MODEL DEVELOPMENT AND ECONOMIC EVALUATION OF A SENSIBLE HEAT STORAGE UNIT UTILIZED IN A SOLAR-DEHUMIDIFICATION LUMBER DRYING SYSTEM

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ABSTRACT

A mathematical model for a rock-bed energy storage system has been developed for a solar-dehumidification lumber dryer and shown to give good correlation with experimental data. The drying rate of yellow poplar lumber was mathematically related to the collector area and storage size. A simple economic model was used to compare solar, solar-dehumidification, dehumidification, and wood-fired boiler drying systems.

Keywords: Solar energy, wood drying, heat pump, drying model, simulation.

NOMENCLATURE

A = bed cross-sectional flow area
A_c = collector surface area
$\overset{*}{A}_c$ = collector surface area per unit wood volume
A_s = heat transfer surface area
Bi = Biot number = $hR^2/(3k(1 - e))$
c_p = specific heat
D = rock diameter
e = void fraction
G = mass flow rate per unit cross sectional area
h = fluid-to-rock volumetric heat transfer coefficient
h_{amb} = heat transfer coefficient for bed-to-ambient air
k = rock thermal conductivity
L = bed length
$\dot{m}$ = mass flow rate
MC = moisture content (oven-dry basis)
N = number of rock-bed layers = $L/\Delta x$
NTU = number of transfer units = $hAL/(\dot{m}c_p)_f$
NTU* = $(U\Delta A_s)i/(\dot{m}C_p)_f$
NTUC = corrected number of transfer units (equation 12)

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ΔP = pressure drop across the rock-bed
R = rock radius
Re = Reynolds number = $\dot{m}D/(A\mu)$
R_w = wood drying resistance
t = time
t^* = $t(\dot{m}c_p)_f/[(\rho c_p)_b(1 - e)AL]$
T = temperature
T^+ = temperature at the new time
U = overall heat transfer coefficient
V = rock-bed volume
$\overset{*}{V}$ = rock-bed volume per unit wood volume
W = humidity ratio of the kiln air (kg-water vapor/kg-dry air)
W_s = saturated humidity ratio at the wet-bulb temperature (kg-water vapor/kg-dry air)
x = distance in the rock-bed from the inlet

Greek symbols

ρ = density
μ = viscosity
Δ = finite change
η = factor, equation 5 and 6

Subscripts

amb = ambient conditions
b = rock conditions
f = fluid conditions
i = layer "i" of the rock bed
in = inlet conditions
w = water

INTRODUCTION

Lumber to be used for most wood products requires drying before it can be manufactured into a stable finished product that will perform satisfactorily. Drying is the most energy-consuming step in lumber processing. If solar energy could be used to dry lumber, a clean, inexpensive, and inexhaustible energy source would be harnessed. However, solar kilns require longer drying times than conventional kilns because of limited kiln temperatures, which are generally less than 60 C. Other factors such as lack of heat supply at night or during cloudy weather and unpredictable drying conditions as a result of changes in the weather also affect the operation of solar kilns.

Another technique currently being used by the lumber industry to reduce the energy cost of drying wood is dehumidification with heat pumps. Moisture in the kiln air is removed in the evaporator instead of during venting as in a conventional kiln. This reduces energy loss from the kiln. Although they consume less energy, dehumidification kilns require about the same amount of energy costs as conventional kilns, but their initial capital cost can be lower.

While there have been several theoretical models presented in the literature for the individual components (e.g., collector, storage, kiln, etc.), none has included the subsystems of a dehumidification unit and energy storage in the complete system model. The purpose of this paper is to present a computer simulation model for a combined solar-dehumidification wood drying system with a heat storage unit to achieve a better initial heat-up of wood and to assist and control the drying schedule. This simulation model can be used in the design and optimization of specific solar-dehumidification kilns. A simple economic model is also used to compare solar-dehumidification drying to other drying methods.

LITERATURE REVIEW

Solar wood drying systems

Even though there is a current energy glut, long-term problems of energy availability and costs will not go away. There is still significant interest in the use of solar energy for drying lumber. Although much research has been done, commercial application of solar drying has been limited. The relatively small capacities of solar kilns developed to date make them impractical for most commercial use in the United States; however, solar kilns can be practical for developing countries.

Successful operation of a number of such units has been reported in the literature. However, only the articles dealing with solar wood drying systems that have included energy storage in their research are discussed here. A good summary paper that outlines the improvements in solar wood drying is presented by Hall et al. (1981) and includes an annotated bibliography.

Read et al. (1974) have studied a solar kiln with the solar collector separate from the kiln and a rockpile thermal storage unit below the kiln. This made it possible to store additional thermal energy during the day and use it at night, thus reducing the effect of daily temperature differences and providing better drying conditions. Drying 2.5 cm alpine ash (*Eucalyptus delegatensis*) required an 80% increase in drying time compared to a conventional steam-heated kiln. They concluded that the rock bed should be isolated from the wood charge to be more effective. Their economics showed that at current back-up fuel prices, their solar system was only marginally effective.

