Dynamic Modeling and Simulation of a Drying System with Recuperation of the Condensate

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***Abstract*— The aim of this work is to build a lumped parameter model of a closed loop drying system with recuperation of the condensate to be used in analysis, simulation and control design. The proposed approach is based on an energy-based modeling technique which guarantees the conservation of energy within the system. The whole system involves thermodynamics, air-water interaction with evaporation and condensation and humid air flows dynamics. The proposed model can be used to make a dynamic analysis of the system, to predict some non-measured variables, to make some sensitivity analysis for different parameters, to investigate the best operation point acting on factors affecting the drying quality and power consumption. Some simulation results are presented and compared to experimental results.**

I. INTRODUCTION

The choice of a modeling technique is a very important issue in the modeling of complex dynamic physical systems. Many graphical energy-based modeling techniques have been introduced in the past years: the Bond Graphs (BG) [1], [2], the Power-Oriented Graphs (POG) [3] and the Energetic Macroscopic Representation (EMR) [4]. All these techniques are based on the concept of energy moving within the system. In this work the main concepts of Power-Oriented Graphs (POG) modeling technique are exploited but with some changing to adapt the main properties of POG to the thermodynamic domain. The main advantages of this approach are the certainty of the correctness of the model from an energy point of view (energy conservation), compactness, direct correspondence with state space equations, possibility to translate block schemes directly into Simulink for simulations. POG schemes clearly show the power flows within the system thus allowing a precise analysis and to keep always the corresponding physical meaning.

This modeling approach allows to have simple implementation of the model in Simulink and to calculate internal variables of the system useful for the design of the system itself. An accurate modeling of the whole system is very useful in the project of the machine (Model Based Design) for the choice of parameters, the evaluation of performances that can be obtained and the building of the control (different control algorithms can be tested in simulation before the implementation on the real machine).

II. DESCRIPTION OF THE CLOSED LOOP DRYING SYSTEM WITH RECUPERATION OF THE CONDENSATE

The physical scheme of the closed loop drying system with recuperation of the condensate is shown in Fig. 1. The air flow path present in the system can be divided into three parts: the heating zone, the evaporation zone and the dehumidifying zone (details on the dehumidification cannot be given for confidentiality reason). The fan imposes a certain pressure drop at its ends causing the air flowing in the hydraulic circuit of the machine. After the fan, air enters the heating zone where two electrical resistances heat up the air passing through them. After the heaters, the air enters the evaporating zone where it comes in contact with some wet substances: the air vapor content increases resulting in the drying of the substances. The humid air then goes in the dehumidifying zone where a certain counter-flow helps the extraction of vapor from humid air. Finally the air returns back to the fan and another cycle begins. The air entering the evaporation zone is hot and with low humidity therefore the evaporation of the water from the substances is facilitated and the humidity of the air flow increases. Afterwards the air enters the dehumidifying zone where its humidity content is reduced. The condensed humidity falls down into a sink in the bottom of the machine and it is drained out by a pump. At the exit of the dehumidifying zone, the air is colder and drier than the air at the dehumidifying zone inlet.

III. DYNAMIC MODELING OF THE SYSTEM

The main elements considered in the modeling of the closed loop drying system with recuperation of the condensate are reported in Table I, where each element is associated to a subscript. The thermal capacities of each element are indicated by C with the corresponding subscript, the temperatures are indicated by T with the corresponding subscript and the thermal conductivities between two elements are indicated by g with the two subscripts corresponding to the two elements. For example C_f is the thermal capacity of the frame, T_f is the temperature of the frame and g_{fe} is the thermal conductivity between the frame and the external air.

The dynamic model of the considered thermal system can be written in a compact way in the state-space form:

$$\begin{cases} \mathbf{L}\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} + \mathbf{h}(\mathbf{z}, T_g, T_s) \\ \mathbf{y} = \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u} \end{cases} \tag{1}$$

The vectors $\mathbf{x}$, $\mathbf{u}$ and $\mathbf{y}$ and the matrices $\mathbf{L}$, $\mathbf{B}$, $\mathbf{C}$ and $\mathbf{D}$ have the following structure:

$$\mathbf{L} = \text{diag}\{C_r, C_2, C_3, C_c, C_a, C_0, C_f, C_b, C_p, C_g, C_R, C_e\}, \tag{2}$$

