

DEHYDRATION: COUPLING CENTRIFUGE DRAINAGE WITH MICROWAVE DRYING OPERATION

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ABSTRACT

In solid-liquid separation, the centrifugal drainage operation is an efficient and economic process for particulate suspensions which found main applications in the pharmaceutical, chemical and textile industries. It is often used before a thermal drying, and its interest relies on the elimination of most of the liquid at low energetic cost. Nevertheless, in many cases, the combination of mechanical and thermal operations in the same machine enables to optimize productivity, energy efficiency and safety aspects and to reduce cleaning fluids volumes and handling operations requirements.

Microwave drying appears to be the most adapted technology to dry thick cakes in a centrifuge as basket rotation allows homogenizing electromagnetic fields leading to homogeneous heating. The heating is more efficient when the filtration cake is saturated but this process is expensive, so it is more interesting to mechanically dewater the cake and assist the process with microwave drying. Microwave heating should be brought in when mechanical dewatering sharply slows.

The objective of this study is the optimization of coupling processes between mechanical dewatering and thermal drying by microwave. To reach this objective the development of a model with complete description of cake desaturation during centrifuge cycles is necessary, to implement thermal energy in order to assist the mechanical operation.

To demonstrate the interest of the coupling process and the validity of the model, an instrumented pilot was developed and the first experiments were performed with model suspensions (talc, PVC) and industrial products (textile spool, Spath, etc.). Experimental results yielded to drainage curves during centrifuge cycle for these different products in various experimental conditions. The use of mathematical model allowed comparing experimental drainage curves with model predictions.

The adaptation of microwaves set up in the centrifuge pilot will also be discussed.

The project perspectives are to optimize energy consumption in the mechanical/thermal dehydration, to demonstrate that from one hand, the coupled process can be more efficient than conventional drying regarding energy consumption at the lab scale, and from the other hand, to demonstrate the interest of such a coupling at industrial scale.

KEYWORDS

Dewatering, Mechanical thermal treatment, Microwave Drying, Energy efficiency

1 INTRODUCTION

In solid-liquid separation, the centrifugal drainage operation is an efficient and economic process for particulate suspensions which found main applications in the pharmaceutical, chemical and textile industry. It is often used before a thermal drying, and its interest relies on the elimination of most of the liquid at low energetic cost. Nevertheless, the combination of mechanical and thermal operations in the same machine is a way to optimize productivity, energy efficiency and safety aspects and to reduce cleaning fluids volumes and handling operations requirements.

Reducing energy consumption through combination of mechanical and other technique (thermal: Couturier [1], ultrasound and electrical effects: Wakeman and Tarleton [2], Tarleton [3]) has given interesting perspectives. The question that arises then is how to assist the mechanical process with the additional technique in order to reach low moisture content at low energy cost. As an example, in the case of filtration as mechanical process assisted with thermal heating, Couturier [1] has shown that mechanical and thermal interactions could lead to unusual effects (cake collapse) accompanied by significant cake moisture content reduction.

In this study, focus is brought into centrifugal filtration assisted with thermal drying.

Microwave drying appears to be the most adapted technology to dry thick cakes in a centrifuge because heat is generated deeply in the material. Moreover, basket rotation allows a good distribution of electromagnetic field leading to homogeneous heating. However, the efficiency of this technology depends on the dielectric properties of the materials involved (liquid and solids) in the separation and does not apply to all cases; therefore microwave drying is effective with dielectric materials.

If solids are transparent to microwaves, conversion of radiant energy into heat is more efficient when the filtration cake is saturated (at the beginning of cake drainage). In order to assist cake dewatering under the action of centrifugal effect, it should be determined how and when heat must be supplied to the system. For this, complete description of cake desaturation during the mechanical process is needed for evaluating optimal conditions for mechanical/thermal coupling.

Accurate description of centrifuge drainage kinetics requires complete models relying on determination of several parameters. Parameters determination is not simple (specifically in a rotating machine) and most of the time is obtained through correlations whose validity is questionable.

The paper discusses about the modification of a pilot centrifuge coupling filtration and microwave drying. The setup was specifically designed to supply microwaves during cake drainage and to determine the empirical parameters related to centrifuge drainage and cake drying.

In this study, centrifugal drainage model is succinctly presented. Theoretical results are compared to experimental data. Liquid pressure distribution in the cake during cake drainage is analyzed and consequences on coupling mechanical and thermal process are given.

Finally, the pilot as it will be in the near future is presented. Details on the setup and specific instrumentation are provided.

2 CENTRIFUGE DRAINAGE MODEL

Centrifugal drainage involves two-phase flow in a porous medium. Different models have been developed to describe cake drainage. On one hand, more sophisticated models are likely to yield the most accurate results. However, those models rely on several parameters requiring experimental determination and in a rotating machine, measurements of physical quantities are difficult. On the other hand, simple models require few input parameters but provide poor description of physical phenomena. Nenniger and Storrow [4] and Shirato et al. [5] developed simplified models to describe cake drainage. The principal advantages of these models are the reduced number of basic parameters. However, accuracy of results is questionable.

