

Modelling and simulation of wool steaming for the efficient management of decatizing processes

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Abstract. Finishing is one of the fundamental steps of textile production and still, nowadays it largely depends on empirical knowledge. Aim of finishing processes is to impart the required functional properties to the fabric and, in particular, decatizing is the process that lends the fabrics dimensional stability, enhances the luster and improves the so-called ‘fabric hand’, corresponding to the sense of touching a textile. In this paper, we consider wool fabrics and, by exploiting the available process physical knowledge, we derive a model that can predict certain fabric characteristics, such as its temperature and moisture content, correlated with the fabric dimensional stability. We also design a simulation environment according to the model and we use it to easily generate synthetic data, obtaining information about the steaming process under different conditions. By analyzing the data, we can obtain knowledge about how to maximize the fabric decatizing process efficiency.

1 Nomenclature

M	fabric moisture regain [%]
C	specific heat of moist wool [$\frac{cal}{g^{\circ}K}$]
Q	heat of adsorption [cal/g]
L_v	latent heat of condensation of water [cal/g]
Y	relative humidity [%]
γ	adjustable parameter
v_m	amount of monolayer coverage
c	coefficient related to the adsorption energy
α	fraction of adsorption sites
n	number of adsorption layers at the primary sites
p	number of adsorption layers at the secondary site

1.1 Subscripts

p	permanent
c	cohesive
r	reference
g	air
f	fabric
e	equilibrium
d	differential
a	average
$fast$	at the end of the heat transfer front
$init$	initial

2 Introduction and motivations

Any operation for improving the appearance or usefulness of a fabric after it leaves the loom or knitting machine can be considered a finishing step. Finishing is the last step in fabric manufacturing and it represents the phase when the final fabric properties are developed [1][2].

A fabric's finish can be either chemicals that change the fabric's aesthetic and/or physical properties or changes in texture or surface characteristics brought about by physically manipulating the fabric with mechanical devices; it can also be a combination of the two.

Textile finishing gives a textile its final commercial character concerning appearance, shine, handle, drape, fullness, usability, etc.

According to function, textile finishing processes can be classified into:

1. Aesthetic finishes, which modify the appearance and/or hand or drape of the fabrics.
2. Functional finishes, which improve the performance properties of the fabric such as durability, strength, etc. Property-changing functional finishes provide the added qualities desired for a particular fabric or they may be used to change an undesirable property to a more desirable one.

Decatizing is an example of a finishing process that represents a combination of the two. It is mainly carried out on wool fabrics, by exploiting the elastic properties of its fibers, thanks to the direct action of the steam.

This treatment provides the following characteristics to the processed fabric [3]:

1. dimensional stability;

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2. reduction of possible glazing effect after calendring, thanks to fiber swelling caused by steam;
3. modification of the hand, which is much more consistent after the treatment;
4. high levels of setting stabilization

In industry, this finishing process is performed by machines such as the one depicted in Figure 1, where the fabric is interleaved in a wrapper which leads it in a steaming section (composed of drum, vessel and sealing devices) and an aspirating one.

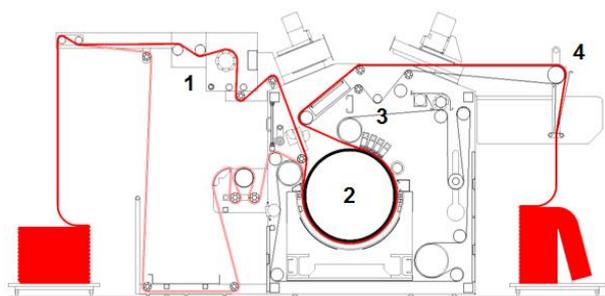


Fig. 1. Example of decatizing machine, composed of an entry unit (1), a steaming section (2), an aspirating section (3) followed by an exit one (4).

2.1. Wool fibers structure and its properties

Wool fiber has a highly complex chemical and physical structure which is responsible for its natural properties. Wool is hygroscopic, therefore relative humidity and temperature of the surrounding air influence the amount of water taken up.