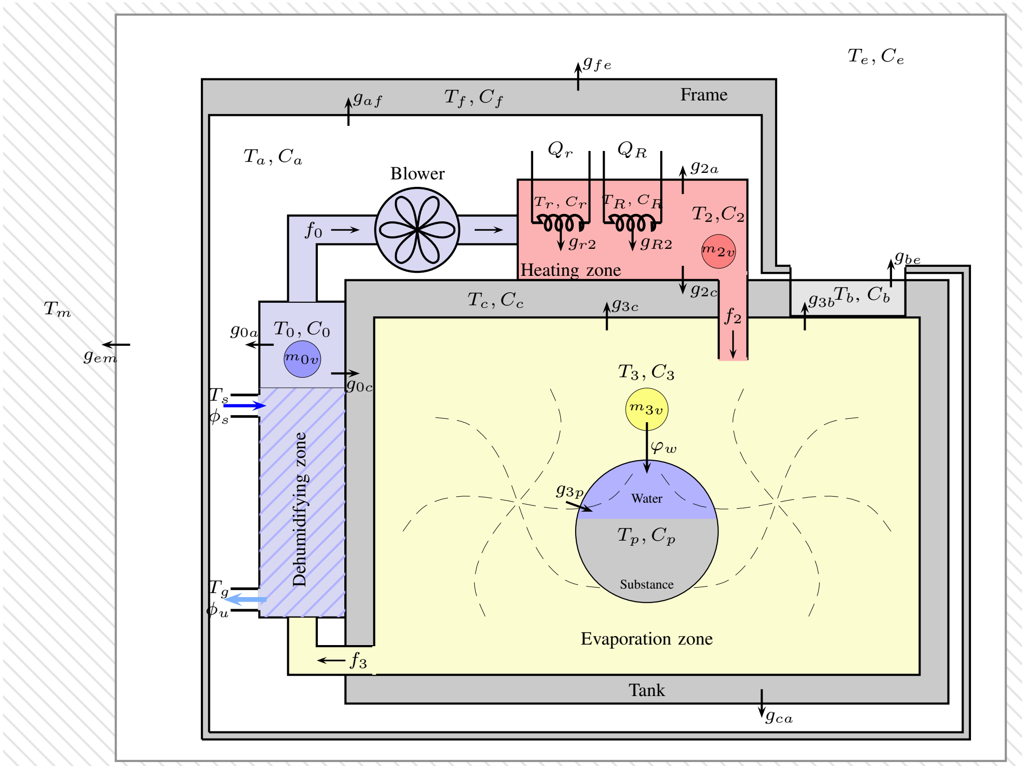


Fig. 1. Thermal model of the drying system.

Subscript	Element
r	electrical resistance up
R	electrical resistance down
2	heating zone
3	evaporation zone
c	tank
a	internal air space
0	dehumidifying zone
f	frame
b	door
p	substance
g	flux in dehumidif. zone
e	external air
s	input flux
m	room walls

TABLE I
VARIABLES SUBSCRIPT DEFINITION.

$$\mathbf{x}=\begin{bmatrix} T_r\\ T_2\\ T_3\\ T_c\\ T_a\\ T_0\\ T_f\\ T_b\\ T_p\\ T_g\\ T_R\\ T_e \end{bmatrix}, \mathbf{u}=\begin{bmatrix} \dot{Q}_r\\ \dot{Q}_R\\ T_m \end{bmatrix}, \mathbf{y}=\begin{bmatrix} T_r\\ T_R\\ \dot{Q}_m \end{bmatrix}, \mathbf{B}=\begin{bmatrix} 1&0&0\\ 0&0&0\\ 0&0&0\\ 0&0&0\\ 0&0&0\\ 0&0&0\\ 0&0&0\\ 0&0&0\\ 0&0&0\\ 0&0&0\\ 0&1&0\\ 0&0&g_{em} \end{bmatrix},$$

$$\mathbf{C}=\begin{bmatrix} 1&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0&1&0\\ 0&0&0&0&0&0&0&0&0&0&0&g_{em} \end{bmatrix}, \mathbf{D}=\begin{bmatrix} 0&0&0\\ 0&0&0\\ 0&0&-g_{em} \end{bmatrix}.$$