Some of sophisticated models rely on description of two-phase flow in the cake by Generalized Darcy's equation: Wakeman and Vince [6], Léger et al [7] and Fournet [8]. Generalized Darcy's equation differs from Darcy's equation because local permeability of each fluid phase is related to local saturation. The dependence of liquid permeability with saturation is taken into account through relative permeability (k_{rl}) whereas capillary effects are introduced through drainage capillary pressure (p_c) curve which links the pressure difference between both fluid phases to local saturation (S_l).

Some simplifications may be introduced for centrifugal drainage:

- Gas mobility is assumed to be large compared to the liquid mobility so gas phase is essentially passive.
- Cake is supposed non compressible, in other words cake is considered as homogeneous porous media (constant porosity (ϵ) and constant permeability (k)).
- Basket angular velocity (ω) is constant during drainage,
- Gravity effects are considered negligible in comparison with centrifugal effects,
- Coriolis force is negligible as compared to centrifugal force.

Fundamentals equations of the model are generalized Darcy's equation and mass balance for liquid phase. Constitutive equations relating liquid relative permeability and capillary pressure to liquid saturations have to be added. The relation between capillary pressure (gas pressure minus liquid pressure) and liquid saturation allows expressing the model as a function of saturation or liquid pressure.

The corresponding formulation of the problem will be termed hereafter as the saturation or pressure formulation. Wakeman and Vince [6] used liquid saturation as privileged variable. However, Léger et al. [7] have shown that this formulation is inappropriate to describe liquid flow in the saturated zone.

In the saturated zone ($S_l=1$), liquid relative permeability equals unity but capillary pressure is no longer defined (except at the saturation front). If the capillary pressure-liquid saturation relationship is nonetheless used to calculate liquid pressure gradient, the result obtained is zero everywhere in the saturated zone except at the saturation front which conducts to eliminate effect of liquid pressure in Darcy's equation. It follows an overestimate of liquid flow rate in the saturated zone. Thus, the saturated zone tends to disappear extremely rapidly in a non-physical manner. An alternative to liquid saturation formulation is liquid pressure formulation.

The set of equations describing centrifugal drainage corresponding to liquid saturation formulation were proposed by Léger et al. [7].

3 EXPERIMENTAL DETERMINATION OF MODEL INPUT PARAMETERS

Some experiments have been conducted in order to validate the model. One of the difficulties is that the model requires several input parameters (Table 1). Some of these parameters describe cake and filter medium properties (porosity, permeability and filter medium hydraulic resistance). Others are related to capillary effects which depend on porous matrix structure and gas/liquid properties (breakthrough pressure, pore-size distribution index and irreducible saturation). These capillary parameters were introduced by Brooks and Corey [9] to mathematically represent the capillary pressure vs saturation relationship. Most of experimental studies on centrifuge drainage estimate cake and capillary parameters with adapted experimental setup (filtration cell, compression permeability cell...) on a cake formed in similar conditions to those in the centrifuge, Borel [10]. However, as the mechanical stress exerted on matrix structure varies with radial position in a rotating machine, it is difficult to form in a static setup a cake presenting equivalent properties. In this study, it is shown that from experimental data (filtration and drainage) obtained with a pilot centrifuge it is possible to determine the set of input parameters (Table 1).

Input Parameter	Notation
ϵ	Cake porosity (-)
$E=rb-rc$	Cake thickness (m)
R_m	Filter medium hydraulic resistance (m^{-1})
k	Cake permeability (m^2)
p_b	Breakthrough pressure (Pa)
λ	Pore-size distribution index (-)
S_∞	Irreducible saturation (-)

Table 1: Input parameters of the model.

The pilot centrifuge used in this study is presented in figure 1.

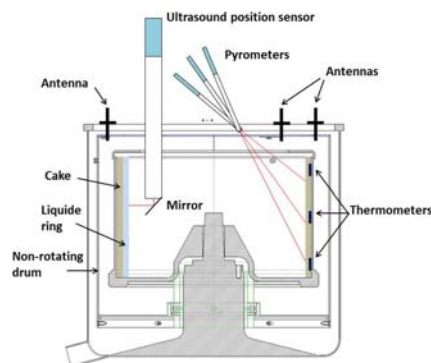


Figure 1 : Pilot centrifuge with sensors and non-rotating drum.

In the following sections, the different methods to determine model input parameters from experimental data are presented.

3.1 CAKE AND FILTER MEDIA PROPERTIES

One of the major problems encountered in estimating model input parameters is to measure accurately instantaneous filtrate mass. Accurate mass balance is indeed necessary for most parameters estimation. The difficulty comes from the fact that liquid mass recovered at the outlet of the centrifuge doesn't correspond to the filtrate mass produced. During filtration and drainage, an important volume of liquid (up to 1l) flowing out the basket is accumulated in the

centrifuge. Thus mass recovered at the outlet differs significantly from filtrate mass produced. To overcome this problem, a double weighing system has been installed to measure firstly the outgoing mass of liquid from the basket and secondly the mass of liquid at the outlet of the centrifuge. A non-rotating drum suspended to a balance and vertically guided was used to temporarily collect filtrate. Mechanical adjustment of the drum in the centrifuge was very tidily realized in order to reduce friction as much as possible. Accumulated filtrate in the drum is allowed to flow in a weighed vessel out of the centrifuge. The sum of the two mass values gives the filtrate mass with good accuracy. From filtrate mass data, volume flow rate might be determined. If, moreover, the input flow rate is known, the filling rate of the basket may be obtained from simple mass balance. Solids distribution in the basket (i.e. cake and liquid ring thicknesses) may then be calculated providing cake porosity is known and sedimentation in the liquid ring is negligible. Then, making use of Darcy's equation, determination of cake permeability and filter media hydraulic resistance is straightforward.

