

CHAPTER 2



THEORY

The principle involved in the design of kiln dryer for drying wood veneer can be explained as follows:-

2.1 Moisture Content

Moisture content can be defined in the ratio of mass of water in veneer by total mass of veneer as shown in the following formula:-

$$U_d = 100 \frac{(m - m_0)}{m_0} \quad (1)$$

Where m is the mass of the wet sample and m_0 is the mass of the dry matter in the sample, this is called the dry basis definition.

Moisture contents may also be defined by the amount of moisture in a sample express as a percentage of the amount of wet sample called wet basis definition, in accordance with the formula

$$U_w = 100 \frac{(m - m_0)}{m} \quad (2)$$

The universally accepted method for determining the moisture content of veneer is the oven-drying method, or oven test. This method is used to calculate veneer moisture content by weighing the sample before and after it has been oven-dried.

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The quantity of moisture removed from veneer is calculated from the initial moisture content, U_i , of the veneer and the desired final moisture content, U_f , with the help of the following equation

$$m_w = m_i \left[\frac{U_i - U_f}{100 + U_i} \right] \quad (3)$$

Where m_i is the initial mass of wet veneer to be dried

m_w is the mass of moisture to be removed out of veneer

The veneer drying process includes the movement of water through the grain interior, and the loss of water vapour from the veneer surfaces. The occurrence of the latter process depends on the difference between the vapour pressure of the moisture in the veneer and the vapour pressure of the drying air. The vapour pressure in the veneer depends on its moisture content temperature. When it is equal to the vapour pressure of the air in contact with the veneer surfaces, the moisture content of the veneer remains constant at a value called the equilibrium moisture content, U_e , if the two vapour pressure are not equal, the veneer will lose or gain moisture content of the veneer is greater than or less than the equilibrium moisture content respectively.

2.2 Humidity of Moist Gases

We consider a moist gas to be composed of two constituents, the utterly dry gas and the moisture vapour, even if the dry gas be a gaseous mixture (as air) and the moisture a mixed vapour, say of co-evaporating solvents. Since the specific volume of a moist gas varies with the concentration of moisture as well as temperature and pressure, it

is usual to describe the fraction of moisture present in terms of mass ratios. A dry-gas basis is chosen for ease of bookkeeping. The humidity of a gas then is defined as the ratio of the mass of moisture vapour to the mass of completely dry gas. This ratio is dimensionless, but at low moisture levels it is often convenient to record humidities in g kg^{-1} .

Since mixtures of air and water vapour commonly occur in drying,, it is appropriate to look at such humid mixtures in some detail. Clean, dry air is obtained when atmospheric air, uncontaminated with minor constituents from man-made activity or natural sources such as forest fires and volcanic action, has had all of the moisture abstracted from it. The nitrogen content is substantially uniform over the earth's surface to a height of at least 100 km, but the small amount of carbon dioxide is variable. At night photosynthesis ceases, and a carbon dioxide content of up to 0.06 percent by volume has been found over woodland in early morning. By contrast, the equilibrium partial pressure of the gas is low over cold seas, and a value of 0.015 percent has been recorded at Spitzbergen (latitude 77°N). [22] Goff [33], in his final report to an international committee for psychrometric data, has defined dry air as shown in Table 2-1. Under this definition, the mean molar mass of dry air is $0.028\ 966\ \text{kg mol}^{-1}$. The molar mass for water is $0.018\ 016\ \text{kg mol}^{-1}$, so the water/air molar-mass ration is 0.522 to three significant figures.

Table 2-1 Composition of dry air

Substance	Molar Mass kg mol^{-1}	Composition mole fraction
Nitrogen	0.028 016	0.7809
Oxygen	0.032 000	0.2095
Argon	0.039 944	0.0093
Carbon dioxide	0.044 01	0.0003

The pressure-temperature behavior of air can be expressed by the virial equation of state

$$Z = \frac{PV}{RT} = 1 + \frac{B_2}{V} + \frac{B_3}{V^2} + \frac{B_4}{V^3} \quad (4)$$

where V is the specific molar volume having units of $\text{m}^3 \text{mol}^{-1}$ and R is the universal gas constant which takes a value of $8.314 \text{ J mol}^{-1} \text{ K}^{-1}$. The coefficients B_i are the so-called virile coefficients and are sole functions of temperature. These coefficients account for molecular interactions not considered by simple kinetic theory and must be determined experimentally. Corresponding values of the compressibility factor Z are listed in Table 2-2 from values listed in "Tables of Thermal Properties of Gases" prepared by the American Bureau of standards.[13]

Table 2-2 Values of $(Z-1) \times 10^5$ for clean dry air where $Z = PV/RT$

Temperature/K	Pressure / kPa		
	10	40	100
300	- 3	-12	-30
400	+2	+ 8	+19
500	3	14	34
700	4	15	38
1000	3	13	33

Clearly the compressibility factor for clean dry air is essentially unity under conditions likely in drying..

Equation (4) can also be used to represent the behavior of water vapour, but the accurate determination of virile coefficients is not easy and reported values are of uncertain accuracy. Some values of the compressibility factor for steam, which are presented by Hilsenrath [13], are listed in Table 2-3.

Table 2-3 Compressibility Factor (*Z*) for Steam at Atmospheric Pressure
(101.325 kPa)

Temperature/K	380	430	480	530	580	630
<i>Z</i>	0.98591	0.99219	0.99509	0.99667	0.99763	0.99824

Steam too may be regarded as an ideal gas with a compressibility factor of unity for drying calculations.

In moist air, various interactions between like and unlike molecules are possible, so that a possible equation of state would be

$$\begin{aligned}
 PV &= RT \\
 &- \left[Y_g^2 B_g + Y_g Y_w B_{gw} + Y_w^2 B_{ww} \right] P \\
 &- \left[Y_g^3 B_{ggg} + 3 Y_g^2 Y_w B_{ggw} + 3 Y_g Y_w^2 B_{gww} + Y_w^3 B_{www} \right] P^2 \\
 &- \dots\dots\dots
 \end{aligned} \tag{5}$$

where Y_g is the mole fraction of dry air and Y_w the mole fraction of water vapour. The virile coefficient for a single molecule of air reacting with another is B_{gg} , B_{gw} represents the coefficient for the interaction of one molecule dry air with one of water vapour, B_{ggg} is the coefficient for a triple interaction of air molecules, and so on. Values of these coefficients are listed by Goff [14] in his report to which reference has already been made.

Should a mixture of m_g kg of air and m_w kg of water vapour behave as an ideal gas, one has

$$p_w V = (m_w/M_w) RT \quad (6)$$

$$\text{and } p_g V = (m_g/M_g) RT \quad (7)$$

in which p_g and p_w are the partial pressures of air and water respectively.