However, only the core of the wool fiber can absorb water to an extent up to 30% o.w.f. (on the weight of the fiber), whereas the fiber surface is water repellent. This apparently contradictory behavior results in the particular wool-moisture-management, which is responsible of the well-known comfort of wool.

In Figure 2, a representation of the morphological wool fiber structure is reported.

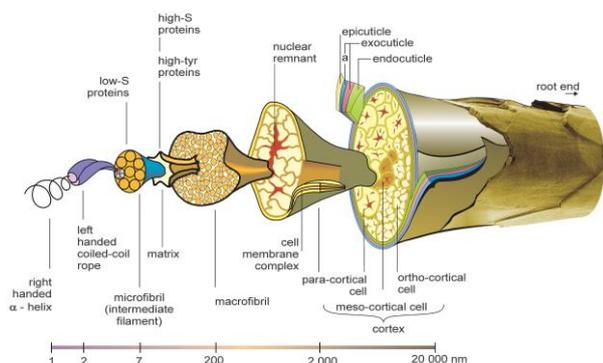


Fig. 2. Schematic diagram of the structure of a fine Merino wool fiber showing its major structural features.

As proteins, wool keratin is mainly characterized by peptide bonds, but, in terms of mechanical and

geometrical properties hydrophobic, hydrogen, ionic and disulphide bonds play an important role [4].

In decatizing, temperature and moisture content (also called regain, which is the mass ratio of water to the oven-dry wool mass, expressed as a percentage) are key aspects for the treatment success since they interact with the aforementioned bonds to achieve the desired level of fiber setting, that can be cohesive if it is lost when the fabric is immersed in water at room temperature or permanent if it is maintained when the fiber is relaxed at 100°C [5].

In this preliminary research, we focus on the thermal processes during decatizing, and we identify the best fabric initial conditions that lead to an optimal setting level.

Specifically, we have derived a model, which is as simple as possible but accurate enough, of the steaming process happening during decatizing and then we develop a Matlab-based simulation environment accordingly. We use a set of Partial Derivative Equations (PDE) to describe the main steam adsorption process phenomena. The model is calibrated by exploiting experimental data provided by an industrial partner. The in silico tests show that the proposed model allows us to generate synthetic data that are related to the input (e.g. fabric initial regain) and output (e.g. percentage of permanent set reached) which correspond to the cause-effect relations (for given boundary conditions).

The remainder of this paper is composed of a section describing the mathematical model developed and a further section providing the Matlab simulation results, followed by some final concluding remarks.

3 Process analysis and modelling

To ensure the wool fabrics proper handle characteristics, set fibers and yarns, and stabilized fabric dimensions, the textiles undergo a series of steam treatments. These treatments are based on the fundamental concept of setting: the set is said to be cohesive if it is lost when the fabric is immersed in water at room temperature whereas it is permanent if it is maintained when the fiber is relaxed at 100°C [5].

The intensity of set reached depends on process parameters such as temperature, moisture content (during steaming) and mechanical action (during decatizing). In particular, wool glass transition curves (see Figure 3), that correspond to the redistribution of fiber hydrogen bonds and disulphide bonds, are expressed with the equations:

$$T_p = -27.05 + \exp(5.25 - 0.04M) \quad (1)$$

$$T_c = 66.63 + \exp(5.04 - 0.07M) \quad (2)$$

Aim of decatizing is to permanently set the fabric, bringing its temperature and regain above the permanent glass transition curve.

To estimate the wool fabrics conditions during decatizing, heat and moisture transfer processes are considered.

In particular, during steaming, when the steam comes into contact with wool fibers, it condenses if the temperature

of wool is below the saturation temperature of steam. This involves the transfer of an amount of heat equal to the latent heat of condensation from steam to wool. If the fabric regain is below the equilibrium regain, the condensed water is absorbed into the wool and an extra amount of heat, called the differential heat of absorption, is released.

