Drying of Sand on a Hot Surface

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Constant layer moisture at the hot surface is found to exist during the constant-rate period of drying of sand on a hot surface in still air. It accounts not only for the constant-rate period of drying itself but also largely for the length of the period.

Temperature of the air-surface interface usually has minor effects on the rate of vaporization because equilibrium between vapor and the bed is not established during periods of rapid vaporization.

Numerical relationships have not been established.

Even though drying on a hot surface is used extensively in industry there seems to be no explanation of the mechanism in the literature. Further understanding of this mechanism could lead to the development of more efficient applications of hot-surface drying.

The theories of air drying have only limited application to hot-surface drying because of fundamental differences in the application of heat and the flow of material. In air drying, heat is supplied at the same surface from which vapor leaves, but in hot-surface drying it is supplied from the other side. In spite of this difference, it has been shown (*10*) that hot-surface drying as well as air drying gives drying-rate curves with constant-rate, first falling-rate, and second falling-rate periods. There must however be different reasons for this similarity. The purpose of these tests is to determine important factors which govern the drying of granular solids on a hot surface in still air and to show why hot-surface drying gives a drying-rate curve of the same general form as that for air drying.

Materials which may be dried include both hygroscopic and nonhydroscopic substances. In order to eliminate the effects that bound water might have upon the process, sand, a nonhygroscopic material of relatively uniform size and shape, is used to begin the study of hot-surface drying. The results can be regarded as applying to the pore moisture between small granules in a bed of material.

PREVIOUS WORK

Air Drying

Rates and theory for the air drying of numerous substances have been quite thoroughly investigated and reported (*1, 2, 13, 14, 16*). Ceaglske and Hougen (*3*) showed that water flow in sand during air drying is due primarily to capillary forces. They used the method of Haines (*6*) to determine the effect of suction in the sand on percentage of saturation, and Haine's terminology to explain how water is held between sand particles at different stages of drying. Complete saturation of the cells between particles is called the *capillary state*. The *funicular state* occurs when the pores are emptied but the particles are covered by a continuous water film. The *pendular state* is formed in the last stages of drying when the small amount of water present is held at the points of contact of the particles. Pearse, Oliver, and Newitt (*12*) summarized and expanded the theory of air drying the granular materials and of the movement of water within the bed. They explained how the movement of water between particles in the bed depends upon gravitational, capillary, and frictional forces, the relative effect of which is determined by particle size and shape.

From the work referred to, an outline of the mechanism during the air drying of sand can be stated much as follows.

The bed is made up of fine particles between which are interconnecting cells or pores of various size. Evaporation during the capillary state causes a curvature of the water surface in the pores and sets up suction within the bed. When "entry suction" is attained, the continuous water film is broken and water is pulled down the large capillaries and supplied to the surface through the small capillaries. As the capillaries are emptied of water, liquid is replaced by vapor and air. Constant-rate drying occurs during this period and continues until surface particles are no longer supplied with enough water to cover them.

The first falling-rate period begins with this critical moisture content, which often occurs when the larger pores are emptied but the smaller cells still contain water. The second falling-rate period occurs when the remaining water is in the pendular state. Since the water does not present a continuous film in the pendular state, heat for vaporization must be transferred from the heated air down through the bed. Vaporization takes place within the bed and vapor passes out to the air surface.

Hot-surface Drying

For the vacuum drying of Prussian blue on heated shelves Ernst, Ardern, Schmied, and Tiller (*4*) found a constant-rate period followed by a variable rate. At lower vacuum the variable rate is irregular until a definite falling-rate period is reached. At higher vacuum the customary falling rate immediately follows the constant-rate period. In the vacuum drying of Sil-O-Cel, Ernst, Ridgway, and Tiller (*5*) obtained the customary type of drying curves. They showed that in vacuum shelf drying heat is supplied not only from the bottom but also from the top of the cake.

Hougen, McCauley, and Marshall (*8*) presented a limited number of curves for the moisture distribution in sand and in lead shot while drying on a hot surface but did not give pertinent information with regard to conditions. McCready (*10*), using a hot surface for drying paper pulp, showed a constant-rate period followed by first and second falling-rate periods. King and Newitt (*9*) reported a pseudoconstant rate in place of a constant rate while drying glass beads on a hot surface and in a stream of air. The pseudoconstant rate, which is a very gradual falling rate, is followed by first and second falling-rate periods.

