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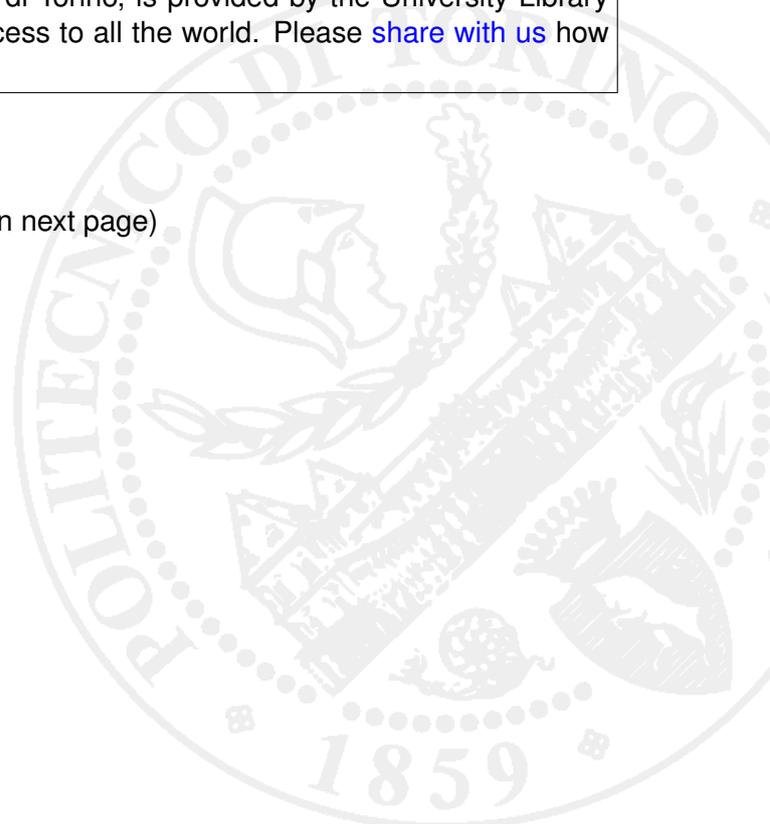
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# POLITECNICO DI TORINO

Dipartimento di Scienza Applicata e Tecnologia



Dottorato di Ricerca in Ingegneria Chimica  
XXVI ciclo (2011-2013)

## **Study and scientific rationalization of the last finishing stages for high quality wool fabrics**

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## **Abstract**

The excellence in quality of Italian wool fabrics, which ensures a worldwide leader position of the Biella district, depends fundamentally on three factors: the design, distinctive of the “Made in Italy”, the choice of very fine fibers and the adoption of particular finishing techniques, which ensure optimal physical characteristics especially for the tailorability of light fabrics with a special “hand”.

All these factors are important to provide highly comfortable garments, comfort itself depending on the mechanical properties of the fabrics submitted to small strains, like those occurring during everyday wear.

Among the fundamental steps of the wool textile production, finishing is certainly the one that, still nowadays, depends largely on empirical knowledge. A critical review, aimed at rationalizing the process considering both the costs and the quality guarantee, requires the realization of two preliminary conditions: understanding physicochemical parameters and laws which rule the process and the development of measuring methods which allow to objectively evaluate the influence of the controlling variables.

In the majority of finishing processes, the fabric is exposed to the action of water or steam, in different conditions. The main goal of finishing is relaxation and/or stabilization of internal stresses at molecular level (the so-called “setting”) generated by the complex macromolecular structure of wool fibers.

Two types of chemical reactions are involved: the break of pre-existing bonds and the formation of new bonds. Indeed, wool fibers are characterized by covalent disulphide bonds (cysteine groups) and hydrogen bonds, numerous but weaker than the previous one.

This can be made by means of three basic operations: steaming, decatizing at atmospheric pressure and decatizing under pressure (KD). Actually, the last operation is the most critical one, because it is realized wrapping the textile material on a perforated

drum, through which steam is fed. The whole operation is led in an autoclave, at variable temperature and pressure, depending on the textile product.

