A MODEL BASED HYBRID NUMERICAL CONTROL ALGORITHM FOR THE CONTINUOUS DRYING OF A THICK WEB IN AN INFRARED DRYER

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Abstract: Experimental results from the transient drying of sheets of polyester in an infrared (IR) dryer were used to derive a performance model. Separate drying experiments were done using sheets of material of various densities and thicknesses. The formulations expressed the core temperature of the web to the surface temperature of the web as a function of the residency time in the dryer and the electric power used. Also, a relationship between the time duration required to achieve a given core temperature of the web as a function of the electric power was derived. These relationships were used to derive an hybrid numerical control algorithm using feed forward and feedback actions to control the core humidity of the web at the outlet of the dryer.

1 INTRODUCTION

The numerical control of the humidity of a thin sheet of material being continuously dried in an infrared oven has been achieved with success in the past (Dhib et al., 1999). However, this is no longer the case when a thick web is considered for drying. Two major difficulties arise. One is linked with the existence of a significant humidity and temperature gradient across the thickness of the sheet of material as it travels in the oven. The second problem is the difficulty of measuring the core humidity and the internal temperature of the web during the drying process. For these reasons, a set of experiments were designed to characterize the evolution of the water content and temperature profile inside the web during drying in an infrared oven. To this end, webs of various densities and thicknesses were used.

2 EXPERIMENTAL SET-UP

Separate batch drying experiments were done using sheets of polyester with densities of 200 g/m^2, 800 g/m^2 and 2000 g/m^2. The sheets were 1.3 mm thick, 5.2 mm thick and 15.8 mm thick respectively. Thermocouples were imbedded at separate locations across the thickness of the web. They permitted the continuous measurements of the internal temperature during the drying process. At given times, samples of material were removed locally at specific depths of the web to determine the average water content. Surface temperature of the web was measured using both surface thermocouples and infrared optical pyrometers (Ircon). Humidity at the surface of the web was also measured using high-frequency humidity meters (Labtec). Infrared flux measurement was done using a Schmidt-Boelter type flux meter. Figure 1 illustrates the experimental set-up.

3 RESULTS

All of the drying experiments were made on stationary sheets in the oven. Evolutions of temperature at different depths across the web thickness were followed as a function of time.

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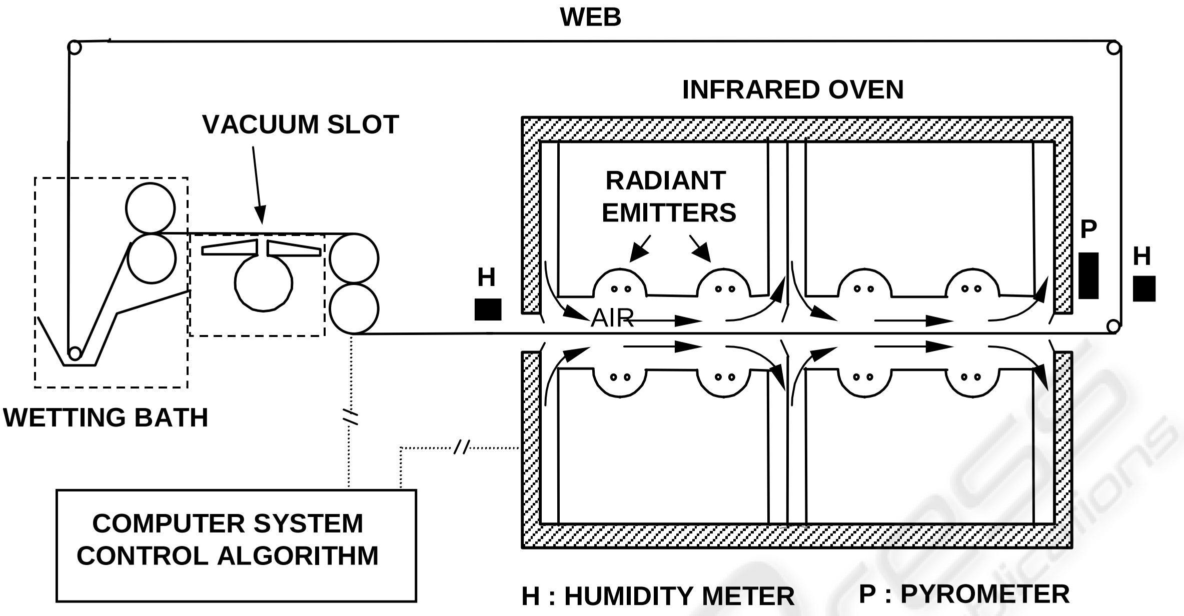