These pressures sum to the total pressure P , i.e.

$$P = p_g + p_w \quad (8)$$

and from back-substitution into equation (7) the expression

$$(P - p_w)V = (m_g/M_g) RT \quad (9)$$

is obtained. From the definition of the humidity Y , we find from equations (6) and (9) that

$$Y = \frac{m_w}{m_g} = \left[\frac{M_w}{M_g} \right] \frac{p_w}{(P-p_w)} \quad (10)$$

The molar-mass ratio (M_w/M_g) has a value of 0.62198.

The maximum value that p_w can normally reach at any given temperature is the saturated-vapour pressure p_{vs} , often known simply as the vapour pressure. A pressure-temperature diagram for the substance water is sketched in Fig. 2.1. The curve follows the unique pressure at which the liquid is in equilibrium with its vapour over a plane interface. There is a similar curve AB for the vapour pressures of subliming ice.

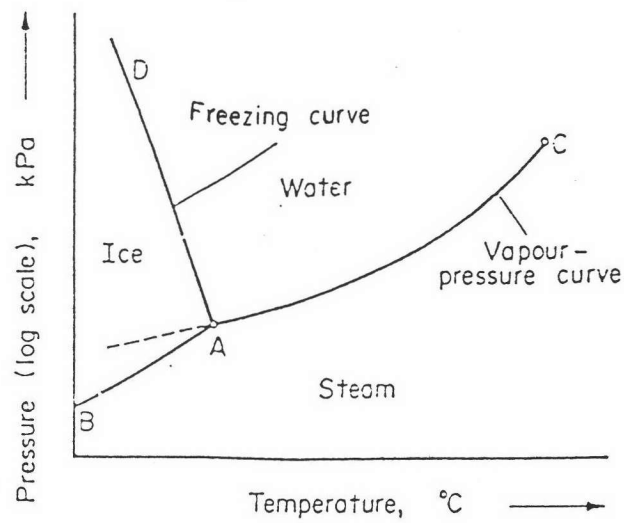


Fig. 2.1 Pressure-temperature diagram for the substance water

The ideal saturation humidity Y_s is thus

$$Y_s = \left[\frac{M_w}{M_g} \right] \frac{p_{vs}}{(P - p_{vs})} \quad (11)$$

and follows from substituting p_{vs} for p_w in equation (10). The true saturation humidity will presumably take a different value and correspond to an apparent function of pressure P and temperature. Values of this coefficient for a total pressure of 100 kPa are reproduced in Table 2-4 from Goff's calculations.[15]

Table 2-4 Values of Goff's Vapour-pressure Coefficient f_S at 100 kPa Total*Pressure*

Temperature / °C	f_S	Temperature / °C	f_S
0	1.0043	50	1.0056
10	1.0043	60	1.0060
20	1.0045	70	1.0032
30	1.0047	80	1.0058
40	1.0051	90	1.0040

The error in ignoring this correction is between 0.4 and 0.62 percent and is thus negligible in drying calculations.

Most published tables of data for the vapour pressure of water are based on those of the International Critical Tables, and more recent compilations such as those of Mayhew and Rogers [16] do not differ significantly. Selected values from this latter source are listed in the Appendix together with values of the corresponding saturation humidity Y_S for a total pressure of 100 kPa.

Equation (11) is, of course, not limited to mixtures of air and water vapour. The expression holds for any ideal vapour-gas pair, and may be invoked whenever vapour-pressure data are available. Comprehensive tables of data may be found in many works, such as the handbook of Chemistry and Physics. [17] Some selected data for common solvents are plotted in Fig. 2.2. Since the change of vapour pressure with temperature p_v/dT is inversely proportional to the absolute temperature, these data are plotted with log.-linear co-ordinates to yield straight lines for each substance.

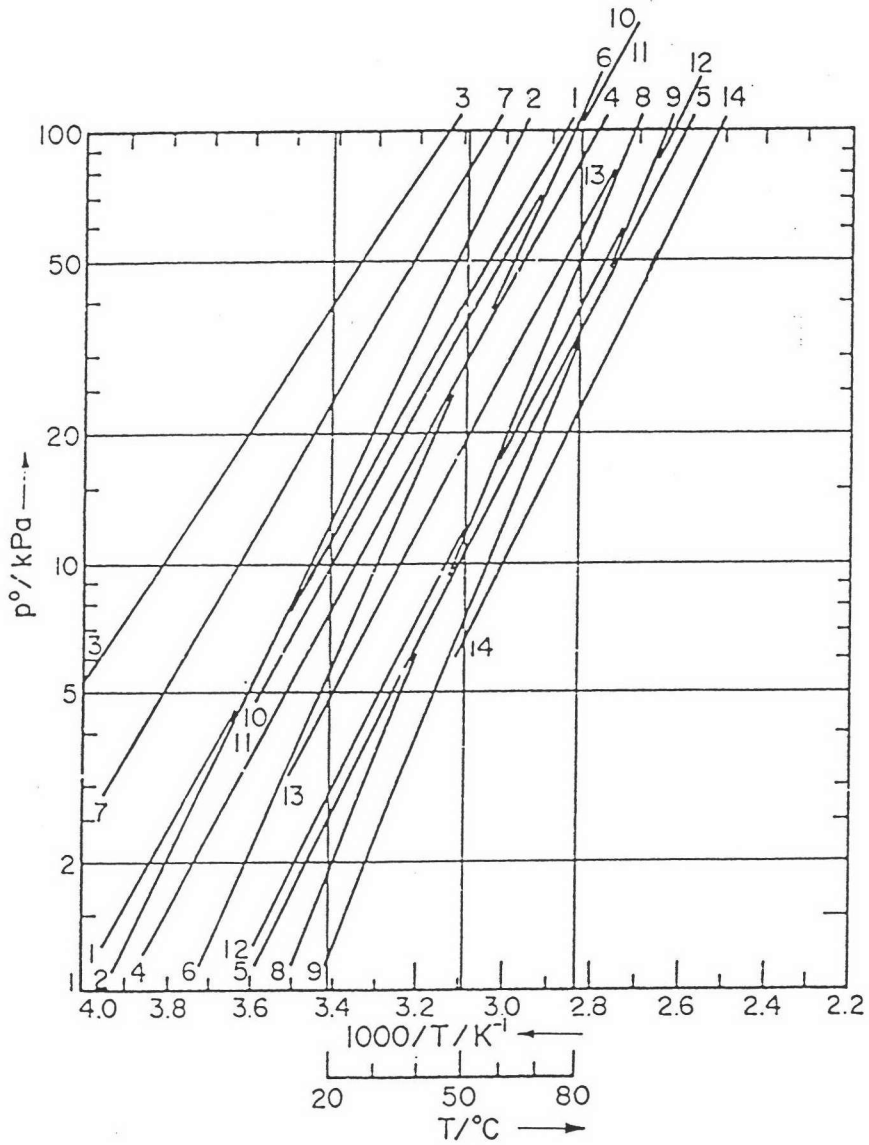


Fig. 2.2 Vapour-pressure chart for common solvents

Key

- | | |
|--|-----------------------------|
| 1. carbon tetrachloride CCl_4 | 8. n-propanol C_3H_8O |
| 2. methanol CH_4O | 9. isobutanol $C_4H_{10}O$ |
| 3. carbon disulphide CS_2 | 10. benzene C_6H_6 |
| 4. trichlorethylene C_2HCl_3 | 11. cyclohexane C_6H_{12} |
| 5. 1, 1, 2, 2,-tetrachlorethane $C_2H_2C_{14}$ | 12. toluene C_7H_8 |
| 6. ethanol C_2H_6O | 13. n-heptane C_7H_{16} |
| 7. acetone C_3H_6O | 14. n-octane C_8H_{18} |