3.2 CAPILLARY PARAMETERS

3.2.1 BREAKTHROUGH PRESSURE

The pressure required for initial gas penetration or "breakthrough" pressure is reachable through the filtrate flow rate reduction when gas starts entering cake's pore space as noted by Nenniger and Storrow [4]. At this moment, capillary phenomena cause a drop in liquid pressure value by breakthrough pressure. Thus, filtrate flow rate drops abruptly and the variation is directly related to breakthrough pressure through Darcy's law. If cake average saturation is plotted versus time, breakthrough pressure determines the initial slope of the curve (see Figure 3b).

3.2.2 PORE-SIZE DISTRIBUTION INDEX AND IRREDUCIBLE SATURATION

The pore-size distribution index provides a quantitative description of the range of pore sizes present in a porous medium. An infinite value of pore-size distribution index corresponds to a uniform pore size whereas a zero value corresponds to an infinitely large pore-size distribution. It is to note that the size of the largest pores is fixed by the value of breakthrough pressure. Brooks and Corey [9] found that typical porous media have values of pore-size distribution index of about 2. However, for naturally occurring sand deposits the pore-size distribution index value is about 5 or 6. In Brooks and Corey's model, pore-size distribution index is introduced in the liquid relative permeability/saturation relationship. Thus pore-size distribution index influences strongly the kinetics of drainage. In order to fit experimental data (average cake saturation vs time see figure 3b) pore-size distribution index is adjusted using adapted optimization techniques.

Irreducible saturation may be defined as the value of saturation at which capillary pressure increases sharply with negligible decrease in saturation.

If cake drainage is continued long enough to reach a liquid distribution close to equilibrium, pore-size distribution index and irreducible saturation may be deduced from cake's average saturation. From Brooks and Corey's model, it may be shown that liquid distribution in the cake at equilibrium is fully determined by breakthrough pressure, pore-size distribution index and irreducible saturation. Figure 2 shows equilibrium saturation profiles for different values of pore-size distribution index (a) and irreducible saturation (b).

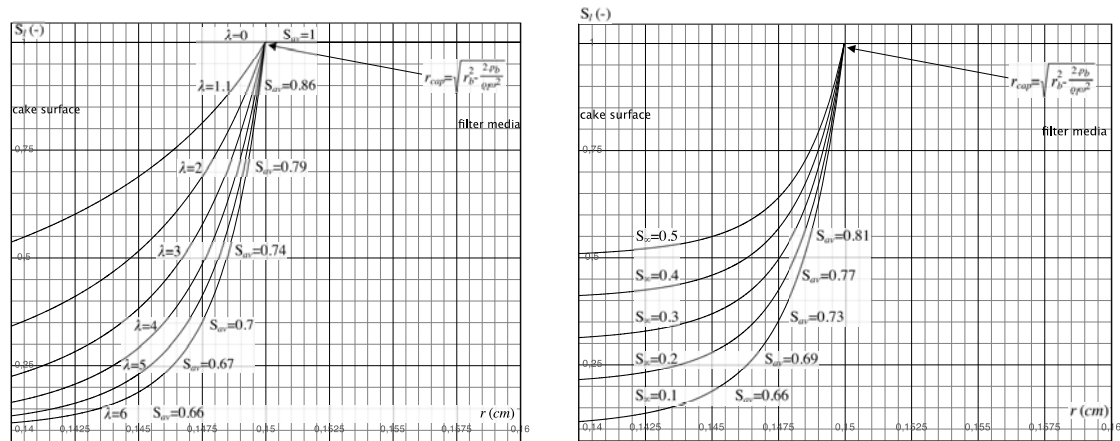


Figure 2: Liquid distribution in the cake as a function of capillary parameters: Influence of
 a) Pore size distribution index and
 b) Irreducible saturation on fluid distribution in the cake at equilibrium

It is thus observed that both parameters have an important effect on final cake saturation. As pore-size distribution index is determined from drainage data, irreducible saturation is obtained from final average cake saturation.

4 MATERIALS AND METHOD

Experiments were performed with a 320 mm diameter pilot centrifuge (Robatel). Suspensions used were prepared from Talc powder (Luzenac, France) and tap water. Average particle diameter was evaluated at 11.6 μm with a particulate density of 2707 kg/m^3 . Suspensions concentration ranged from 47 to 250 g/l. Fresh suspensions were prepared prior to each experiment.

Input mass flow rates were measured with a Coriolis flow meter. Cake thickness profiles were measured with a laser sensor for different angular position in the basket. Cake volume were then determined and cake porosity calculated (knowing solids density). Cake water content was determined gravimetrically from measurements performed on several different samples. Cake final saturation was then calculated.