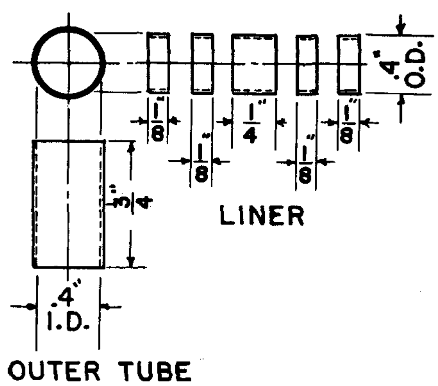

Fig. 1. Sampler for sand-layer moisture.

EQUIPMENT

Drying was carried out on a $\frac{3}{4}$-in. thick by 12-in.-diam. steel heating plate. The heating plate rested on a similar steel plate, which in turn rested on an electric hot plate. Insulation around the plate edges helped to give an even temperature distribution across the plate. Small holes were drilled radially halfway between the two faces of the heating plate. One hole terminated at the center of the plate and the others on graduated radii at 1-in. intervals. At the end of each hole was welded a 20-gauge fiber-glass–covered copper-constantin thermocouple. The thermocouple wells within the plate were packed with asbestos fiber.

The hot-plate temperature was regulated by resistance coils in series with the hot plate. A voltmeter across the hot-plate coils indicated voltage to the hot plate.

PROCEDURE

Ottawa sand of 40-60 U. S. standard mesh with a void volume of 40.6% was used in all tests. Most of the data were taken with a sand-bed thickness of $\frac{3}{4}$ in. One drying-rate and one temperature-distribution series were run with a sand bed $\frac{1}{4}$-in. thick.

Wetted-sand samples were put in a steel ring of 6.25-in. diameter and then placed on the heating surface. Since movement of the sand disturbed the even distribution of moisture, the bed was again saturated while it was on the hot plate. A cardboard cover was then supported 6 in. above the sand surface.

Atmospheric pressure, temperature, and wet-bulb temperature of the surrounding air were taken and reported with the data.

On the basis of the work of McCready

(10), atmospheric conditions above the sample are of little importance. When using variations of air temperature, humidity, and velocity, he found that temperature of the air had little effect and that, provided that the difference in temperature between hot surface and drying air was large, humidity had little effect.

The present data were also used to find the effects of atmospheric conditions. Plots of drying rate vs. temperature and drying rate vs. atmospheric pressure indicated no correlation. A plot of rate vs. relative humidity indicated a slight trend toward variation that was within variations of the data. Since the effects of all these variables seemed insignificant with respect to the accuracy of the data, they were neglected. These plots are not shown.

Moisture

While the sand was drying, samples were removed at intervals to determine moisture. It was found that any pressure on the sand changed the moisture distribution in the surrounding sand. Sampling tubes were placed in the sand at the beginning of the run and were spaced to avoid moisture changes in surrounding rings. Eight or nine glass sampling tubes were used for an individual run on drying rate.

Sampling tubes were also used to determine the moisture of the layers. The assembly, shown in Figure 1, was made up of a brass tube of 0.4-in. diameter by ¾-in. length into which were fitted five sectional micarta tubes or liners. When a sample was taken, the entire sampling unit was removed from the sand and the micarta tubes were slipped from the brass tube and separated in individual-layer samples. Results with the brass-micarta unit were compared with those with glass tubes and found to be within the general accuracy. The greatest source of error seemed to be caused by exposure of the sand between time of removal from the hot plate and time that the sample was placed in a closed weighing bottle. Manipulation was speeded up with the use of the brass-micarta unit.

All moisture values were reported on the dry basis.

The method of Haines (6) was used to determine the suction-moisture relationship for sand of ¾-in. thickness at room temperature. This method was used and described by Ceaglske and Hougen (3).