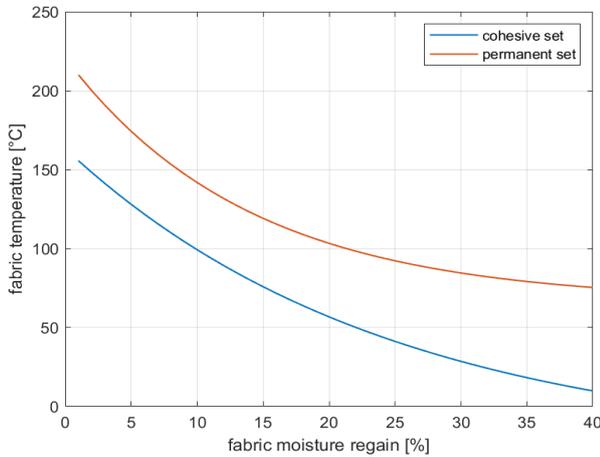


Fig. 3. Wool glass transition temperatures as a function of the moisture regain.

The transient equilibrium condition is established when the wool temperature reaches the steam temperature. The heat balance for the adsorption of condensed water into wool can be expressed as [6]:

$$C \partial T_f = (Q_d + L_v) \partial M \quad (3)$$

Where

$$C = 0.068 + 0.85M + 0.00077T_f \quad (4)$$

$$Q_d = \exp(-11.3009M + 5.7064) \quad (5)$$

$$L_v = 594.64 - 0.45265T_f - 0.00104T_f^2 \quad (6)$$

It is therefore possible, thanks to the above equations and given an increment of the absorbed moisture, to calculate the fabric temperature rise. The temperature rise stops when the wool temperature reaches the steam temperature or when the moisture regain in wool exceeds the equilibrium regain at the process steam relative humidity. This behavior is depicted in Figure 4, where the black dotted line represents the equilibrium regain at different T_f and steady steam relative humidity.

The just mentioned fabric equilibrium regain is the amount of moisture absorbed at any specified humidity of the external environment. It depends on environment relative humidity and temperature according to Equation 7.

$$M_e = M_{e,r} \frac{\exp\left[\frac{Q_a}{R}\left(\frac{1}{T_g} - \frac{1}{T_r}\right)\right] \left[1 + \gamma Y_g \exp\left(\frac{Q_a}{RT_r}\right)\right]}{1 + \gamma Y_g \exp\left(\frac{Q_a}{RT_g}\right)} \quad (7)$$

Where the term $M_{e,r}$ is the reference equilibrium moisture fitted to adsorption data at 20°C.

$$M_{e,r} = v_m \frac{cY_g}{1 + cY_g} \left[\frac{1 - \alpha Y_g^n - (1 - \alpha)Y_g^p}{1 - Y_g} \right] \quad (8)$$

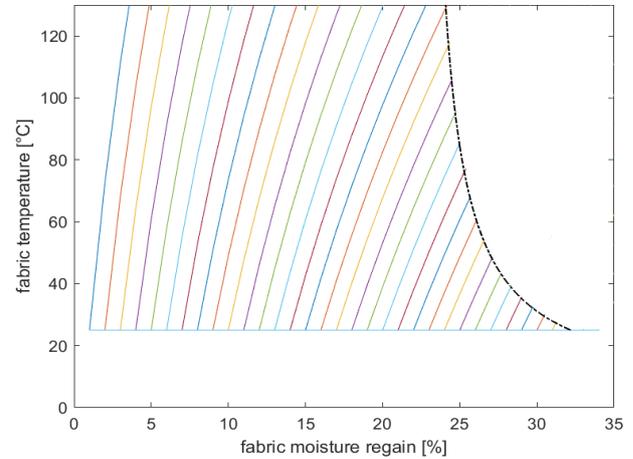


Fig. 4. Temperature rise predicted as steam condenses and absorbs into wool fabric during steaming, shown at different fabric regain.

The constants v_m, c, α, n, p in Equation 8 are introduced to fit the experimental isotherms and change according to the fabric [6][7].