Process parameters are known only at the inlet of the autoclave but not in between the layers of the textile roll, where the actual physicochemical effects of setting take place. In recent years, mathematical models have been developed to overcome the problem and describe the system behavior and its dynamics; however they have never been verified experimentally.

From a practical point of view, KD treatments cover a wide technological interest, allowing the realization of several effects and results, marked or soft, depending on the types of involved bonds.

A KD operation affects disulfide bonds, bringing about their redistribution, with a permanent effect. This action, called setting, is given by a fine tuning of the process variables: temperature, moisture content, treatment time and mechanical pressure. All these four variables interact reciprocally but their relationships have not been fully understood; therefore a scientific criterion is fundamental for rationalizing sequence and intensity of the operations.

In recent years, mathematical models have been developed to overcome the problem and describe the system behavior and its kinetics; however, they have never been verified by an experimental procedure. Under a scientific point of view, verifying or modifying the existing theoretical models will be of fundamental importance to accurately validate the process steps, develop new diagnostic methods and possibly devise new and more complete models.

The main potential innovation implies the possibility of working with a continuous treatment (KD is usually carried out in autoclave, as a batch operation) with a consequent increase in reproducibility, as well as a better treatment evenness (avoiding usual problems related to the different longitudinal position in the textile material). As a consequence, the finished product may gain in terms of quality, thus increasing its economical value.

To reach these goals, two different approaches were adopted in the present work.

The first one was based on a set of experiments on suitable bench scale equipments, carried out to monitor the process parameters (particularly temperature and moisture content) during the treatments and within the textile structure.

The second approach concerns the development of theoretical models, whose application in a computer algorithm, thanks to a finite elements based simulation software, allowed to simulate the system behavior.

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## **Chapter 1**

### **1. Finishing and wool fabric properties**

#### **1.1 Introduction**

Among the fundamental textile processing stages, finishing is surely the one that still nowadays is based mostly on empirical knowledge.

There are a lot of reasons because a modern company should improve this aspect, in particular:

- finishing has a remarkable effect, especially on high quality wool fabrics, developing and enhancing the intrinsic quality already present in the textile materials;
- the finishing stage could be efficiently optimized: unlike spinning and weaving, which are carried out with a continuous flow of materials and can be easily kept under control, some finishing operations are run in the batch mode. This means a large quantity of material to be stored, treatment repetitions and frequent dead times;
- the rationalization of the process is restrained by the complexity of some treatments, whose real need is questionable, if analyzed with scientific criteria;
- from a quality point of view, the lack of accurate scientific information can cause non homogeneous operations. Some treatments can be repeated or modified due to

undesirable effects on similar fabrics, with a consequent reduction of the quality of the final product.

The knowledge of the scientific criteria that rule the treatments has already been available for years, especially concerning the chemical and physical properties of textile fibers, but only minimally applied. On the other hand, the quality of the final product is often evaluated empirically, just watching or touching the material, also because the testing methods are quite complex, time consuming and can't be used online or within the production.

Thus, analyzing the type of modifications occurring on the material, during the treatment and within the machine, will be extremely useful both to understand the process and to correlate the process variables to the characteristics of the final product.

The present chapter is focused on the theoretical aspect of finishing, concerning the wool fiber characteristics, behaviors and inner transformations, with a particular attention to the so-called "setting" phenomena.

## **1.2 Wool fabric finishing**

Textile finishing is the sequence of operations aimed at developing the properties of wollen and worsted fabrics to meet customer requirements. The desired fabric properties are only achieved when the sequence of operations is carried out in a specific order and in an appropriate manner. Finishing operations are carried out to achieve four main goals [1]:

- to remove unwanted contaminants, mainly lubricants and anti-static agents, introduced during yarn and fabric production;
- to develop and improve fabric handle and appearance;
- to control the dimensional properties of the fabric (relaxation shrinkage and hygral expansion);
- to add functional performances, when required (shrink resistance, flame retardancy, water proofing, etc.).

In order to achieve the previous goals, fabrics undergo a series of operations that can be bundled into two main groups: wet and dry finishing.

