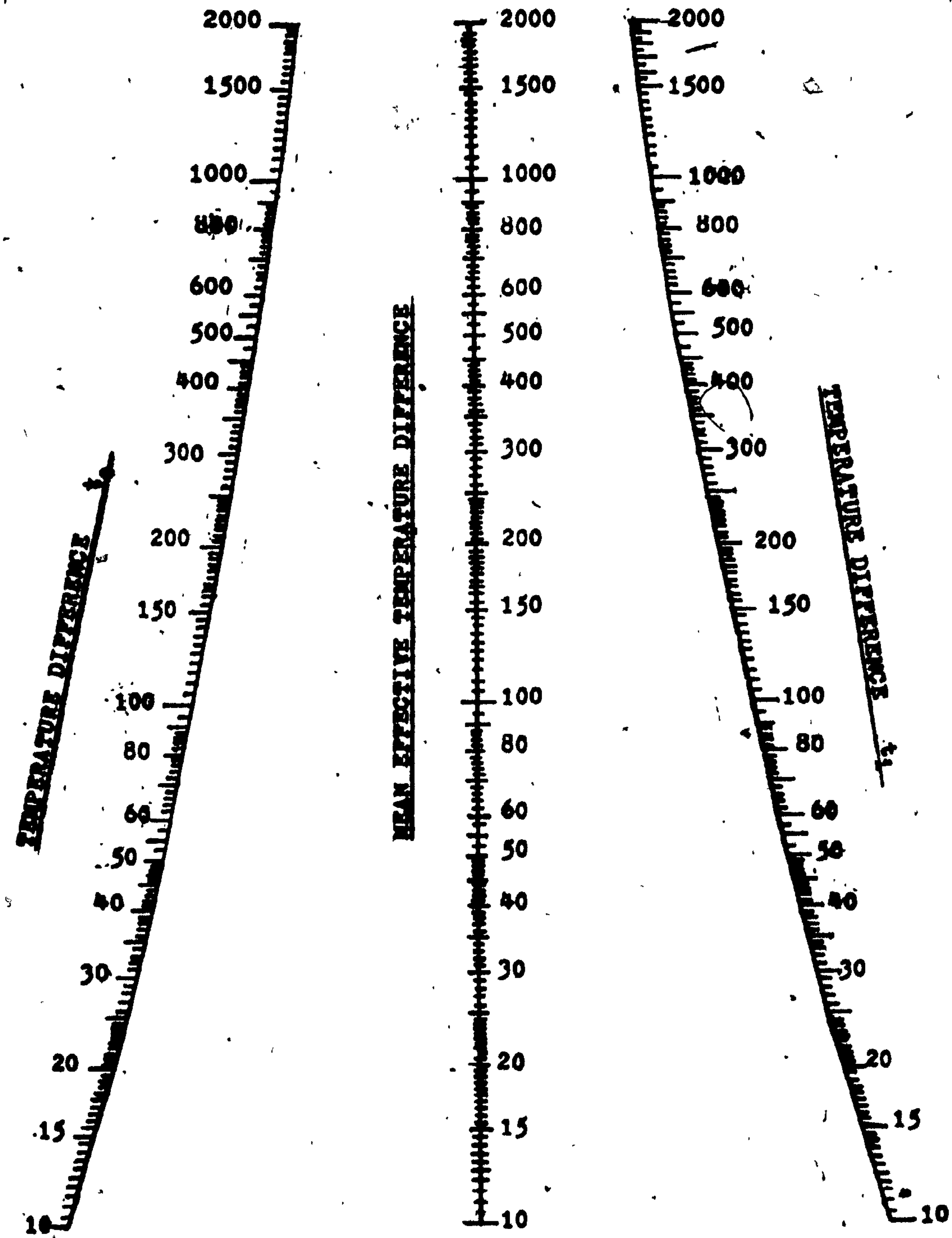

TEMPERATURE DIFFERENCE t_2
2000
1500
1000
800
600
500
400
300
200
150
100
80
60
50
40
30
20
15
10
MEAN EFFECTIVE TEMPERATURE DIFFERENCE
2000
1500
1000
800
600
500
400
300
200
150
100
80
60
50
40
30
20
15
10
TEMPERATURE DIFFERENCE t_1
2000
1500
1000
800
600
500
400
300
200
150
100
80
60
50
40
30
20
15
10