The relative humidity of a damp gas is a measure of its fractional saturation with moisture. Almost always the relative humidity is defined as the ratio of the partial pressure of moisture p_w to the saturated-vapour pressure p_{vs} , although some reference works such as the Smithsonian Meteorological Tables [18] use a ratio of humidities instead. In this book, the former, and commoner, definition is adopted. The relative humidity is thus given by

$$H = \frac{p_w}{p_{vs}} \quad (12)$$

Clearly, equation 2.7 for the humidity may be written as

$$Y = \left[\frac{M_w}{M_g} \right] \frac{H p_{vs}}{(P-H p_{vs})} \quad (13)$$

Re-arrangement of equation (13) yields an explicit expression for H :

$$H = \frac{Y p}{(Y + M_w/M_g) p_{vs}} \quad (14)$$

2.3 Air and Water Vapour

When a liquid water surface is exposed in an enclosed space the vapour pressure, defined as the amount of water vapour in the air, above the surface in equilibrium conditions has a definite value called the saturation vapour pressure. The saturation vapour pressure is a function of temperature only; it is independent of the amount of air in the space. Value of the saturation vapour pressure of water for the temperature range of 0 to 200 °C is shown below (ASHRAE HANDBOOK, 1985);

$$\ln(p_{vs}) = \frac{C_1}{T_A} + C_2 + C_3 T_A = C_4 T_A^2 + C_5 T_A^3 + C_6 \ln(T_A) \quad (2.3-1)$$

where

$$C_1 = -5800.2206$$

$$C_2 = 1.3914993$$

$$C_3 = -0.04860239$$

$$C_4 = 0.000041764768$$

$$C_5 = -0.000000014452093$$

$$C_6 = 6.5459673$$

$$p_{vs} = \text{saturation vapour pressure, Pa}$$

$$T_A = \text{absolute temperature, K (K = C + 273.15)}$$

The humidity ratio, Y , of air containing water vapour is defined as the ratio of the mass of water vapour, m_v , in a given volume of air to the mass of dry air, m_a , in the same volume, thus:

$$Y = \frac{m_v}{m_a} \quad (2.3-2)$$

Since the water vapour and air behave as ideal gas, thus:

$$Y = \frac{0.62198 p_v}{p - p_v} \quad (2.3-3)$$

$$N = \frac{R_a T_A (1 + 1.6078 Y)}{P} \quad (2.3-4)$$

$$H = \frac{p_v}{p_{vs}} \quad (2.3-5)$$

where p_v = partial pressure of water vapour

P = total mixture pressure, 101.325 Kpa.

N = volume of moisture air per unit mass of dry air

R_a = the gas constant for dry air, 0.287 kJ/kg K.

H = relative humidity

The absolute humidity, $X_a(T)$, is the ratio of the mass of water vapour, m_v , to the total volume, V , of the sample. This may be written as :

$$X_a = \frac{m_v}{V} = \frac{Y}{N}$$

2.4 Mass Balance

The analysis of continuous drying is somewhat simpler as the process conditions remain steady apart from minor process upsets. Suppose a solid is being continuously dried from a moisture content U_i to U_f with corresponding air humidities of Y_{Ggo} and Y_{gz} at the solids inlet and outlet positions respectively (Fig. 2.3). Leakages at laces where the solids enter and leave will be assumed to be negligible.

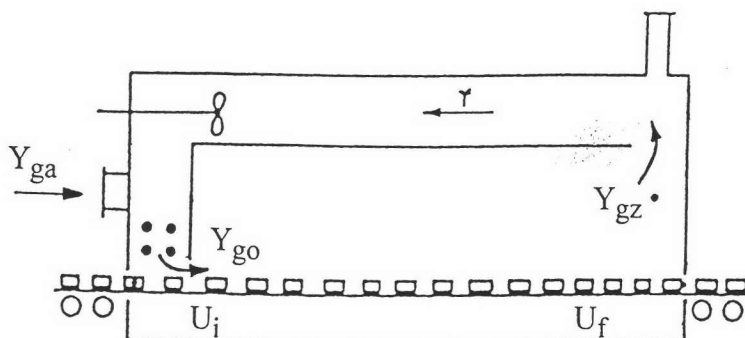


Fig. 2.3 A continuous dryer with recycle

The overall mass balance is obtained by equating moisture lost from the solids to moisture gained by air:

$$\pm G (Y_{go} - Y_{gz}) = L (U_i - U_f) \quad (19)$$

in which the negative sign is taken when the solids and air progress in the same direction and the positive sign when the solids and air go in opposite directions. Since often $\Delta y/\Delta x \sim 0.01/1$, the airflow can be of order one hundredfold greater than the dry-solids flow.

Suppose some of the moist air to be discharged is sent back to air intake to improve the thermal economy of the dryer. Let r be the mass of dry gas so recycled per unit mass of gas flowing through the dryer. A mass balance over the mixture of the recycled and freshly admitted airstreams yields for the co-current case shown in Fig. 2.3

$$Y_{go} = r Y_{gz} + (1 - r) Y_{ga} \quad (20)$$

Re-arranging this equation, one gets for the recycle ratio r

$$\begin{aligned} r &= (Y_{go} - Y_{ga}) / (Y_{gz} - Y_{ga}) \\ &= 1 - (Y_{gz} - Y_{go}) / (Y_{gz} - Y_{ga}) \end{aligned} \quad (21)$$

As the recycle ratio increases, so the humidity change across the dryer ($Y_{gz} - Y_{go}$) becomes smaller with respect to the humidity rise above ambient ($Y_{gz} - Y_{ga}$). A smaller quantity $(1-r)$ of fresh air has to be heated, but the gas in the dryer has a lower potential for picking up moisture and a bigger dryer is needed. The greater capital cost of the dryer is offset by the smaller heating charges, but eventually the gain in thermal economy ceases to become worthwhile.

The state paths for the air, when drying with recirculating air, are shown in Fig.

2.4. Point A corresponds to the state of the fresh air, B the mixed air at the inlet, C the same air after heating, D the air leaving the dryer. Since $AB/BD = r / (1-r)$ by the Lever Rule, $AB/AD = r$. This result also follows directly from equation (21).