In wet finishing, water and solvents are used to remove undesirable substances and to improve the quality of the textile. Operations like washing and carbonizing can be included in this group.

The main aim of washing is to remove dirt and impurities caused by previous treatments and to perform a basic relaxation of the internal stresses. This can be done by using water or solvents.

Sulfuric acid is used in carbonizing to completely remove foreign substances of cellulosic origin.

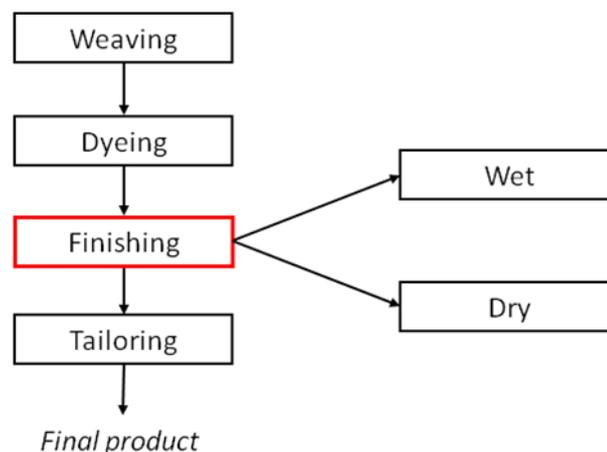
In dry finishing fabrics are treated with hot air and/or steam to remove the internal stresses due to previous treatments (e.g. spinning and weaving); in this way the product is improved in terms of appearance and comfort. Within this group, steaming and decatizing are known as fundamental operations for worsted wool fabrics.

The tensionless steaming process of wool fabrics is the most widely used technique to obtain a good dimensional stability. The steam action involves the hygroscopic swelling of the fibers with a subsequent relaxation of the fabric, which recovers its "natural" shape.

Decatizing (atmospheric or under pressure) is probably the most difficult process to perform. This process is mainly carried out on wool fabrics, by exploiting the elastic properties of wool fibers, thanks to the direct action of the steam. This treatment gives to the processed fabric the following characteristics:

- dimensional stability;
- reduction of possible glazing effect after calendering, thanks to fiber swelling caused by steam;
- modification of the hand, which is much more consistent after the treatment;
- high levels of setting stabilization (decatizing under pressure, also known as KD).

A synthetic scheme showing the position of finishing in the textile production chain can be seen in Figure 1.1.



**Figure 1.1** - Finishing in the textile production chain.

Finishing operations can be carried out by means of discontinuous, continuous and semi-continuous systems.

- *Discontinuous or batch-type systems*: all the operations are carried out on a single machine; it is therefore necessary to load the machine, carry out the treatments (following a predetermined cycle) and unload the machine (eventually washing it before starting a new cycle). This work process is extremely flexible and is suitable for processing small lots. For the production of large lots, the discontinuous process is labor-intensive (it requires many operators to load and unload the material) and, above all, it entails long processing times and results that can vary from one batch to the other.
- *Continuous systems*: the operations are carried out by means of a series of machines; every machine carries out always and solely the same process. Every machine is assembled according to specific production requirements. A system like this entails high start-up costs and a complex setup but, once the system has started, requires a smaller staff and grants excellent repeatability and high output rates; continuous systems are therefore suitable for manufacturing large lots of products with the highest cost-efficiency.
- *Semi-continuous systems*: in these mixed systems, several operations are carried out with both continuous and discontinuous machines. For example, a continuous pad-batch machine is used to wet the fabric and a discontinuous system is successively used for other treatments. These mixed systems are suitable for processing small and medium lots; they require reasonable start-up costs and grant quite good reproducibility [2].

### 1.3 Wool fiber: structure and 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 is able to absorb water to an extent up to 30% o.w.f. (on the weight of the fiber), whereas the fiber surface is water repellent due to the hydrophobicity of the outer surface of cuticle. This apparently contradictory behavior results in the particular wool-moisture-management, which is responsible of the well-known comfort of wool. The hydrophobicity of wool fiber is caused by covalently bound fatty acid, which form the outer cuticle layer. In addition, both hydrophobic nature of the fiber surface and the high cross-linking density of the protein layer

immediately below the fatty layer, act as a natural diffusion barrier; this aspect highly influence all the wet wool processing.

