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NUMERICAL INVESTIGATION OF WOOD DRYING WITH INTERMITTENT ENERGY SOURCE AT LOW EXERGY CONTENT

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Abstract: The possibility to dry heat-sensitive timber with solar energy or residual energy from industrial processes with low exergy content, may be of double interest: the use of energy sources with very low price and the reduction of thermal pollution. The important issue when using such energies is to adapt the process control to the availability of the energy. Additionally, there is a major concern that this energy saving could be done at the detriment of drying quality or drying time. This paper proposes a numerical investigation of the possibility to use intermittent energy source to dry wood drying by comparing different strategies.

Keywords: wood drying, intermittent energy source, low exergy, multiscale modeling

INTRODUCTION

The drying schedules, were originally developed to get a good product quality with a reasonable drying time, while assuming the kiln to be able to maintain the prescribed drying conditions. As the energy concern was not important when they were established, these schedules need to be revisited to focus on energy issues^[1-4]. This is true not only to focus more deeply on energy consumption, but also to adapt the process control when the energy is not always available at the desired level of temperature.

The use of intermittent energy source (solar energy, residual energy from industrial processes, electricity available in smart grids) including energy with a low level of exergy, may be of interest in the future to

address energy issues compared with conventional drying^[5,6]. The first interest is the very low price of these energy sources. In addition, for power or industrial plants, which use water as a coolant and subsequently discharge warm water in the environment, the use of this energy with low exergy content is likely to reduce the thermal pollution.

Obviously, the problem for such intermittent energies is to adapt the process control as a function of the availability of the energy (in terms of quantity and temperature level). Indeed, the drying schedules tuned for each wood species, mainly based on empirical knowledge to get a good product quality, could not be used when using an energy source, which is not continuously available. In this case, the question then rises regarding the reduction of energy cost while

keeping a satisfactory product quality and a reasonable drying time.

This paper proposes to investigate the possibility to use intermittent energy source for wood drying.

We first provide a brief overview of the multiscale and multiphysics model. Thereafter, selected simulations with different drying control strategies are proposed to emphasize the effect of intermittent energy source on the drying quality and time, the drying time.

BRIEF DESCRIPTION OF THE COMPUTATIONAL MODEL

Board-stack-kiln coupling

In order to compute the evolution of energy consumption in a kiln during the drying process, a multiscale model considering the kiln level, the stack level, and the board level was employed (Fig. 1). The physical formulation used at the board level is comprehensive in terms of heat and mass transfer and mechanical aspects, so that quality issues can be addressed [7]. The stack level takes into account the airflow/boards interactions by computing simultaneously hundreds of boards; it is then able to deal with the variability of wood [8]. Each board of the stack is represented by one module of the code *TransPore*. The entire set of modules is updated throughout the entire process. A comprehensive computational strategy was implemented to progress simultaneously the drying of each board, dealing with the coupling within the stack and managing the different time scales required by this physical coupling. The air parameters at each board location, used in *TransPore* as boundary conditions, constitute the macro to micro coupling. In the opposite way, the evolution of the air temperature and air humidity is determined from balance equations that involve the heat and mass fluxes computed at the board surface by each module of *TransPore*. This effect builds up the micro to macro coupling (see Perré and Rémond [8] for more details).

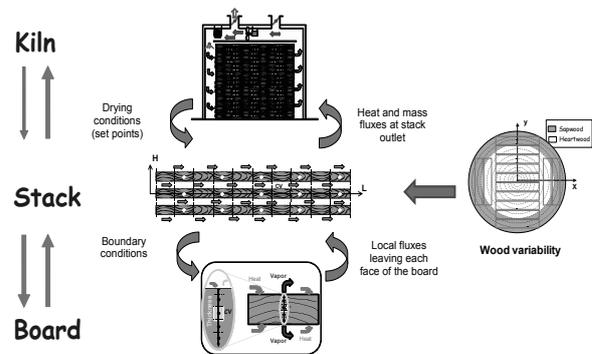


Fig. 1. Structure of the multiscale approach applied in the present work for the drying of a whole stack of boards.

Wood variability

Our multiscale approach offers the decisive potential to account for the wood variability, but a relevant procedure is needed to supply the model with input data. A Monte-Carlo method is chosen to generate boards from the log (see Perré and Rémond [8] and Perré et al. [4] for more details).