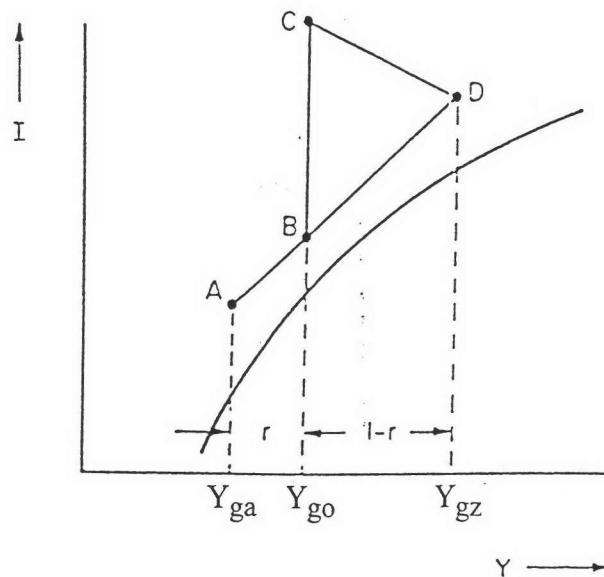


Fig. 2.4 State paths for air on drying with recirculation

2.5 Energy Balance

The elements of a typical continuous-drying installation are shown in Fig. 2.5 for the co-current movement of air and solids. Air is drawn in at an enthalpy I_{ga} , heated to raise its enthalpy and mixed with recycled exhaust air so that the humidity of the combined stream is I_{go} at the inlet end of the dryer. When the solids progress in the opposite direction to the drying gas, then I_{go} is the resultant air enthalpy at the solids outlet. The air humidifies on its passage through the dryer and emerges at the exhaust with enthalpy I_{ge} . The enthalpy of the solids changes from a value I_{so} on entering to I_{sz} on leaving.

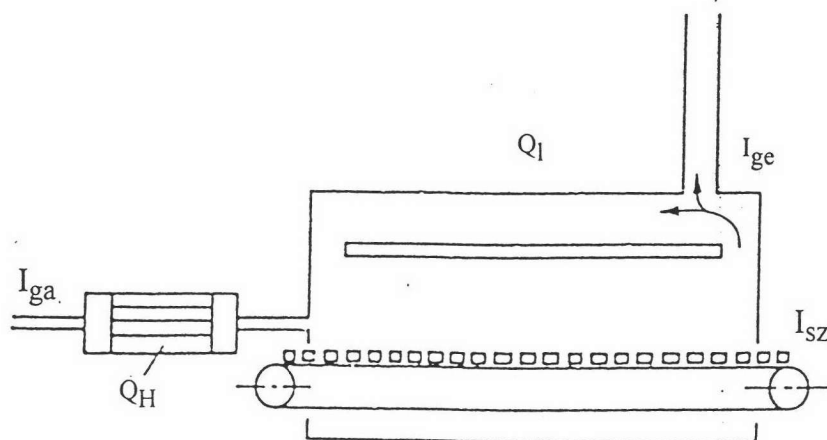


Fig. 2.5 Continuous dryer

The energy balance may be written for an intake of $G \text{ kg s}^{-1}$ dry gas and a throughput of $L \text{ kg s}^{-1}$ of drying goods (bone-dry solids basis) as follows:

$$I_{ga} G + Q_h + I_{s0} L + W_f + W_s - I_{ge} G - Q_l - I_{sz} L = 0 \quad (23)$$

$$\text{or } I_{ga} + Q_h/G + I_{s0} L/G + W_f/G + W_s/G - I_{ge} - Q_l/G - I_{sz} L/G = 0 \quad (24)$$

Since L/G normally range between 0.01 and 0.1, often the lumped solids-enthalpy term $(I_{s0} - I_{sz}) L/G$ in equation (24) is relatively minor. Values of Q_h are obtained from simple considerations of heat transfer, while estimates of the heat loss can be obtained from Table 2-5. Again, often the fan-work W_F is a small item, but the work extended in conveying the solids W_S may not be. The fan-work for a cross-circulated band dryer is of order 1 kw m^{-2} (band area), but of through-circulating the air through a perforated band the energy losses rise to about 2.5 kw m^{-2} . [19]. The power needed to convey solids by suspending them in a fast airstream, as in an airlift dryer, is about

TABLE 2-5 : Total heat loss from vertical surfaces in still air, W/sq. m.

Calculated from data of Spiers [16]

Temperature of surface / Deg.C	Emissivity 1.0				Emissivity 0.7				Emissivity 0.4				Emissivity 0.1			
	Air temperature				Air temperature				Air temperature				Air temperature			
	15 Deg.C	20 Deg.C	25 Deg.C	15 Deg.C	20 Deg.C	25 Deg.C	15 Deg.C	20 Deg.C	25 Deg.C	15 Deg.C	20 Deg.C	25 Deg.C	15 Deg.C	20 Deg.C	25 Deg.C	
30	145	95	45	118	77	36	92	58	27	65	41	17				
40	267	208	155	216	170	125	170	132	96	123	94	66				
50	392	339	279	323	275	228	255	216	177	187	156	126				
60	533	474	415	440	389	339	347	306	264	255	222	189				
70	696	625	564	564	515	461	446	404	360	328	293	258				
80	848	787	722	700	647	591	553	508	461	404	368	331				
90	1023	960	896	844	789	734	665	618	574	485	447	408				
100	1214	1143	1078	994	939	882	787	734	687	568	530	490				
110	1405	1340	1274	1155	1099	1039	905	856	808	655	615	575				
120	1615	1549	1482	1326	1266	1209	1035	985	935	745	704	662				
130	1867	1771	1702	1504	1445	1386	1171	1120	1070	838	795	754				
140	2071	2004	1935	1692	1633	1572	1313	1261	1270	933	889	847				
150	2318	2250	2180	1889	1829	1765	1459	1408	1356	1031	988	944				

9 kw for each 1 m³ s⁻¹ employed [20]. The power demands for some of the principal types of continuous dryers are listed by Lapple and co-authors [21].

The various heat quantities involved may be displayed on an enthalpy-humidity chart, as depicted in Fig. 2.6

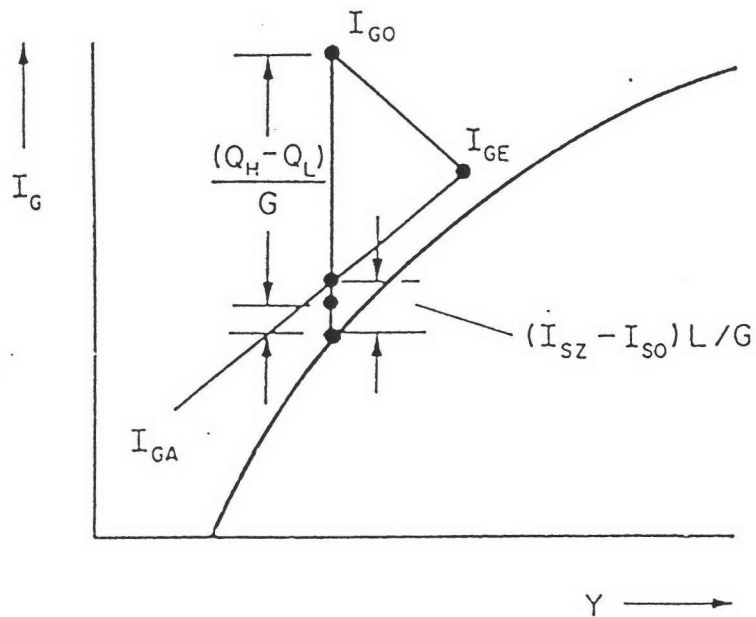


Fig. 2.6 Heat quantities for a continuous dryer on an enthalpy-humidity chart.