CHART 4

DRYER EFFICIENCY

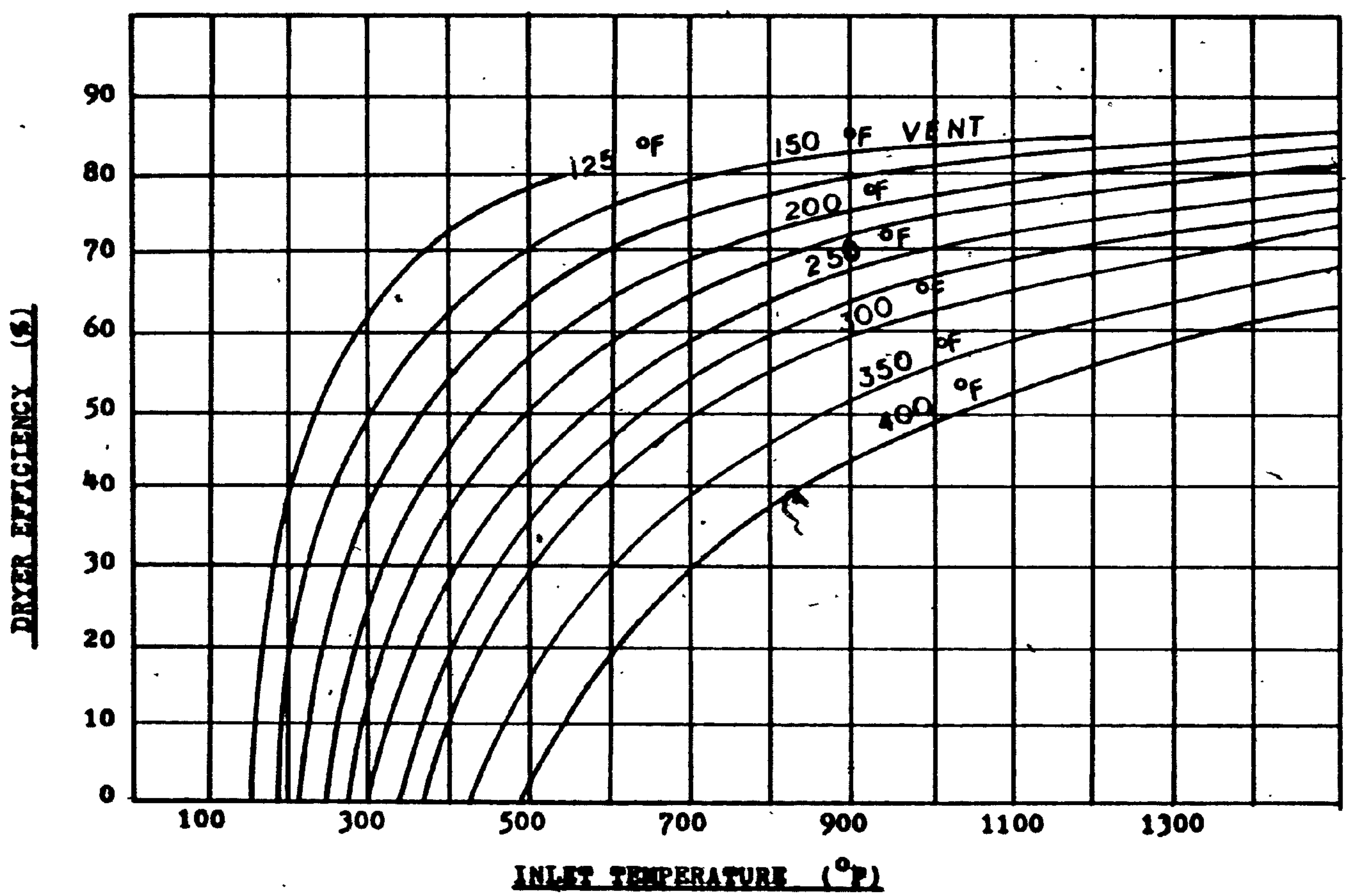


CHART 5

SPECIFIC VOLUME

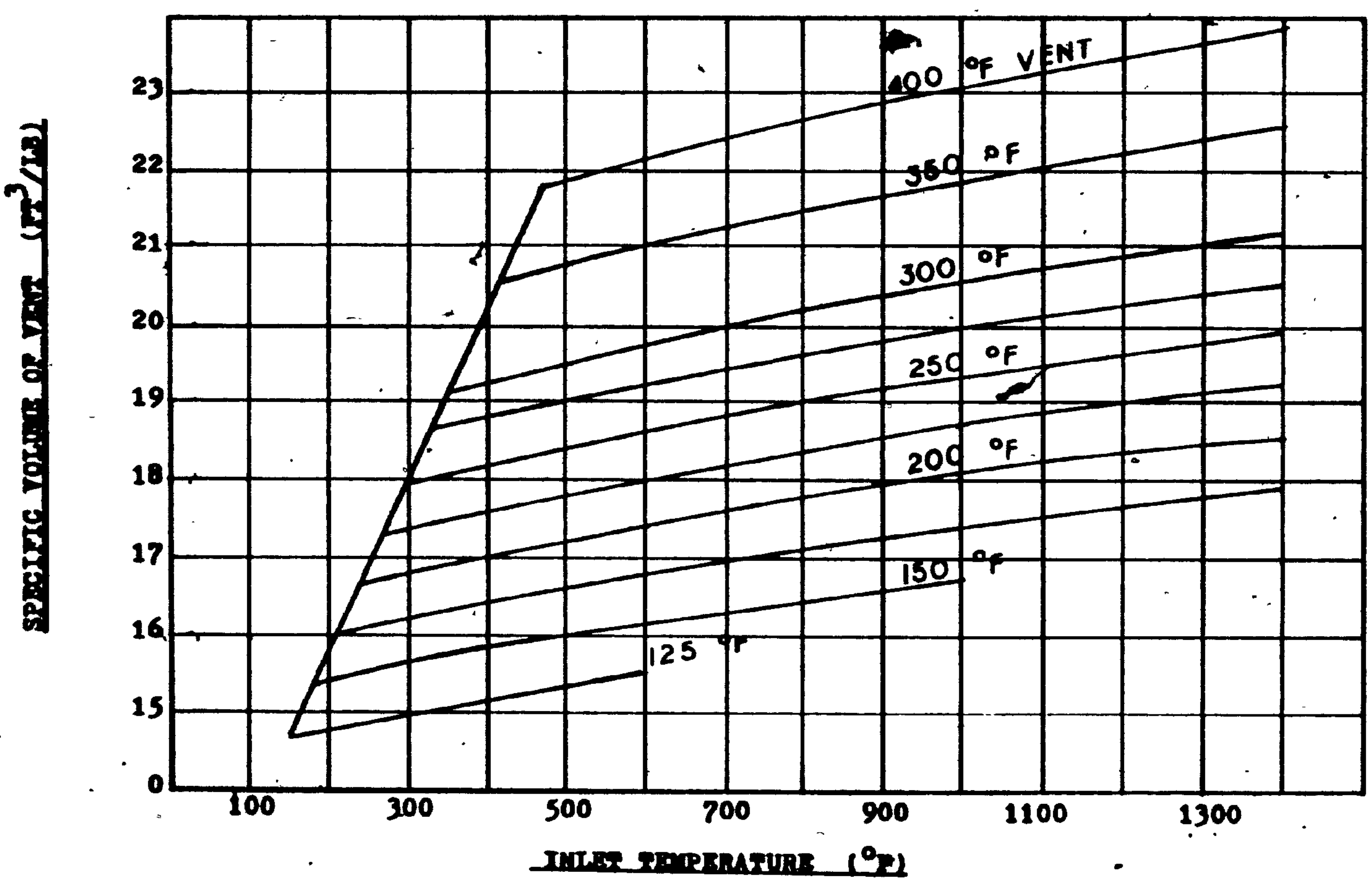