5 EXPERIMENTAL RESULTS

Results of five different experiments are presented referred hereafter to as EXP1 to EXP5. Operating conditions, suspension solids volume fraction as well as cake and filter media properties are summarized in Table 2.

Exp.	ω (rad/s)	Q (Kg/h)	f_{vs} (-)	E (mm)	k (m^2)	ϵ (-)	R_m (m^{-1})
EXP1	422	228	8.4E-2	11.5	9.0E-16	0.50	5.0E11
EXP2	424	209	8.4E-2	11.5	7.5E-16	0.49	5.0E11
EXP3	416	229	1.7E-2	6.0	1.8E-15	0.53	6.5E11
EXP4	418	215	8.4E-2	16.0	9.0E-16	0.46	6.0E11
EXP5	420/369	208	8.4E-2	10.8	6.0E-16	0.49	4.0E11

Table 2: Operating conditions and properties of suspension, cake and filter media.

EXP1 and EXP2 were performed in similar conditions. Drainage of EXP3 was performed with a thinner cake than for EXP1 and EXP2 whereas cake for EXP4 was thicker. Drainage for EXP5 was performed at significantly lower centrifugal effect.

Evolution of the sum of cake and liquid annular ring thicknesses (r_b-r_l) could be measured by two methods. First method consists in direct measurement of inner liquid surface position in the bowl. The second method is based on mass balance equation (mass conservation in the bowl). Data obtained for EXP1 and EXP2 are plotted in figure 3 a). Clearly, the two methods lead to very similar results. This shows that double weighing method for determining filtrate mass is accurate and will be useful to obtain cake saturation during drainage.

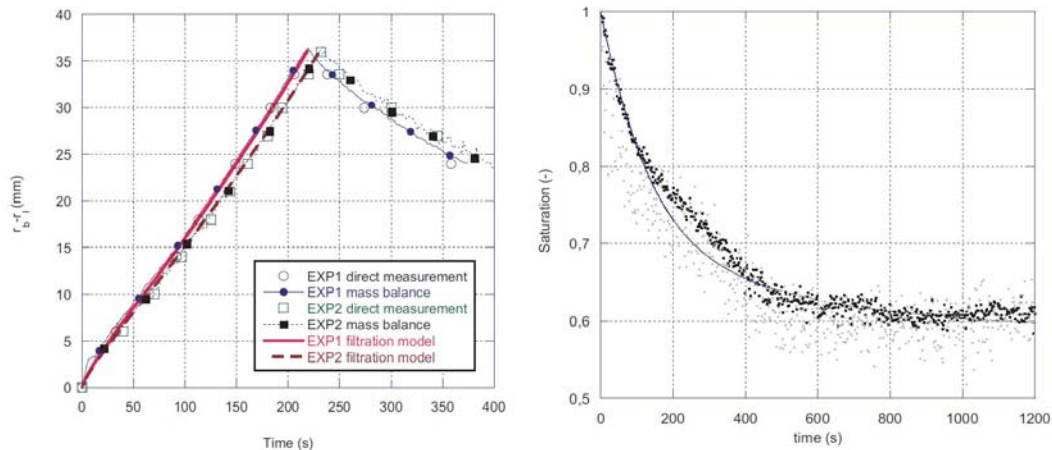


Figure 3: a) Comparison of r_b-r_l as function of time obtained by direct measurement and mass balance,
 b) Experimental desaturation curves-comparison with numerical result (EXP1 and EXP2).

Desaturation curves for these two experiments are shown on figure 3b. It is seen that both curves have the same trend and despite higher dispersion of saturation points for EXP2, results are consistent.

Capillary parameters for EXP1 to EXP5 are reported in Table 3. Comparison between model and experimental data show good agreement.

Exp.	λ (-)	p_b (Pa)	S_∞ (-)	$r_b - r_{cap}$ (mm)
EXP1	6	1.4E5	0.04	5.0
EXP2	6	1.4E5	0.04	4.9
EXP3	7	1.0E5	0.04	3.7
EXP4	6	1.6E5	0.04	5.8
EXP5	6	1.5E5	0.04	7.0

Table 3: Cakes capillary parameters for EXP1 to EXP5.

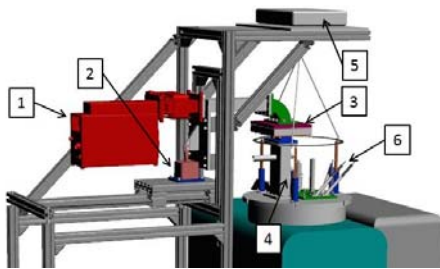
Moreover, all the capillary parameters obtained for Talc cakes are consistent. Breakthrough pressures and pore size distribution index evaluated for the different experiments are close (Table 3).

Numerical results obtained with the set of input parameters experimentally determined provide liquid distribution in the cake as a function of time as well as liquid pressure. These results provide better understanding of centrifuge drainage and are useful to design a hybrid process coupling mechanical dewatering by centrifugation and micro-wave drying.