Chen and Helton (1985) used black painted concrete blocks in a passive type solar kiln to augment the drying of yellow poplar lumber. Little (1984) has reported experimental work done on a commercial size lumber dryer 240 m^3 (100,000 board feet) that uses solar energy to augment the heat supplied from natural gas. Water-filled solar collectors (232 m^2) heat an 18,170-liter (water) energy storage tank that heats the kiln through an air-to-water heat exchanger. After some initial operational problems were solved, the system seemed to perform adequately. No detailed economic comparison was performed in their research. Other work describing solar-dehumidification drying enhanced by an energy storage has not been found in the literature.

Dehumidification wood drying systems

Dehumidification wood drying systems, though used in Europe and Asia for a number of years, are now used in the United States. Current dehumidification systems are able to heat up to 100 C and thus dry at a rate comparable to conventional steam kilns. Wood-drying quality is at least as good as in conventional kilns, and it appears that capital costs are less than steam kilns with operating costs about the same (since expensive electrical energy is used to drive the system). Several articles in the literature compared dehumidification with other drying systems (Wengert 1980; Milota and Wilson 1984; Lee and Harris 1984).

One source (Hogan et al. 1976) has developed a detailed computer code that calculates the heat transfer and thermodynamic states of the refrigerant at various points in the cycle of the dehumidifier. While this approach is very exact, it can be very expensive in terms of computer time. It is usually more convenient to curve-fit the output (moisture removal rate, compressor power, etc.) as a function of kiln operating conditions (usually kiln dry-bulb and wet-bulb temperature) (Helmer et al. 1982). This is the technique used in the present model.

Mathematical models of wood dryers

Several detailed mathematical models for kilns have been found in the literature. D. J. Close (1975) has presented the simulation of a solar timber dryer with a rock-bed storage system. Experimental data were used to establish reasonable values for such kiln and timber parameters as the collector area, collector inclination to the horizontal, kiln size and insulation, storage size, storage material properties, and power ratings of the circulating fan and auxiliary electric heaters. The system operated in the following manner: The dryer was made to follow a set schedule of kiln airdry- and wet-bulb temperatures. If the kiln temperature dropped 5 C below this set schedule, then heat was added to the kiln from the collector through the flow of hot air. If the kiln temperature rose above the scheduled value, air from the collector was passed through the storage unit. If the kiln temperature dropped by more than 2 C below the scheduled value, then heat would be added through the electrical heaters and not from the storage unit. The storage unit would add heat only if the kiln temperature was maintained at a satisfactory level. The reasons why such control strategy was used are unclear.

The solar radiation input was modelled by assuming a sine function with half period the same as the day length and with the integrated input over the period equal to the measured input. An hourly record of total insolation was made from a pyranometer for a period of twenty days. Ambient humidity was assumed constant, but recorded ambient dry-bulb temperature variations were input to the program.

The comparison of simulation results with the experimental data showed that the program could not predict the level, as well as the diurnal variations in the kiln dry-bulb temperature. Unfortunately, discrepancies of the order of 7 C to 10 C beween the simulation and the experimental results for the kiln temperatures were reported, indicating that the general results of their simulation study are of questionable value.

Duffie and Close (1978) have presented a simulation model that was used for determining the optimized design of a solar timber dryer equipped with a gravel bed and an adsorbent bed. The annual costs of systems using oil, solar energy, and electricity as the energy source were estimated at $919, $1,088, and $1,459, respectively. The adsorbent storage system proved to be superior to the gravel bed with all the auxiliary energy sources and collector designs.

PaLancz (1984) developed a similar simulation program for a solar-dehumidification dryer system but had no data to compare with his model. Wengert et al. (1984) have recently developed a solar kiln model for use on a microcomputer.

MODEL DEVELOPMENT

Helmer et al. (1982) have developed a solar-dehumidification kiln model. Knowing the ambient weather conditions, the dehumidifier parameters, the kiln geometry, the type of solar collector, and the initial conditions of the wood and air, the change in air humidity and air dry-bulb temperature can be calculated at any time period. The model also calculates wood moisture content, air temperature and humidity, and electrical energy consumptions of compressor and blowers for any time period. Their experimental results agreed well with their computer simulation. This model forms the base for the simulation model presented here. Only the changes in the computer model will be mentioned.

The drying rate equation was slightly modified as indicated in the equation to use a driving potential based on the difference between the humidity ratio saturated at the kiln wet-bulb temperature and the humidity ratio evaluated at the kiln conditions:

$$\dot{m}_w = (W_s - W)/R_w \tag{1}$$

where

$$R_w = -0.00360 + 0.342/MC \tag{2}$$

Figure 1 illustrates the drying rate correlation used in the program. This equation is in a simpler form than previously used and yet it shows good comparison to the previous drying data for yellow poplar extracted from the work presented by Chen and Helmer (1984).