CHART 6

DEW POINT

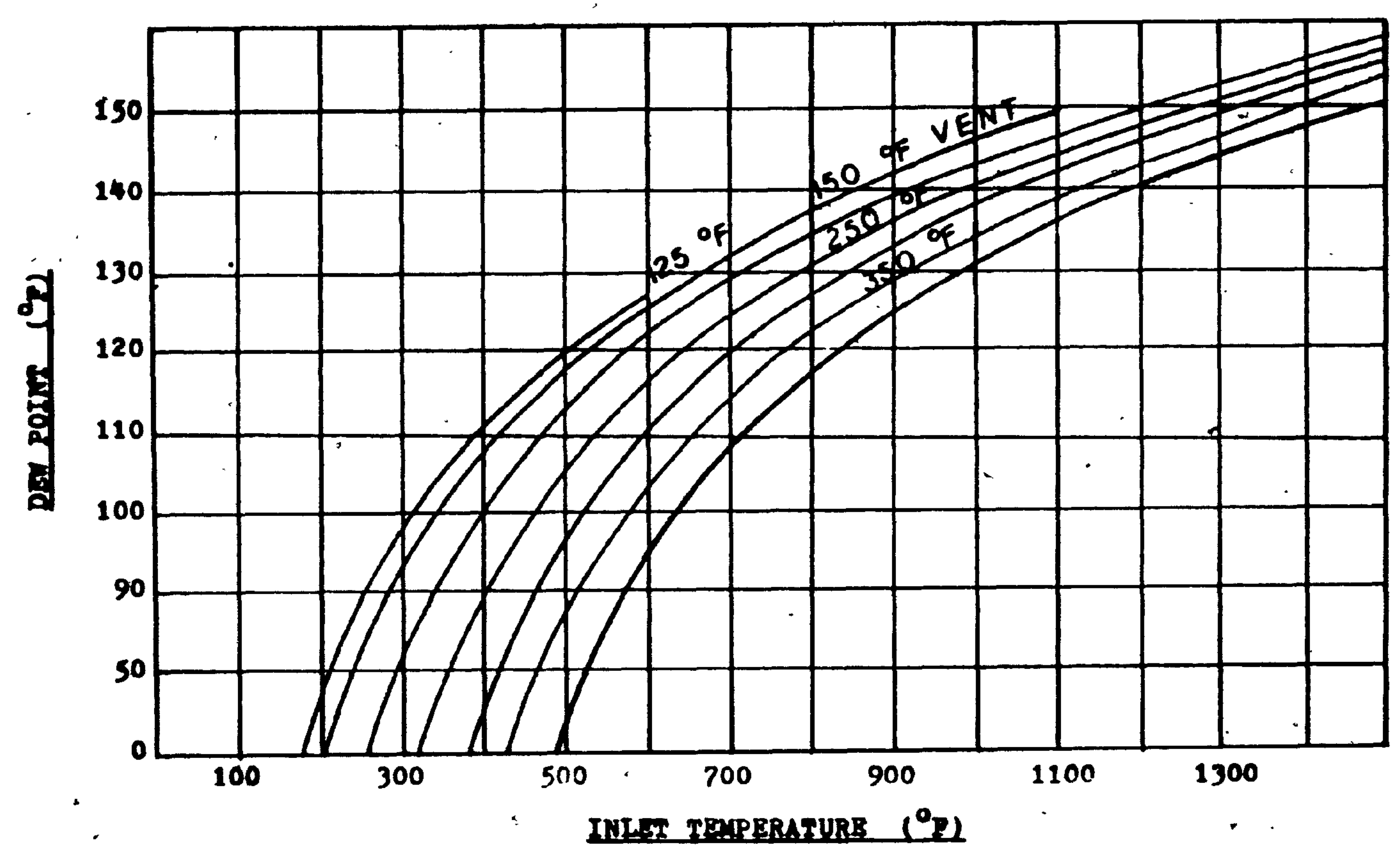


CHART 2

MOISTURE IN VENT