As can be noticed from Figure 5, the equilibrium regain in wool at given humidity changes markedly with temperature, with the fibers absorbing less moisture at high temperatures.

Equation 7 can also be used to construct the isosteres of temperature versus regain at constant relative humidity, like those depicted in Figure 6.

This diagram is very useful in the considered context because it shows important information in steaming or decatizing wool fabric, i.e. the regain change as a function of temperature and at constant humidity.

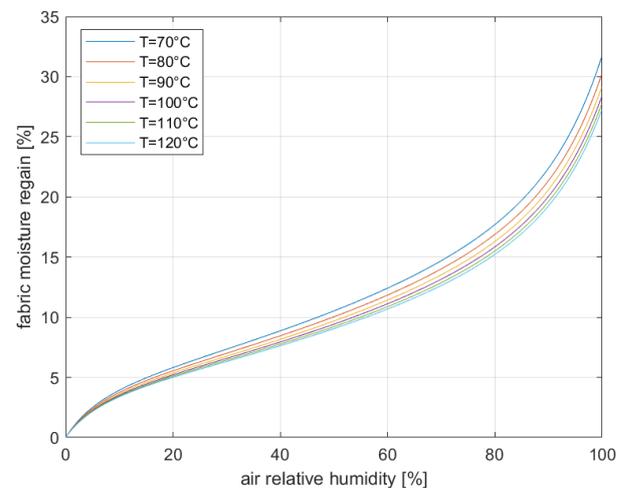


Fig. 5. Adsorption of moisture in wool at various temperatures predicted by Equation 7.

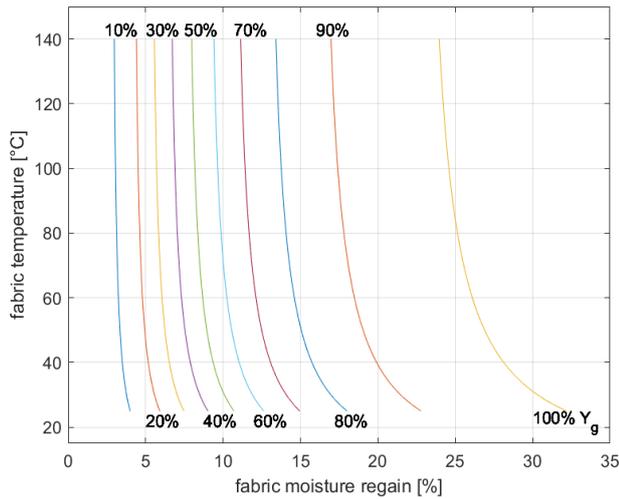


Fig. 6. Adsorption of moisture in wool at various relative humidities predicted by Equation 7.

Our purpose is, given a specific steam temperature T_g and relative humidity Y_g , to find out the wool fabrics' best initial conditions that lead their transient conditions directly towards the equilibrium point M_e .

In fact, if the fabric has low initial regain, it is still absorbing moisture as fabric reaches the steam temperature and the rate of adsorption at this stage is controlled by the slow dissipation of the heat of adsorption [8]. On the other hand, if the fabric has high initial regain, it reaches the saturation regain before getting to the steam temperature; in this case, any further rise in fabric temperature requires a large amount of heat to reduce the equilibrium moisture regain in the fabric.

Figures 7-8 are representative of these two situations.

In particular, imagining to have the steaming process at 100°C and 95% relative humidity and raw wool at different initial regains, it is possible to notice that, if $M_{init} = 12\%$, the fabric is still absorbing moisture when it reaches T_g (Figure 7), if instead its initial regain is $M_{init} = 17\%$, the fabric saturates before getting to T_g (Figure 8).

To quantify the efficiency of the decatizing process, it has been defined a fitness function F indicating the effort needed to reach equilibrium when the fast heat transfer front has finished its effects (in the two cases mentioned above).

This function is defined as follows:

$$fitness = (M_e - M_{fast})^2 + (T_e - T_{fast})^2 \quad (9)$$

where M_e and T_e represent the regain and the temperature reached at equilibrium (blue star in Figures 7-8) whereas M_{fast} and T_{fast} are respectively regain and moisture reached during the fast heat transfer front (green star in Figures 7-8).

