VACUUM - HEAT PUMP DRYER

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INTRODUCTION

This investigation was undertaken because there is apparently much room for improvement in methods of drying corn and other farm products. The system to be described is an energy related device, Pa. U. S. Serial No. 3914874. Its main components are a combination heat pump and vacuum system. The discussion and calculations are based on corn drying, but it would serve for drying a wide variety of products. The calculations are preliminary to designing and testing and for the most part are considered as rough approximations.

The functioning of the system is based on two principles: (1) Water will boil at a comparatively low temperature in a partial vacuum compared to its boiling point at atmospheric pressure. When its vapor is confined over water in a closed vessel, the pressure exerted by the vapor depends on the temperature only i.e., there is a one to one correspondence between temperature and vapor pressure at equilibrium. If equilibrium is disturbed by either lowering the pressure or increasing temperature, the water will boil. Thus, when the drying chamber is evacuated, water will vaporize from the corn. (2) Corn virtually breathes in a chamber which is alternately evacuated and let up to atmospheric pressure. The inhalation upon letting up to atmospheric pressure is quite small, only about 1/40 of the volume of the corn. The exhalation upon evacuation is enormous in comparison. It occurs because a partial pressure gradient is established within the kernel. The important result is that a stream of water vapor issues from the micropyle end of the kernels.

OPERATION

Heat is imparted to the corn in which a blower forces air over coils indirectly heated by the hot coils of a heat pump and thence through the corn column. This is followed by a vaporization period in which the vacuum pump evacuates the corn chamber, and most of the water vapor is collected on the cold coils of the heat pump.

The system is shown in Figure 1. The main heat pump is shown at the left in the figure. Its hot coils heat water in a tank shown below the compressor. The hot water circulates through coils located in the blower chamber below the blower. The cold coils of this heat pump are located in a condensing chamber at the bottom of the figure. Here most of the moisture is condensed as water, and "water level" is indicated.

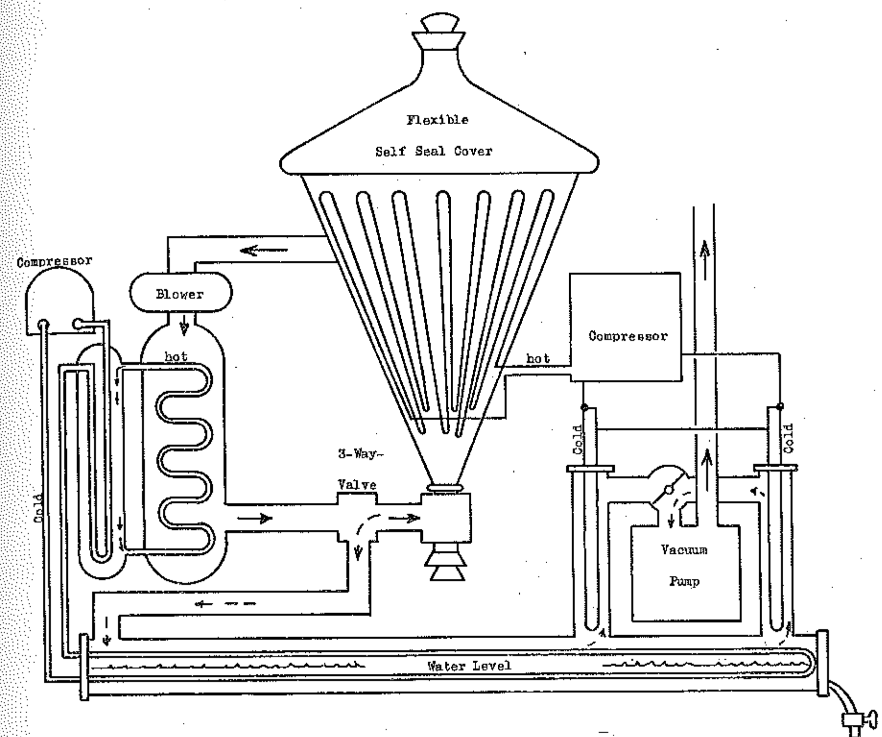

Figure 1

The auxiliary heat pump whose compressor is shown at the right in the figure collects moisture as ice on its cold coils while its hot coils are arranged around the periphery inside the conical drying chamber. They supply some heat to the corn to supplement that supplied by the main heat pump.