Temperatures

Temperatures were taken with no. 20 copper-constantin thermocouples provided with a cold junction. Readings, made on a Leeds and Northrup Portable Precision Potentiometer, were recorded to the nearest degree. Thermocouples for the measurement of layer temperatures in the sand were mounted in a frame built of micarta and brass. The hot junctions extended ¾ in. from the micarta face into the sand. The entire frame was covered with sand and the wires were passed through the sand at the same level for 4 in. The same thermocouples suspended vertically in the sand at different levels gave errors up to 6°F.

Layer temperatures were taken in separate tests in a range approaching temperatures used in the drying-rate tests. Plate temperatures midway between the faces of the heating plate were taken at the center and at radii of 1 and 2 in. The three values were averaged and reported to the nearest degree as plate temperature. This plate temperature did not give surface temperatures and should be regarded as approximate surface temperature.

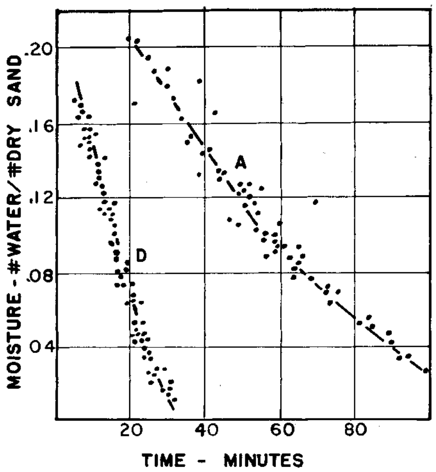

Fig. 2. Drying-rate data.

	Curve *A*	Curve *D*
Average hot-plate temperature	165°F.	168°F.
Surroundings:		
Barometer, mm.	740, +6, −11	740, +16, −9
Temperature, °F.	79, +9, −7	74, +4, −3
Relative humidity, %	38, +26, −22	24, +13, −9
Bed depth, in.	3/4	1/4

Presentation of Data*

From six to nine drying tests were used for each series of drying-rate data. Data from each of these tests were plotted individually and also on a common moisture-time graph. The composite data only are shown in Figures 2 and 3. Drying rates were obtained by measuring the slopes. Rates from the composite data were compared with the averages of the individual runs and were found to be within reasonable agreement. The drying rates are plotted in Figures 4 and 5 with points from the composite data.

From two to four runs were used for each series of layer moisture. The data for a given sand depth were plotted on a common-layer-moisture–compositive-moisture graph, a typical example of which is shown in Figure 6. A curve was drawn through the points; from the smoothed curve, readings were taken at given moisture contents to give the values shown in Tables 1, 2, and 3.

RESULTS

Drying Rates

Drying-rate curves for sand of ¾-in. thickness (Figure 4) show constant-rate periods followed by falling-rate periods. At the lower plate temperatures the constant-rate period terminates at about 10% moisture, as compared with 6% moisture for a plate temperature of 220°F. This agrees with the conclusions of Ernst, Ardern, Schmied, and Tiller (4) on Prussian-blue vacuum drying. They found that increased plate temperatures give a longer constant-rate period.

The drying-rate curve for sand of ¼-in. thickness and 168°F. plate temperature (Figure 5) also has a critical point at about 6% moisture. A comparison with the curve for sand of ¾-in. thickness in this temperature range shows that the thinner bed gives a longer constant-rate period but about the same constant rate. This is a conclusion that should not be extended to other bed

*Tabular material has been deposited as document 5301 with the American Documentation Institute, Photoduplication Service, Library of Congress, Washington 25, D. C., and may be obtained for $2.50 for photoprints or $1.75 for 35-mm. microfilm.

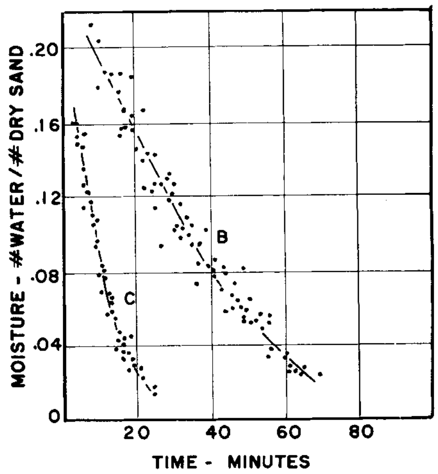

Fig. 3. Drying-rate data.