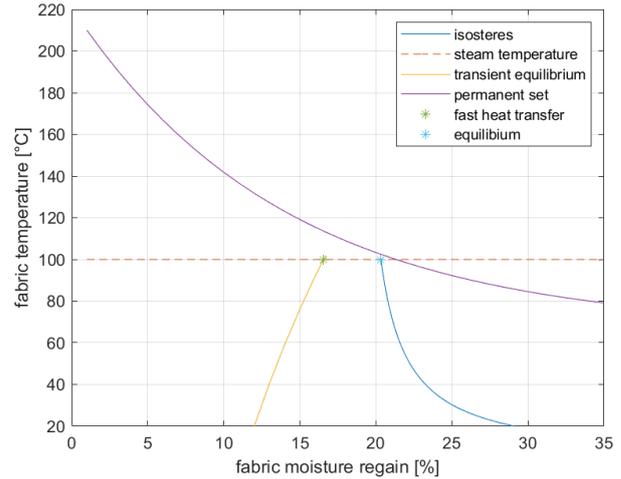


Fig. 7. Temperature rise predicted when the initial regain is low (yellow curve) and comparison with the equilibrium isosteres, enlightening the temperature the fabric should reach for being permanently set (purple curve).

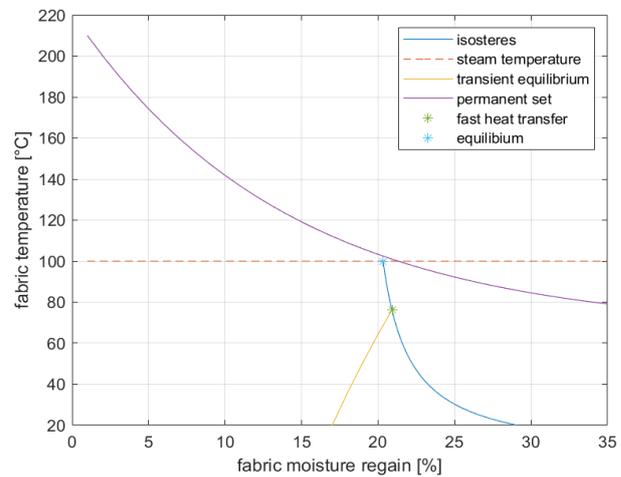


Fig. 8. Temperature rise predicted when the initial regain is high (yellow curve) and comparison with the equilibrium isosteres, enlightening the temperature the fabric should reach for being permanently set (purple curve).

4 Results and discussion

By exploiting the Matlab-based simulation environment designed accordingly with the PDE model, we can simulate the steam adsorption process during decatizing at different operative and initial conditions.

In particular, we have simulated the process for different steam temperatures and relative humidities and, for four varieties of wool fibers, the designed algorithm calculates the best initial moisture regain the fabric should have to take the least time to equilibrate.

Moreover, keeping in mind the wool glass transition curves, it calculates the percentage of permanent set reached both at equilibrium and at the end of the fast heat transfer front.

The four varieties of wool fabric are listed in Table I, together with their identification number and the numerical value taken by the parameters introduced in Equation 8.

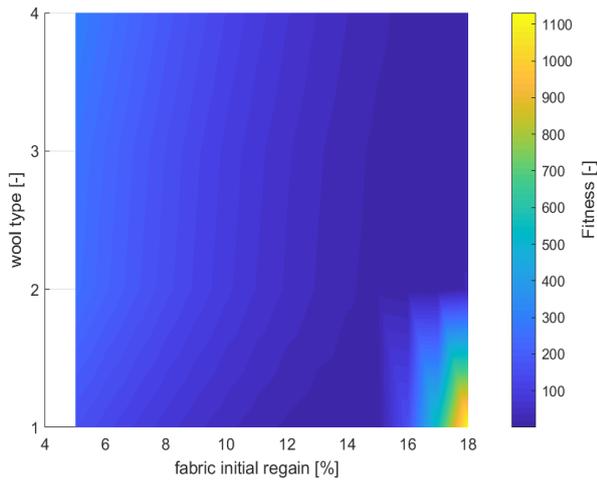


Fig. 9. Fitness function for four kind of fibers.

