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Drying 2004 – Proceedings of the 14th International Drying Symposium (IDS 2004)
São Paulo, Brazil, 22-25 August 2004, vol. B, pp. 1263-1270

MODELLING OF PAPER DRYING: A COMPREHENSIVE COMPUTATIONAL MODEL USED BY THE INDUSTRY

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Keywords: paper, infrared, coat drying, quality, computational model.

ABSTRACT

In paper industry, drying simulation programs can be used in order to calculate new drying arch or to optimize paper quality through better moisture profile or adequate non-contact dryer location. Few years ago, LERMAB and SOLARONICS IRT developed a drying model to address those needs. A simplified set of equations, deduced from realistic physical assumptions, was used as first step. This set allowed us to finalize an easy-to-use computer tool, developed in VBA (Visual Basic Application) and running with all graphical facilities provided by Excel. This tool has been used on actual industrial plants for several applications and a large range of process data to size innovative solutions. In most cases, the simplified assumption proved to be relevant. Nevertheless, in some specific cases, some discrepancies happened between simulated results and data measured on site. This paper describes a new model that has been developed to take into account the moisture distribution across paper thickness and its internal gaseous pressure. Because this second set of equations is dramatically more demanding in numerical strategy, the initial computational solution had to be revisited. However, it was very important for the SOLARONICS IRT company and its staff to keep the same graphical facilities. A solution has been found in which a very efficient computational heart is written in Fortran with up-to-date numerical strategies and compiled as a dynamically linked library used by the former VBA software. By this way, the improvement of the physical description of paper drying is just invisible for final users: neither the interface, nor the computational time changed, but the results are more relevant.

INTRODUCTION

Drying of paper is a complex mechanism that involves several components (cellulose fibers, water, air, mineral additives ...) and often includes the three mechanisms of heat transfer (conduction, convection and radiation). Taking into account the worldwide yearly paper and board production, it is more than 300 M tones of water that have to be evaporated by all existing machines. This figure helps us to better understand why the paper industry has traditionally looked to reduce the production costs linked to the evaporation processes without impairing the quality of the final product. On the reverse, papermakers are facing higher and higher quality demands corresponding to added value papers that are sometimes to be produced on very wide and very high speed machines.

Drying simulation programs can be used both to optimize the energy consumption and the quality, provided that they are able to encompass internal physical phenomena occurring during the drying process. This is especially true when producing coated papers as heat and mass transfers are even more complex (presence of two different media with migration between coating layer and base paper) and as the drying process itself has a significant effect on the quality of the final product (Hagen, 1985, Renvall and Rautiainen, 1990, Kim, 1997, Xiang and Bousfield, 2000).

Several model have been developed (Noboa and Seyed-Yagoobi, 1999) in order to simulate the drying of coated paper but it appears that there is still a need for more complete model together with confrontation to field measurements.

The model presented in this paper is based on numerous field experiences and on a former simplified program that was nevertheless able to simulate any means of energy transfer along the paper machine (Lescanne, 2001). Applications such as hot-pressing, pre-heating, profiling and non-contact drying after metering size-presses or coating stations were calculated by this program (Noclain, 2003).

For coating applications, this former model calculated average moisture content of base paper and coating layer and it appeared that it had to be improved to take into account heat and mass transfer between coating and base paper. Then, it would be possible to calculate the dewatering and to more accurately design drying arches by implementing the drying systems at their optimum location to follow adequate drying strategy. On top of cross direction temperature calculations, the model described here takes into account internal gaseous pressure to calculate cross moisture-profiles across the thickness of a paper web. Furthermore, the 1-D version of *TransPore* has been enhanced to accommodate coating layers on one or both sides of a base paper web.

Such a tool, linked with an easy-to-use interface, will have the capacities to faithfully reproduce physical phenomena taking place all along a paper machine, including coating operations, for all grade of paper or board and for every drying systems such as infrared or air dryers, every kinds of cylinders drying sections and free draws.