For calculation purposes, it is convenient to put equation (24) in a somewhat different form by neglecting the moisture brought in with the fresh air. With this assumption, the change in humid enthalpy of the gas across the dryer becomes:

$$I_{ge} - I_{ga} \cong C_{pg} (T_{ge} - T_{ga}) + H_{gw} G_v / G \quad (25)$$

where T_{ge} and T_{ga} are the outlet and intake-air temperatures respectively and G_v is the rate at which moisture evaporates. With little error, one can take H_{gw} as the enthalpy of saturated moisture vapour at the air-outlet temperature T_{ge} . This assumption implies that the fraction of moisture driven off is heated to T_{GE} at which temperature it evaporates. Consequently the change in humid enthalpy of the moist solid is thus calculated by

$$I_{sz} - I_{so} \cong (C_s + C_l U_f) (T_{sz} - T_{so}) \quad (26)$$

where U_f is the moisture content of the solids being discharged from the dryer. With these foregoing assumption, equation (24) can now be rewritten as

$$-C_{pg} (T_{ge} - T_{ga}) - H_{gw} G_v/G - (C_s + C_l U_f) (T_{sz} - T_{so}) L/G + (Q_h + W_f + W_s - Q_l)/G = 0 \quad (27)$$

so that the heat demand Q_H becomes

$$Q_h = C_{pg} (T_{ge} - T_{ga})G + H_{gw} G_v + (C_s + C_l U_f) (T_{sz} - T_{so}) L + Q_l - W_f - W_s \quad (28)$$

2.6 Air Flow Requirement

The drying of veneer by passing air over and through a veneer may be idealized as an adiabatic saturation process. After the kiln has passed through and initial warm up period, the surface temperature of veneer and therefore the temperature of the evaporating moisture will come to the wet bulb temperature assuming that the air passing through veneer becomes totally saturated. At less than 100 percent saturation, e.g., 75 percent saturation, the surface temperature of the veneer will come to the wet bulb temperature plus 25 percent of the difference between the wet and dry bulb temperatures. No heat is

added or lost since there is no external heat exchange; the process is therefore adiabatic. The heat required for evaporation of water from the veneer is supplied by the hot air. The question normally arises, therefore, as to how much air is required to dry the veneer. One way to approach this problem is to first calculate the amount of air required to evaporate 1 pound of moisture from the veneer and then multiplied this value by the total amount of water to be evaporate to obtain the total air requirements. To do this, let us first find the heat carrying capacity of 1 ft³ of air.

Let us assume that air is passing over the veneer at a dry bulb temperature of T_f and a relative humidity of H percent. To find the heat carrying capacity of the air, we must first find the “water content” or specific humidity of the air under this condition. The relationship between specific humidity and relative humidity is given by the expression

$$Y = \frac{Hp_w}{1.608 (p_{at} - Hp_w)} \quad (29)$$

where Y = specific humidity in pound of vapour per pound of dry air
 p_w = pressure of water vapour at temperature in question, (psi)
 p_{at} = atmospheric pressure, (psi)
 H = relative humidity, (%)

Note : For this paragraph of air requirements calculations, it is calculated in British units because of relevant tables and charts are available in British. Transformation into S.I. units will be done as end results

Referring to Table 2-6, we can get the pressure of the water at dry bulb temperature, T_f , which is p_v so that the pressure of the water in the air is therefore

$$p_w = H p_v$$

so the amount of moisture in the air at T_F and percent relative humidity is

$$Y = \frac{p_w}{1.608 (p_{at} - p_w)}$$

However, the specific humidity may be found more conveniently by use of a psychometric chart. The intersection of the right hand side of the chart opposite the intersection of the dry bulb temperature and relative humidity line (Fig. 2.7)

But as a matter of convenience, this conversion can be made by means of the graph which may be seen in Figure 2.8

Now one pound mole of gas at a temperature of 32°F and 14.7 psi will occupy a volume of 359 ft^3 (Mooney, 1955). Thus 28.97 pounds of air (or 18.02 pounds of water vapor) will occupy a volume of 359 ft^3 under these condition,

At other temperatures, the volume of one mole of a gas can be predicted by the expression.

$$V = \frac{359 (T_F + 460)}{(32 + 460)} \quad (30)$$

The volume of 1 lb of dry air, V_a , at this temperature is therefore

$$V_a = \frac{V}{28.97}$$

Similarly, the volume occupied by Y lbs of water vapor, V_v , at this temperature is

$$V_v = V \times \frac{Y}{18.02}$$

Table 2-6 Vapor pressure and latent heat of vaporization of water at various temperature.

Temperature Deg. F	Temperature Deg. C	Vapor pressure of water		Latent heat of evaporation	
		psi	Pa	Btu	Jule
32	0.00	0.08854	610.46	1075.8	1135029.24
35	1.67	0.09995	689.13	1074.1	1133235.65
40	4.44	0.12170	839.09	1071.3	1130281.49
45	7.22	0.14752	1017.11	1068.4	1127221.83
50	10.00	0.17811	1228.02	1065.6	1124267.67
55	12.78	0.21410	1476.17		
60	15.56	0.25630	1767.13	1059.9	1118253.85
65	18.33	0.30560	2107.04		
70	21.11	0.36310	2503.49	1054.3	1112345.54
75	23.89	0.42980	2963.37		
80	26.67	0.50690	3494.95	1048.6	1106331.72
85	29.44	0.59590	4108.58		
90	32.22	0.69820	4813.92	1042.9	1100317.90
95	35.00	0.81530	5621.29		
100	37.78	0.94920	6544.50	1037.2	1094304.08
110	43.33	1.27480	8789.43	1031.6	1088395.77
120	48.89	1.69240	11668.68	1025.8	1082276.44
130	54.44	2.22250	15323.59	1020.0	1076157.12
140	60.00	2.88860	19916.19	1014.1	1069932.29
150	65.56	3.71800	25634.70	1008.2	1063707.46
160	71.11	4.74100	32688.03	1022.3	1078583.75
170	76.67	5.99200	41313.37	996.3	1051152.29
180	82.22	7.51000	51779.60	990.2	1044716.45
190	87.78	8.33900	57495.35	984.1	1038280.61
200	93.33	11.52600	79468.93	977.9	1031739.26
210	98.89	14.12300	97374.61	971.6	1025092.41
212	100.00	14.69600	101325.30	970.3	1023720.84