6 MECHANICAL/THERMAL MW EXPERIMENTAL SETUP

6.1 SETUP MODIFICATIONS FOR MW DRYING

The pilot which is under development is presented in figure 4. A micro-wave generator is coupled to the pilot centrifuge. The micro-wave generator frequency and power are respectively 2.45GHz and 1.2kW. In a first version of the pilot, micro-wave generator was mounted directly on the machine's cover. Experiments conducted with the initial version of the pilot (Léger, 2008) have shown that vibration level, particularly during filtration, was too high and could lead to damage to magnetron's filament. However, study of the coupling between mechanical and thermal effects imposed to operate centrifugal and electromagnetic fields simultaneously.



- 1: micro-wave generator
- 2: air cylinder
- 3: quarterwave length trap
- 4: impedance tuner
- 5: balance
- 6: IR pyrometer

Figure 4: Contactless coupling system between magnetron head and pilot centrifuge.

The solution found to circumvent this problem was to design a wave guide divided into two segments without mechanical contacts between the two elements. To avoid leakage radiation, a specific quarterwave length trap has been designed (Figure 4). Details of the wave trap are given in figure 5.

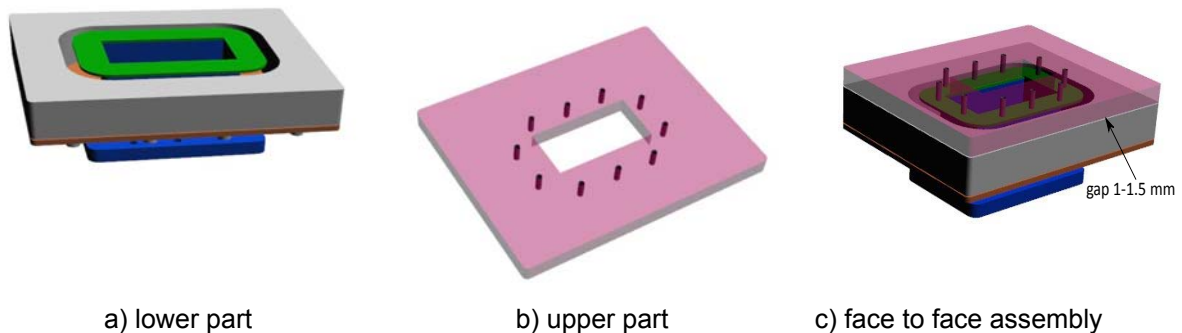


Figure 5: Details of the "contactless" wave trap.

Careful measurement of electromagnetic field has shown that the setup was very efficient for separation distances between lower and upper part up to 1.5 mm (figure 5). Thus, in this new configuration microwave setup can be maintained in position during the whole separation. This point is particularly important because the goal of the project is to evaluate the energy efficiency of the coupling between mechanical (centrifugation) and thermal (microwave) effects.

During drying, a mismatched load can induce important reflected power. To control the reflected power, an impedance tuner was also included in the wave guide (figure 6).

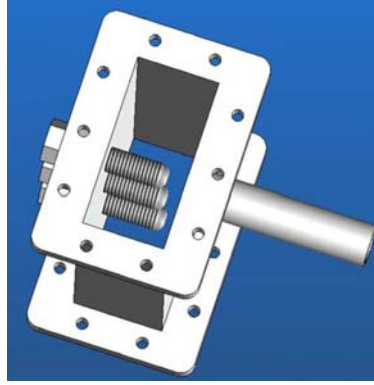


Figure 6: impedance tuner and view of the three stubs controllable in position.

Measurement of several parameters is needed to follow evolution of dehydration during the process. However, due to the electromagnetic field, sensors measuring physical quantities inside the centrifuge have to be deported at the end of electrical conductor tubes in order to avoid electromagnetic perturbations. Figure 4 shows the position of infrared pyrometers on the cover of the centrifuge. These sensors record surface cake temperature during drying. Liquid ring position during filtration and cake thickness during cake drainage and drying are measured with an ultrasonic position sensor.

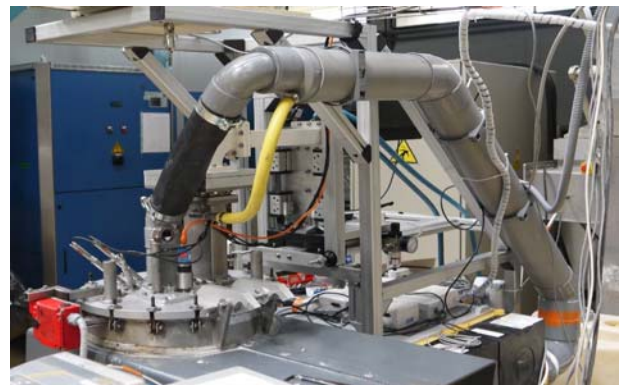
Three antennas are also positioned on the cover of the centrifuge to measure electrical field in the body of the machine.