PHYSICAL FORMULATION

Whitaker (1977, 1998) presented in detail the set of equations that govern heat and mass transfer in porous media. This formulation has been successfully adapted to media such as wood for which bound water plays an important role and applied to several configurations of drying, including those which generate intense mass transfer due to an internal overpressure (Perré and Degiovanni, 1990; Perré *et al.* 1993, Perré and Turner, 1996, 1999). These equations are shortly presented in the following sections:

Water conservation

$$\frac{\partial}{\partial t}\left(\phi_\ell \rho_\ell + \phi_g \overline{\rho}_v^g + \overline{\rho}_b\right) + \nabla \cdot \left(\rho_\ell \overline{\mathbf{v}}_\ell + \overline{\rho}_v^g \overline{\mathbf{v}}_g + \overline{\rho_b \mathbf{v}_b}\right) = \nabla \cdot \left(\overline{\rho}_g^g \overline{\overline{\mathbf{D}}}_{\text{eff}} \nabla \omega_v\right) \qquad [1]$$

Enthalpy conservation

$$\frac{\partial}{\partial t}\left(\phi_\ell \rho_\ell h_\ell + \phi_g(\overline{\rho}_v^g h_v + \overline{\rho}_a^g h_a) + \overline{\rho_b h_b} + \rho_o h_s - \phi_g P_g\right)$$
$$+ \nabla \cdot \left(\rho_\ell h_\ell \overline{\mathbf{v}}_\ell + (\overline{\rho}_v^g h_v + \overline{\rho}_a^g h_a)\overline{\mathbf{v}}_g + h_b \overline{\rho_b \mathbf{v}_b}\right) \quad [2]$$
$$= \nabla \cdot \left(\overline{\rho}_g^g \overline{\overline{\mathbf{D}}}_{\text{eff}} (h_v \nabla \omega_v + h_a \nabla \omega_a) + \overline{\overline{\mathbf{\Lambda}}}_{\text{eff}} \nabla T\right) + \Phi$$

In this equation, Φ is the volumetric source term (W.m^{-3}), which allows the radiative heating due to infrared emitters to be allocated throughout the sheet thickness using a Lambert attenuation law.

Air conservation

$$\frac{\partial}{\partial t}\left(\phi_g \overline{\rho}_a^g\right) + \nabla \cdot \left(\overline{\rho}_a^g \overline{\mathbf{v}}_g\right) = \nabla \cdot \left(\overline{\rho}_g^g \overline{\overline{\mathbf{D}}}_{\text{eff}} \nabla \omega_a\right) \quad [3]$$

In these expressions, the velocity of gaseous and liquid phases are respectively expressed using the generalized Darcy's law:

$$\overline{\mathbf{v}}_i = -\frac{\overline{\overline{\mathbf{K}}}_i \overline{\overline{\mathbf{k}}}_i}{\mu_i} \nabla \varphi_i \ , \ \nabla \varphi_i = \nabla P_i - \rho_i g \nabla \chi \quad \text{pour } i = \ell, g \quad [4]$$

The quantities φ are known as the phase potentials and χ is the depth scalar. All other symbols have their usual meaning. The liquid and gaseous pressures are related through the capillary pressure. The latter is assumed to be dependent on the moisture content only:

$$P_\ell = P_g - P_c(X) \quad [5]$$

Boundary conditions

There are two types of boundary conditions that need to be discussed, namely, conditions at external boundaries and conditions at symmetry planes. The boundary conditions proposed for the external drying surfaces of the sample are assumed to be of the following form :

$$\mathbf{J}_w \cdot \mathbf{n} = k_m c M_v \ln\left(\frac{1 - x_\infty}{1 - x_v}\right)$$
$$\mathbf{J}_\mathbf{e} \cdot \mathbf{n} = k_h (T - T_\infty) + h_v k_m c M_v \ln\left(\frac{1 - x_\infty}{1 - x_v}\right) \quad [6]$$

where $\mathbf{J}_w$ and $\mathbf{J}_e$ represent the fluxes of total moisture and total enthalpy at the boundary respectively. The pressure at the external drying surfaces is fixed at the atmospheric value. Recalling that one of the primary variables used for the computations is the averaged air density, the Dirichlet boundary condition $P_g = P_\infty$ has to be modified to form an appropriate non-linear equation for this primary variable:

$$\varepsilon_g (P_v - P_\infty) + \frac{\overline{\rho}_a R T}{M_a} = 0 \quad [7]$$

Equations [6] must be resolved, along with the conservation laws [1] and [2], during the non-linear iterations for every external boundary control volume within the computational domain. Equation [7] is solved as a Dirichlet condition instead of the air conservation equation [3].