The wool fiber core-shell structure is characterized by an inner protein core, the cortex, covered by a shell constituted by overlapping cuticle cells with scale edges pointing in the direction of the fiber tip. In Figure 1.2, a representation of the morphological wool fiber structure is reported.

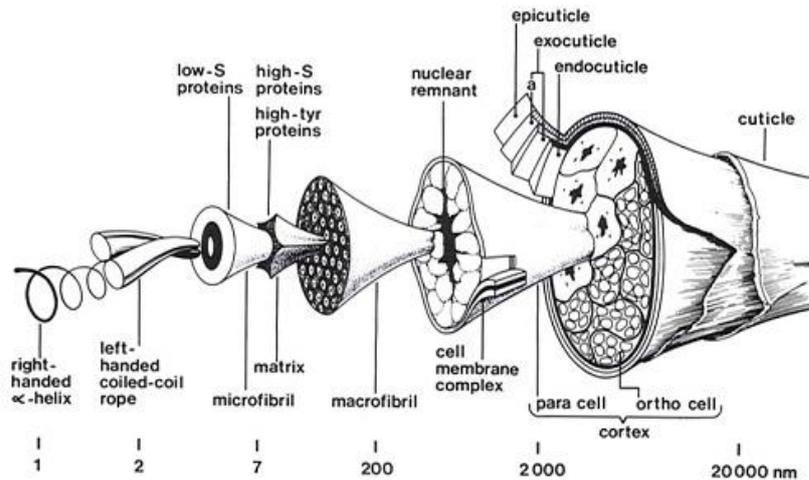


Figure 1.2 - Wool fiber morphological structure.

The cortex consist of two main kind of cells: ortho-cells and para-cells, which divide the stem of fiber in two halves. This bilateral asymmetry results in the natural crimp of wool fiber, which results from differential moisture absorption and swelling. The cortex contains macrofibrils formed by microfibrils (alfa-elical keratin protein) embedded in a cystine-rich, higly cross-linked protein matrix. Cystine is responsible for fiber resilience, high wet strength, moderate swelling and insolubility of the fiber. The cuticle can be subdivide into four coaxial layers of different chemical composition:

- the outermost hydrophobic epicuticle (3 ÷ 6 nm thickness), mainly consisting of covalently bounded fatty acids;
- the exocuticle (about 0.3 μm thickness) immediately below the epicuticle, which is divided into an A- and B-layer, and is highly cross-linked via cystine disulphide bridges;
- the less cross-linked endocuticle (about 0.2 μm thickness) beneath the exocuticle;
- the cell membrane complex (CMC) (about 25 nm thickness) a proteinaceous membrane between cuticle and cortex.

Approximately 1% of the wool fiber mass is constituted by lipids, most of which are placed in the intercellular region. About 40% of this lipids are sterols, 30% are polar lipids such as cholesterol and the remaining part is made up of fatty acids, ranging from C<sub>7</sub> and C<sub>26</sub>.

Wool is a keratin fiber; the average amino-acid composition of a commercial Merino wool is reported in the following table.

**Table 1.1** - Average amino-acid composition of a commercial Merino wool fiber.

<b>Amino-acid</b>	<b>Nature of side-chain</b>	<b>mole %</b>	<b>Amino-acid</b>	<b>Nature of side-chain</b>	<b>mole %</b>
Glycine	hydrocarbon	8,6	Aspartic acid	acidic	6,4
Alanine	hydrocarbon	5,3	Glutamine	basic	11,9
Phenil-alanine	hydrocarbon	2,9	Histidine	basic	0,8
Valine	hydrocarbon	5,5	Arginine	basic	6,9
Leucine	hydrocarbon	7,7	Lisine	basic	3,1
Isoleucine	hydrocarbon	3,1	Methionine	sulphur-containing	0,5
Serine	polar	10,3	Cysteine	sulphur-containing	10,5
Threonine	polar	6,5	Tryptophan	heterocyclic	0,5
Tirosine	polar	4,0	Proline	heterocyclic	5,9

### 1.3.1 – Intermolecular bonds

As proteins, wool keratin is mainly characterized by peptide bonds, but, in terms of mechanical and geometrical properties, other bonds play an important role [3]:

- hydrophobic bond;
- hydrogen bond;
- disulphide bond;
- ionic bond.