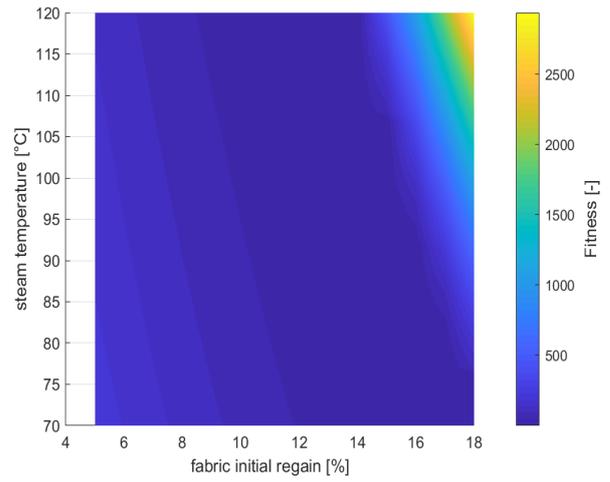


Fig. 12. Fitness function at different steam temperatures.

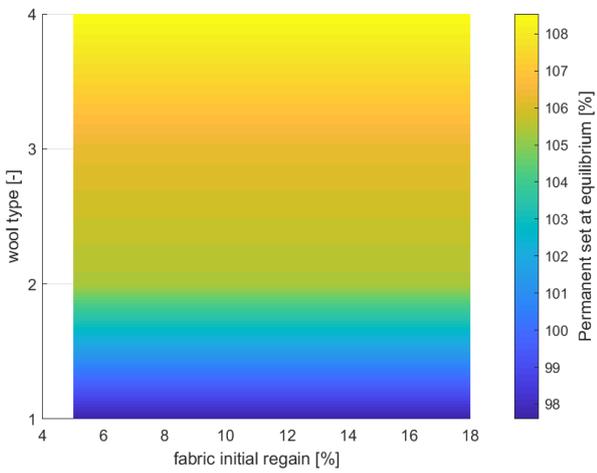


Fig. 10. Percentage of permanent set (equilibrium).

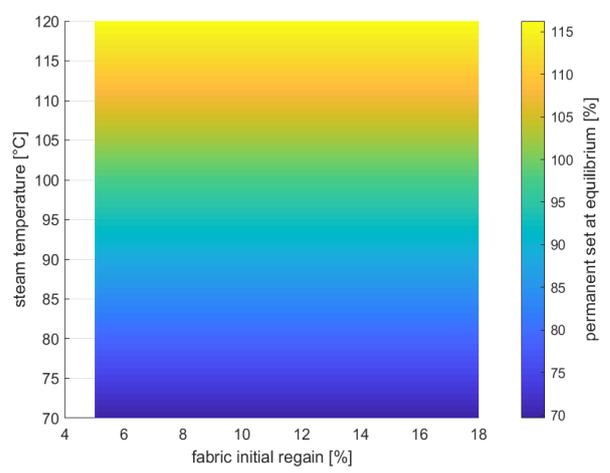


Fig. 13. Percentage of permanent set (equilibrium).

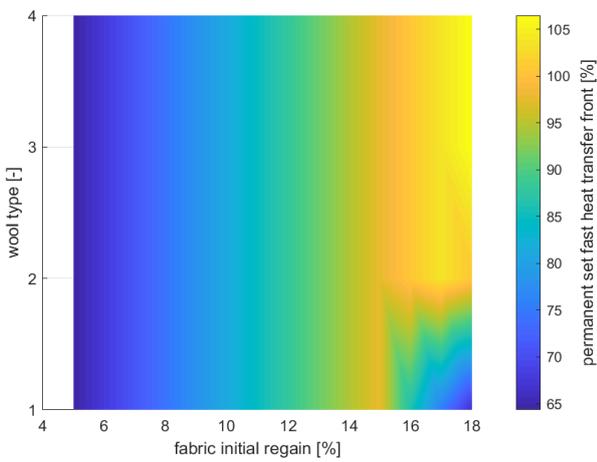


Fig. 11. Percentage of permanent set (heat transfer front).