COMPUTATIONAL STRATEGY

The previous set of conservation equation (enthalpy, moisture and dry air) is solved over the computational domain using the Control Volume approach (Patankar, 1980). The discretisation proceeds by integrating the balance law over a typical control volume. In this work, the 1-D version of *TransPore* is used for that purpose.

After integrating over each control volume within the computational domain, a system of non-linear equations results whereby each line is the discrete form of a conservation equation. Along the computational procedure, the state of each *CV,* is defined by a whole set of variable. In fact, out of this variable set, only three variables, known as the *primary variables*, will be treated as the unknown independent variables for each *CV*. The values of all variables are presumed known at the n^{th} time level. Once the nonlinear functions are assembled for each *CV* within the computational domain, the result is a system of nonlinear equations of the form $\boldsymbol{F}(\mathbf{u}) = \mathbf{0}$**.** The solution vector **u** contains the primary variables (in triplets) for each *CV* within the mesh. This system must be solved, at each time step, in order to advance all of the primary variables in time.

The system of non-linear equations is linearized according to a Quasi-Newton scheme. The estimate of the solution vector at the $(n+1)^{th}$ level is computed from the current solution at the n^{th} level by writing

$$\mathbf{u}^{(n+1)} = \mathbf{u}^{(n)} + \delta\mathbf{u}^{(n)} \qquad [8]$$

and solving the system of linearized equations

$$\mathbf{B}(\mathbf{u}^{(n)})\delta\mathbf{u}^{(n)} = -\boldsymbol{F}(\mathbf{u}^{(n)}) \qquad [9]$$

for the correction vector $\delta\mathbf{u}^{(n)}$. In equation [9], **B** represents an approximation to the true Jacobian matrix (Perré and Turner, 1996). Because the Jacobian matrix involves all primary variables at each node of the mesh, the treatment of both the coupling between equation and the non-linear behaviour of the equation is very efficient. System [9] is solved by employing the *Bi-Conjugate Gradient Stabilised Method*, together with an Incomplete Factorisation level zero, *ILU*(0), preconditioning technique. Thank to these up-to-date computational strategies and in spite of a dramatically demanding physical formulation, an entire simulation with 51 nodes requires less than one second of CPU time using a 3 GHz Pentium processor !

However, it was very important for the SOLARONICS IRT company and its staff to keep the graphical facilities offered by the previous tool written in VBA (Visual Basic Application) and running with all graphical facilities provided by Excel. A solution has been found in which the very efficient computational engine *TransPore*, written in Fortran 90, has been compiled as a dynamically linked library used by the former VBA software (Figure 1). By this way, the improvement of the physical description of paper drying is just invisible for final users: the interface is exactly the same and the computational time has even been reduced.

The present Fortran dll comprises two main subroutines : *Init* and *Compute* :

- ✓ Subroutine *Init* allows the medium properties to be transferred to the memory storage zone of the dll and builds the CV mesh, which may includes one, two or three layers with different physical properties and different initial fields of variables. A relevant set of input parameters is used for this purpose. As output parameters, *Init* transfers to VBA and Excel the geometrical description of the mesh and the initial field of variables (temperature, moisture content and air density).

- ✓ Subroutine *Compute* allows the drying process to advance from time t_1 to time t_2 (two input parameters). VBA has to provide the boundary conditions on both faces of the computational domain and the present field of variables. As output parameters, it transmits the new variable fields and the average moisture content, dry basis, computed in *TransPore* using the moisture content of each node, the size of each control volume and the local density of the medium.