6.2 VAPOR EXTRACTION

Special care to vapor extraction is needed to optimize drying conditions. Intense heat produced in the cake by microwaves creates an important amount of vapor. Vapor transfer from cake to air is promoted by difference in vapor pressure between air and cake surface. Thus, maintaining low moisture content in the centrifuge is necessary to reach high drying rates. Basket rotation induces an air flow from the open part of the cover to the bottom outlet. However, first experiments have shown massive condensation on the centrifuge walls. This shows that this "natural" flow is insufficient to reduce air moisture during MW drying. To improve vapor extraction, a mechanical ventilation system equipped with a heat exchanger as been added to the system. Exhaust air passes through the heat exchanger to heat the fresh air injected in the centrifuge. Details of the setup are shown in figure 7.



a) view of extraction duct



b) view of injection line

Figure 7: system of vapor extraction.

Hot wire anemometers and thermo hygrometers are positioned in the flow to determine exhaust and input flow properties (flow rate, enthalpies).

6.3 AIR FLOW IN THE MACHINE

Numerical simulations of air flow in the centrifuge have been also performed. An example of result is shown in figure 8. As expected, high velocities (in red) are located in the vicinity of basket wall. Figure 8c shows that position of air inlet allows a sweep of basket volume even though a layer of air seems to be linked to the basket. Numerical simulation was performed for a basket rotational speed of 1500 rev/min. This phenomenon should be exacerbated at higher rotational speeds.

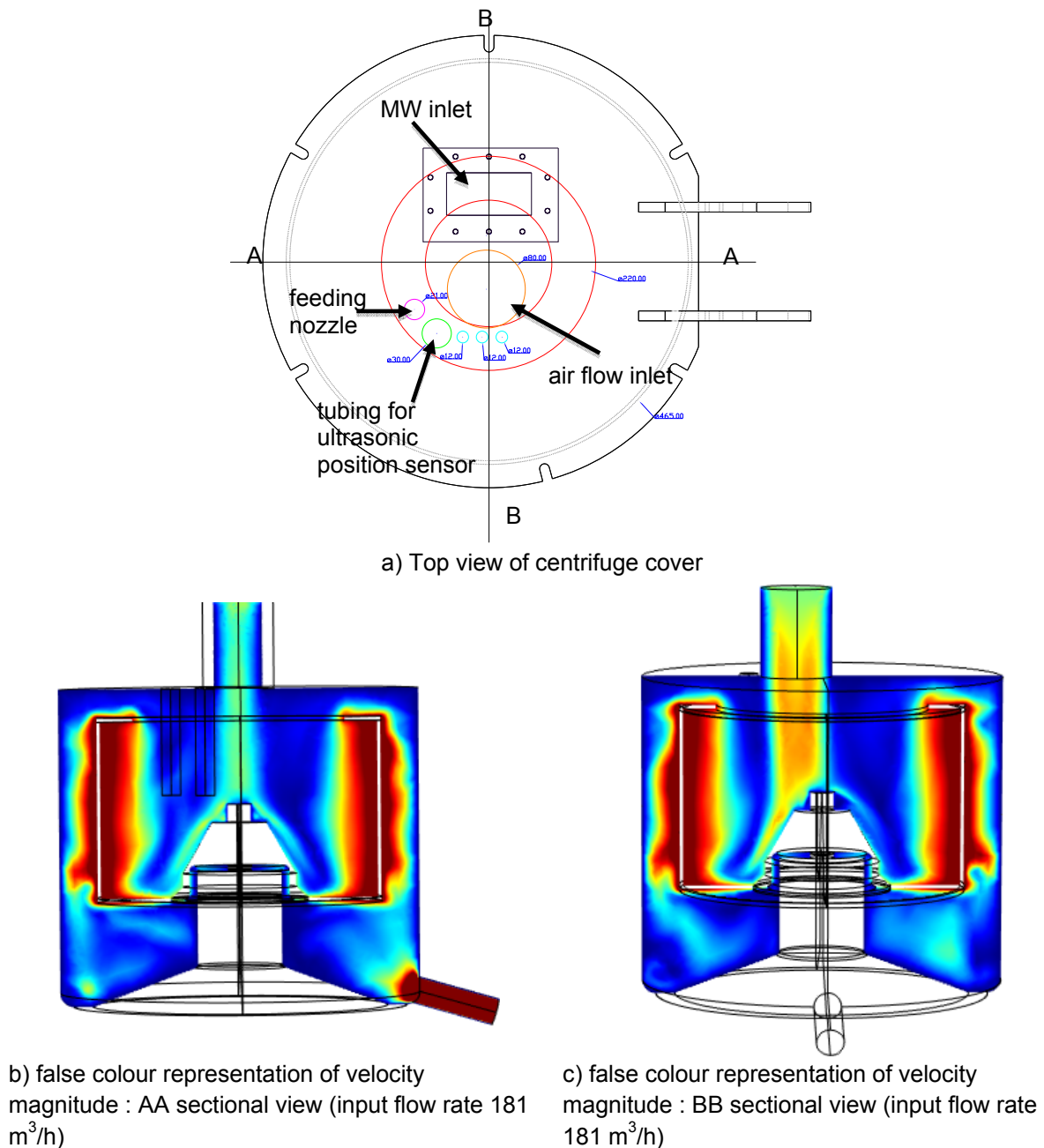


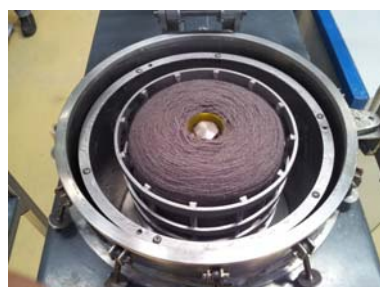
Figure 8: numerical simulation of air flow in the machine.