The drying configurations

The configuration tested in this work consists of 24 beech boards placed edge to edge on the same tier in a stack. Each board is 30 mm thick and 100 mm wide. The material properties input in the model are summarized in Perré et al. [4].

The drying schedule recommended by the Technical Centre for Wood and Furniture in France (FCBA) for this specie was chosen here as the reference schedule (Reference configuration). In our model, the global averaged moisture content (global AMC), i.e. the averaged moisture content over the whole stack, is used as wood moisture content (MC) to change the drying conditions. This choice is consistent with common industrial practice, where the average value of several sensors placed in representative boards is used to control the kiln. The drying trial is stopped when the average moisture content of the stack goes below 10%.

The other configurations use an intermittent energy source, in which phases of heating (50°C) alternate with phases of cooling

(20°C). The dry bulb temperature in the kiln chamber is assumed to follow a sine function with a period of 24 hours. For example, this could be the case with a solar energy source coupled with an inertial buffer tank. The problem for intermittent energy is to adapt the relative humidity and airflow velocity in order to keep a satisfactory compromise between the product quality and the drying time. In this work we focus the discussion on the effect of different control strategies:

- Configuration A: The partial vapor pressure in the kiln chamber is adjusted to the dry bulb temperature to maintain a constant equilibrium moisture content (EMC). The value of EMC changes with AMC in the same way as for the reference configuration
- Configuration B: The partial vapor pressure in the kiln chamber is kept constant when the dry bulb temperature changes. Its value is determined via the sorption isotherm to give the same EMC as for the reference test at the lowest dry bulb temperature (20°C here). As before, the value of EMC changes along the process according to the evolution of AMC.

The airflow velocity is maintained constant during the drying at $2\text{m}\cdot\text{s}^{-1}$ (configurations A and B). In order to reduce condensation, an airflow reversal period of three hours is adopted for configuration A.bis.

For low dry bulb temperature, the low value of the partial vapor pressure in the kiln chamber at the end of the drying may be impossible to achieve by air renewal. To be more realistic, our simulations consider that the dew point temperature cannot be lower than the external dew point, set at 10°C here.

ANALYSIS OF DIFFERENT DRYING SCENARIOS

The drying behavior is computed for each case by the multiscale model considering the kiln level, the stack level, and the board level. In this paper, all boards are identical because we wanted to focus the analysis on the effect of the drying conditions. The stack consists of flatsawn boards with an initial moisture content of 65%.

Drying conditions and MC evolutions

Let us first analyze the reference configuration (Fig. 2). The boards close to the stack inlet dry faster than those close to the outlet side. This is a direct consequence of the stack effect: the dry-bulb temperature decreases along the airflow because it has to supply the heat of vaporization, whereas the dew point increases due to the vapor flux coming from the boards.

Regarding the drying time, all boards reach an AMC below 10% after 7.5 days. The dispersion of AMC at the end of drying reduces significantly just at the end of drying, when the drying schedule imposes drying conditions with a very low EMC.

Compared to this reference configuration, strategy A leads to a much longer drying, as the same EMC is imposed, but at a lower temperature than for the reference test (Fig. 3). On the contrary, strategy B imposes the same EMC at the lowest temperature level at constant partial pressure of vapor. Consequently, the EMC seen by the load is generally much lower than the EMC of the drying schedule. For example, at 96 hours of drying, the AMC is around 40% for the reference test against 20% for test B (Fig. 2 and 5). However, because of the minimum value of dew point, the drying rate is significantly reduced at the end: eventually, the drying time is larger for test B than for the reference test. The total drying time is 1.8 times longer for the configuration A and 1.25 times longer for the configuration B.

It is also interesting to analyze the evolution of MC difference. For the reference test, the difference between inlet and outlet increases

quite rapidly from the beginning of drying, attains its maximum during the second third of the drying time and eventually decreases at the very end of drying, once the airflow has a low RH.

The effect of airflow reversal is obvious for the test A.bis (Fig. 4), where the difference of MC between inlet and outlet is hardly perceptible. More interesting are the two other configurations, for which the difference remains much lower than for the reference test. This could be partly explained by the fact that the overall drying rate is lower than for the reference test, but this explanation is not enough. As already stated, test B was much faster than the reference test for the first 96 hours (Fig. 5), yet the MC difference remains very low. It may be concluded that the alternation of high and low input temperature plays a role analogue to airflow reversal. If this fact is confirmed over a wider range of drying conditions, this would be a crucial interest of using intermittent energy sources.

