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A CROP DRYING MODEL FOR WASTE HEAT UTILIZATION ASSESSMENT*

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ABSTRACT

This is the sixth in a series of articles on the development of a methodology for assessing waste heat utilization technologies and optimizing the mix of technologies used on a site-specific basis. As part of this effort, a model for simulating the crop drying option has been developed. The model uses readily obtainable site-specific data such as climatic information and the temperature of the heated water. The outputs include the exit air conditions (temperature and relative humidity), the mass flow rate of the circulating heated water, and the exit water temperature. This model has been used in simulations in order to assess the economic feasibility of this method of utilizing waste heat.

INTRODUCTION

Agricultural crop drying requires 1.0×10^{17} J (10×10^{14} Btu) of heat energy per year [1, 2]. Progress in solar crop drying has led to speculation regarding the use of waste heat as the energy source for this function [3]. Traditionally, grain has been dried rapidly at high temperatures; savings from the shorter duration of

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* This is the sixth in a series of articles on the development of a methodology for assessing waste heat utilization technologies and optimizing the mix of technologies used on a site-specific basis. Earlier articles provided an overview of the methodology and defined the aquaculture model and the evaporative pad and surface heated greenhouse models. A later contribution will describe the model for the wastewater treatment components of an integrated waste heat utilization complex.

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electrical consumption by fans compensates for the higher heating costs and the larger initial capital investment [4]. Low temperature drying requires 3.3 m^3-min^{-1}-ton^{-1} (3 ft^3-min^{-1}-$bushel^{-1}$) flows of air raised 5°C (9°F) above ambient, on average. Moisture removal may take several weeks at these moderate temperatures [5], which leads to a greater risk of grain deterioration [6].

In addition to corn and various grains such as sorghum, other crops which may be dried at relatively low temperatures include peanuts and tobacco. Peanuts are good candidates for waste heat drying due to the relatively low temperatures of 35°C (95°F) which are used in current operations [7]. Yearly energy consumption is approximately 6.3×10^{15} J (6.3×10^{12} Btu) [1]. Tobacco curing consumes 3.4 $\times 10^{13}$ Btu) annually [1]. Curing occurs in barns at 77°C (170°F) and is a complex biochemical process. Byrd describes a facility designed to serve as a greenhouse in the spring and as a tobacco curing barn in the fall [8].

Low temperature storage and drying of crops is one of fifteen options which has been included in an assessment of waste heat utilization technologies [9, 10]. In order to properly assess this option and to develop a technique for optimizing the mix of options which could be used at a particular site, it was necessary to develop a model for simulating the behavior of a crop storage and drying facility. The purpose of this article is to present the details of that model. The model has been derived by means of a materials balance and a heat balance.

CONFIGURATION OF GRAIN DRYING AND STORAGE FACILITY

Grain can be dried at low temperatures by forcing air upward through a perforated floor in the storage bin [11]. A typical grain drying and storing bin is shown in Figure 1. A standard bin has a diameter of 24 ft, and contains 6000 bushels (7450 ft^3). This corresponds to a grain depth of 16.47 ft [5]. A 9-horsepower (6.71 kw) fan will provide 2.5 ft^3/min (cfm) per bushel, for a total air flow rate of 15000 cfm [12]. This air flow rate is more than adequate for low-temperature grain drying [13].

After the grain has dried, it may remain in storage for over seven months at 40°C [14]. Assuming that the grain is harvested around October 15th [13], this means that it can be dried and remain in storage until June, if necessary. While the grain is in storage, it must be aerated. Fortunately, the air flow requirements are small. They are easily provided by running the fan at its minimum speed [11], generally about 20 percent of the rated horsepower [15]. At this level, the fan is extremely inefficient. However, at lower air flows, the pressure drop through the grain is substantially lower, which offsets the loss of efficiency [16]. Therefore, during the grain drying phase, the fan uses 6.71 kwh/hr, and, during the grain storage phase, 1.34 kwh/hr.