6.4 ADAPTATION TO TEXTILE PRODUCTS

For microwave drying, conversion of radiant energy into heat is strongly dependent on material dielectric properties. For this, different real materials as opposed to model materials have been selected. Among those reel of woolen thread (figure 9a) have been chosen because industrial process for this product involves both centrifugation and high frequency drying. Modifications of the basket design had to be realized in order to maintain the reel and to avoid wave reflections. View of the basket is shown in figure 9b.



a) reel of woollen thread



b) view of the basket used with reels

Figure 9: pilot configuration to treat reel of woolen thread.

7 FIRST EXPERIMENTS

7.1 EVOLUTION OF REFLECTIVE POWER

The first experiments have been performed with talc suspensions whereas impedance tuner was not mounted in the circuit. Talc cakes have been dried in same conditions (centrifuge ran at moderate rotational speed) to evaluate performances of the system. In these conditions (no impedance tuner) reflected power measured by the MW generator is an important parameter because it traduces evolution of drying. As cake water content decreases, amount of radiant energy absorbed by the product decreases and reflected power should follow a monotonic increase during drying. Figure 10 shows evolution of reflected power for three different cases.

In case1 (figure 10), while incident power is maintained constant at 1.2 kW, reflected power shows important variation with a non-monotonic trend. This peculiar behavior has been attributed to condensation of water on the protection sheet in teflon disposed in the wave guide to prevent access of water drops, dust or particles to the MW generator.

In case2 (figure 10), an air flow downstream the teflon sheet was imposed to avoid water condensation. Reflected power behavior shows less oscillations even though the curve is not strictly increasing. It is important to note that reflected power level, even at beginning of drying is high (greater than 300 W). This is caused by a mismatched load. This power is dissipated in a water load to protect the MW generator. Thus, reflected power corresponds to energy consumed but not used to heat the product. This is why it is crucial to reduce reflected power to reach high energy efficiency.

In case3 (figure 10), impedance tuner has been positioned in the wave guide and adjusted to the initial load. Chaotic variations of the curve correspond to manual adjustment of the

impedance tuner due to the evolution of the load (drying). With the impedance tuner it is thus possible, in most cases, to maintain reflected power at a low level (typically less than 100 W).

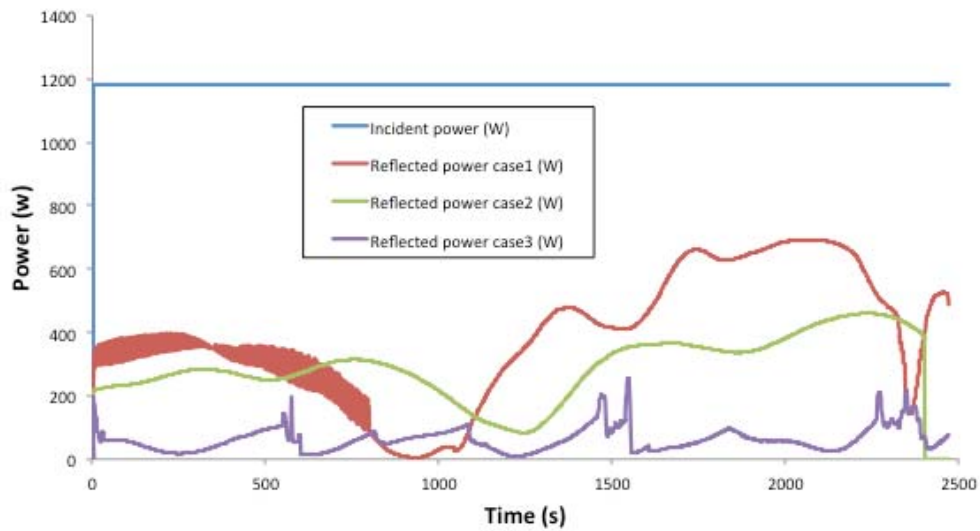


Figure 10: Examples of evolution of reflected power during cake drying.

7.2 EFFICIENCY OF VAPOR EXTRACTION

As mentioned previously, vapor extraction is necessary to insure high drying rates. Relative humidity of exhaust air is a good indicator of vapor removal in the centrifuge.