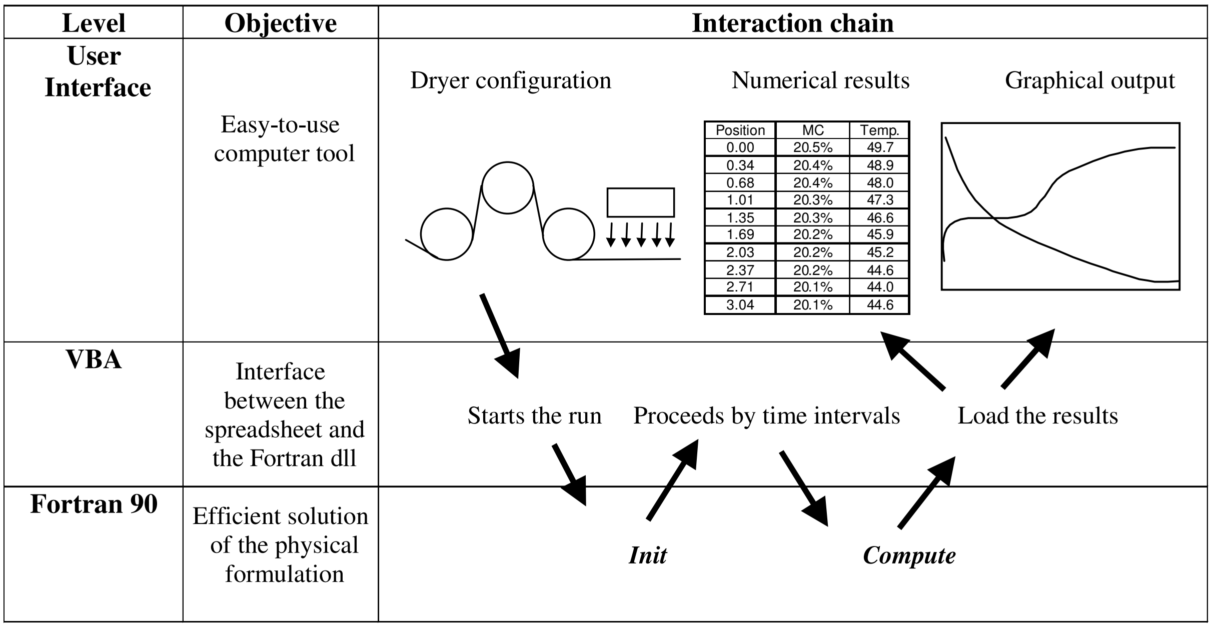

Fig. 1 – The structure of the new simulation tool.

By dividing the whole drying time in small intervals (successive values of times t_1 and t_2), it is possible to update the plots during the calculation using the graphical possibilities offered by Excel. Moreover, at the end of the drying run, all data remain available in the spreadsheet, which allows further investigations and specific graphs. Although the computational process starts again at each call to *Compute*, the total CPU time just slightly raises compared to the standalone Fortran version.

SOME SIMULATION POSSIBILITIES

One example is proposed in this section which depicts the possibilities offered by the new computational tool. Figure 2 presents the machine layout: a double-sided coating with high initial moisture content is applied to a dry paper support. A first free draw, an infrared section, eight cylinders and a last convective free draw ensure the drying process. The machine speed is equal to 800 meter per second, the paper basis weight is 100 g/m², and each coating layer (15 g/m²) has a initial moisture content of 50% (wet basis).

The computational code allows not only the average moisture content, but local values of the moisture content to be plotted (Figure 3). Obviously, the average moisture content evolution confirms that the drying rate is high when the energy supplied to the paper is high (IR emitters or cylinders). In addition, thank to the evolution of some local values of moisture content, one can note the effect of non-symmetrical energy flux, for example from one cylinder to the other. Note also that the center moisture content increases first and then decreases. The increasing period is simply due to internal moisture migration from the coating layer towards the paper support.

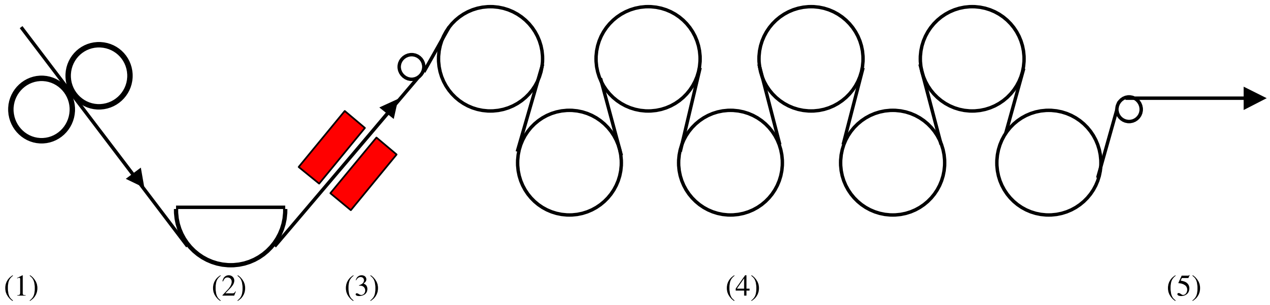

Figure 2 - Layout description of the example used in this section: 1) Coater, 2) Convective Free Draw (including a non-contact deviator), 3) Infrared section: 1 m, face to face, 250 kW/m² by face, 4) Conductive section: 8 steam heated cylinders of 1.5 m diameter and 5) Convective section: Free Draw of 4 m.