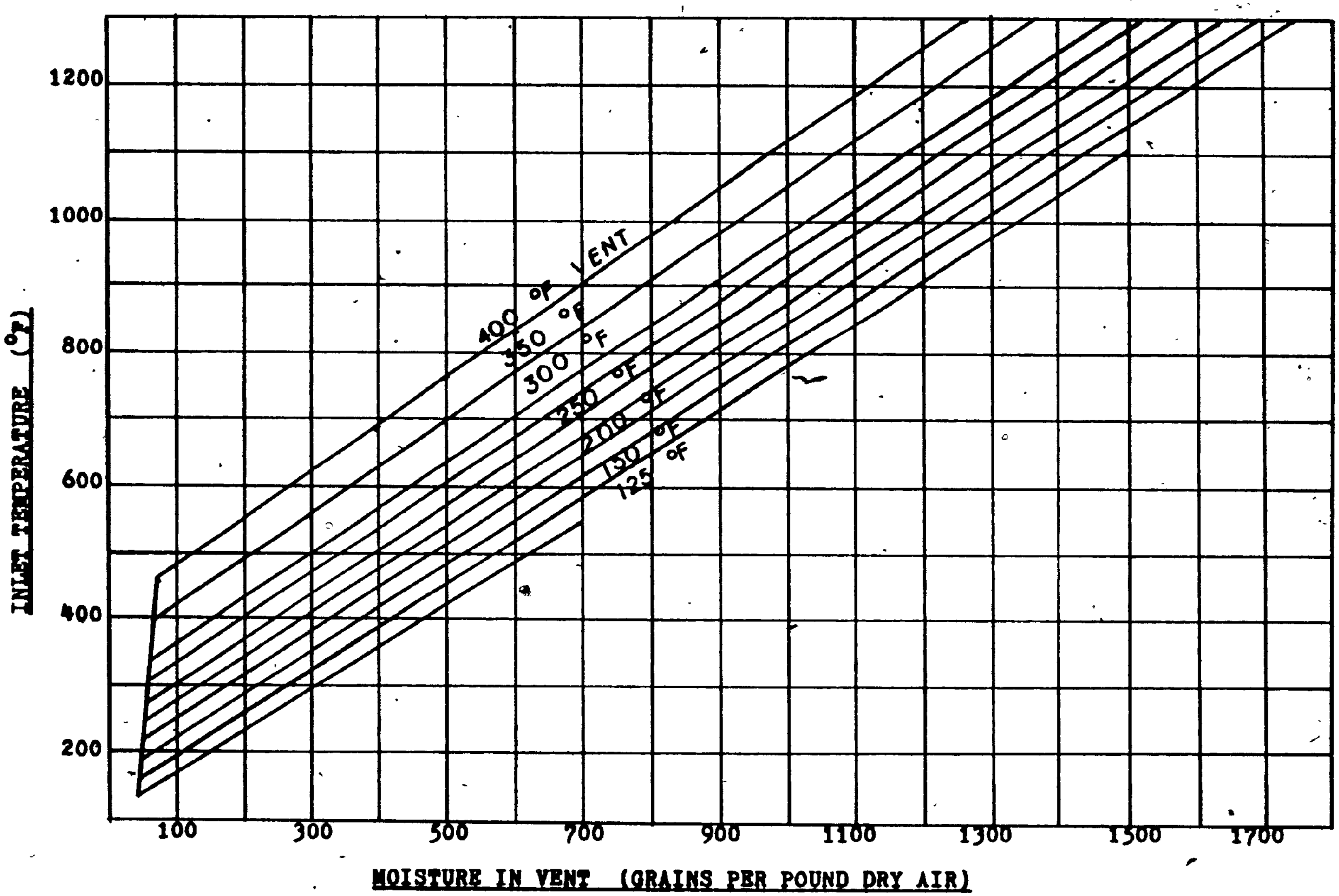
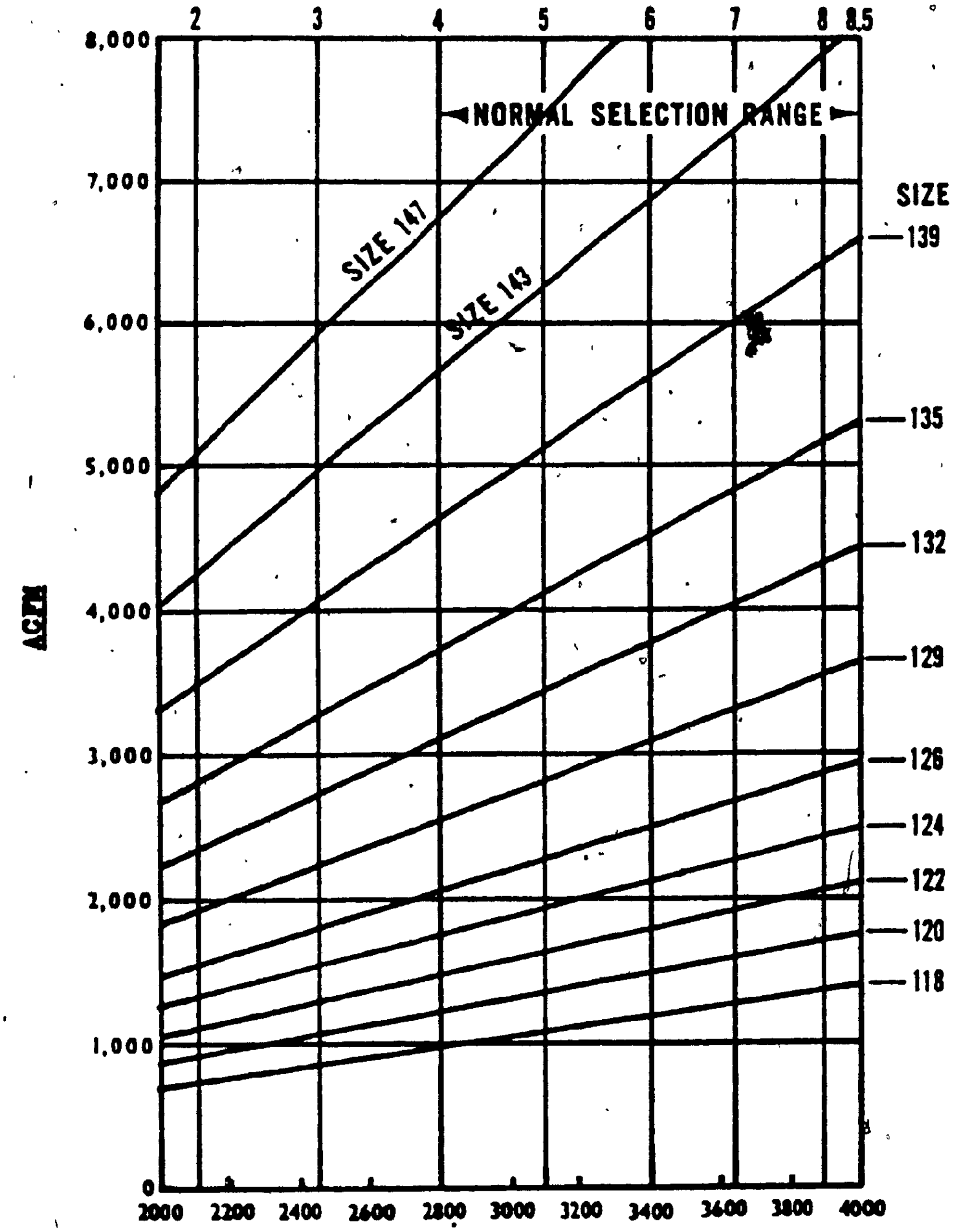
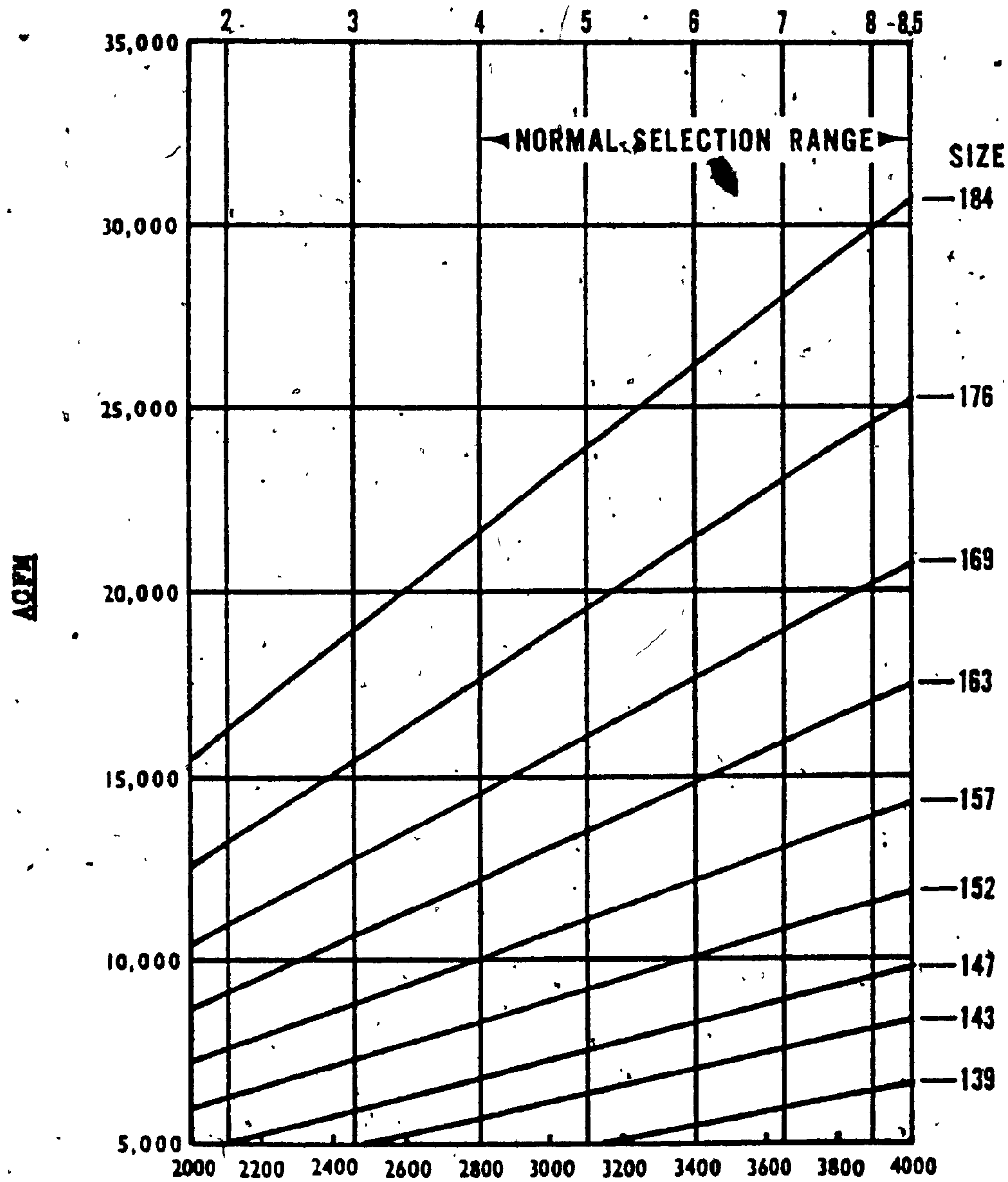