Matrix $\mathbf{A}$ is reported in Fig. 2. Matrix $\mathbf{L}$ is diagonal and contains all the thermal capacities of the model, that can be constant or time-variant. The state vector $\mathbf{x}$ is characterized only by temperatures. The input power on the electrical resistances are $\dot{Q}_r$ and $\dot{Q}_R$. Matrix $\mathbf{A}$ is characterized only by all the thermal conductivities $g_{i,j}$ and by the specific power coefficients f_i. The thermal conductivity $g_{i,j}$ that relates two elements i and j within the system, always appears 4 times in matrix $\mathbf{A}$ in a symmetric position (as an example coefficient g_{2a} highlighted in blue in matrix $\mathbf{A}$). Considering g_{2a} a heat flux given by product $g_{2a}(T_2 - T_a)$ goes from the heating zone (at temperature T_2) to the internal air (at temperature T_a): the term $g_{2a}(T_2 - T_a)$ appears with a negative sign in the energy balance of the heater and with a positive sign in the energy balance of the internal air. This particular structure of matrix $\mathbf{A}$ guarantees that all heat fluxes within the system occur without generation nor dissipation of energy/power. Similar considerations can be done concerning the thermal power $f_2 T_2$, $f_3 T_3$ and $f_0 T_0$ associated to the mass flows $\boldsymbol{\phi}_2$, $\boldsymbol{\phi}_3$ and $\boldsymbol{\phi}_0$ present within the system. Each thermal power goes out from one element and goes in another therefore it appears, with opposite signs, in two different positions of matrix $\mathbf{A}$. The term $\mathbf{h}(\mathbf{z}, T_g, T_s)$ indicates the heat fluxes related to the evaporation/condensation of water within the system, to the input flow ϕ_s at temperature T_s and

$$
\mathbf{A}=\begin{bmatrix}
-g_{r2} & g_{r2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
g_{r2} & -f_2-g_{r2}-g_{R2}-g_{2c}-g_{2a} & 0 & g_{2c} & g_{2a} & f_0 & 0 & 0 & 0 & 0 & g_{R2} & 0\\
0 & f_2 & -f_3-g_{3c}-g_{3b}-g_{3p} & g_{3c} & 0 & 0 & 0 & g_{3b} & g_{3p} & 0 & 0 & 0\\
0 & g_{2c} & g_{3c} & -g_{2c}-g_{3c}-g_{ca}-g_{0c} & g_{ca} & g_{0c} & 0 & 0 & 0 & 0 & 0 & 0\\
0 & g_{2a} & 0 & g_{ca} & -g_{2a}-g_{ca}-g_{0a}-g_{af} & g_{0a} & g_{af} & 0 & 0 & 0 & 0 & 0\\
0 & 0 & f_3 & g_{0c} & g_{0a} & -f_0-g_{0c}-g_{0a}-g_{0g} & 0 & 0 & 0 & g_{0g} & 0 & 0\\
0 & 0 & 0 & 0 & g_{af} & 0 & -g_{af}-g_{fe} & 0 & 0 & 0 & 0 & g_{fe}\\
0 & 0 & g_{3b} & 0 & 0 & 0 & 0 & -g_{3b}-g_{be} & 0 & 0 & 0 & g_{be}\\
0 & 0 & g_{3p} & 0 & 0 & 0 & 0 & 0 & -g_{3p} & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & g_{0g} & 0 & 0 & 0 & -g_{0g} & 0 & 0\\
0 & g_{R2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -g_{R2} & 0\\
0 & 0 & 0 & 0 & 0 & 0 & g_{fe} & g_{be} & 0 & 0 & 0 & -g_{fe}-g_{be}-g_{em}
\end{bmatrix}
$$

Fig. 2. Matrix $\mathbf{A}$ of system (2)

to the flow ϕ_u of condensed water at temperature T_g drained out of the dehumidifying zone. Vector $\mathbf{z} = \begin{bmatrix} m_w \, m_g \end{bmatrix}^{\mathrm{T}}$ indicates the vector of additional state variables (mass of water in the wet substance m_w, mass of the flux in the dehumidifying zone m_g) different from variables contained in vector $\mathbf{x}$. The vector $\mathbf{h}(\mathbf{z}, T_g, T_s)$ is expressed as follows:

$$
\mathbf{h}(\mathbf{z}, T_g, T_s) = \begin{bmatrix} 0 \\ 0 \\ -\,\mathrm{P}(\varphi_w, T_3, T_p) \\ 0 \\ 0 \\ -\,\mathrm{P}(\varphi_g, T_0, T_g) \\ 0 \\ 0 \\ h_{pl} + \mathrm{P}(\varphi_w, T_3, T_p) \\ h_{gl} + h_{sg} + \mathrm{P}(\varphi_g, T_0, T_g) \\ 0 \\ 0 \end{bmatrix} \tag{3}
$$