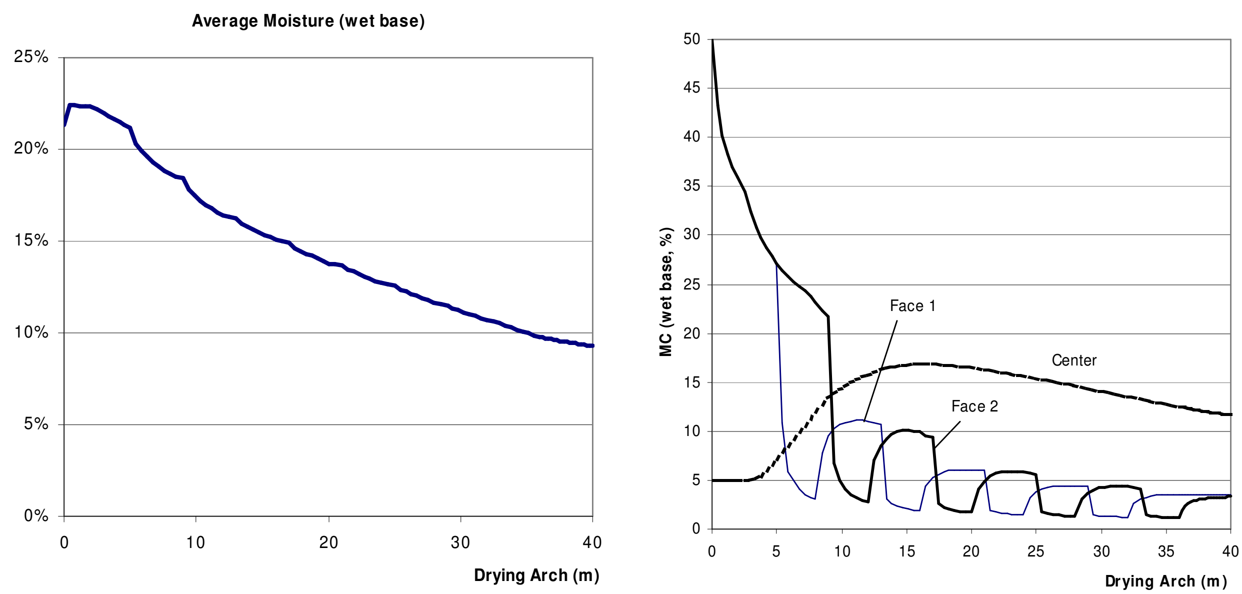

Figure 3 – Average and local moisture content value along the drying arch.

As already stated, because the simulation runs are controlled from a spreadsheet, any results can be to be plotted afterwards. Figure 4 depicts the evolution of the surface temperature at each face during the drying process. The infrared section increases rapidly both temperatures by the same amount (symmetrical energy flux) while the cylinder heats alternatively one and the other face.

Finally, figure 5 summarizes the evolution of moisture content profiles as a function of distance along the arch. The internal migration from the layer towards the support, as well as the alternative drying of each face from one cylinder to the other are clearly displayed.