CHART 8



Inlet Velocity, (LFM)



Inlet Velocity. (LFM)

CHART 9

PRESSURE DROP FOR CHANGE IN TEMP. & ELEVATION

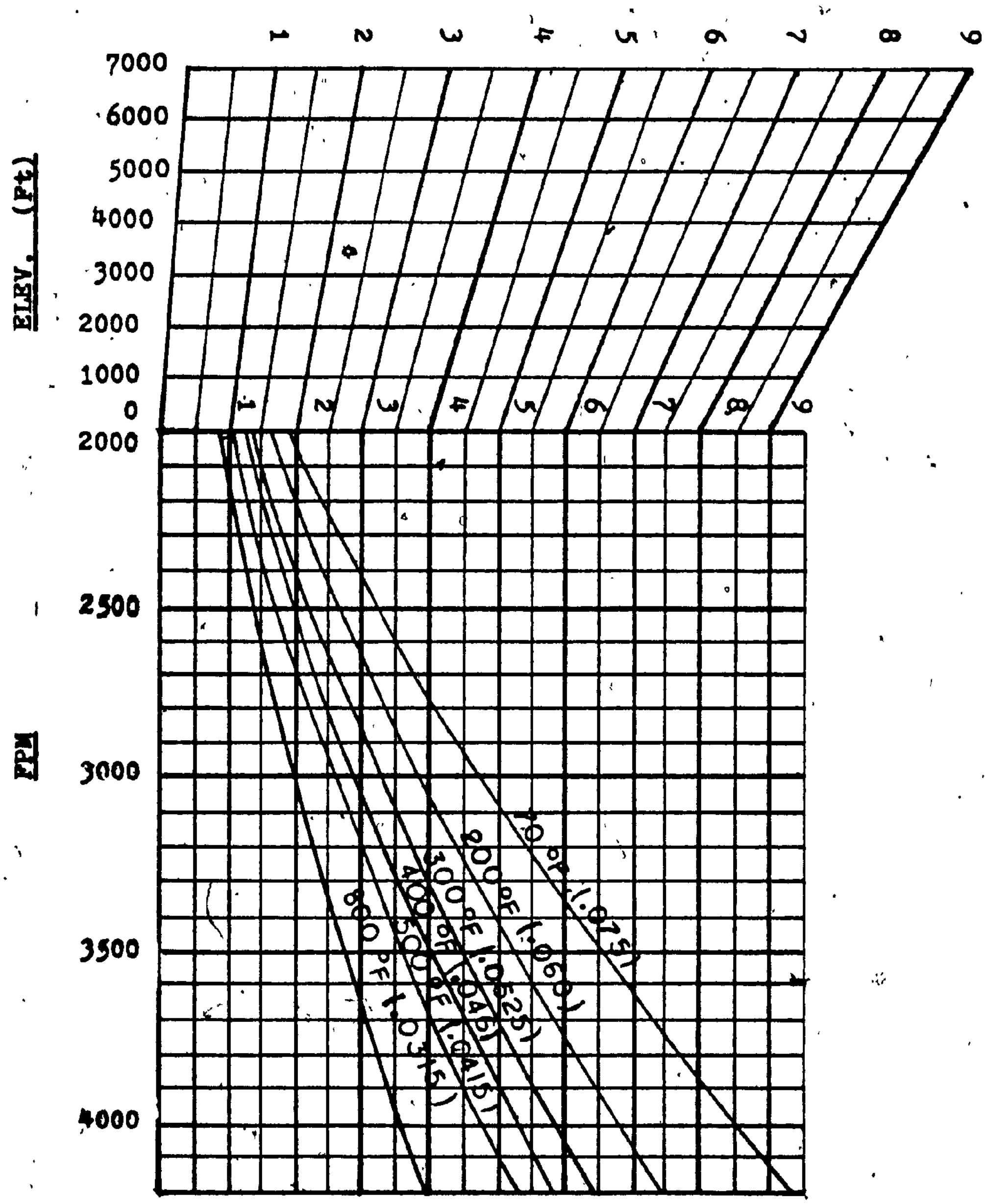


CHART 10