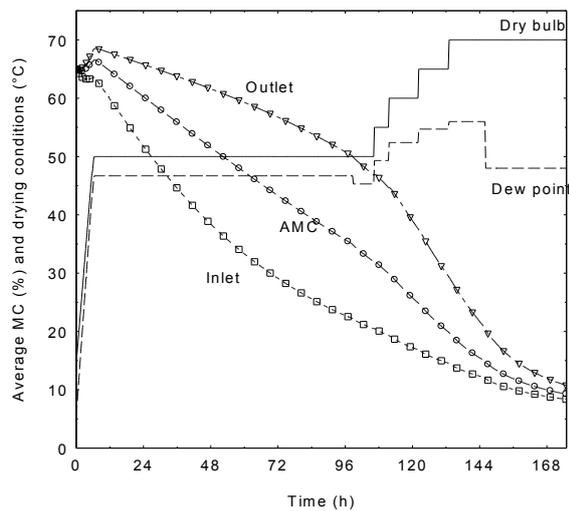


Fig.2. Evolution of drying conditions at the stack inlet and MC evolution of identical boards of the same layer (Reference configuration)

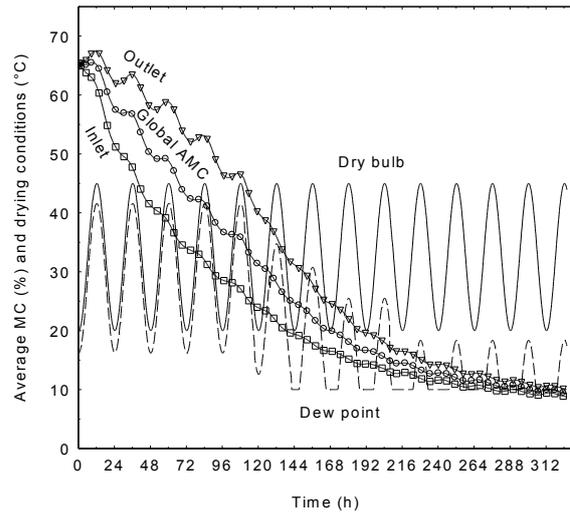


Fig.3. Evolution of drying conditions at the stack inlet and MC evolution of identical boards of the same layer (Configuration A).

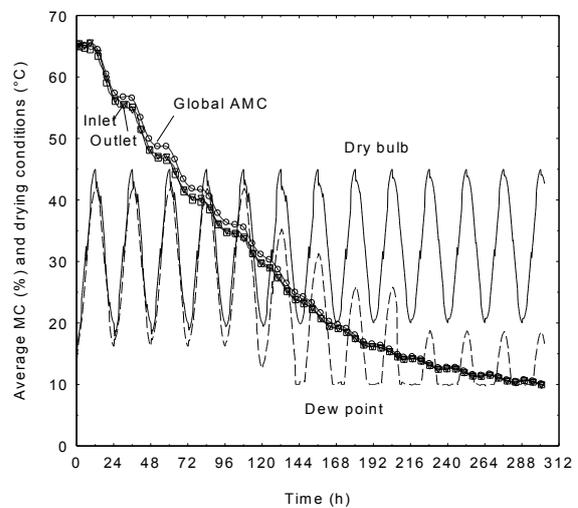


Fig.4. Evolution of drying conditions at the stack inlet and MC evolution of identical boards of the same layer (Configuration A.bis)

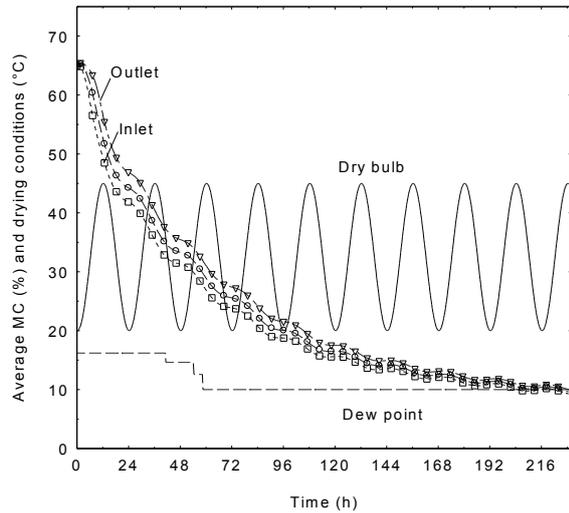


Fig.5. Evolution of drying conditions at the stack inlet and MC evolution of identical boards of the same layer (Configuration B)