Figure 1: Infrared dryer system

Separate experiments were done using electrical power ranging from 1300 watts to 2180 watts. Results are reported for the 15,6 mm thick polyester sheet having a density of 2000 g/m^2. Figure 2 illustrates the results obtained when operating the oven at 1740 watts. At each separate location, the temperature tends to level off until the water is fully evaporated. When this occurs, about one hour after start-up, the temperature will rise sharply (not shown on Figure 1). Also, the humidity of the sheet at different depths of the web was determined at specific times after start-up. Figure 3 illustrates the humidity profile observed after 3000 seconds. Radiant energy is furnished on both sides of the web and a very nearly symmetrical humidity profile is observed. During drying the water content is always highest at the web mid-depth and lowest at the top and bottom of the web. Similar results were obtained with sheets of different densities and thicknesses when operating the oven at other electrical power levels in the range indicated. The humidity patterns observed show similarities to the ones reported by (Jones, 1969) during contact drying of a thick sheet of paper.

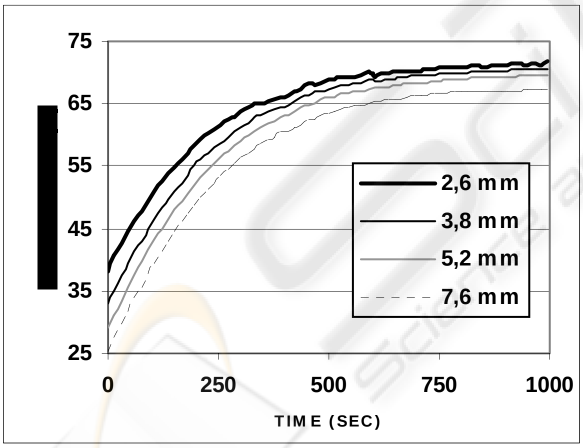

Figure 2: Evolution of temperature at different depths of a 2000g/m^2 polyester sheet - 1740 watts

Nonetheless, it is impossible to measure the internal humidity and temperature of the web during continuous drying as the web travels inside the oven.

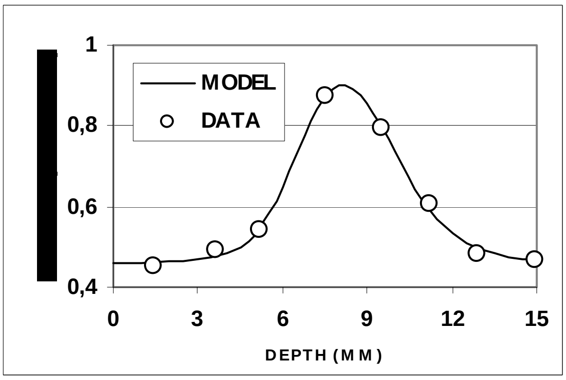

Figure 3: Humidity inside a 15,6 mm thick 2000g/m^2 polyester sheet after 3000 seconds - 1740 watts

