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EXECUTIVE SUMMARY OF THE THESIS

Efficient dynamic modeling of tumble dryer drums

LAUREA MAGISTRALE IN COMPUTER SCIENCE AND ENGINEERING - INGEGNERIA INFORMATICA

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1. Introduction

Drying processes appear in numerous domains, both industrial and civil, and among the said domains, a particularly relevant one is that of *fabric* drying.
Fabric dryers are present in various forms, from large units designed for laundries and textile processes in general, down to small household appliances for everyday use. Along the years, their technology has evolved a lot and in several directions, see e.g. [1, 2, 5]. Nevertheless, the energy consumption of dryers can still be relevant, as noted e.g. in [6] for the residential use case. As such, an energy efficient design and management is important, and in this design control plays a relevant role.
To design dryer controls, simulation models are necessary that allow for efficient system-level studies. Moreover, the phenomena inside a dryer are complex, and as the typical household device cannot afford the instrumentation that would be necessary for an accurate tracking of their evolution, "proxy" measurements for important quantities (most notably the remaining water content in the fabric being dried) have to be used. As such, the requirements for a dryer model for system-level control design (as opposite e.g. to a model targeted to detailed component sizing) are quite peculiar and essentially two, namely (i) a high computational efficiency to allow for simulation-based optimization, and (ii) the capability of representing operation-to-operation variability with as few parameters as possible. exposing to the analysis a credible representation of the quantities that could actually be measured in a commercial device.
This work aims for providing a contribution to efficient dryer modeling geared to control design in the sense just sketched, concentrating on the component where the most important phenomena take place — that is, the drum.

2. Context

A clothes tumble dryer is a household appliance, whose purpose is to dry clothes et similia contained in it by using a high-temperature airflow. Wet clothes are stored inside the drum, a rotating cylindrical component: its rotation allows the fabric the dry more uniformly, as water evaporation occurs mostly on surfaces that are in contact with the inlet airflow. Air gets heated up by either a stove, an electric heater or a heat pump, depending on the topology of the dryer, and looses heat through convection while gaining water vapour. It then flows out of the drum, containing a high value of moisture, and, based on the topology of the dryer, it either passes through a condenser, so that is looses most of its vapour, or it flows outside the dryer as it is. The drying cycle ends when the fabric remaining moisture content (RMC) is below a certain threshold. Its duration is very variable, even if the same load conditions are repeately used, due to non-predictable aspects.

3. Contributions

All of the above said, this thesis offers two main contributions. First, the literature models [3, 4, 7–9] for tumble dryer drums – deemed representative within a larger screened set to provide the required coverage – are analyzed as for structure and involved parameters. As a result of this analysis, a proposal is formulated to cast the said models into a unified form. The purpose of this proposal is to allow for straightforward and meaningful comparisons.
Second, the specific topic of the so called "water activity" – that appears in several literature models – is discussed, and an alternative proposal is made for representing the decreasing efficiency of the drying process with a fundamentally geometric approach. The purpose of this proposal is to allow a drum model to represent control-relevant process variability, with as few parameters as possible, so that simulation-based optimization can be (ideally) carried out in a parameter space with the minimum necessary number of dimensions.
Simulation results are reported to assess the proposed unified model form, as well as to show that the above geometric approach, or at least some of its considered variants, can effectively describe the drying process variability in a suitable manner for setting up controls, with particular reference to detecting the end of the drying operation based on measurements available on commercial products. This is a very important point in dryer control, because the energy class of an appliance is determined based on an "energy index" that accounts for the consumed energy in some reference drying operations, and keeping the machine unnecessarily active when the fabric is dried is clearly detrimental — up to a very significant extent nowadays, especially for high-end products and energy classes.
Though the reached results are in fact still preliminary, as explained in the thesis, it appears from the simulations carried out that the proposed ideas are promising. We send a few words on this in the following section.

4. Results

4.1. Unified drum model structure

Though this thesis focuses on the drum and represents the rest of the appliance as prescribed boundary conditions, the results of the study will need converting to a component model with ports to connect to others — a straightforward process that we do not describe, but that was taken into account in defining the proposed model structure.