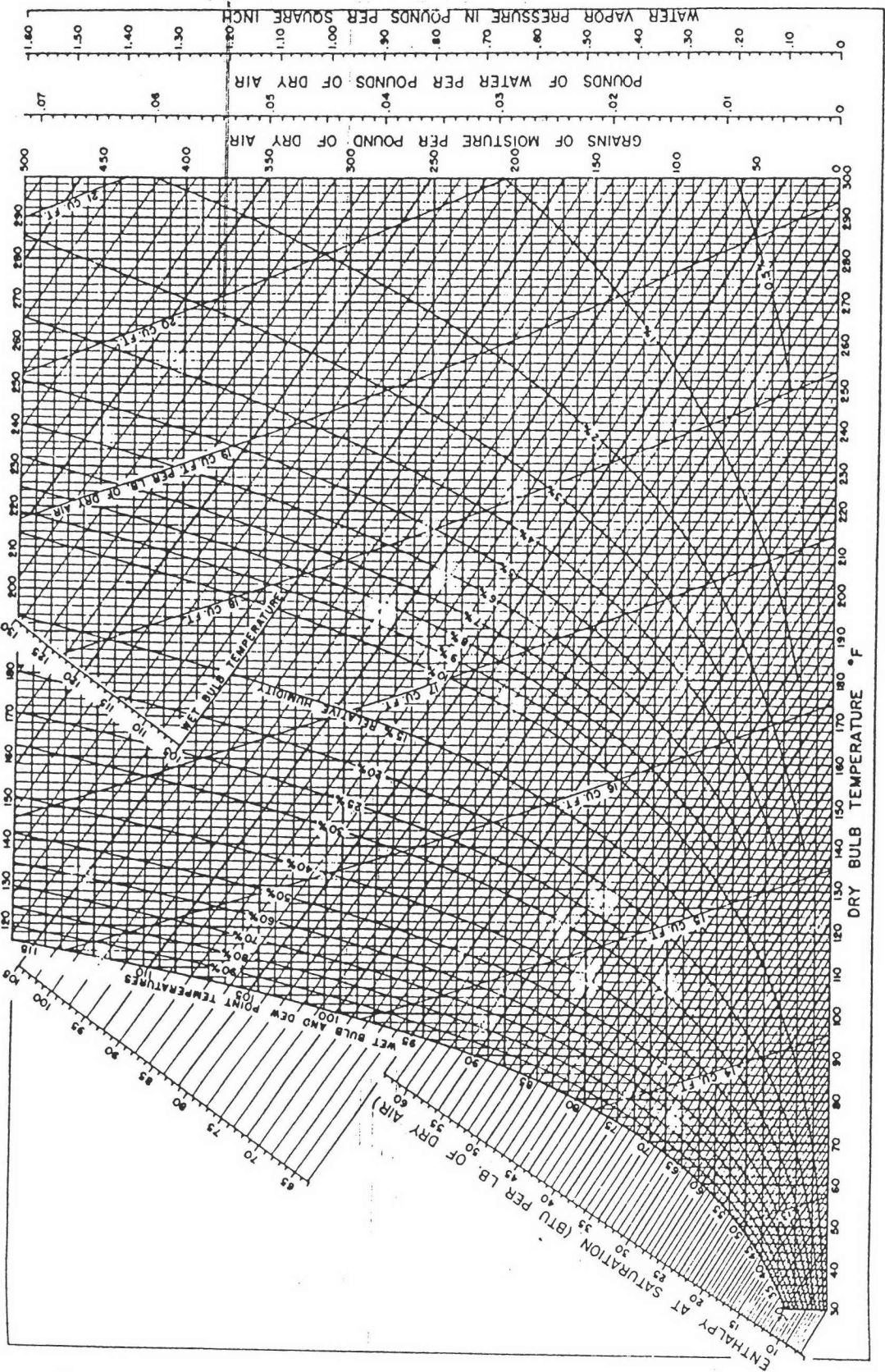


Fig. 2.7 Psychrometric chart

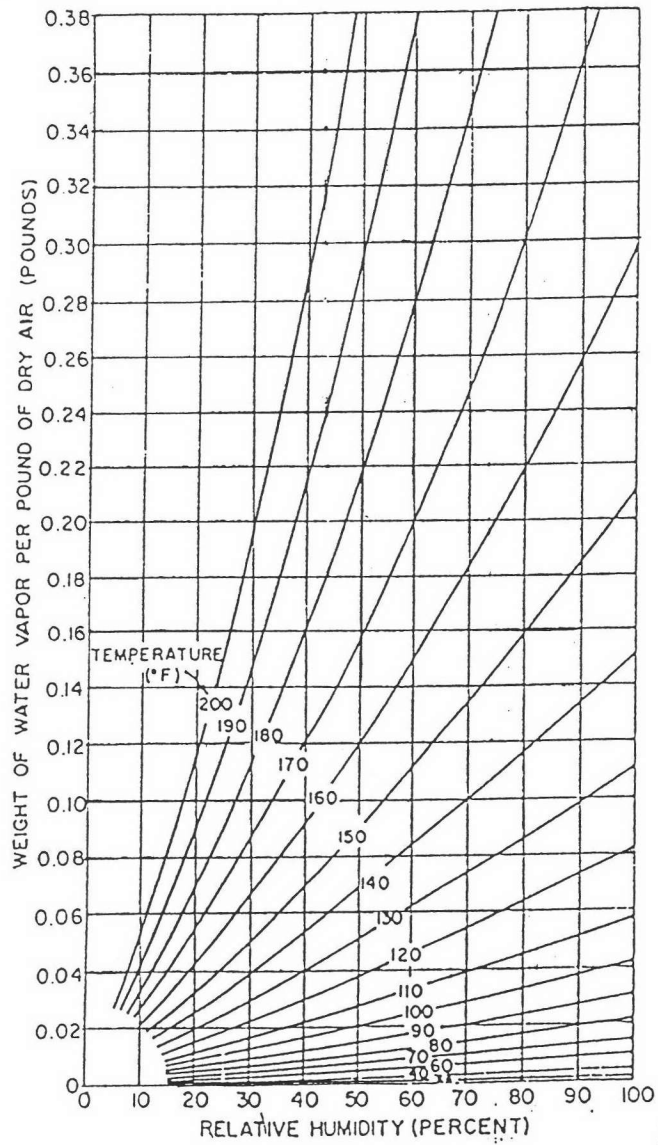


Fig. 2.8 Weight of water vapor in pounds per pound of dry air at various combinations of temperature and relative humidity at a barometric pressure of 29.92 inches of mercury

The total volume of the air plus the water vapor, V_t , is

$$V_t = V_a + V_v$$

In practice specific volume is usually read directly from a psychrometric chart. Specific volume is shown as diagonal lines on the chart with the table, ft^3 . This volume can also be found by means of the graph which is given in Figure 2.9.