where

$$
h_{pl} = c_l \, \varphi_w, \qquad h_{gl} = c_l \, \varphi_g,
$$

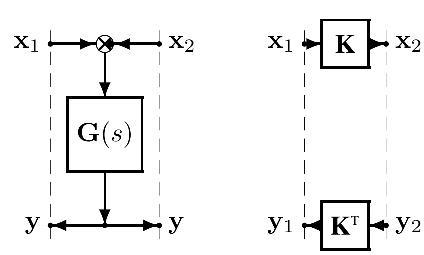
with c_l the latent heat of vaporization and c_w the specific heat of water. The function $\mathrm{P}(\varphi, T_1, T_2)$ represents the heat flux (associated to water or vapor) passing from temperature T_1 to temperature T_2. Function $\mathrm{P}(\varphi, T_1, T_2)$ is defined as:

$$
\mathrm{P}(\varphi, T_1, T_2) = \frac{\varphi}{2} \left[c_v (1 + \mathrm{sgn}\varphi) T_1 + c_w (1 - \mathrm{sgn}\varphi) T_2 \right].
$$

where c_v is the specific heat of vapor. When the flux is positive, $\varphi > 0$, the vapor condenses to water, therefore the specific heat of vapor c_v must be used in the calculation of the heat flux. Viceversa, when the flux is negative, $\varphi < 0$, the water becomes vapor and therefore in the calculation of the heat flux the specific heat of water c_w must be used. The term h_{sg} takes into account the net heat flux associated to the input flux in the dehumidifying zone and the output flow of condensate. The term $-c_l \, \varphi_w$ represents the evaporation heat flux that is taken from the thermal capacity C_p of the substance when the water flow φ_w evaporates from substance and goes in the air of the evaporating zone in form of vapor. Similarly the term $c_l \, \varphi_g$ represents the condensation heat flux in the dehumidifying zone. In general, the flux of output condensed water depends on the efficiency of the dehumidifying zone.

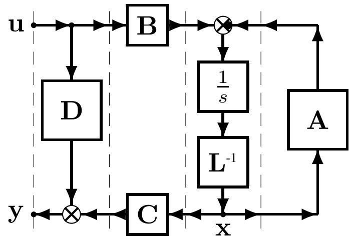
IV. Power-Oriented Graphs basic features

The POG block schemes are standard block diagrams combined with a particular modular structure essentially based on the use of the two blocks shown in Fig. 3.a and Fig. 3.b: the *elaboration block* (e.b.) stores and/or dissipates energy (i.e. springs, masses, dampers, capacities, inductances, resistances, etc.); the *connection block* (c.b.) redistributes the power within the system without storing nor dissipating energy (i.e. gear reduction, transformers, etc.). The e.b. and the c.b. are suitable for representing both scalar and vectorial systems. In the vectorial case, $\mathbf{G}(s)$ and $\mathbf{K}$ are matrices: $\mathbf{G}(s)$ is always a square matrix composed by positive real transfer functions; matrix $\mathbf{K}$ can also be rectangular. The circle present in the e.b. is a summation element and the black dot represents a minus sign that multiplies the entering variable. The POG put in evidence the power flows within the system and keep a direct correspondence between the dashed sections of the graphs and real power sections of the modeled systems: the scalar product $\mathbf{x}^{\mathrm{T}}\mathbf{y}$ of the two *power vectors* $\mathbf{x}$ and $\mathbf{y}$ involved in each dashed line of a power-oriented graph, see Fig. 3, has the physical meaning of *power flowing through that particular section*. Another important property of the POG technique is the direct correspondence between the POG schemes and the corresponding state space dynamic equations. For example, the POG scheme shown in Fig. 4 can be represented by the state space equations (4). It can be easily shown that when $\mathbf{D} = 0$ it follows that $\mathbf{C} = \mathbf{B}^{\mathrm{T}}$. For a POG linear system expressed in the compact form (4) the following properties hold: **1)** the energy matrix $\mathbf{L}$ is symmetric positive definite: $\mathbf{L} = \mathbf{L}^{\mathrm{T}} > 0$; **2)** the *energy E_s stored in the system* can be expressed as: $E_s = \frac{1}{2}\mathbf{x}^{\mathrm{T}}\mathbf{L}\,\mathbf{x}$; **3)** the *dissipating power P_d in the system* can be expressed



a) *e. b.* b) *c. b.*

Fig. 3. POG basic blocks: a) *elaboration block*; b) *connection block*.



$$\begin{cases}\mathbf{L}\,\dot{\mathbf{x}} = -\mathbf{A}\,\mathbf{x} + \mathbf{B}\,\mathbf{u}\\ \mathbf{y} = \mathbf{C}\,\mathbf{x} + \mathbf{D}\,\mathbf{u}\end{cases} \quad (4)$$

Fig. 4. POG block scheme of a generic dynamic system.