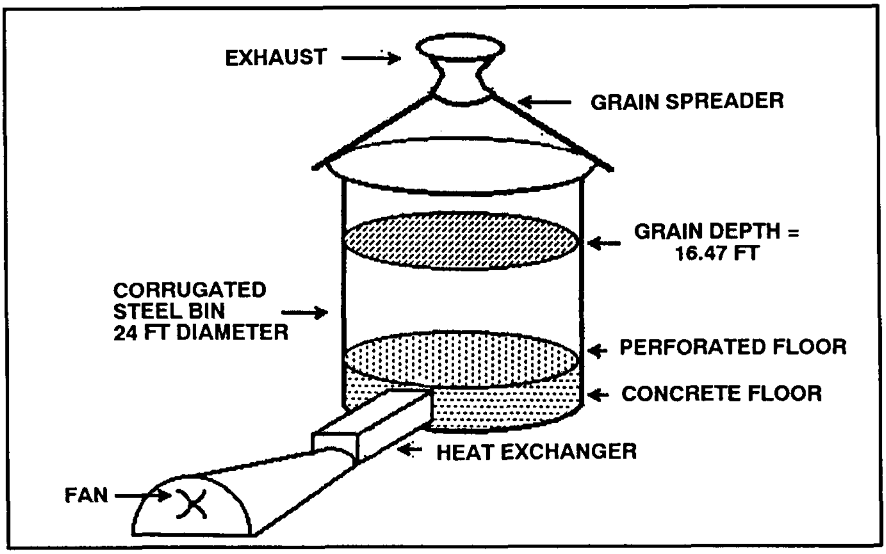

Figure 1. Typical grain drying and storage facility.

MATERIALS BALANCE

A simple method of grain drying is given by Hukill [16]. It is based on the derived relationship:

$$m_a C_{p_a} \frac{\partial T}{\partial x} = \rho h_{fg} A \frac{\partial M}{\partial t} \tag{1}$$

where

m_a = mass flow rate of air, lb/hr
C_{p_a} = specific heat of air, Btu-lb^{-1}-°F^{-1}
T = temperature, °F
x = depth in grain bed, ft
ρ = density of dry matter in grain bed, lb/ft^3
h_{fg} = latent heat of vaporization of water, Btu/lb
A = cross-sectional area of dryer, ft^2
M = moisture content of grain at a given time and location, dry basis, decimal
t = drying time, hr

Define the dimensionless moisture ratio:

$$M_R = \frac{M - M_e}{M_o - M_e} \tag{2}$$

where

M_R = moisture ratio, decimal
M_o = initial moisture content of grain, decimal
M_e = equilibrium moisture of grain (dry basis) for initial conditions of air entering grain dryer, decimal

Hukill determined the following approximations [16]:

$$M_R = \frac{e^D}{e^D + e^\theta - 1} \tag{3}$$

where

θ = Kt
K = thin-layer drying constant, hr^{-1}

and

$$D = \frac{xA\rho h_{fg}K\,(M_o - M_e)}{m_a C_{p_a}\,(T_o - T_G)} \tag{4}$$

where

D = depth factor
T_o = temperature of air entering grain dryer, °F
T_G = temperature at which air would be in equilibrium with grain at the initial moisture content of the grain after the air has cooled along a wet-bulb temperature line, °F

Drying Time

Barre et al. extended this analysis to derive an expression for the amount of drying time required to achieve a desired grain moisture content [17]. Define

$$M_{R_{ave}} = \frac{M_{ave} - M_e}{M_o - M_e} \tag{5}$$

where

$M_{R_{ave}}$ = mean moisture ratio
M_{ave} = average moisture content of grain

Then

$$t_D = \frac{1}{K}\ \ln\left[\frac{e^D - 1}{e^{M_{R_{ave}}D} - 1}\right] \tag{6}$$

where

t_D = drying time required for grain having depth factor, D, to reach a given average moisture content, hr

The equilibrium moisture content can be found using an equation derived by Henderson [18]:

$$M_e = 0.01 \left[\frac{\ln(1 - R_a)}{-a(T_a + 460)}\right]^{\frac{1}{b}} \tag{7}$$

where

R_a = relative humidity of the drying air, decimal
T_a = temperature of the entering air, °F
a = constant for material being dried, dimensionless
b = constant for material being dried, dimensionless
0.01 = factor to convert from percent to decimal

For shelled corn, the values of a and b are, 1.59×10^{-6} and 2.68, respectively [18]. Values of these constants for other crops are given by Henderson [18].

Barre et al. suggest that the drying constant, K, may be found using [17]:

$$K = K_o P_S^{c_1} v^{c_1} \tag{8}$$

where

K_o = constant, hr^{-1}
P_S = saturation vapor pressure, psi
v = air velocity through the grain per unit area, $cfm\text{-}ft^{-2}$
c_1 = dimensionless constant
c_2 = dimensionless constant

A procedure developed by Young and Dickens eliminates the unknown K_o and has been verified using experimental data [4]. The constant K was measured under reference conditions (denoted by the subscript r):

$$K_r = K_o P_{S_r}^{c_1} v_r^{c_2} \tag{9}$$

Divide equation (8) by equation (9) and solve for K:

$$K = K_r \left(\frac{P_S}{P_{S_r}}\right)^{c_1} \left(\frac{v}{v_r}\right)^{c_2} \tag{10}$$

For convenience, we can use the grain depth and air flow rate per unit volume instead of the air flow rate per unit area, since:

$$v = 1.2444\, Q\, x \tag{11}$$

where

Q = air flow rate per unit volume, cfm/bu
1.2444 = conversion factor from bushels to ft^3.