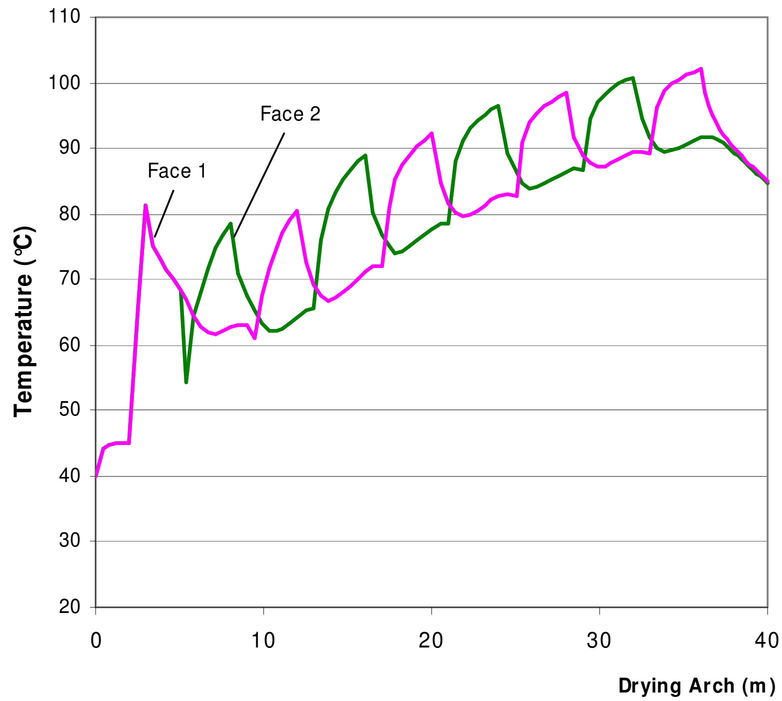

Figure 4 – The evolution of the surface temperature of each face along the dryer.

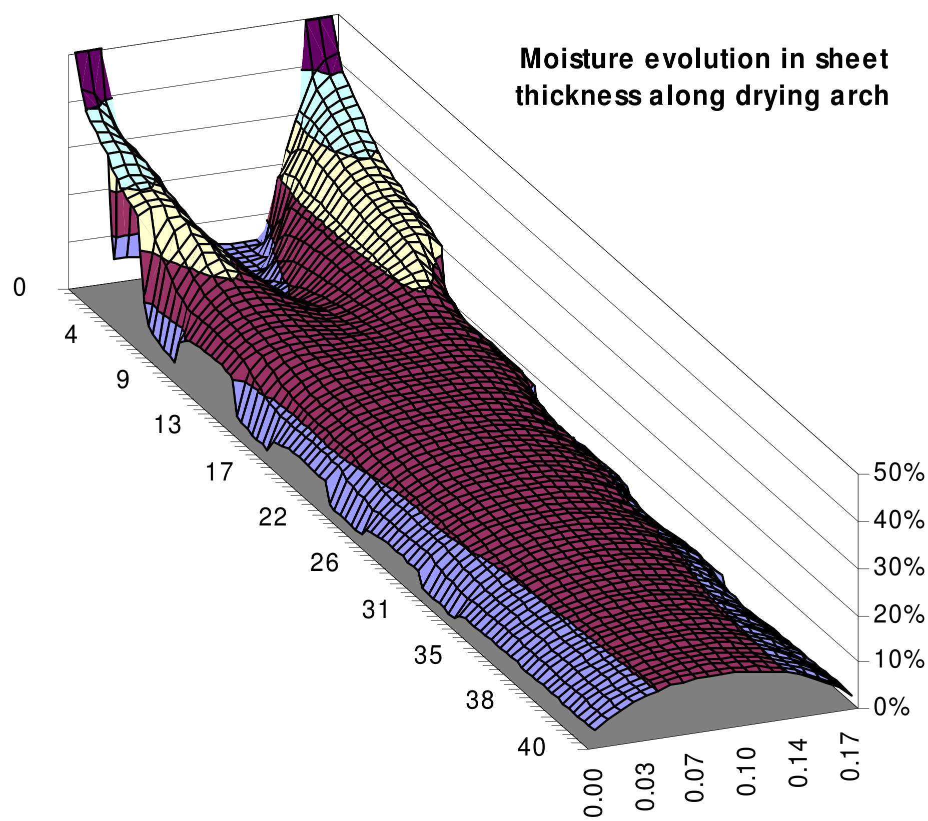

Figure 5 – The evolution of the moisture content profile in the three layer support the dryer.

CONCLUSIONS

In this work, a new software has been developed and used to simulate paper drying in actual industrial conditions. This model accounts for the moisture content distribution across the paper thickness and the internal gaseous pressure. Up to three layers of different thickness, properties and initial moisture content and temperature can be distinguished. In order to face the highly demanding computational effort, the engine is written in FORTRAN 90. Then, it is compiled as a dynamically linked library used by the former VBA software under Excel. This solution allows the user to work with a very usual environment.

Just one example of simulation is presented here, but the potential of this software for industrial applications is endless. In the future, the works will be focused on comparison with experimental measurements, in order to gain some information concerning internal parameters, namely moisture transfer between the coating layers and the support.

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