A complete cycle consists of a heating period, in which heat is stored in the corn, followed by a vaporization period. The heating is accomplished in a closed system. The blower forces air through the chamber containing hot water coils and thence it is routed through the conical corn chamber. The 3-way valve closes the exit to the condensing chamber and vacuum pump. The heavy arrows show the path of the air during the heating period. The sole purpose of the heating period is to impart heat to the corn which furnishes the heat of vaporization during the subsequent period. Vaporization is initiated when the 3-way valve isolates the blower chamber and opens the path from the conical corn chamber to the condensing chamber and thence to the vacuum pump. Most of the water vapor is collected in the form of water and ice and thus does not reach the vacuum pump.

CALCULATIONS

The conical corn chamber is a truncated cone. The diameters of the top and bottom are 9.59 and 1 ft, respectively. The height of the truncated cone is 5.25 ft. From these dimensions the volume is calculated as 125 ft^3. A cylinder having the same volume and height as this truncated cone has a cross-sectional area of 125/5.25 or 24.8 ft^2.

Further calculations are made to determine the following:

(1) The quantity of heat required to vaporize the moisture in 100 bu of corn to the extent of bringing about a change of moisture content, wet basis, from 24% to 14%.

(2) The number of cycles of heating necessary to store the required heat of vaporization in the corn if the arbitrarily chosen temperature variation during each cycle is to be 11 F°.

(3) The capacity of a heat pump required and the total time required for heating, for vaporization, and for drying.

(4) Various approximate temperatures and the type of hot water coils required for transferring heat by forced convection to the corn.

(5) The mass rate and volumetric rate of air flow required of the blower.

(6) The convective heat transfer coefficient.

(7) The rating of the blower motor.

(8) The approximate amount of energy required in kw hrs/bu to dry corn. The above calculations follow:

(1) At 56 lb/bu, 100 bu of corn weighs 5600 lb. This weight of corn of 24% moisture content, wet basis, contains 1344 lb of water and 4256 lb of corn devoid of water. If this corn is dryed to 14% moisture content, it will contain an amount of water, W_w lb, given by the equation

$$W_w/(4256 + W_w) = 0.14$$

This gives the weight of water as 693 lb. Thus, the weight of water to be removed in drying the corn from 24% to 14%, wet basis, is the difference, 1344-693, or 651 lb. The heat of vaporization of moisture in shelled corn is a function of temperature and of moisture content. Othmer[1] found it to be 1120 BTU/lb for corn of 22% moisture content, dry basis, and this was taken as the basis for calculations. The required quantity of heat is the product of 651 and 1120 which is 729,000 BTU.

(2) 729,000 BTU of heat is required to be stored in the corn; and this number can be equated to the product of mass, specific heat, and temperature change of the corn. The specific heat[2] of corn, C_c is calculated from

$$C_c = 0.34 + 0.0085\ (\%\ \text{moisture, wet basis})$$

which yields $C_c = 0.51$ for corn of 20% moisture content. The required temperature change is given as

$$\Delta T_c = (729{,}000)/(5600)(0.51) = 255\ F^\circ$$

Heat is to be stored in the corn in steps, each of which is followed by a vaporization period. The temperature change for each step is obtained from the data in Table 1. In obtaining this data the temperature, as measured at the geometric center of mass of the corn, was caused to vary through a range of 11 F°. Apparently, this does not represent the average temperature variation of the corn; and the data was used to calculate the average temperature variation, ΔT_{ca}. The average loss in weight per period is 2.01 g. ΔT_{ca} can be found by equating the product of mass, specific heat, and temperature change of the corn to the product of loss of weight and heat of vaporization of water. Thus,

$$M_c C_c\ \Delta T_{ca} = M_w L_w$$

$$\Delta T_{ca} = (M_w L_w)/(M_c C_c) = (2.01)(622)/(266)(0.51)$$
$$= 9.22\ C^\circ = 16.6\ F^\circ$$

The number of cycles of operation can now be found as the ratio of 255 to 16.6 which is 15.4.