The only measurements possible are the external humidity and temperature at the surface of the web under these conditions. Moreover, this can only be done at the outlet of the oven considering the radiant flux of energy inside the oven. A way of dealing with this problem is to relate ultimately the humidity and temperature at the web surface to the internal humidity and temperature of the web using a model. A phenomenological model for the radiant drying of thick sheet of porous material derived by Kuang et al. (1994) considering the many transport phenomena involved during drying offered the potential of doing that. Unfortunately, the mathematical solution of this partial differential model is too time intensive and the formulation does not lead itself easily to implementation for real time control. This is especially true when operating the oven at higher electrical power levels for which much shorter drying time responses would be observed. However, further analysis of the results obtained during the set of experiments done here has indicated drying characteristics that can be used to profit in a control algorithm.

First, as illustrated in Figure 4, results have indicated that the time interval required such that the core temperature at the mid-depth of the web achieves 100 ºC (a completely dry condition) is a linear function of the electrical power used in the oven. Also, as indicated in Figure 5, results have shown that the temperature at the external surface of the web, corresponding to a internal temperature reaching 100 ºC at mid-depth of the web, is also a linear function of the electrical power used in the oven. These characteristics have been shown to hold with webs of different densities and thicknesses in the range of the electrical power indicated.

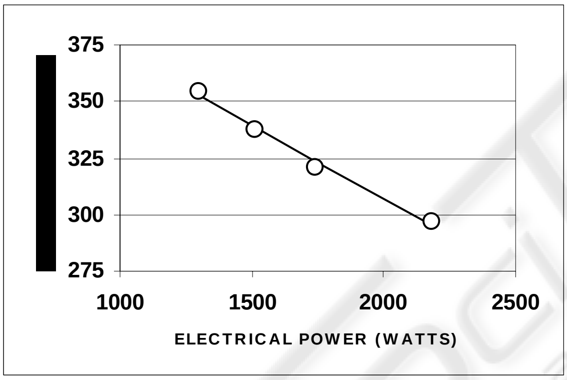

Figure 4: Time required achieving 100 ºC at mid-depth of a 15,6 mm thick 2000g/m^2 polyester sheet as a function of power input

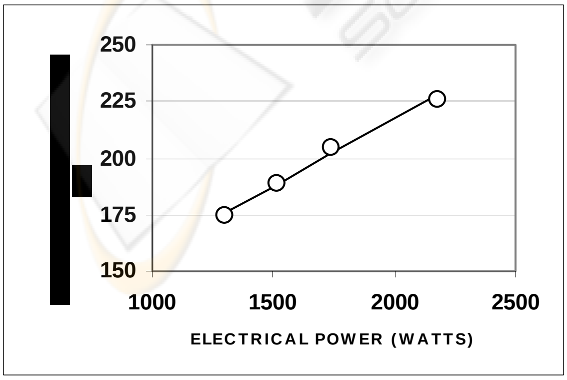

Figure 5: Surface temperature of a 15,6 mm thick 2000g/m^2 polyester sheet when reaching 100 ºC at mid-depth as a function of power input

4 MODEL BASED CONTROL

The experimental results have shown that the surface temperature of the web T_{SS} at the outlet of the oven is linearly related to the electrical power used:

$$T_{SS} = A_S \,.\, P + B_S \;.\, \theta \tag{1}$$

Also, the residency time required to achieve a given temperature T_{CC} at mid-depth across the thickness of the web at the outlet of the oven was shown to be linearly related to the electrical power used. In a more general fashion :

$$T_{CC} = A_C \,.\, P + B_C \;.\, \theta \tag{2}$$

In both cases, A_S, A_C, B_S and B_C are scalars whose values depend generally on the humidity of the web H_{inlet} at the inlet of the oven and must be determined through experimentation (Slitine et al., 2001). Generally, this would need to be done for a range of humidity (water content of the web) typical of the ones existing at the point of entry to the oven. Fortunately, the humidity of the web entering the oven is often limited to a small range of values. In effect, excess water has normally been removed since the material entering the oven is generally passed through a free water removing device rollers or vacuum slot (see Figure 1). Nevertheless, the scalars A_S, A_C, B_S and B_C need be determined specifically for each type of material (density and thickness) considered for drying. For a given residency time in the oven, Equation (2) may be used to compute the *a priori* electrical power required to achieve a desired core temperature T_{CC} at mid-depth across the thickness of the web :