	Curve *B*	Curve *C*
Average hot-plate temperature	182°F.	220°F.
Surroundings:		
Barometer, mm.	740	739, +7, −11
Temperature, °F.	80	77, +6 −14
Relative humidity, %	26	35, +24, −14
Bed depth, in.	3/4	3/4

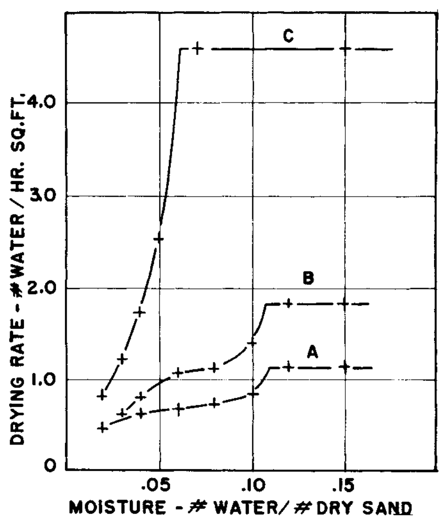

Fig. 4. Hot-surface drying rates.

Curve	Bed depth, in.	Plate temperature, °F.
A	3/4	165
B	3/4	183
C	3/4	220

thicknesses because thickness is probably a factor in this type of drying.

Increased plate temperature increases the value of the constant rate, but other factors also appear to influence the rate. A direct correlation is not apparent from the data on drying rates alone.

Moisture Distribution

Values for the moisture-distribution curves (Figures 7, 8, and 9) are taken from Tables 1, 2, and 3. Plate temperatures for the runs average 161°, 204°, and 213°, respectively, but the sand thickness for each is ¾ in.

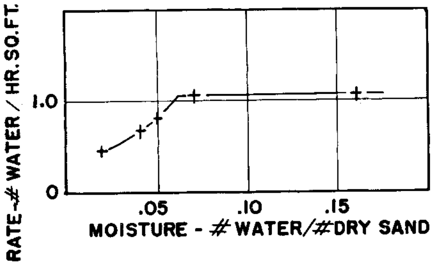

Fig. 5. Hot-surface drying rate: plate temperature, 168°F.; bed depth, 1/4 in.

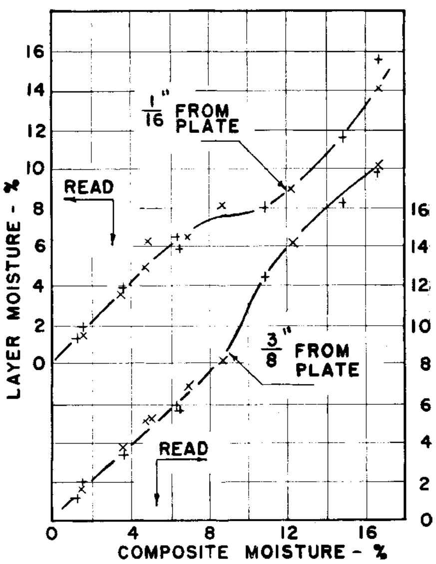

Fig. 6. Typical layer moisture: average hot-plate temperature, 213°F.; sand depth, 3/4 in.; moisture, lb. water/lb. dry sand.

TABLE 1.—SMOOTHED LAYER MOISTURES

Average Plate Temperature: 161°F.

Surroundings: 739 mm., 74°F. (+15°, −2°), 46% relative humidity (+3, −4)

Composite moisture / Distance from plate, in.	0.190	0.180	0.160	0.140	0.120	0.100	0.080	0.060
1/16	0.194	0.170	0.152	0.144	0.136	0.120	0.096	0.072
3/16	0.193	0.183	0.162	0.136	0.110	0.090	0.070	0.053
6/16	0.199	0.193	0.168	0.133	0.108	0.085	0.068	0.059
9/16	0.190	0.180	0.162	0.147	0.128	0.105	0.081	0.060
11/16	0.175	0.163	0.148	0.140	0.134	0.120	0.088	0.062

TABLE 2.—SMOOTHED LAYER MOISTURES

Average Plate Temperature: 204°F.