At the beginning of drying with configuration A, the moisture content of boards close to the stack outlet alternate adsorption/desorption phases respectively during the heating/cooling period (Fig.3). In order to explain this behavior, figure 6 zooms in on one period at the stack outlet and the surface temperature of the board close to the same location. The curves of the dry bulb temperature and dew point at the stack outlet are very close due to the stack effect. A phase shift occurs on the surface temperature because of the thermal inertia of the board, which causes the surface temperature to be equal to the dew point during the heating phase and condensation of vapor to occur at the board surface. These curves leave each other and drying restarts during the cooling phase.

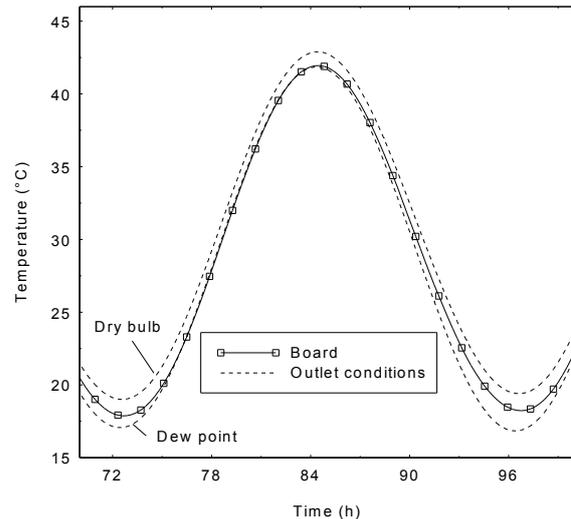


Fig.6. Enlargement on one period of the drying conditions and the surface temperature close to the stack outlet (Configuration A).

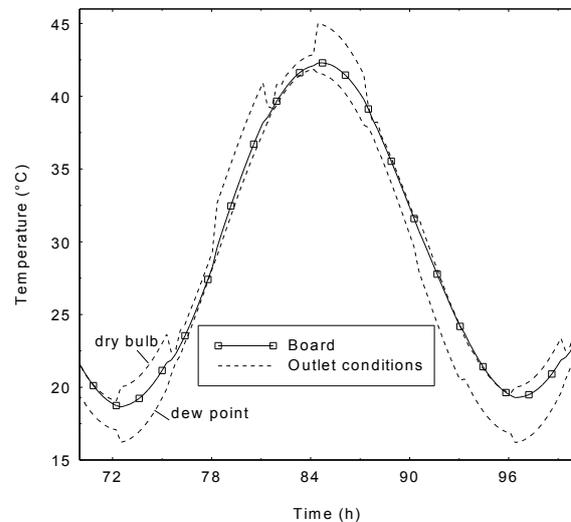


Fig.7. Enlargement on one period of the drying conditions and the surface temperature close to the stack outlet (Configuration A.bis)

The airflow reversal allows a more homogenous MC distribution within the stack to be obtained (Fig.4). The oscillations of the air conditions at the stack outlet produces a cyclic increase/decrease of the dry bulb temperature with a cyclic decrease/increase of the dew point in opposition of phase (Fig.7). This phenomenon attenuates the problem of condensation on the boards.

Drying quality

The maximum average tensile stress is 0.66MPa and 0.17MPa, for the surface and core respectively, in the reference configuration. The stress at surface is 2.2 times higher for intermittent energy sources with respectively, 1.49MPa, 1.50MPa, 1.36MPa for the configurations A, A.bis, and B. The average tensile stress at core is about 10 to 30% higher with respectively 0.23MPa, 0.19MPa, 0.22MPa.

Indeed, the higher temperature of the reference drying schedule (Fig.2) activate more intensely the viscoelastic creep and reduce the stress level. Concerning, the stress levels reached in the drying *A* and *B*, the order is not really as expected. Figure 8 depicts the drying stress within the board close to the stack inlet. The compressive and tensile stresses at core are higher with drying *B*, and similar at the surface. However, the constant drying rate period, without internal stress, is extended for the board dried with strategy *A* due to water vapor condensation close to the stack outlet (Fig.9). After 120h, the EMC decrease (Fig.3), and this board undergoes more severe conditions when its drying starts (Fig.9) than the same board dried with strategy *B*.