(3) The heat transfer required per period is 729,000/15.4 which is 47,300 BTU. For heat pumps the capacity rating in tons is equivalent to 12,000 BTU per ton. A 10 ton heat pump is arbitrarily chosen in view of the fact that its rating is inversely proportional to the total time required for the heating periods. This total time, T_h is given by

$$T_h = (47{,}300/120{,}000)(15.4) = 6.07\ \text{hr}$$

From Table 1, the total vaporization time is the sum of the numbers indicated for the first 15 periods which is 180 plus 0.4 of 87 minutes for period 16. The result is 215 min or 3.58 hr; and the total drying time is 9.65 hr.

To obtain the experimental data shown in Table 1, a vacuum container to hold about 300 grams of corn was constructed from plastic pipe and plexiglass. 8-inch lengths of 3 and 5 inch diameter

TABLE 1

Moisture Loss and Vaporization Time for 80°F to 69°F Temperature Variation at Center of Mass of Corn

Period	Vaporization Time in Minutes	Loss of Moisture in Grams	Cumulative Loss of Moisture
1	3	2.25	2.25
2	4	2.25	4.50
3	5	2.00	6.50
4	4	2.55	9.05
5	5	2.25	11.30
6	4	2.00	13.30
7	6	1.95	15.25
8	8	1.70	16.95
9	8	2.50	19.45
10	8	2.20	21.65
11	14	1.90	23.55
12	18	1.45	25.00
13	25	1.40	26.40
14	23	1.70	28.10
15	45	1.75	29.85
16	87	2.40	32.25

pipes were used; and the smaller pipe was placed inside the larger one concentric with it. The space between was insulated with asbestos paper. A copper wire heating element was formed to fit the inside periphery of the smaller pipe. Plexiglass was used for the top and bottom of the container. The cover was fitted with an O-ring, and openings through the cover were made for connecting to the vacuum pump and for measuring temperature. A sample of 266.3 g of 24% moisture content corn, wet basis, was heated to 80°F by applying an adjustable voltage to the heating element. The container was then connected to a vacuum pump. Evacuation was continued until the temperature dropped to 69°F. This process was repeated 16 times.

(4) Temperatures of the corn and of the air must now be considered. Up to this point the only assumption with regard to temperature was that the average temperature of the corn was to increase 16.6 F° during the heating period and decrease the same amount during the vaporization period. The temperature of the water in the hot water coils is taken to be 140°F, the temperature

of the Freon in the condensing coils of the heat pump. At the exit of the hot coils or inlet to the corn, a temperature of 130°F is assumed. The initial temperature of the corn will be that of the surroundings. In any case the average temperature of the corn should be brought to 80°F; otherwise the rate of vaporization would be too slow. It is well known that the convective heat transfer coefficient for fixed beds such as corn is very large; in other words, it readily exchanges heat with a fluid flowing through it. Therefore, the temperature of the air at the exit of the corn or inlet to the hot water coils is taken as 80°F, the corn temperature.

Finned coils are needed to circulate the hot water in the blower chamber. A typical set of data for such coils is shown in Figure 2 (courtesy of Bohn Aluminum & Brass Corporation). The data is displayed in the form of a graph of transfer factor, F_x versus face velocity for various arrangements with respect to number of rows and number of fins per inch. The value of the ordinate on the graph is found by substituting the known values in the equation

$$F_x = (\text{Total load})/(1.08)(\text{CFM})(T_i - T_{ea})$$

T_{ea} represents the temperature at the inlet to the coils and is 80°F. T_i represents the temperature of the fluid in the coils and is 140°F. The total load is 120,000 BTU per hr, and the value of CFM is 2030 ft^3 per min as calculated in (5). Thus,

$$F_x = (120{,}000)/(1.08)(2030)(60) = 0.912$$

Seven configurations of number of rows and number of fins per inch satisfy the requirements. Each requires a different face velocity. The coil set selected requires a face velocity of 370 ft per min and has 5 rows with 12 fins per in.

(5) The mass flow rate and volumetric flow rate of air can now be calculated by equating the product of its mass, specific heat, and temperature change to 120,000 BTU per hr. Thus,

$$M_a C_a \Delta T_a = 120{,}000$$

$$M_a = (120{,}000)/(0.277)(130 - 80) = 8650 \text{ lb/hr}$$

Taking the density of air as 0.071 lb per ft^3, the volumetric flow rate is determined as

$$\text{Flow rate} = 8{,}650/0.071 = 122{,}000 \text{ ft}^3\text{/hr or } 2{,}030 \text{ ft}^3\text{/min}$$

where specific heat[3] of air, C_a, is calculated from

$$C_a = 0.2405 + 0.448\ w$$

where w represents lb of water vapor[3] per lb of dry air and was taken as 0.0813 for saturated air at 120°F.