CYCLONE SELECTION

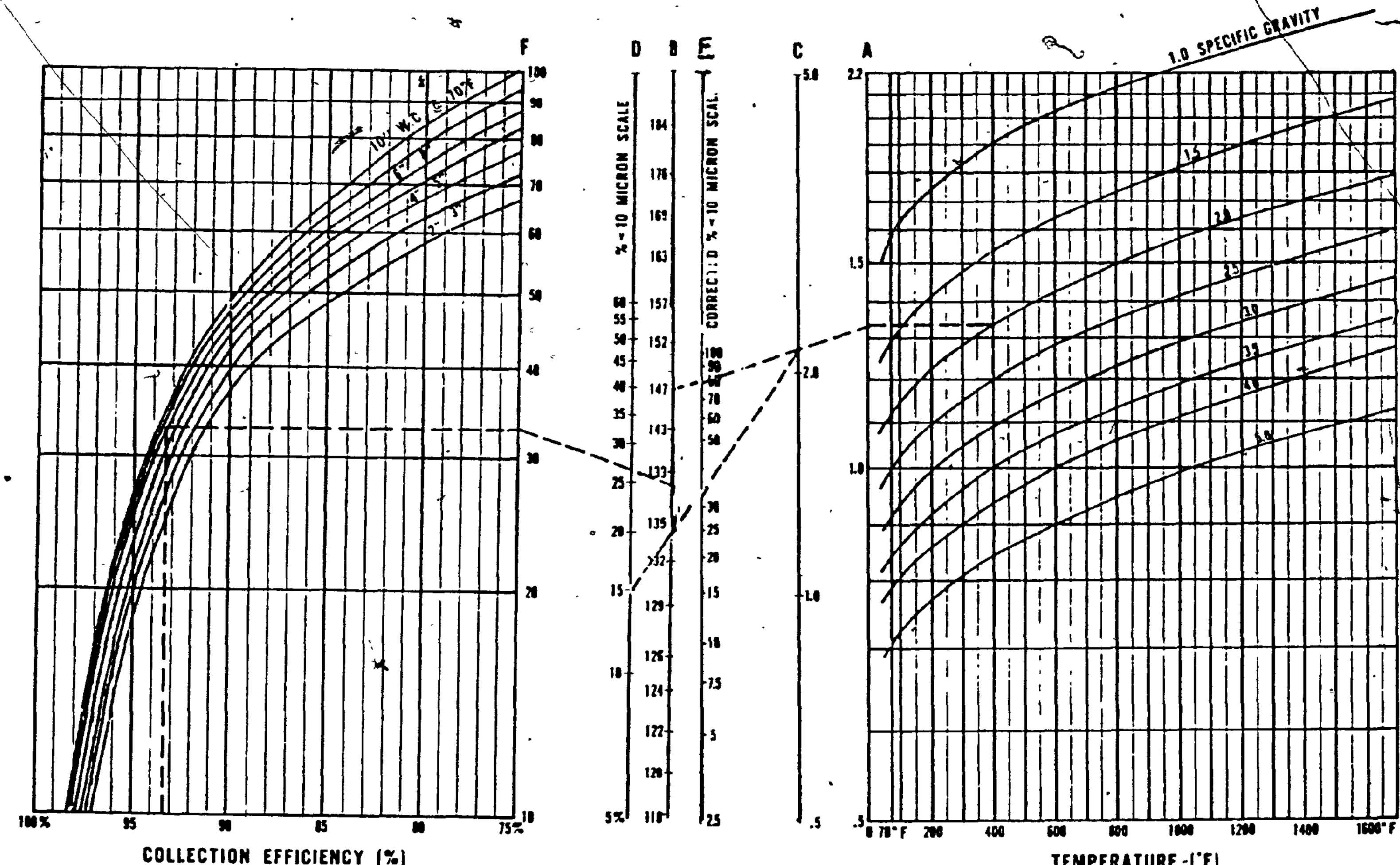


CHART 11

SCRUBBER EFFICIENCY CHART

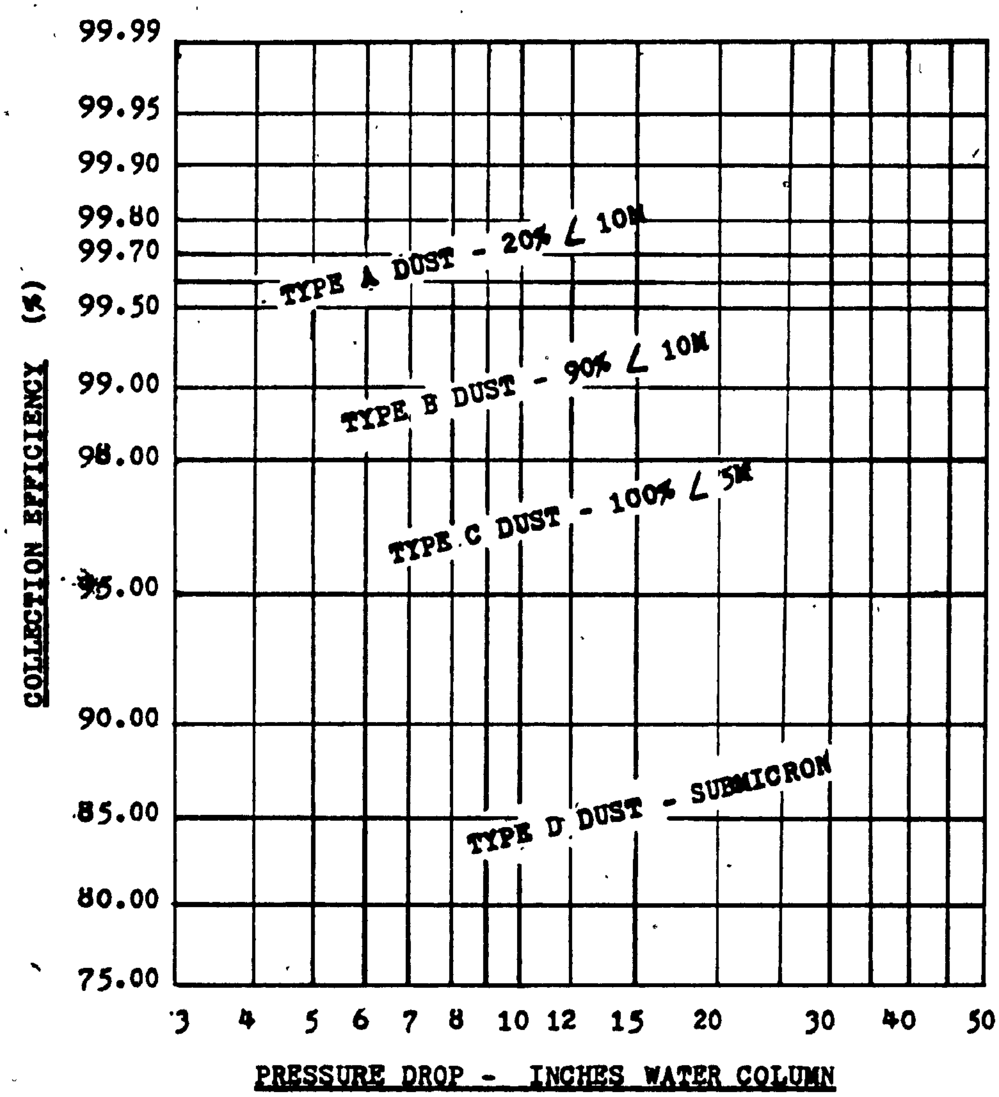
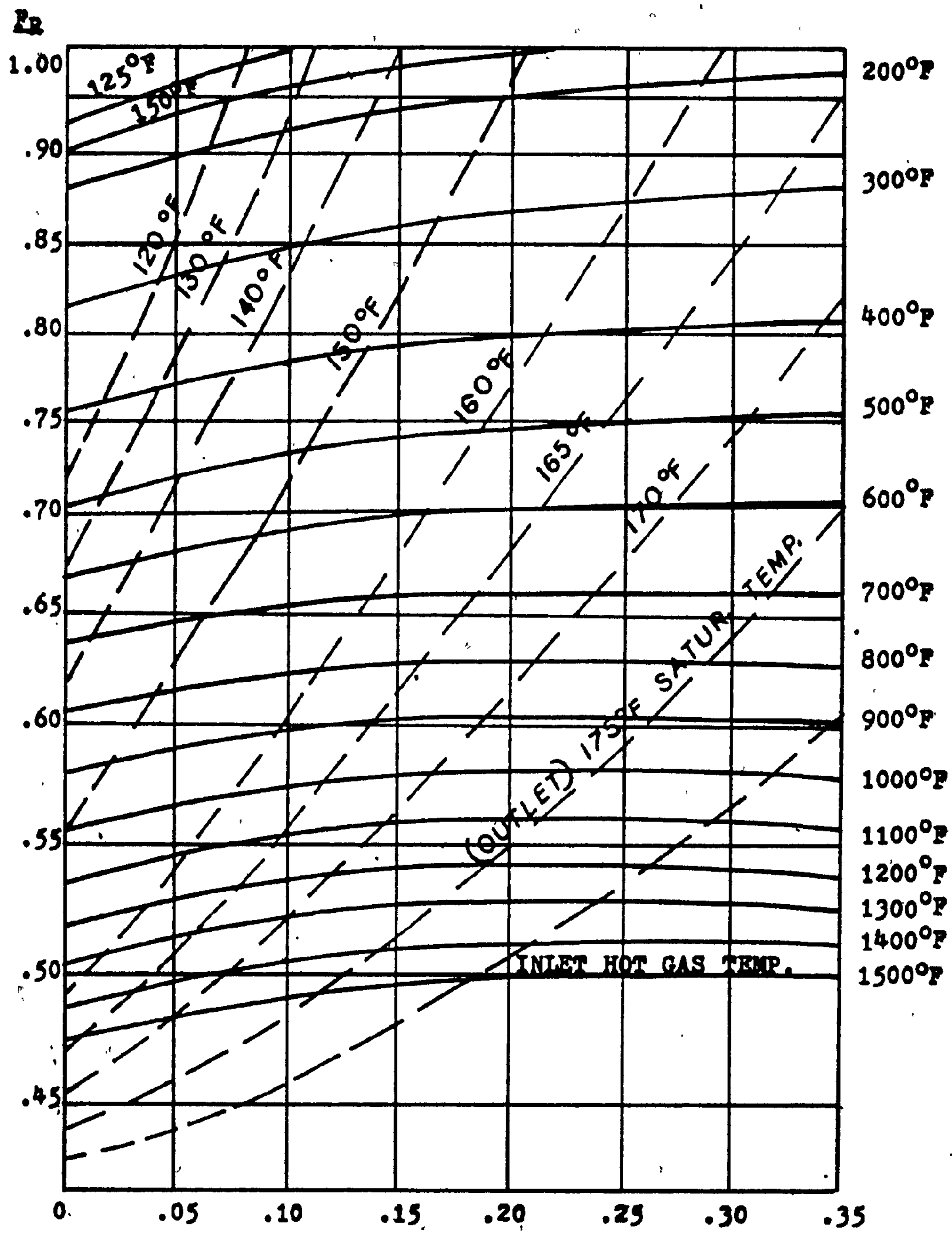