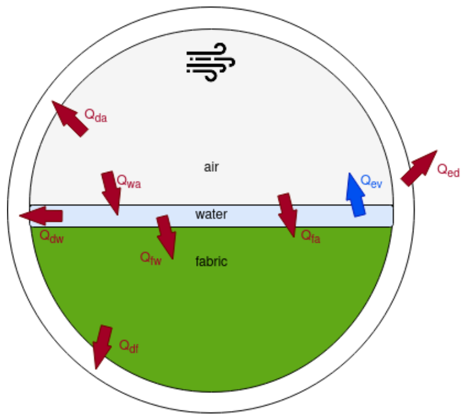

Figure 1: Mass and heat exchanges in a dryer drum.

The said structure (details here omitted are in the thesis) refers to the mass and heat exchanges summarized in Figure 1, and is organized in two sections:

- a "standard" section contains the balance equations (and will host the interface ones in the component version) and defines the mass and heat exchanges according to the identified storages and their interconnections;
- a "specific" section expresses the exchange flows as per the particular model.

The most relevant part of the work consisted in re-formulating the expressions in each model so as to case them in the specific section above — a task more complex than it may seem, since not all the papers in the examined literature introduce a clearly separation between the model and its solution, and not all aim for a drum model to be isolated as a component (i.e., the abstraction of interfaces is not evident). No criticism to previous research is involved here, however we suggest that the adoption of some standard model structure (the proposed one as well as possible improvements or alternatives) would be beneficial for model assessment and comparison.

4.2. Water activity and equivalents

Synthesizing for the scope of this summary, the driving force of drying in a drum is the difference between the absolute humidity of saturated moist air at the temperature of the fabric and the absolute humidity in the drying air flow. To represent the behaviour of water content in the fabric along the drying process, in the literature it is standard practice to multiply the former term in the difference by a variable coefficient termed "water activity".

A large number of correlations are available to compute water activity based on the type and the conditions of the fabric. These are most often obtained by extensive experimental campaigns, and although each of them is supported by results that prove its ability to fit the considered operating conditions, from the specific point of view of the presented research – strongly geared to control and simulation-based optimization, we recall – the underlying approach has some criticalities. Briefly, these reside in the presence of several parameters that are connected to different factors difficult to generalize, in particular the type of fabric, hence for which reliable values can be hard to find. Apparently, both the number of parameters and the said difficulty in giving them a value do not help when models have to be used for optimizations that may involve a huge number of simulation runs.

Without any intention to diminish the validity of the water activity approach, we therefore formulate the alternative ideas to represent the increasing difficulty of extracting water form the fabric as the drying process evolves with geometric considerations. In a nutshell, the idea is that as water diminishes, the surface exposed to evaporation diminishes as well: the coefficient to multiply the saturated air humidity at the fabric temperature, therefore, should me just multiplied by a term coming from some relationship between water mass and evaporating surface.

Such a mass-surface relationship can be devised on the basis of different considerations, in the end related to the type of fabric and the way water can lie on its surface, be trapped in between its fibers, or penetrate the fibers themselves. Our idea is that without attempting a detailed analysis of water position in the fabric – apparently not a good idea if the goal is to obtain efficient models – simplistic geometries can be assumed *a priori* so as to involve a minimal number of parameters. In detail, we examined the alternatives below.

- linear surface area decrease with water mass contained in fabric;
- exponential surface area decrease with water mass contained in fabric;
- exponential surface area decrease with fabric RMC;
- surface area decrease base on the folowing multiplicative factor: $1 - \left(\frac{X_{f_{ini}} - X_f}{X_{f_{ini}} - X_{cr}}\right)^n$;
- exponential decrease with conditional equations for each of the drying phases;
- different approximation: water drops instead of the water layer on top of fabric; same evaluations as could be carried out.

We then chose the ranges for the parameters involved in each alternative so that the simulated durations of the drying process operation cover the expected range for the considered load, and within the said ranges we compared the "geometry-based" models first against a water activity reference, and then for

1. the realism of the obtained transients, with particular references to the water content (for obvious reasons) and to the air temperatures, quite often used as a means to determine the drying termination;
2. the ability of the used parameters to sweep the variability of the above transients completely and uniformly, i.e., the attitude of those parameters to serve as variability representatives for optimization, for example referring to some termination detection algorithm.

Figures 2 and 3, by comparing the RMCs and outlet temperatures of the model with water activity (red curve) and the most appealing alternative (blue curve), show a sample of the obtained result (a more extensive set is in the thesis).