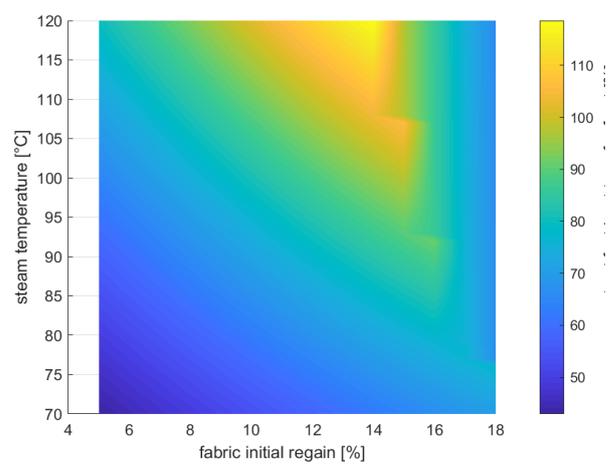


Fig. 14. Percentage of permanent set (heat transfer front).

Table 1. Constants for Isotherm Equations for the Adsorption of Water Vapor in various Wool Fibers.

Wool type	ID. number	c	v_m	n	p	α
Raw	1	10.63	7.64	3.3	18	0.88
Merino	2	9.10	7.59	3	16	0.85
Corriedale	3	7.57	8.32	3	13	0.85
Lincoln	4	9.05	7.74	3	16	0.83

Figures 9-10-11 respectively show the fitness function and the percentage of permanent set reached at equilibrium and at the end of the heat transfer front if the steam temperature is 100°C and the humidity is 95%. Figure 9 suggests the optimal initial regain for each type of fabric available and it can be noticed that, except for fiber with ID.1, having the optimal regain between 13% and 15%, all the others all the other fibers need to be conditioned between the 15% and 18% of regain.

This result is confirmed also looking at Figures 10-11: while the permanent set is always reached at equilibrium (Figure 10), at the end of the fast heat transfer front it is reached only in the aforementioned initial regain ranges (Figure 11).

Another simulation we made consists in having a fix wool type and steam humidity, and evaluating the best fabric initial regain at different steam temperatures.

Figures 12-13-14 respectively show the fitness function and the percentage of permanent set reached at equilibrium and at the end of the heat transfer front if only raw wool (ID.1) is available and the steam humidity is 95%. As expected, Figure 12 shows that an increase of T_g corresponds to a decrease of M_{init} , that ranges between 13% and 18 % for low temperatures and between 10% and 15% for higher ones. Figure 13 indicates that the percentage of permanent set reached at equilibrium only depends on the steam temperature, which should be higher than 100°C. This is an expected result, that could have been deduced already looking at Figure 6 in the previous section. Finally, Figure 14 confirms the previous reasoning and highlights that, at constant Y_g , the range of M_{init} widens as the steam temperature increases.

5 Conclusions

In this paper, the steaming phase of a decatizing process is considered.

By taking advantage from both knowledge of the physical phenomena and data which characterize the process we have developed a mathematical model describing the wool transient-equilibrium condition during steaming.

Nowadays, modelling and simulation tools offer new possibilities to dominate the increasing complexity of industrial processes and they enable to accelerate innovation cycles, rapidly exploring and exploiting quickly new possible solutions.

With this in mind, in this paper, we have exploited the developed model to design a Matlab-based simulation environment which can be potentially used as guideline for a fabric conditioning phase before decatizing.

Indeed, we have proven that both the kind of fiber and the steam conditions influence the initial moisture regain needed to reach the equilibrium as soon as the fast heat transfer front has passed through the textile.

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