Surroundings: 734 mm. (+3, −3), 84°F. (+4°, −7°), 50% relative humidity (+13, −10)

Composite moisture / Distance from plate, in.	0.170	0.150	0.130	0.110	0.090	0.070	0.050	0.030	0.010
1/16	0.158	0.142	0.128	0.114	0.098	0.078	0.057	0.033	0.008
3/16	0.166	0.147	0.125	0.100	0.075	0.057	0.042	0.029	0.016
6/16	0.185	0.163	0.130	0.102	0.082	0.064	0.047	0.030	0.012
9/16	0.172	0.154	0.135	0.116	0.097	0.077	0.056	0.034	0.007
11/16	0.152	0.145	0.137	0.127	0.107	0.083	0.056	0.029	0.006

TABLE 3.—SMOOTHED LAYER MOISTURES

Average Plate Temperature: 213°F.

Surroundings: 738 mm. (±4), 79°F. (±3°), 53% relative humidity (±11)

Composite moisture / Distance from plate, in.	0.170	0.150	0.130	0.110	0.090	0.070	0.050	0.030	0.010
1/16	0.160	0.120	0.099	0.086	0.082	0.071	0.054	0.033	0.013
3/16	0.166	0.147	0.108	0.083	0.078	0.060	0.043	0.025	0.008
6/16	0.182	0.168	0.150	0.125	0.077	0.065	0.047	0.030	0.011
9/16	0.171	0.161	0.148	0.125	0.098	0.075	0.053	0.031	0.010
11/16	0.161	0.150	0.136	0.120	0.103	0.083	0.047	0.021	0.007

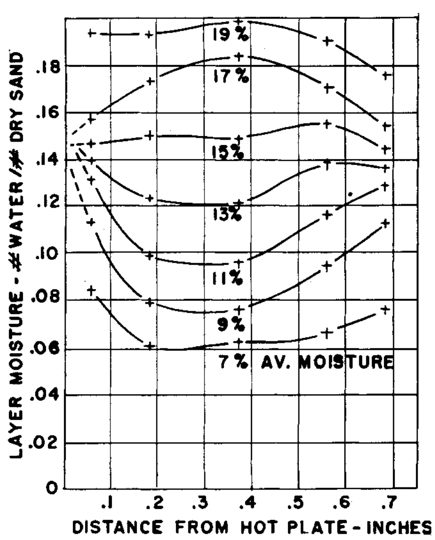

Fig 7. Moisture distribution in sand bed.

Average hot-plate temperature	161°F.
Surroundings:	
Barometer, mm.	739
Temperature, °F.	78, +11, −6
Relative humidity, %	46, +3, −4
Bed depth, in.	3/4

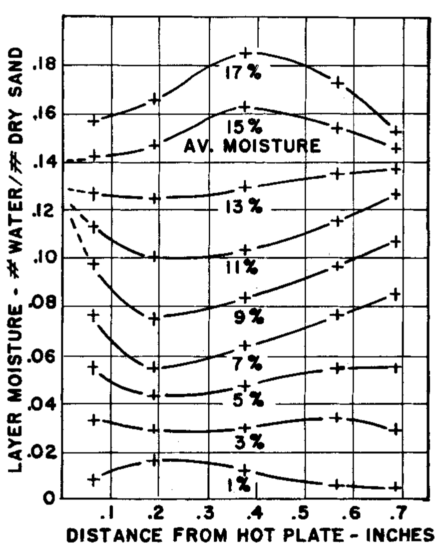

Fig. 8. Moisture distribution in sand bed.

Average hot-plate temperature	202°F.
Surroundings:	
Barometer, mm.	734, +3, −3
Temperature, °F.	84, +4, −7
Relative humidity, %	50, +13, −10
Bed depth, in.	3/4

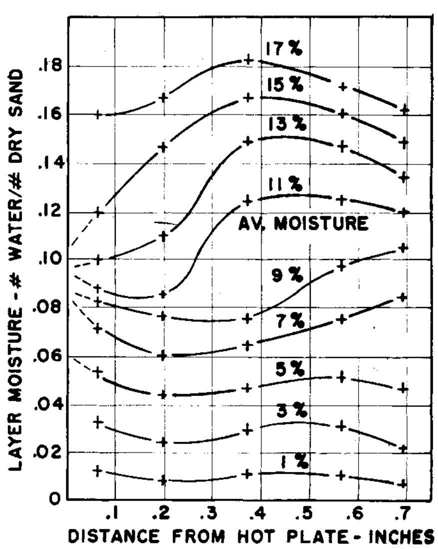

Fig. 9. Moisture distribution in sand bed.