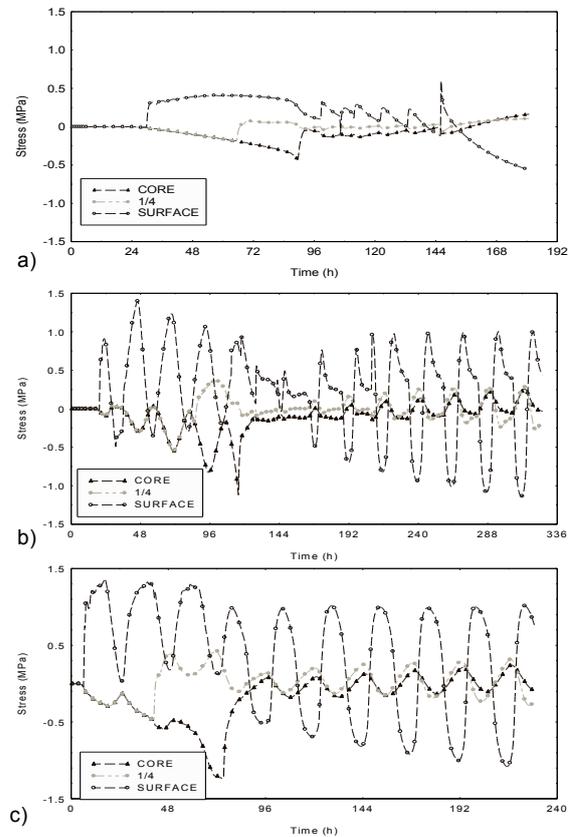


Fig.8. Drying stress within the board dried with the reference schedule (a), the strategy A (b) and B (c). Board is located at the stack inlet.

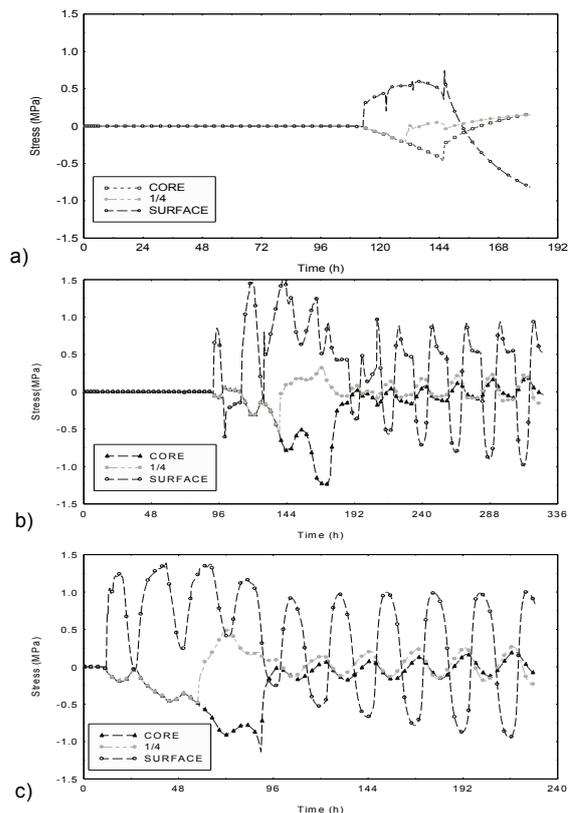


Fig.9. Drying stress within the board dried with the reference schedule (a), the strategy A (b) and B (c). Board is located at the stack outlet.

CONCLUSIONS

In this paper, we observed that the reference drying schedules, originally developed to get a good product quality with a limited drying time, meets these goals successfully.

The use of intermittent energy source with a low level of exergy may be of interest in the future to address energy issues compared with conventional drying. However, the strategy for reducing the drying stresses and limiting the drying time is not simple to achieve. Two contrasting strategies were tested in this work for the choice of the relative humidity in the room as the kiln temperature varies due to the intermittent character of the energy source. The first strategy follows the equilibrium moisture content of the reference schedule. This strategy is probably difficult to achieve because it induces a complex control of the relative humidity inside the kiln.

In addition, the thermal inertia of boards produces water vapor condensation at the boards surfaces when the temperature level varies in time. This effect lowers the drying rate. The second strategy, easier to control, provides a lower drying time, with a similar final quality. In both cases, we found a better uniformity of the final moisture content of boards thanks to the reduction of the stack effect.

Embedded computational models with predictive possibilities in the process controller would certainly be of great help in addressing all these questions.

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