Therefore,

$$K = K_r \left(\frac{P_s}{P_{s_r}}\right)^{c1} \left(\frac{Qx}{Q_r x_r}\right)^{c2} \tag{12}$$

The reference values are [4]:

K_r = 0.2382 ht^{-1}
P_{s_r} = 1.272 psi
Q_r = 146.5 cfm/bu
x_r = 0.5 ft
c_1 = 0.46
c_2 = 0.70

Thackston and Parker present a relationship to express P_s in terms of temperature [19]:

$$P_s = 0.491 \exp\left[17.62 - \left(\frac{9501}{T_a + 460}\right)\right] \tag{13}$$

Exit Air Temperature and Humidity

In order to calculate the equilibrium temperature, T_G, we note that the wet-bulb temperature of the air remains constant. For the entering air [19]:

$$T_{wb} = (0.655 + 0.36T_a)\, T_a \tag{14}$$

where

T_{wb} = wet-bulb temperature of the air, °F

After the air has cooled to equilibrium:

$$T_{wb} = (0.655 + 0.36R_G)\, T_G \tag{15}$$

where

R_G = relative humidity of the air at equilibrium with the grain

We have implicitly assumed that the drying process is adiabatic: that is, the loss in the air sensible heat is utilized only in evaporating moisture from the grain. At the temperatures and pressures which we will encounter, constant wet-bulb temperature is a good approximation [20].

From Henderson, we know that the air will be in equilibrium with the grain when [18]:

$$R_G = 1 - \exp\left[-a(T_G + 460)\,(100M_o)^b\right] \tag{16}$$

where the factor of 100 is used to convert from decimal to percent. We have used M_o instead of M_e because of the definition of T_G: we are looking for equilibrium with the grain at its initial moisture content. This is a subtle point which follows from the theory behind Hukill's equation. Essentially, M_e refers to the final air-grain equilibrium, whereas T_G refers to the initial air-grain equilibrium.

We now have two equations and two unknowns: equations (15) and (16), with the unknowns T_G and T_G. Values are known for T_{wb}, a, b, and M_o. Unfortunately, these equations cannot be solved by ordinary algebraic techniques. Instead, an iterative procedure is usually used, wherein an assumed value of T_G is used, and R_G calculated using equation (16). This value for R_G is used in equation (15) to provide an improved estimate of T_G and the procedure is then repeated until convergence is achieved. Convergence is rapid, especially when the initial guess for T_G is good. The wet bulb temperature is a very good guess for T_G. For wet grain (greater than 35% moisture), they are identical. For drier grain, they differ by only a few degrees. In fact, for present purposes, it is not worthwhile to use the iterative procedure. We will assume that $T_{wb} \approx T_G$, and, therefore:

$$R_G = 1 - \exp\left[-a(T_{wb} + 460)\,(100M_o)^b\right] \qquad (17)$$

Thus the procedure is to use equation (14) to determine T_{wb}. Next, R_G is calculated with equation (17); and, finally, T_G is evaluated using equation (15). This gives values which are in close agreement with the experimental data obtained by Hukill [20].

HEAT BALANCE AND FLOW REQUIREMENTS

It is not necessary to evaluate heat losses from the bin, since the drying model requires only the inlet air temperature and flow rate. Actually the sensible heat losses are not significant, because the air is only a few degrees above ambient and moves in large volumes. The primary heat transfer is latent, which occurs during the drying process.

The air flow rate of 2.5 ft^3/min per bushel corresponds to a mass air flow rate of 67416 lb/hr. The specific heat of air is 0.24 $Btu\text{-}lb^{-1}\text{-}°F^{-1}$ [21]. Commercial air handlers designed to operate at these temperatures and flow rates have an overall heat transfer rate, UA, of 30000 $Btu\text{-}hr^{-1}\text{-}°F^{-1}$ [22].