Average hot-plate temperature	213°F.
Surroundings:	
Barometer, mm.	738, +4, −4
Temperature, °F.	80, +2, −3
Relative humidity, %	53, +11, −11
Bed depth, in.	3/4

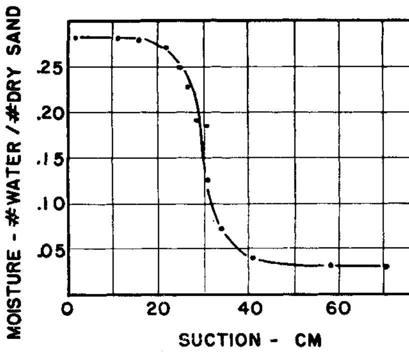

Fig. 10. Suction potential–moisture.

Surroundings:	
Barometer, mm.	738
Temperature, °F.	87
Relative humidity, %	70
Bed depth, in.	3/4

At high moistures, above 18%, the bed tends to rise from the plate owing to the formation of vapor. At about 16% moisture the bed settles down and the normal constant-rate period begins. The moisture-distribution curves become convex with the maximum moisture near the center of the bed. At intermediate moistures they become or tend to become concave. At very low moistures the curves again become convex. The last case is not clearly shown on the charts but is apparent from inspection of samples tested. Moisture right at the hot surface and at the air surface of the bed is not measured directly, but extrapolation gives an indication of the values.

With a plate temperature of 161°F. moisture at the hot surface appears to remain constant at about 15% between the composite moisture contents of 17 and 10%. A constant layer moisture at the hot surface during the period of constant-rate drying is evident in the runs at other temperatures.

Extrapolated values of moisture at the hot surface for all plate temperatures are tabulated in Table 4. The constant hot-surface layer moisture decreases with increased plate temperature and persists during the period of constant-rate drying as indicated by the drying-rate curves.

Vaporization takes place at the hot surface where heat is supplied. The rising vapor displaces water from the large pores in an amount which depends upon the amount of vapor flowing. At higher plate temperatures more water is displaced, resulting in a lower constant

TABLE 4.—MOISTURE DURING CONSTANT-RATE DRYING

Bed Thickness: ¾ in.

Moisture: lb. water/lb. dry sand

Plate temperature, °F.	Hot-surface layer	Range for constant layer moisture	Range for constant rate
213	0.09	0.15–0.07	0.16–0.06
203	0.13	0.15–0.10	0.17–0.105
161	0.15	0.17–0.10	0.17–0.11

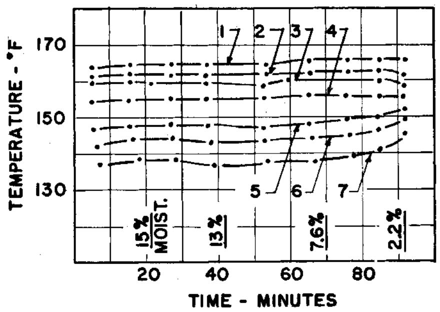

Fig. 11. Typical plate and sand temperatures.

Curve	1	2	3	4	5	6	7
Distance from plate, in.	Plate	0.06	0.15	0.28	0.45	0.56	0.71

Moisture is expressed in lb. water/lb. dry sand

hot-surface layer moisture.

Water displaced from the region of the hot surface is forced to the center of the bed, which then acts as a reservoir to supply the hot surface through the small pores. As long as a sufficient supply of water exists and the rate of vaporization is constant, constant hot-surface layer moisture is maintained.

Inspection of the moisture-distribution curves shows that a concave curve with low moisture near the center of the bed is the forerunner of the first falling-rate drying period. The location of the critical point is a function of both the constant hot-surface moisture and the moisture supply at the center of the bed. Under the conditions of these moisture-distribution tests, low hot-surface moisture corresponds to low critical moisture and a long constant drying-rate period.