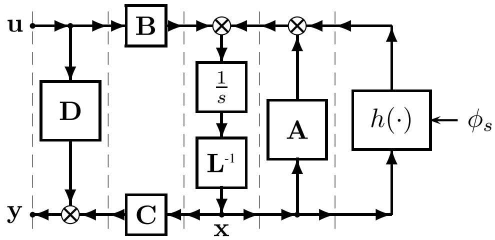


Fig. 5. Block scheme of the thermodynamic system (1).

as: $P_d = \mathbf{x}^{\mathrm{T}}\mathbf{A}_s\,\mathbf{x}$ where $\mathbf{A}_s = \frac{(\mathbf{A}+\mathbf{A}^{\mathrm{T}})}{2}$ is the symmetric part of the power matrix $\mathbf{A}$; **4)** the skew-symmetric part $\mathbf{A}_w = \frac{(\mathbf{A}-\mathbf{A}^{\mathrm{T}})}{2}$ of the power matrix $\mathbf{A}$ represents the *power redistribution within the system "without losses"*, i.e. $P_d = \mathbf{x}^{\mathrm{T}}\mathbf{A}_w\,\mathbf{x} = 0$.

The thermodynamic system (1) can be represented by the block scheme shown in Fig. 5. The structure of this scheme is very similar to the scheme shown in Fig. 4 but in this case the thermodynamic domain is considered, therefore some remarks are mandatory. First of all in the block scheme of Fig. 5 the dashed sections do not represent *power sections* but involves the two variables heat flux $\dot{Q}$ and temperature T. Matrix $\mathbf{L}$ is always symmetric and positive definite. The following properties hold.

1) The thermal energy E_t stored in the system is given by:

$$E_t = [1]_n^{\mathrm{T}}\mathbf{L}\mathbf{x}, \qquad (5)$$

where $[1]_n$ is the all-ones column vector of dimension n. This relation (5) means that the thermal energy E_t is equal to the sum of all thermal energies C_iT_i stored in all the thermal capacities C_i of the system.

2) Matrix $\mathbf{A}$ describes the power redistribution within the system. The components of vector $\mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} + h(\mathbf{z}, T_s, T_g)$ represent the thermal powers in input to the thermal capacities C_i: $\mathbf{A}\mathbf{x}$ represents the thermal fluxes inside the system, $\mathbf{B}\mathbf{u}$ represents the thermal fluxes in input and output and $h(\mathbf{z}, T_s, T_g)$ represents the thermal fluxes due to evaporation/condensation of water.

3) The skew-symmetric part $\mathbf{A}_w = (\mathbf{A} - \mathbf{A}^{\mathrm{T}})/2$ of matrix $\mathbf{A}$ is only function of parameters f_0, f_2 and f_3, therefore when fluxes f_0, f_2 and f_3 are zero matrix $\mathbf{A}$ is symmetric and then $\mathbf{A}_w = 0$.

4) If $f_0 = f_2 = f_3$ the eigenvalues of matrix $\mathbf{A}$ are all *"real or complex conjugate with negative or zero real part"*. If $f_0 = f_2 = f_3 = 0$ the eigenvalues are *"zero or negative real"*. These properties come from the physical meaning of matrix $\mathbf{A}$, moreover the whole thermal system is always stable in every operating condition and for any matrix $\mathbf{L}$. Therefore if the inputs are constant then the system always reaches a stable operating point.

5) If $f_0 = f_2 = f_3$ and $g_{em} = 0$ there is no thermal interaction of the system with the environment and it holds: $\mathbf{A}[1]_n = 0$, that is the sum of all the columns of matrix $\mathbf{A}$ is equal to the null vector.

6) If $g_{em} = 0$ then matrix $\mathbf{A}$ satisfies the following relation: $[1]_n^{\mathrm{T}}\mathbf{A} = 0$, i.e. the sum of all the rows of matrix $\mathbf{A}$ is equal to the null vector and this means that the sum of all the thermal fluxes in the system is always zero: generation or loss of energy can never occur within the system.