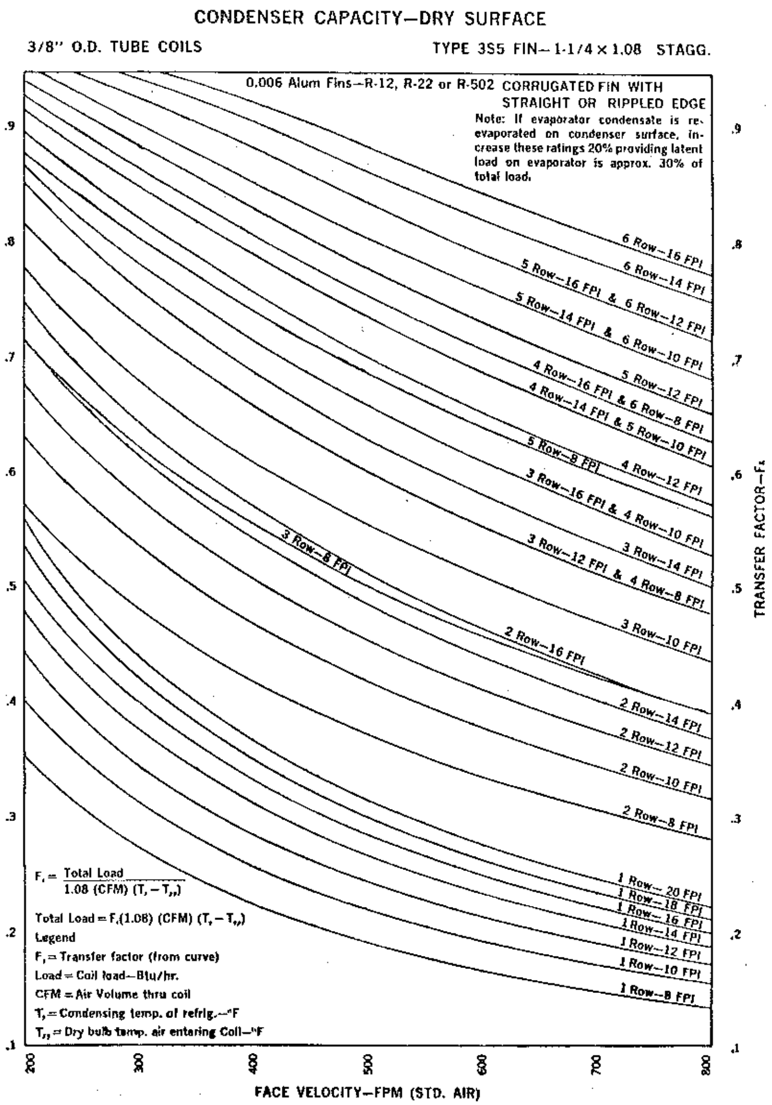

Figure 2

(6) The convective heat transfer coefficient for air flow through shelled corn is calculated from the empirical equation[4]

$$h_c = 1.95\ (GD_e/\mu) - 0.51$$

The mass flow rate per ft^3, G is calculated as

$$G = M/S = 8{,}650/24.8 = 348\ \text{lb hr}^{-1}\ \text{ft}^{-2}$$

where S is taken as the cross sectional area of a cylinder having the same volume as the conical chamber. D_e, the effective hydraulic diameter, is determined by experimentally finding the volume of a kernel of corn and then calculating the diameter of a sphere which has this same volume. For Northrup King field corn used, it was found that there are 118,000 kernels per ft^3. Since 0.375 of the volume occupied by the corn is void space, the volume of a kernel is given as

$$V_k = (0.625)/118{,}000 = (5.30)10^{-6}\ \text{ft}^3$$

The effective hydraulic diameter, D_e is calculated from

$$(\pi/6)D_e^3 = (5.30)10^{-6}$$

$$D_e = (2.16)10^{-2}$$

Viscosity of air has the value 0.046 $lb_m ft^{-1} hr^{-1}$ at 100°F. The heat transfer coefficient can now be calculated as

$$h_c = (1.95)(348)(2.16)(10^{-2})/(0.046) - 0.51 = 319\ \text{BTU hr}^{-1}\text{ft}^{-2}\ {}^\circ\text{F}^{-1}$$