CHART 12

CORRECTION FACTOR (F_R)



INLET GAS HUMIDITY - H_2O/DRY GAS (Lbs)

CHART 13

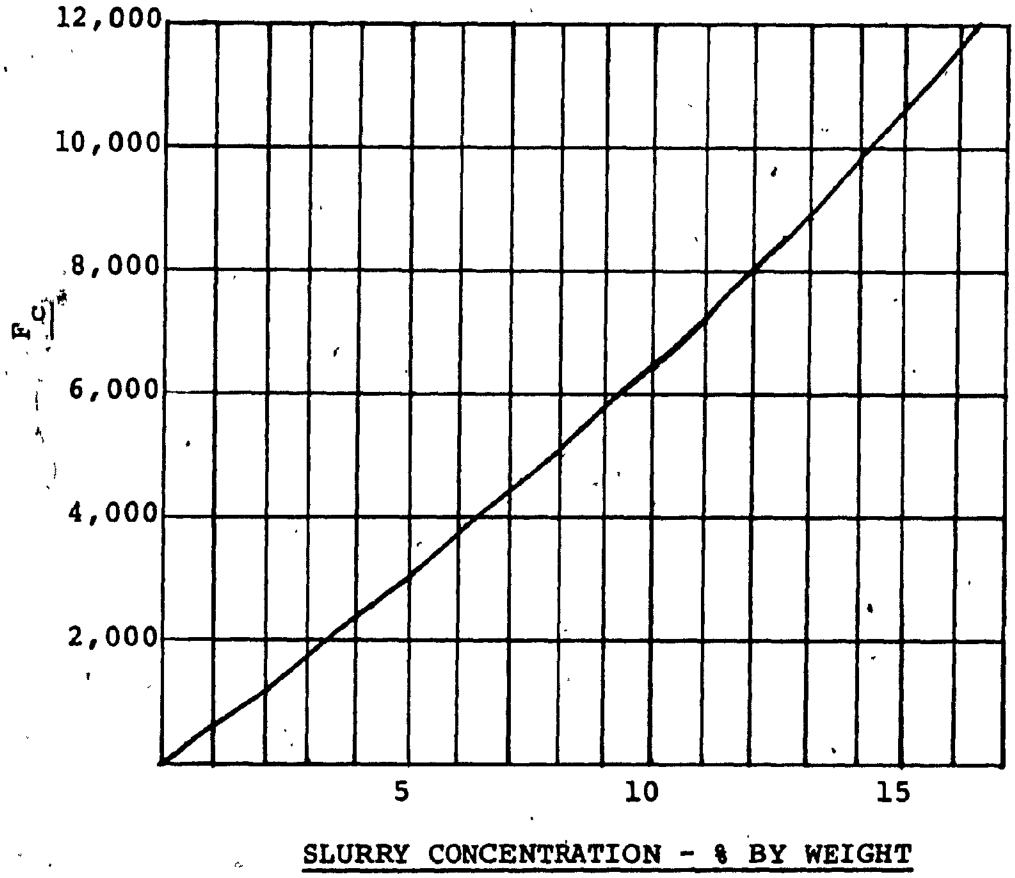
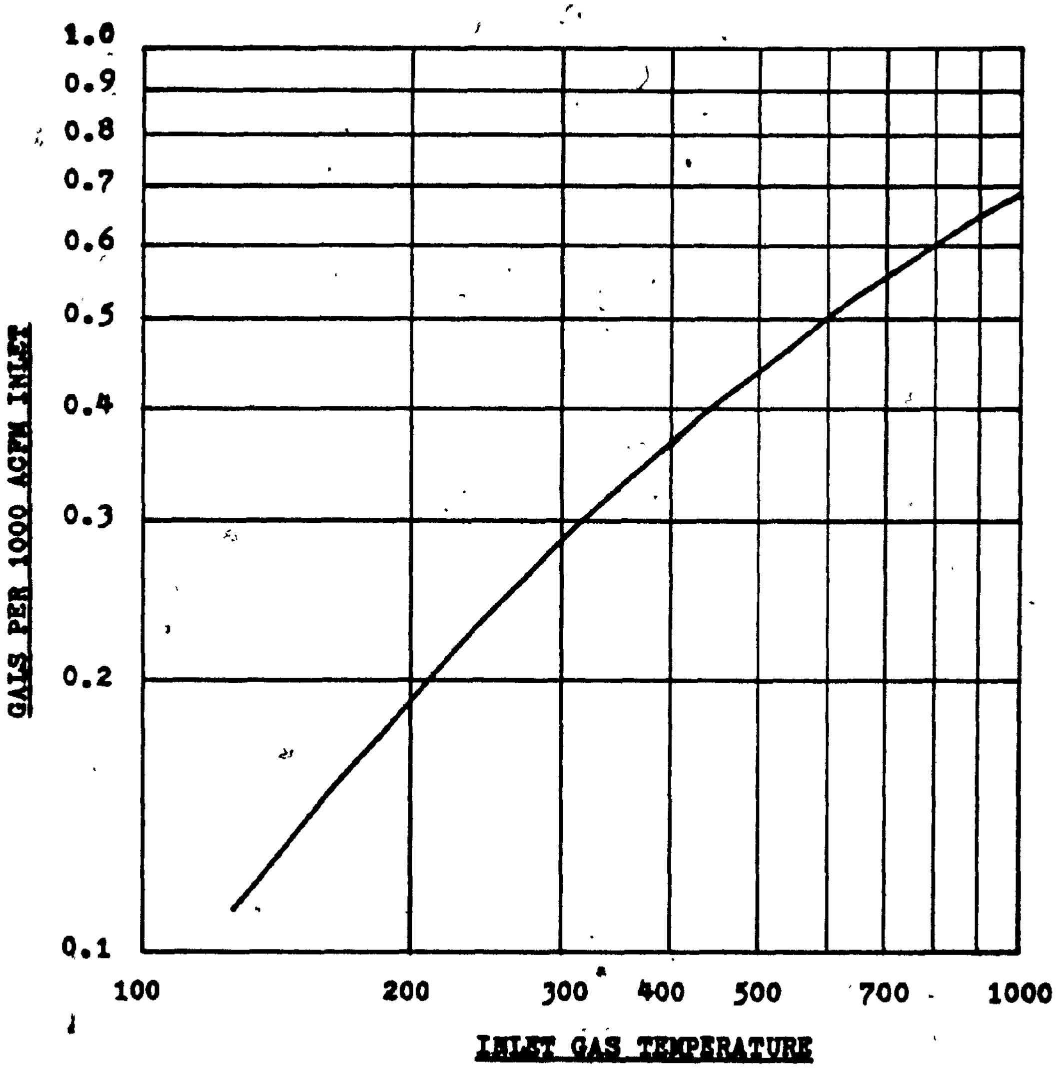
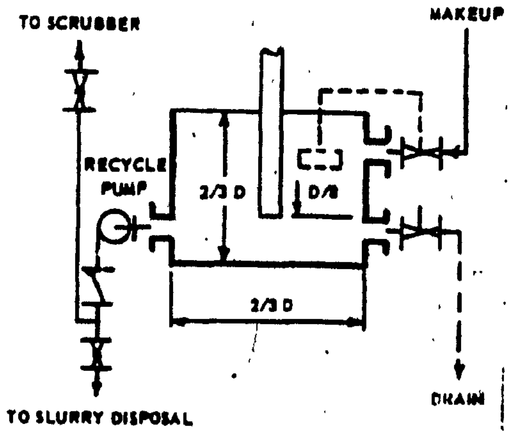