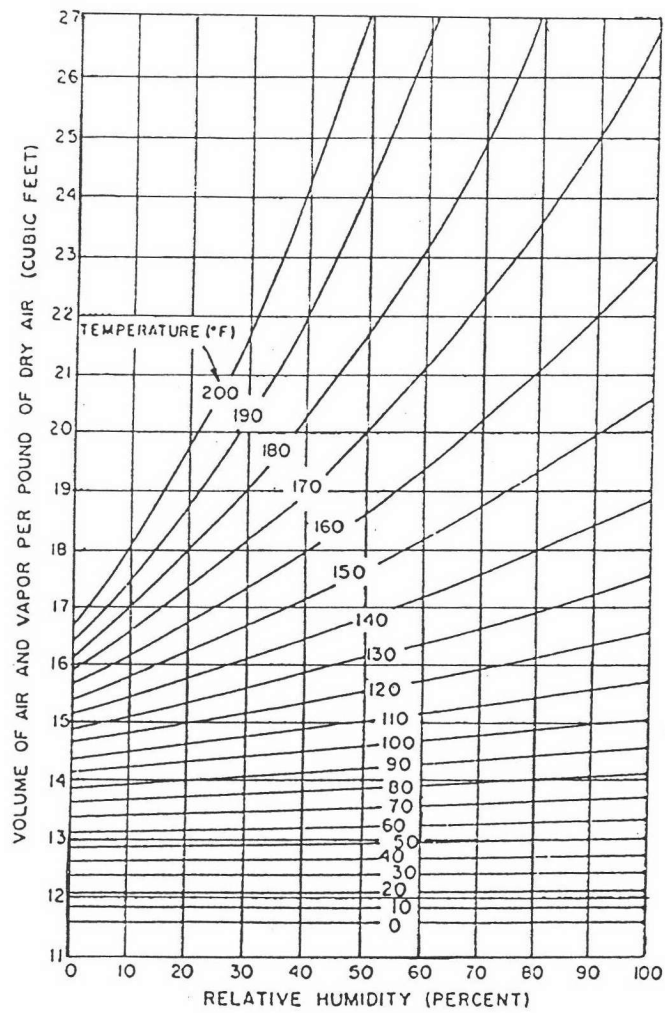


Fig. 2.9 Volume of air and water vapour in cubic feet per pound of dry air at the conditions of temperature and pressure shown and atmospheric pressure of 29.92 inches of mercury.

If we now calculate the weight of the mixture per unit volume, D , we obtain

$$D = \frac{1 + Y}{V_t}$$

Furthermore, the weight of dry air, D_a , contained in a cubic foot of this mixture is

$$D_a = \frac{1}{1 + Y} \times D$$

Similarly, the weight of water vapor, D_v , contained in a cubic foot of this mixture is

$$D_v = \frac{Y}{1 + Y} \times D$$

Now, if the specific heat of dry air is C_{pa} and the specific heat of water vapor is C_{ps} . The total heat, q , which may be obtained for evaporative purpose from 1 cubic foot of mixture is then

$$q = D_a \times C_{pa} + D_v \times C_{ps}$$

If it is assumed that the drying process is truly adiabatic, then the amount of heat required to separate water from veneer is relatively small so that the heat of wetting can be neglected. Under this condition, the only heat required is the latent heat of vaporization, h_{fg} . The volume of air-vapor mixture, V_t , required to evaporate one pound of water from the veneer per degree of temperature drop, therefore, is

$$V_t = \frac{h_{fg}}{q}$$

The amount of air required to evaporate 1 pound of water at various temperature and humidity is also for convenience in Fig. 2.10

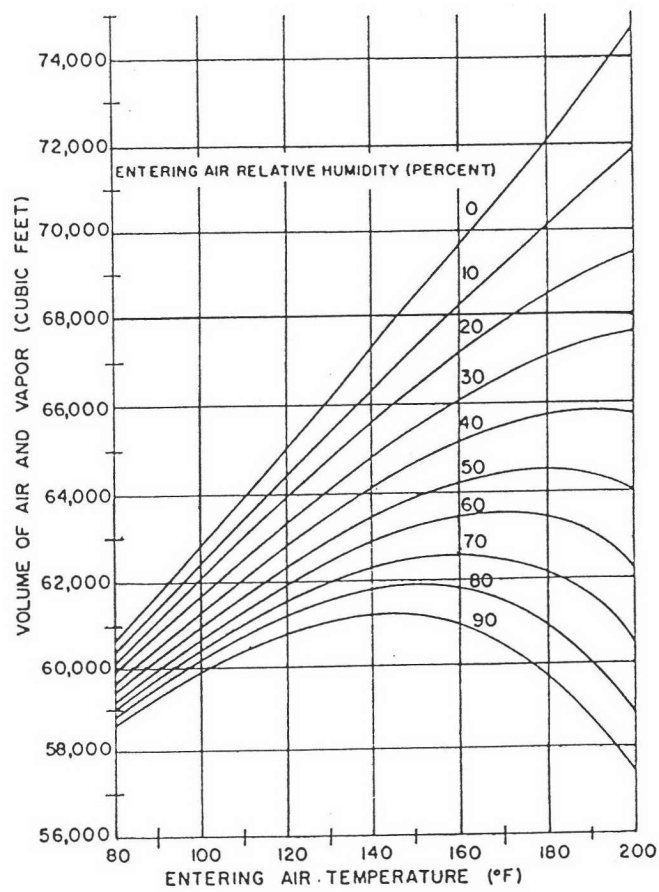


Fig. 2.10 Amount of air and vapor needed to evaporate one pound of water when the temperature drop across veneer sheet is one degree Fahrenheit

By assume the condition of following

T_f	=	130	$^{\circ}\text{F}$
H	=	67	%
p_v	=	2.2225	psi
C_{pa}	=	0.24	Btu/lb/ $^{\circ}\text{F}$
C_{ps}	=	0.45	Btu/lb/ $^{\circ}\text{F}$
C_{ps}	=	1020	Btu/lb

We obtain V_t by calculation is $62,130 \text{ ft}^3/\text{lb-}^{\circ}\text{F}$

As can be seen from the graph, the intersection of the 130°F dry bulb temperature line with a line representing 67% relative humidity gives a required volume of air of slightly over $62,000 \text{ ft}^3$. By using this graph or by carrying out similar calculations, the amount of air to dry a veneer at a given rate can readily determined.

Rate of drying, air circulation and temperature drop across the veneer are interrelated, and, once any two are know, the third can be calculated.

2.7 Density of Dry and Moist Air

Assuming that air behaves as an ideal gas, the density of dry air may be calculated by means of the formula

$$D = \frac{D_o T_o p}{T p_a} \quad (31)$$

where D = density of an air-water vapor gaseous mixture.
 D_o = density of dry air at specified reference temperature and pressure.