We can form a heat balance equation:

$$m_w C_{p_w}(T_1 - T_2) = m_a C_{p_a}(T_G - T_a) = UA(LMTD) \qquad (18)$$

where

$$(LMTD) = \frac{(T_1 - T_G) - (T_2 - T_a)}{\ln\left(\dfrac{T_1 - T_G}{T_2 - T_a}\right)} \qquad (19)$$

and

m_w = mass flow rate of water, lb/hr

C_{p_w} = specific heat of water, 1.0 $Btu\text{-}lb^{-1}\text{-}°F^{-1}$

UA = heat transfer rate per degree, Btu-hr^{-1}-°F^{-1}
T_1 = temperature of entering water, °F
T_2 = temperature of exiting water, °F
LMTD = log mean temperature difference

The only unknowns here are T_2 and m_w. We know the air flow rate, the ambient air temperature, T_a, the exit air temperature, T_G, and the incoming water temperature, T_1. The solution of this equation is discussed in detail by Stoecker [23]. Here we present only an iterative solution, based on his findings, which enables us to estimate the necessary water flow rate:

1. Set $T_2 = T_G + 1$.

2. Use equation (18) to determine m_w:

$$m_w = \frac{m_a C_{p_a}(T_G - T_a)}{C_{p_w}(T_1 - T_2)} = 16180 \left[\frac{T_G - T_a}{T_1 - T_2}\right]$$

3. If $|m_w - 16180| < 1$, then

$$T_2 = T_1 - \left[\frac{T_1 - T_a}{1 + \frac{16180}{30000}}\right]$$

otherwise,

$$T_2 = T_1 - (T_1 - T_a)\left[\frac{1 - e^E}{\frac{w_1}{w_2} - e^E}\right]$$

where

$$E = UA\left(\frac{1}{w_1} - \frac{1}{w_2}\right)$$

$$w_1 = m_w C_{p_w} = m_w$$

$$w_w = m_a C_{p_a} = 16180$$

4. Then,

$$m_{w_{new}} = 16180\left[\frac{T_G - T_a}{T_1 - T_2}\right]$$

5. If,

$$|m_{w_{new}} - m_w| > \varepsilon$$

then set $m_w = m_{w_{new}}$ and repeat steps 3 through 5.

This iterative procedure will yield the mass flow rate of water, m_w, needed for the operation of the grain drying and storage bin. The required inputs are limited to T_G (determined in section 3), site-specific weather data (T_a, T_{wb}, and R_a), and the design parameters (T_1, m_a, and x). The outputs of the overall modelling effort include the drying time (t_d), the exit air conditions (T_G and R_G), and the exit water conditions (m_w and T_2).

SUMMARY AND CONCLUSIONS

A model describing the thermal properties of a grain storage and drying facility has been developed. The heat source for this facility is waste heat in the form of heated water. This simulation model requires, as input, basic weather data, design information, and the incoming water temperature. This model yields, as output information, the exit air and water conditions, and the drying time.

NOMENCLATURE

A = cross-sectional area of dryer, ft^2
C_{p_a} = specific heat of air, Btu-lb^{-1}-°F^{-1}
C_{p_w} = specific heat of water, 1.0 btu-lb^{-1}-°F^{-1}
D = depth factor
K = thin-layer drying constant, hr^{-1}
K_o = constant, hr^{-1}
LMTD = log mean temperature difference
M = moisture content of grain, dry basis, decimal
M_o = initial moisture content of grain, decimal
M_R = moisture ratio, decimal
$M_{R_{ave}}$ = mean moisture mean
M_{ave} = average moisture content of grain
M_e = equilibrium moisture of grain (dry basis) for initial conditions of air entering grain dryer, decimal
P_s = saturation vapor pressure, psi
Q = air flow rate per unit volume, cfm/bu
R_a = relative humidity of the drying air, decimal
R_G = relative humidity of the air at equilibrium with the grain
T = temperature, °F
T_o = temperature of air entering grain dryer, °F
T_G = temperature at which air would be in equilibrium with grain at the initial moisture content of the grain after the air has cooled along a wet-bulb temperature line, °F
T_a = temperature of the entering air, °F
T_{wb} = wet-bulb temperature of the air, °F
T_1 = temperature of entering water, °F
T_2 = temperature of exiting water, °F

UA = heat transfer rate per degree, Btu-hr^{-1}-°F^{-1}
a = constant for material being dried, dimensionless
b = constant for material being dried, dimensionless
c_1 = dimensionless constant
c_2 = dimensionless constant
h_{fg} = latent heat of vaporization of water, Btu/lb
m_a = mass flow rate of air, lb/hr
m_w = mass flow rate of water, lb/hr
t = drying time, hr
t_D = drying time required for grain having depth factor, D, to reach a given average moisture content, hr
v = air velocity through the grain per unit area, cfm-ft^{-2}
x = depth in grain bed, ft
θ = Kt
ρ = density of dry matter in grain bed, lb/ft^3

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