12,000
10,000
8,000
6,000
4,000
2,000
F_c
5
10
15
SLURRY CONCENTRATION - % BY WEIGHT

CHART 14

WATER LOST BY EVAPORATION

(BASED ON DRY GAS)



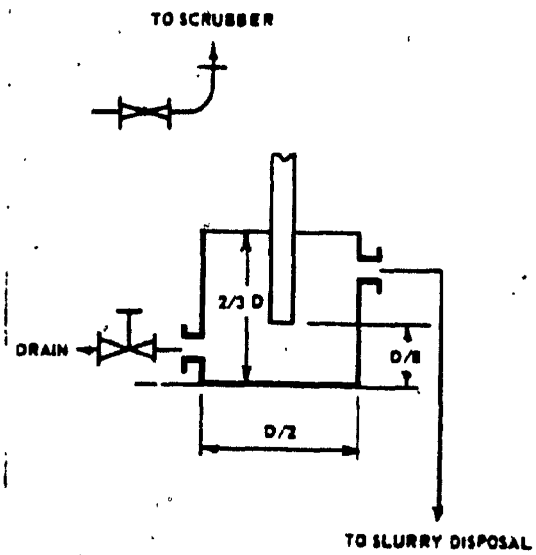


SURGE TANK

Piping System No. 2

SEAL POT

Piping System No. 1



SETTLING TANK

Piping System No. 3

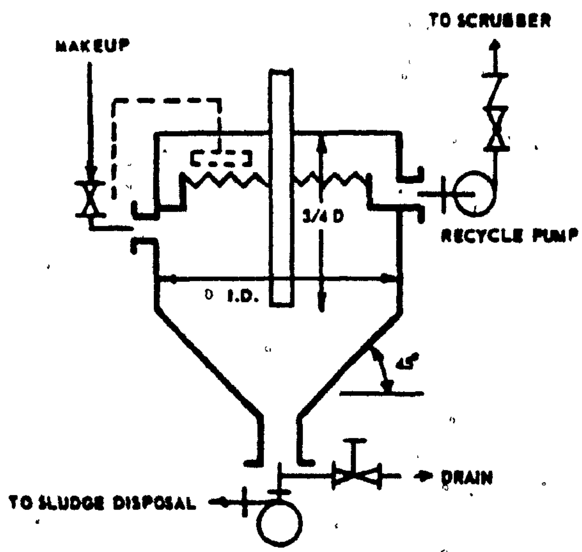


Fig. 26. Model D scrubber

CONCLUSION

Drying has gone many innovations in recent years, although they have not brought major equipment changes, they have succeeded in presenting a better understanding of the drying mechanisms. Unfortunately, which mechanism or combination of several mechanisms control the drying phenomena and their range of applicability to certain types of solids are not yet fully understood.

The comparison between different scientific discussions reveals that the capillary-flow mechanism predominates in the early stages of drying and the diffusional-flow mechanism together with the possibility of interior evaporation of liquid moisture may be important at the later stages.

The drying rate in a conventional type dryer depends on the following principal factors.

(i) The amount of the exposed surface of the wet material in contact with the flow of the drying gases.

(ii) The difference between the temperature of the heating medium and the temperature of the material being dried.

(iii) The degree of agitation of the material with the ingoing gases which promotes higher drying rates.

(iv) The size of the particles being processed. Drying is accomplished by evaporating moisture from the surface of a particle. The transfer of moisture is taking place more rapidly in a well granulated product.

(v) The physical characteristics of the feedstock control the rate of the moisture movement inside a solid. Since the moisture must reach the surface of a particle in order to be evaporated, materials having capillaries are dried relatively easier than those having no voids.

Today drying still remains an art, in which the important design variables differ markedly from one piece of equipment to the other. The ability of integrating this principal into a process proves the necessity of considering these variables which influence the rate of drying and the design of the drying equipment.

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