Suction Potential

The suction–water-content curve (Figure 10) is shown for sand of ¾-in. thickness at room temperature. It can be expected to give an indication of the location of critical points in the drying-rate curves, but correlation with hot-surface drying is limited. First it was run at room temperature and not at the drying temperature. Second, the moisture distribution in sand is not the same for the test as for hot-surface drying.

The suction-moisture curve shows that the sand is saturated at about 28% moisture. Between 28 and 11% moisture the large pores are being emptied of water. Between 20 and 6% the curve approaches a straight line with only a small increase in suction. It represents a period when constant-rate drying should be possible if other influences are not more important. All these experimental drying-rate data show a constant rate in this range of moisture.

Between 10 and 4% moisture, suction increases quite rapidly with decrease in moisture because the smaller capillaries are being emptied. It is the period during which the critical point of the drying-rate curve can be expected to occur. The exact location of the critical point will be

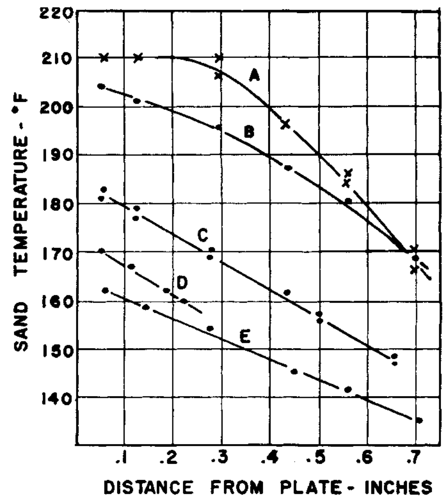

Fig. 12. Sand temperatures above hot plate.

Curve	*A*	*B*	*C*	*D*	*E*
Bed depth, in.	3/4	3/4	3/4	1/4	3/4
Plate temperature, °F.	211	208	181-83	175-76	165-66
Range, % moisture	19-11	6	17-3	16-6	17-3
Surroundings:					
Barometer, mm.	746	746	740	742	736
Temperature, °F.	92	92	88	84	78
Relative humidity, %	42	42	29	24	39

Moisture is expressed in lb. water/lb. dry sand.

determined by the constant layer moisture at the hot surface. At 9% constant layer moisture the critical point occurs at about 6%; at 15% critical layer moisture it occurs at about 10%.

Between 4 and 3% moisture, suction increases very rapidly with decrease in moisture. The smallest capillaries are about empty. In a very short time liquid water will touch the particles only at points of contact of the particles. The second falling-rate period will have begun.

Temperature

Temperature-time data for sand of ¾-in. thickness at a plate temperature of 165°F. are shown in Figure 11. These data as well as those for other runs are shown by temperature-sand depth plots in Figure 12.

Curve *A* of Figure 12 shows the temperature-depth relationship for sand at a plate temperature of 211°F. between moisture contents of 19 and 11%. The distance that the uniform temperature extends up in the sand decreases with decrease in moisture. The curve gradually changes to the form of curve *B* at 6% moisture.

At plate temperatures of 165° and 185°F. the sand temperatures are essentially linear with sand depth and at given depths remain nearly constant over moisture ranges of 15 to about 3%. This range of moisture includes both constant- and first falling-rate periods. Below 3% moisture, which represents the pendular state of moisture, the temperature-depth relationship becomes nonlinear.

During the constant- and first falling-rate periods heat is transmitted through the bed principally by the latent heat of the vapor. The vapor at a given point tends to go to physical and thermal equilibrium with the wet bed. This results in the condensation of some vapor as it rises through the bed because of decreasing temperatures. The gradual condensation of vapor combines with liquid in the bed and flows down to the hot surface to help replace liquid which has been vaporized. A large flow of liquid to the hot surface is indicated by Tambling (*15*), who by using salt solution in place of water showed that at 12% moisture 60% of the salt is concentrated near the hot surface and about 15% at the air surface. The flow of liquid concentrates most of the soluble material at the hot surface, where most of the vaporization takes place. Some movement of liquids to the air surface also occurs.