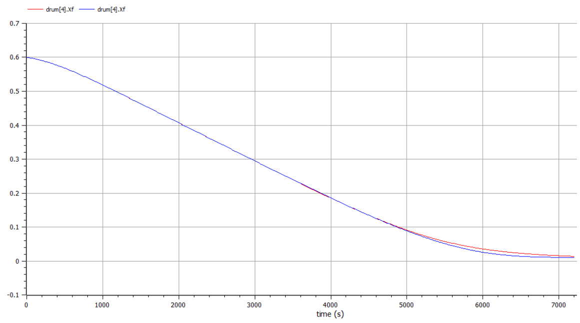

Figure 2

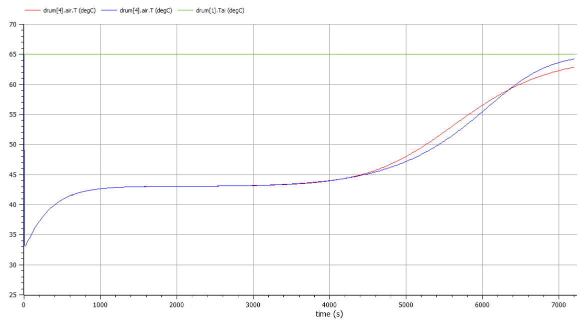

Figure 3

The two models, with water activity (fig. 4) and without it (fig. 5), were compared with different load masses as well, so to see check the behaviour of the models with different initial conditions.

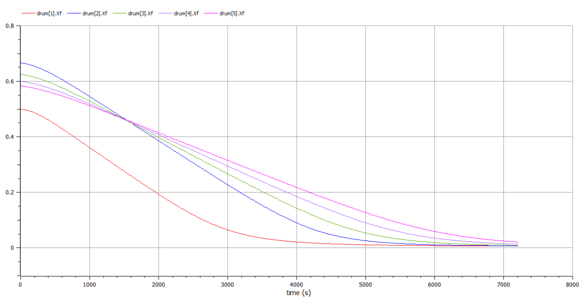

Figure 4

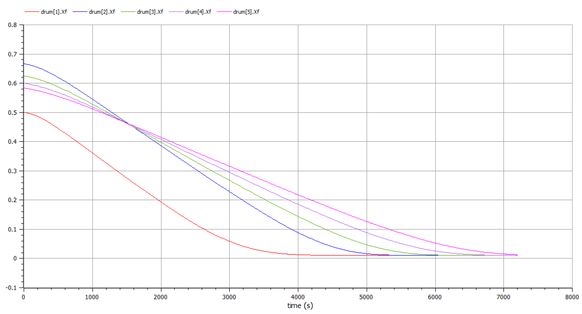

Figure 5

5. Conclusions

The thesis aimed to offer the following contributions:

- to propose a unified model of the drum, based on the analysis of past literature;
- an efficient representation of the drying process, based on the fabric remaining moisture content, without the parameter called "water activity".

Concerning the first goal, we analyzed 5 papers that dealt with the drum modelisation. Their characterisation of the drum is quite etherogenic, hence we came to the conclusion that a drum model that could be representative of all of them would have been of great use, especially for future studies. The drum models we analysed (and ours too) usually have two parts: one more general, where the mass and heat exchanges balance; the other more specific, where each flow is characterised alone. We showed how the general model framework is represented in each analysed paper.

Concerning the second goal, we introduced a purely geometric approach, in an attempt to relate evaporating surface and water mass in the fabric. We analyzed different alternatives as for realism and number of parameters, and we decided that the best behaviour was represented in simulation sets 7a. In this model, the area of evaporation decreased accordint to the following formula:

$$A_{ev} = \frac{M_{w,f_{ini}} \cdot \left(1 - \left(\frac{X_{f_{ini}} - X_f}{X_{f_{ini}} - X_{cr}}\right)^{10X_{f_{ini}}}\right)}{\rho_w \cdot r_t} \; [m^2] \tag{1}$$

Where X_{cr} is the RMC level that the fabric has when it is considered fully dry (the drying process could end a few moments before). The varying parameter is r_t, but h_m could be a viable choice as well.

We finally (briefly) addressed the use of the presented models for determining the termination of a drying operation concluding that the last two presented ways to describe variability appears adequate for testing possible detection methods, which we exemplified in a simplified manner herein. The former relies on the difference between the inlet and the outlet air temperatures, as they eventually reach the same value. The latter relies on the relative humidity value sensed on the outlet of the drum; even though it is reliable, technical difficulties in measuring the humidity arise, and therefore it is (for now) not a good stopping method.

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