7) If the input are zero the free response $\mathbf{x}_l(t)$ of the system $\mathbf{x}_l(t) = e^{\mathbf{L}^{-1}\mathbf{A}t}\mathbf{x}_0$ do not modify the total energy E_t stored in the system:

$$E_t = [1]_n^{\mathrm{T}}\mathbf{L}\,\mathbf{x}_l(t) = [1]_n^{\mathrm{T}}\mathbf{L}\,e^{\mathbf{L}^{-1}\mathbf{A}t}\mathbf{x}_0 = [1]_n^{\mathrm{T}}\mathbf{L}\mathbf{x}_0 = \text{constant}.$$

This relation holds for every initial condition $\mathbf{x}_0$.

8) The state vector $\mathbf{x}$ is composed only by temperatures. It can be proved that the temperatures can be expressed both in Kelvin and Celsius degrees without modifying the dynamics of the whole thermal system and this follows from the particular structure of matrices $\mathbf{A}$ and $\mathbf{B}$.

Some similar properties of compact thermal models can be found in [6] and [7].

V. Modeling of Humid Air Dynamics and Evaporation/Condensation Phenomena

A. Dry air and vapor flows dynamics

The dynamics of mass flows of dry air and vapor within the considered thermal circuit can be described by the following system of differential equations:

$$\dot{\mathbf{m}} = f(\boldsymbol{\phi}_V, \mathbf{m}, \varphi_w, \varphi_g)$$

The explicit form of function $f(\cdot)$ is not shown for confidentiality reasons. The mass vector $\mathbf{m}$ is defined as:

$$\mathbf{m} = \begin{bmatrix}\mathbf{m}_2\\ \mathbf{m}_3\\ \mathbf{m}_0\\ \mathbf{m}_e\end{bmatrix} \qquad \text{where} \qquad \mathbf{m}_i = \begin{bmatrix} m_{ia}\\ m_{iv}\end{bmatrix}$$

for $i \in \{2,\ 3,\ 0,\ e\}$ represent the masses of dry air and vapor respectively within the heating zone, the evaporating zone, the dehumidifying zone and the room. The symbol $\boldsymbol{\phi}_V$ represents the vector of volumetric flows and its components are $\boldsymbol{\phi}_{V_i}$, for $i \in \{2,\ 3,\ 0,\ e\}$ and can be calculated using the ideal gas law and remembering that the blower imposes a pressure drop ΔP_v between the inlet and outlet sections. The two inputs φ_w and φ_g represent the amount of water that condenses/evaporates per unit time within respectively the evaporation zone and the dehumidifying zone.

B. Evaporation function

In the literature some equations for the calculation of evaporation rate have been proposed, see [5]. In this paper a new function $\psi(T)$ for the evaporation rate is proposed, see Fig. 6: $\psi(T)$ gives, as a function of temperature T expressed

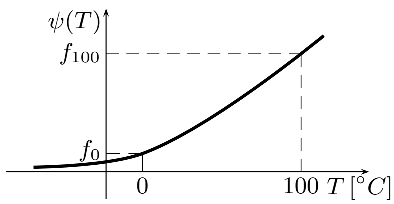


Fig. 6. Shape of the evaporation function.

in Celsius degrees, the rate of water for unit surface that evaporates in dry air at ambient pressure:

$$\psi(T) = f_0\, e^{h\,T}, \qquad h = \frac{1}{100} \ln\left(\frac{f_{100}}{f_0}\right).$$

The parameters f_0 and f_{100} represent the rate of water evaporation at temperatures 0°C and 100°C respectively.

C. Evaporation zone and dehumidifying zone

The dynamic model of water evaporation within the evaporation zone is described by the block scheme of Fig. 7. The symbol m_{w0} indicates the initial amount of water in

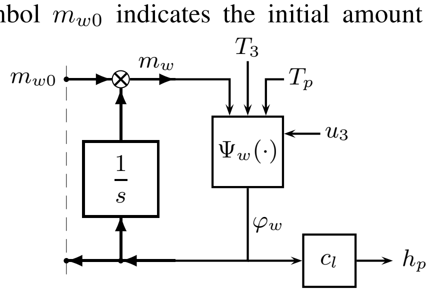
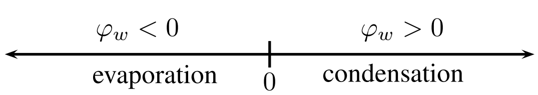


Fig. 7. Dynamic model of water evaporation within the evaporation zone.

the substance. Variable φ_w represents the rate of condensing (evaporating) water within the evaporation zone. The following convention will be assumed:



When the flow φ_w is positive, $\varphi_w > 0$, there is *condensation of vapor* from air to the substance, while when φ_w is negative, $\varphi_w < 0$, there is *water evaporation* from the substance to the air. The specific humidity u_3 in the evaporation zone is defined as $u_3 = \frac{m_{3v}}{m_{3a}}$. The specific humidity u_3 must be always positive and lower than the specific humidity at saturation $u_{sat}(T_3)$ corresponding to temperature T_3:

$$0 \le u_3 \le u_{sat}(T_3).$$

The function $\Psi_w(\cdot)$ in Fig. 7 describes the rate φ_w of water evaporating or condensing in the evaporation zone and is expressed as: $\varphi_w = \Psi_w(T_3, T_p, u_3, m_w, s_w)$, where m_w is the mass of water within the substance, T_3 is the temperature of the air in the evaporation zone, T_p is the temperature of the substance and u_3 is the specific humidity in the evaporation zone. The coefficient s_w indicates the water surface for unit mass and takes into consideration the distribution of water within the wet substance. The explicit form of function Ψ_w is omitted for confidentiality reason.

The condition $\varphi_w = 0$ corresponding to absence of evaporation/condensation arises when there is no water in the substance ($m_w = 0$) or when humidity u_3 is equal to a particular value u_{3eq}. If the temperature of the substance is equal to the temperature of the air in the evaporation zone ($T_p = T_3$) then the condition of no evaporation/condensation arises for $u_3 = u_{sat}(T_3)$ that is when the humidity in the air is equal to the humidity at saturation at temperature $T_3 = T_p$. The dynamic model of the condensation of water within the dehumidifying zone is reserved and cannot be given in detail.

VI. Simulation

The proposed model of the drying system with recuperation of the condensate has been implemented in Matlab-Simulink. The parameters of the model have been identified on the basis of the experimental data collected on six tests with different loads of wet substances. The simulation results shown in this section are compared with experimental data. Both simulation results and experimental data are normalized for confidentiality reasons. The flux entering the dehumidifying zone to help the condensation is constant and at constant temperature. The input given to the model is the measured input power given to the real system, which has an hysteresis controller on the heater temperature. The simulation results are shown in the following figures where all the plots are normalized and the duration of the simulated cycle is normalized to 1. The experimental data are in black line, while simulation results are in color line. Fig. 8 shows the input power and the temperatures T_r and T_R of the electrical resistances in the heating zone. Fig. 9

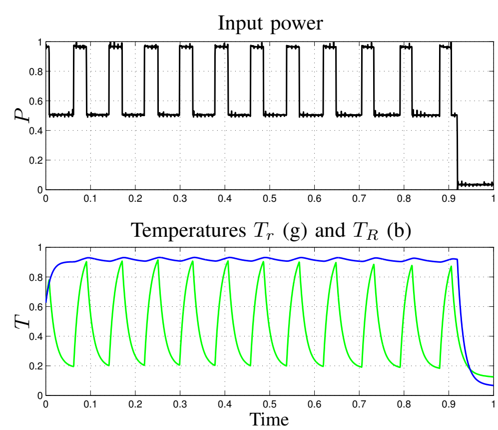


Fig. 8. Input power and temperatures T_r and T_R.

shows the temperature T_2 (air in the heating zone) compared with temperature measured by thermo-couple $TC16$ and the simulated temperature T_{NTC} compared with the measured temperature of the NTC present in the heating zone. Fig. 10 shows temperatures T_3 (air in the evaporation zone) and T_0 (air in the dehumidifying zone) compared with temperature measured by $TC14$ located at the exit of the dehumidifying zone. Fig. 11 shows temperature T_g (flux in the dehumidifying zone) compared with the temperature of the drained water measured by $TC3$ and the temperature of the substance T_p compared with the mean temperature measured by sensors

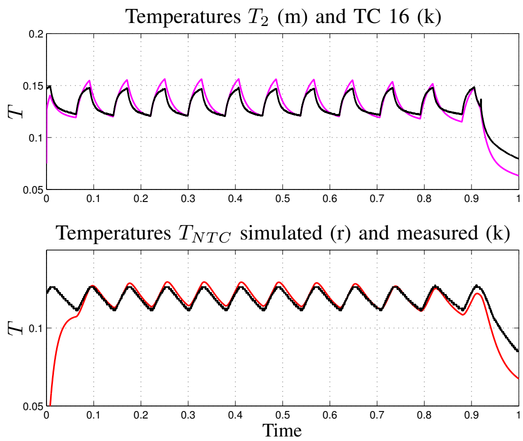


Fig. 9. Top: T_2 (m) and $TC16$ (k). Bottom: T_{NTC} (r) and T_{NTC} (k).