T_o = standard reference temperature

p = pressure

p_a = pressure of dry air

According to this expression, the density of dry air at any temperature and pressure may be computed by means of the above general formula, if the density of dry air under standard conditions of temperature and pressure is known. The density of both dry air and water vapor can readily be computed to utilizing Avogadro's hypothesis (Barrow, 1961; which states that one gram mole of gas occupies a volume of 22.414 liters. Although air does not have a true molecular weight as do pure substance, a standard and equivalent weight of 28.97 is usually assigned to it based on an air composition (percent by volume) of nitrogen, 78.03; oxygen 20.99; and argon 0.98 (Mooney, 1955;). Thus 28.97 grams of air has a volume of 22.414 liters, at 0 °C and 29.92 in. of Hg. similarly; 28.97 pounds of air has a volume of

$$V = 28.97 \text{ lb} \times 453.59 \frac{\text{g}}{\text{lb}} \times \frac{1}{28.97} \frac{\text{mole}}{\text{g}} \times 22.414 \text{ ltrs} \times \frac{1}{28.32} \frac{\text{ft}^3}{\text{ltrs}} = 359 \text{ ft}^3$$

At 32 °F and 29.92 in. of Hg. The density of dry air under standard conditions of temperature and pressure, D_o , may be accordingly calculated as

$$D_o = 28.97 \text{ g} \times \frac{1}{22.414} = 1.2925 \frac{\text{g}}{\text{ltrs}} \quad \text{or}$$

$$D_o = \frac{28.97 \text{ lbs}}{359.0 \text{ ft}^3} = 0.08070 \frac{\text{lbs}}{\text{ft}^3}$$

In the energy system of units, the density of dry air at any temperature and pressure may be found by substituting the appropriate values into equation (33) i.e.,

$$D_a = 0.08070 \frac{\text{lbs}}{\text{ft}^3} \times \frac{(460 + 32)}{(460 + T_f)} \times \frac{p_a}{29.92 \text{ in. of Hg}} \quad (32)$$

simplifying gives

$$D_a = \frac{0.08631}{1 + 0.00217 T_f} \times \frac{p_a}{29.92} \quad ; \frac{\text{lbs}}{\text{ft}^3} \quad (33)$$

where D_a = density of air (lbs/ft³)

p_a = air pressure (inches of Hg)

T_f = temperature (°F)

If, for purpose of discussion, we take the density of pure air to be 0.08073 (lbs/ft³) at 32 °F and at a pressure of 29.92 in. of Hg, and the absolute temperature to be $T_f = 460$, equation (32) can then be reduced to the form

$$D_a = \frac{1.325 p_a}{460 + T_f} \quad (34)$$

Similarly, the density of dry air in the metric system of units may be calculated by means of the expression

$$D_a = 1.2925 \frac{\text{g}}{\text{ltrs}} \times \frac{273}{(273 + T_c)} \times \frac{p_a}{(760 \text{ mm. Hg})}$$

simplifying gives

$$D_a = \frac{1.2925}{1.0 + 0.00366 T_c} \times \frac{p_a}{760 \text{ mm.}} \quad ; \frac{\text{g}}{\text{ltrs}} \quad (35)$$

where D_a = density of air (g/ltrs)

p_a = air pressure (mm. of Hg)

T_c = temperature (°C)

To illustrate the use of equation (33), let us find the density of dry air at 70 °F and a pressure of 29.92 in. of Hg. Substituting the appropriate values into equation (33) gives.

$$D_a = \frac{0.08631}{1 + 0.00217 \times 70} \times \frac{29.92}{29.92}$$

$$= 0.0749 \text{ lbs/ft}^3$$

In fan work, a standard air density of 0.075 lbs/ft³ is used which corresponds to the above value (Mc Donal, 1958). Had we worked this problem using equation (36), we would have obtained

$$D_a = \frac{1.325 \times 29.92}{460 + 70} = 0.0749 \text{ lbs/ft}^3$$

as expected.

The density of moist air can be obtained in a manner similar to that used to obtain the density of dry air. Referring to equation (31), it is seen that the density of dry air in a mixture of gases is given by the expression

$$D_a = \frac{D_o T_o p_a}{T p_o} \quad (36)$$

where p_a = the partial pressure of the air in the mixture.

p_o = standard reference pressure

Furthermore, we can write

$$p_a = p_{at} - p_w \quad (37)$$

where p_{at} = the atmospheric pressure

p_w = the partial pressure of the water vapor in the air

So that we may also write

$$D_a = D_o \frac{T_o}{T} \frac{p_{at} - p_w}{p_o} \quad (38)$$

We next note that the specific or absolute humidity of the moisture in the air, G , is given by the expression (Mooney, 1955; Barry, 1958)

$$Y = \frac{p_w}{1.608 (p_{at} - p_w)} \quad (39)$$

Since absolute humidity is started in term of pounds of moisture per pound of dry air (or in other comparable units), the density of the water vapor in the air is given by the expression.

$$D_v = G \times D_a \quad (40)$$

The density of the mixture is equal to the sum of these; i.e., the density of the mixture is equal to the weight of air plus the weight of water vapor per cubic foot, so that

$$D_m = D_a + D_v = D_a (1 + G) \quad (41)$$

where D_m = the density of mixture

performing the appropriate substitutions gives

$$\begin{aligned} D_m &= D_o \frac{T_o}{T} \frac{(p_{at} - p_w) \times 1.608 (p_{at} - p_w) + p_w}{p_o \quad 1.608 (p_{at} - p_w)} \\ &= D_o \frac{T_o}{T} \frac{(p_{at} - 0.3781 p_w)}{p_o} \end{aligned} \quad (42)$$

In the metric system where $T_o = 273$ K. and $p_o = 760$ mm. Hg
this equation takes the form

$$D_m = 1.2925 \times \left[\frac{273}{273 + T_c} \right] \left[\frac{(p_{at} - 0.3781 p_w)}{760} \right] \quad (43)$$

where p_{at} and p_w are measured in mm. of Hg (Hodgman, 1970). In the English system where $T_o = 460$ deg. Abs. and $p_o = 29.92$ in. of Hg., equation (38) takes the form

$$D_m = 0.08070 \times \left[\frac{460 + 32}{460 + T_f} \right] \left[\frac{(p_{at} - 0.3781 p_w)}{29.92} \right] \quad (44)$$

where p_{at} and p_w are measured in inches of Hg.

simplifying this expression gives

$$D_m = \frac{p_{at} - 0.3781 p_w}{0.7536 (460 + T_f)} \quad (45)$$

(Berry, 1958)

Normal procedure to evaluate the density of air at a given temperature, relative humidity and air pressure is to use a psychrometric chart. Consider air at 70 °F and standard pressure of 29.92 in. of Hg. and a relative humidity of 45 percent. The specific volume is 13.5 cubic feet per pound of dry air (Fig. 2.7). The density is then found as the reciprocal of this; i.e.,

$$D_m = 1/13.5 \quad \text{ft}^3/\text{lb} = 0.074 \text{ lbs/ft}^3$$

dry air at the above conditions yields a density of

$$D_a = 1/13.375 \quad \text{ft}^3/\text{lb} = 0.0749 \text{ lbs/ft}^3$$