The Newton rate equation is not applicable because the film temperature, ΔT_f is a function of both time and space in the corn; but it will be used here in calculating an average value as

$$\Delta T_{fa} = Q/(h_c S_c)$$

S_c represents the total exposed surface area of the kernels of corn. By direct measurement and treating the kernel as a section of a rectangular pyramid, this was found to be 290 ft^2/ft^3. Bakker-Arkema[5] et al. determined it as 239 ft^2/ft^3. The average of these two values, 265, was used in calculation

$$\Delta T_{fa} = (120{,}000)/(319)(265)(125) = 0.0114$$

This very small required value of average film temperature suggests that 120,000 BTU/hr can readily be transferred to the corn by forced convection.

(7) There are blowers on the market to meet the required volumetric flow rate with the accompanying pressure drop through the corn column. The pressure drop[6] through the 5.25 ft depth of corn was obtained from a graph of volumetric air flow rate per

unit area, 81.9 versus pressure drop per ft depth of shelled corn. The ordinate, 81.9 corresponds to 1.8 inches of water per ft depth. This gives the pressure drop as the product of 1.8 and 5.25 which equals 9.45 inches of water. The specifications of W. W. Grainger, Inc., Sioux City, Iowa, indicate that a blower to meet these conditions requires a 5 HP, 60 Hz, 3-phase motor to drive the blower.

(8) The approximate energy requirement in kw hrs per bu for drying corn by this method from 24% to 14% can be calculated from a knowledge of the power and operation time required for the several components of the system. A 10 HP motor for the 10 ton heat pump and a 5 HP motor for the blower operate for 6.07 hr. The combination has an output of 15 HP or 11.2 kw. The efficiency of each is approximately 90%. Thus, the input energy, W_1 is

$$W_1 = (11.2)(6.07)/(0.90) = 75.5 \text{ kw hr}$$

A 3 HP motor for the 3 ton heat pump and a 1 HP motor for the vacuum pump operate for 3.58 hr for vaporization. The combination requires an output of 4 HP or 2.98 kw. The average efficiency of the combination is approximately 85%. Thus, the input energy, W_2 is

$$W_2 = (2.98)(3.58)/(0.85) = 12.6 \text{ kw hr}$$

The energy required for defrosting can be approximated by determining the quantity of heat required to melt the ice collected on the cold coils. It is assumed that of the 693 lb of moisture to be collected, only 0.10 of it is collected as ice. Taking the heat of fusion as 144 BTU per lb, the energy required, W_3 is calculated as

$$W_3 = (693)(0.10)(144) = 9{,}980 \text{ BTU} = (9{,}980/3413) \text{ kw hr} = 2.92 \text{ kw hr}$$

The sum of W_1, W_2, and W_3 gives the approximate energy required as 91 kw hr. Thus, the cost of drying 100 bu is $2.73 if the energy cost is 3 cents per kw hr. This is 2.73 cents per bu.

DISCUSSION

The outstanding feature of the dryer is that it employs a heat pump. Compressed gaseous Freon gives off heat as it is condensed to the liquid state. This change of state accounts for the heat pump's large ratio of heat produced in its condenser coils to input energy to its compressor. The ratio of heat produced to input energy for other conventional methods of supplying heat, such as resistive, dielectric, and microwave heating, is less than unity; but for the heat pump it is normally 4 or more. In view of the energy crisis, its use in a dryer offers a significant contribution to energy conservation.

As stated in the Introduction, corn virtually breathes when subjected to a varying pressure. If a sample of corn is placed in a vessel of oil at room temperature, bubbles of water vapor can be observed to issue from the micropyle end of the kernels when the vessel is evacuated. This happens because a pressure is attained which is below the vapor pressure of water at room temperature. If a vessel of corn is evacuated and then let up to atmospheric pressure, inhalation occurs. Although the inhaled volume is but a few percent of the volume of the corn, it contributes to heat transfer to the interior of the kernels.

The rate of vaporization of water from the corn varies directly with the rate at which heat is supplied and directly with the vapor pressure gradient. It is expected that the mass of corn has little or no effect on vaporization time which should be the same for 100 bu and 266 g. Thus, the experimental data and calculations would indicate that 100 bu of corn can be dried in less than 10 hrs and at a comparatively low cost.

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