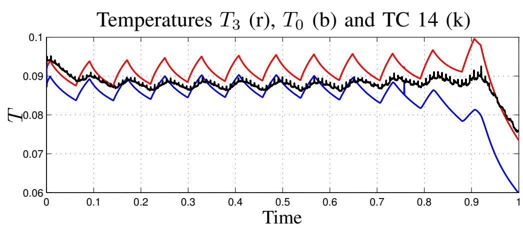


Fig. 10. Temperatures T_3 (r), T_0 (b) and $TC14$ (k).

put within the wet substance. Fig. 12 shows temperature

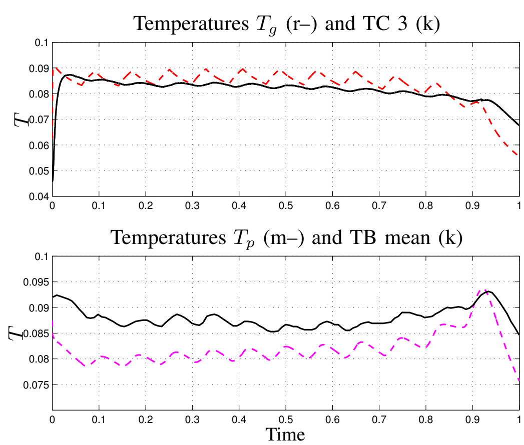


Fig. 11. Top: T_g (r–) and $TC3$ (k). Bottom: T_p (m–) and mean TB (k).

T_a (internal air space) compared with temperature measured by $TC7$ (over the tank) and $TC8$ (under the tank) and temperature T_b (door) compared with temperature measured by $TC20$ and $TC21$ respectively on the internal and external side of the door. In the top part of Fig. 13 the mass of water in the wet substance is shown together with the measured weight of the load (minus the weight of the substance). In the bottom of Fig. 13 the evaporation flux is shown together with the derivative of the weight of the load.

VII. Conclusion

The modeling approach based on the Power-Oriented Graphs technique has been applied to a closed loop drying

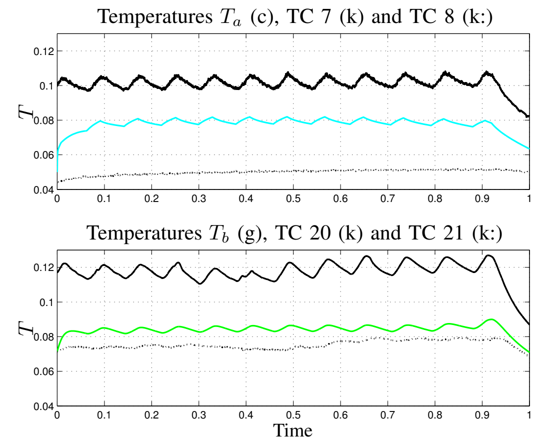


Fig. 12. Top: T_a (c), $TC7$ (k) and $TC8$ (k:). Bottom: T_b (g), $TC20$ (k) and $TC21$ (k:).

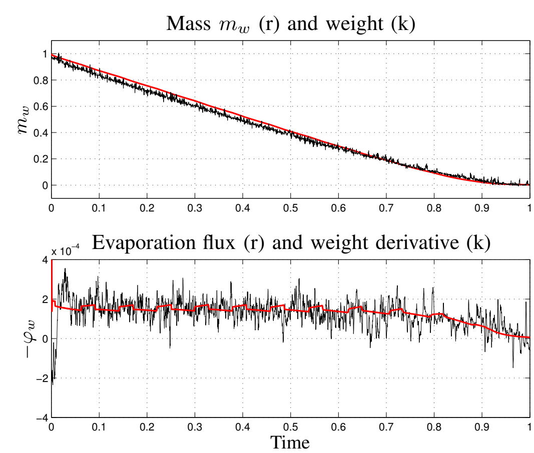


Fig. 13. Top: mass m_w (r) and weight (k). Bottom: evaporation flux (r) and derivative of the weight (k).

system with recuperation of the condensate. The model parameters have been identified using data collected on a real prototype. The simulation results show the effectiveness of the realized model which can be used for both analysis and control purposes.

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