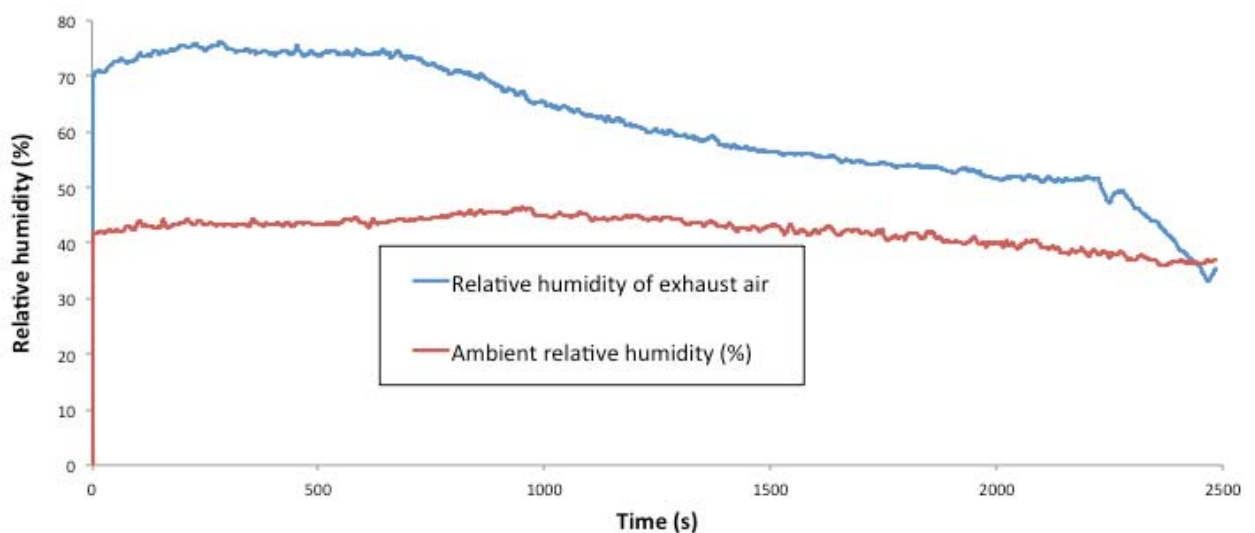


Figure 11: Example of evolution of relative humidity of exhaust air during MW drying.

Figure 11 shows exhaust air relative humidity as a function of drying time. The high level of relative humidity during drying proves that air flow rate is not sufficient. This aspect should be improved in the near future.

7.3 SURFACE CAKE TEMPERATURES

The three pyrometers positioned on the cover of the centrifuge record surface cake temperature at three different heights (figure 4). Figure 12 shows temperatures curves as a function of time. The similarity between the evolutions shows cake is heated homogeneously. This aspect is important, because apparition of hot spots could yield to thermal runaway phenomenon.

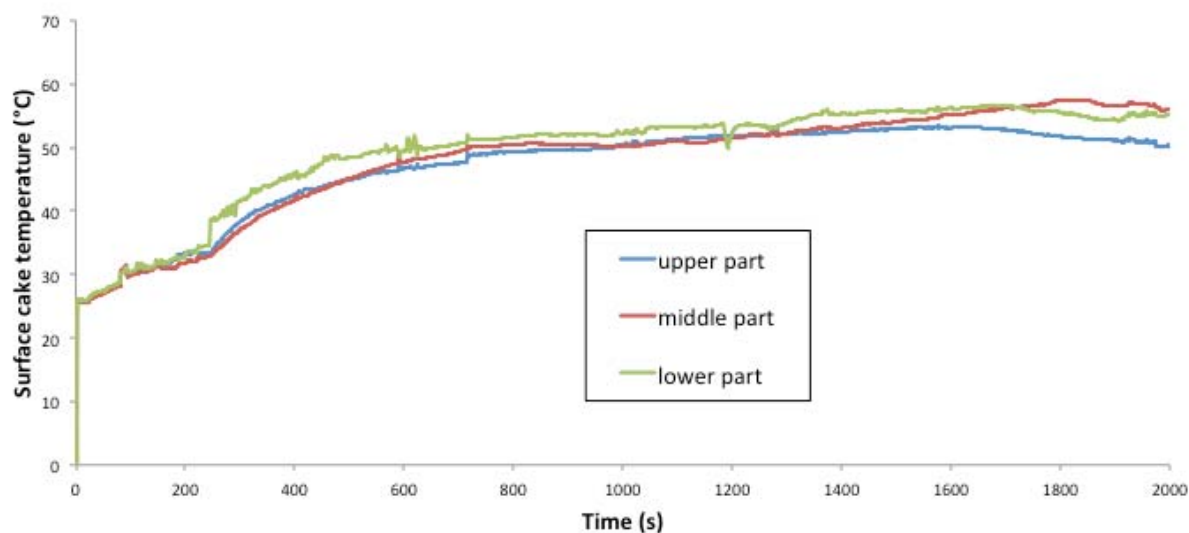


Figure 12: Evolution of surface cake temperature during drying.

8 CONCLUSIONS

The development of a hybrid process involving centrifugal drainage and micro-wave drying requires a good knowledge of physical mechanisms of drainage. Use of generalized Darcy's model for centrifugal drainage has been revisited. Moreover, it is shown that it is possible to determine (or estimate) from experimental data (filtration and drainage) the set of input parameters.

A pilot combining centrifugal filtration/drainage and micro-wave drying has been developed. Instrumentation of the pilot and accurate measurements of power consumption will allow evaluating the synergetic effects of centrifugal force and heat transfer by micro-waves. Pilot design has been validated. Experimental work is ongoing. Evaluation of process performances will be available soon.

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