Sensible thermal storage systems

Thermal storage systems, in general, involve storing of energy either as a sensible heat in liquid or solid medium, or as heat of fusion in selected phase change materials. Air-heated collectors, used mostly for wood drying, typically have rock-beds as sensible energy storage systems.

The optimum diameter of the pebbles may vary from 1.2 to 7.6 cm. Uniform diameters give more uniform air flow passages. Rocks with smaller diameters provide more surface area to the air flow, so they are more efficient in terms of heat transfer between the rocks and the air flow.

Static pressure drop through rock storage depends on the velocity, rock-bed length, void fraction, rock surface area factor, and rock size. The fan energy consumption is, of course, greatly dependent upon the air flow pressure drop. Larger rock sizes minimize pressure drops; but their centers are not used to store heat. So a compromise is sought for the rock size since rocks should be small enough to affect good heat transfer but large enough to minimize pressure drop.

Numerous storage models have been reported in the literature. The reader is referred to Schmidt and Willmott (1981) for an excellent reference book on the subject.

Though rock-beds are widely used for thermal storage in conjunction with solar energy systems, necessary data for determining design parameters such as bed dimensions, rock size, and air flow rates are available only in the form of rules of thumb; and even when available, these experimental data are applicable only for the specific situations and experimental conditions. Though a few closed-form analytical solutions exist for heat transfer processes inside a rock-bed, their use-

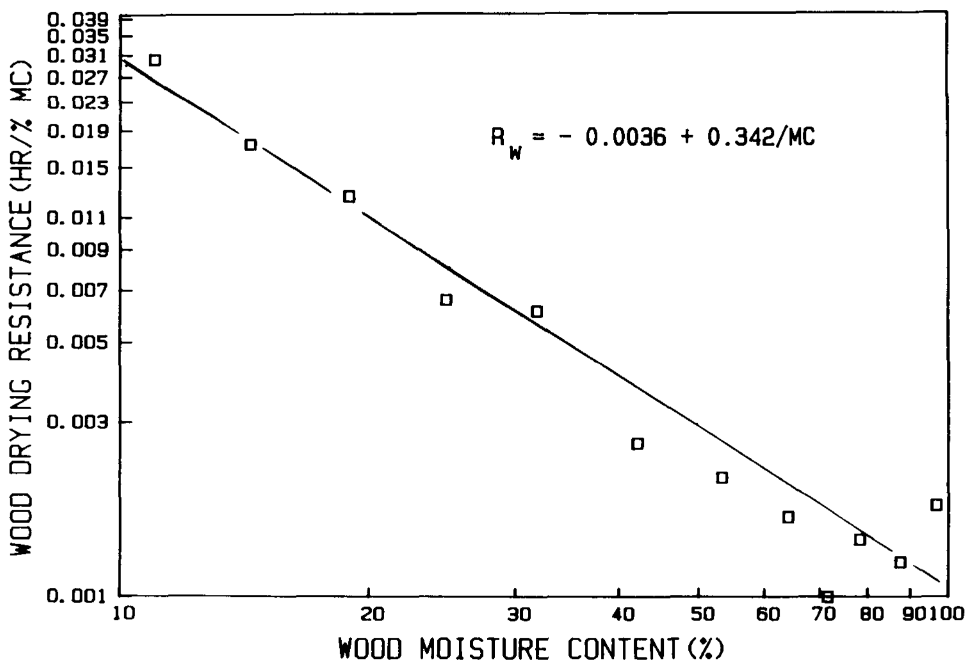

FIG. 1. Yellow poplar wood drying resistance variation with moisture content.

fulness for innovative designs involving variable flow rates, rock sizes, and circulation patterns is limited to simple unrealistic boundary conditions. But a numerical solution obtained by solving the basic equations makes it possible to simulate various design parameters easily.

The model used in the present simulation was derived from work done by Hughes et al. (1976) and Mumma and Marvin (1976). In this method of modelling, the rock-bed is assumed to be divided in N layers, each of thickness Δx, as shown in Fig. 2. The rock-bed temperature is assumed to be uniform in any layer. The air velocity through the bed is also assumed constant. The air temperature inside the bed is assumed to have an exponential temperature profile in the direction of flow.

Heat exchanger theory applied to this bed layer gives the air temperature variation in the direction of flow,

$$\frac{T_{f,i+1} - T_{b,i}}{T_{f,i} - T_{b,i}} = \mathrm{Exp}[-NTU(\Delta x/L)] \tag{3}$$

The energy added to the air then becomes

$$(\dot{m}c_p)_f(T_{f,i} - T_{f,i+1}) = (\dot{m}c_p)_f(T_{f,i} - T_{b,i})(1 - \mathrm{Exp}(-NTU/N)) \tag{4}$$

The bed temperature variation with time can be obtained from an energy balance on the rock-bed layer yielding

$$\frac{dT_{b,i}}{dt^*} = \eta N(T_{f,i} - T_{b,i}) \tag{5}$$