$$P \;= (T_{CC} / A_C) - \;(B_C / A_C) \,.\, \theta \tag{3}$$

Also, through equations (1) and (2) T_{SS} is related to T_{CC} and P in the following manner:

$$T_{SS} = (B_S/B_C).\, T_{CC} + B_D \,.\, P \tag{4}$$

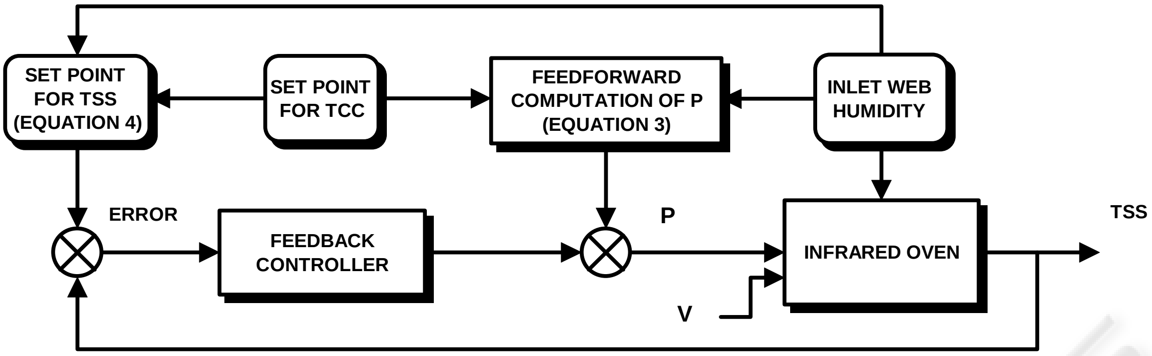

Figure 6: Hybrid feedforward and feelback control scheme

Therefore, the *set point* for the surface temperature at the outlet of the oven achieving a given core temperature of the web at mid-depth, reflecting a chosen drying condition, may be computed by equation (4). Although choosing T_{CC} = 100 ºC will ensure full and rapid drying of the web, this is not a requirement and may even not be desirable. In effect, such a choice will lead to a much higher temperature at the surface of the web (see Figure 5) that could adversely affect the surface quality of the material. Results shown in Figure 2 and results from other drying experiments with thick sheets of material in an IR oven (Thérien, 1997) have indicated that much lower values of T_{CC} can be used to produce satisfactory results.

Based on the previous relationships it is possible to design a hybrid control strategy for the drying of thick webs in an IR oven. The basic structure of the control strategy is illustrated in Figure 6. The following algorithm gives the necessary steps required to implement it:

1) Reading of the web velocity V in the oven
2) Computation of the residency time θ of the web in the oven of length L, $\theta = L/V$
3) Reading of the web humidity H_{inlet} at the oven inlet
4) Computation of coefficients A_C, B_C, B_S and B_D corresponding to H_{inlet}
5) Computation from equation (3) of the electrical power required P (feedforward action) for a chosen value of T_{CC}
6) Computation from equation (4) of the set point for T_{SS}
7) Measurement of T_{SS} at the oven outlet
8) Adjustment of P (feedback mode) through a given controller (PID, Dahlin, etc) to correct for the model prediction error (feedforward action) in step 5

5 CONCLUSION

Drying experiments of thick webs in an IR oven have shown linear relationships between the surface temperature of the web and the core temperature at mid-depth across the thickness of the web and the electrical power used for drying. These relationships have permitted the elaboration of a hybrid feedforward-feedback control strategy for the drying of thick sheets of material in an IR oven.

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