The temperature-depth relationship for sand of ¼-in. depth at a plate temperature of 176°F., shown with curve *D*, is also linear until the moisture is decreased to about 6%. This curve may be compared with curve *E* for sand of ¾-in. depth. Plate temperatures for the two are different but are within the same range and should give about the same constant-rate drying. For sand of ¼-in. depth the air interface temperature is about 159°F., corresponding to a vapor pressure of 4.6 lb./sq. in. abs. For sand of ¾-in. depth, the air interface temperature is about 133°F.; if an adjustment is made for difference in plate temperatures, 141°F. can be used. It corresponds to a vapor pressure of 2.9 lb./sq. in. abs. These vapor pressures represent the partial pressure of water vapor at saturation at the temperature of the respective air-sand interfaces. Vapor in excess of these relative amounts would be condensed in the bed if equilibrium were established. Under this condition the drying rates should tend to be proportional to 4.6 and 2.9, the vapor pressures. Actually the vapor does not condense to that extent, for the constant drying rates are shown by the drying-rate curves to be about the same. This comparison indicates that equilibrium between the vapor and the sand is not established during periods of high rate of vaporization; it emphasizes the importance of plate temperature during hot-surface drying.

Drying Process

Combining the results of previous work with the foregoing results gives a description of the mechanism of the drying of sand on a hot surface.

When the bed is saturated with water, the pores between the sand particles are filled with water. Contact with the hot surface causes an evolution of vapor which may lift the bed from the plate. At higher plate temperatures blow holes, which allow much of the vapor to escape, may form. After sufficient water has been vaporized, the bed settles and the normal constant rate of drying begins.

During the constant-rate period vapor formed at the hot surface forces its way up through the large pores of the sand by displacing water. The extent of water displacement governs the moisture content of the sand in contact with the hot surface. Since the rate of vaporization is constant, constant hot-surface layer moisture persists throughout this constant-drying-rate period. This accounts for the constant drying rate which exists during hot-surface drying.

At a higher plate temperature more vapor is formed and must force its way through the large pores by displacing more water from them. The constant hot-surface moisture decreases with increase in plate temperature and is automatically regulated to allow free passage of the vapor formed.

Vapor rising from the hot surface passes through sand of decreasing temperature as it approaches the air interface. Some of the vapor is condensed and the condensate combines with water in the bed to increase the supply available for flow through the small pores to the hot surface. The constant rate period continues as long as sufficient water is available in the center of the bed to maintain the constant hot-surface moisture.

At high rates of vaporization the vapor passes through the sand at such a rate that it does not go to physical and thermal equilibrium with the sand bed. The result is that plate temperatures rather than air-interface temperature are the controlling factor for constant drying rate. Influences such as conduction of heat through the sand, convection from the air interface, and the passage of air through the bed can be expected to have some effects but they are minor.

Besides the cycle for the circulation of water within the bed, there must also be a cycle for air. The large pores contain not only vapor but also air. Air enters the top of the bed, mixes with vapor in the large pores, and flows out into the air as a mixture.

The first falling-rate period begins when a constant hot-surface moisture can no longer be maintained. If the constant hot-surface moisture is high, there is a tendency for the critical moisture to be high; if the constant hot-surface moisture is low, the critical moisture of the drying-rate curve is low.

The second falling-rate period begins when the pendular state of water is reached. Vaporization then occurs to a great extent by heat of conduction through the bed. Heat transfer through the bed is a function of not only the normal heat of conduction but also the flow of hot vapors to a zone of lower temperatures. Harbert, Cain and Huntington (*7*) show that when heat is transferred from a hot surface through wet sand the flow of heat cannot be accounted for entirely by conduction.

CONCLUSIONS

1. Constant layer moisture at the hot surface during constant-rate drying is instrumental in maintaining the constant rate during hot-surface drying.
2. The constant hot-surface layer moisture is an important factor in determining the critical moisture of the drying-rate curve.
3. Plate temperature is normally the most important factor in determining the constant drying rate. It also determines the constant hot-surface layer moisture.
4. Bed thickness influences the critical moisture but within the limits of these tests has little effect on the constant drying rate.
5. Equilibrium between the vapor rising through the bed and the water on the wet sand does not exist during periods of high vaporization rate.

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