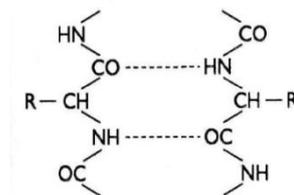
#### *Hydrophobic bond.*

The hydrocarbon groups of Ala, Phe, Val, Leu and Ile (see Table 1.1), when placed in a medium containing water molecules can interact together in order to get away water from their chains. During this phenomenon the hydrophobic chain get closer and, because of their high affinity, a relative high force is required to get far apart the

involved chains. This situations occur in wool fiber characterized by a certain moisture content, where hydrophobic bonds confer to wool mechanical resistance. This effect is noticeable in wet conditions.

*Hydrogen bond.*

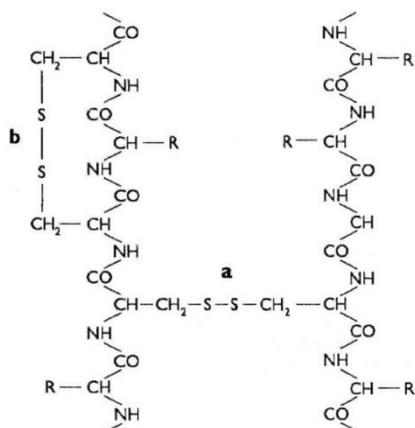
This is a low energy bond (about 5 kcal/mol) that can link together the oxygen of the carbonilic group and the hydrogen of the amino group. These two atoms can be part of the same protein chain or part of two separated chains; in the first case the hydrogen bond gives a particular spatial configuration to the protein, whereas in the second one it generates protein cross-linking (Figure 1.3). The hydrogen bond plays an important role in the mechanical resistance of wool, conferring robustness and a compact structure to the fiber.



**Figure 1.3** - Inter-chains hydrogen bonds.

*Disulphide bond.*

The disulphide bond is a covalent bond which links together two particular amino-acids, the cysteine, to form a compound called cystine. Disulphide bonds can generate cross-links in the same or between different chains (Figure 1.4) and create particular spatial disposition of protein chains such as arcs, rings and others. This behavior depends on the positioning of the two involved cysteines along the keratin molecule.



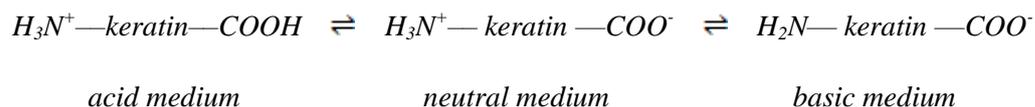
**Figure 1.4** - Disulphide bonds: a) between two chains, b) within the same chain.

In addition, disulphide bonds confer high chemical resistance to keratin because they are much more stronger than hydrogen bonds. However, both disulphide and hydrogen bonds have a fundamental role in the setting of wool fabrics, as will be shown hereinafter.

*Ionic bonds.*

The side amino and carboxylic groups, plays an important role in the chemical reactivity of keratin with respect to alkali and acids.

When wool is placed in an acid medium, the amino group takes the form of a cation, and when it is placed in a basic medium, the carboxylic group takes the form of an anion. A representation of the wool chemical structure in acid, neutral and acid media is reported in Figure 1.5.



**Figure 1.5** - Wool chemical structure in acid, neutral and acid media.

### 1.3.2 – Stereostructure

According to the model developed by Atsbury and Street [4], in a relaxed fiber the polypeptide molecules are organized in a folded configuration (alpha-keratin), stabilized by the hydrogen bonds. If the fiber is stretched in an aqueous medium, the break of hydrogen bonds allows reaching a different configuration (beta-keratin) in which the macromolecules are completely extended (Figure 1.6).

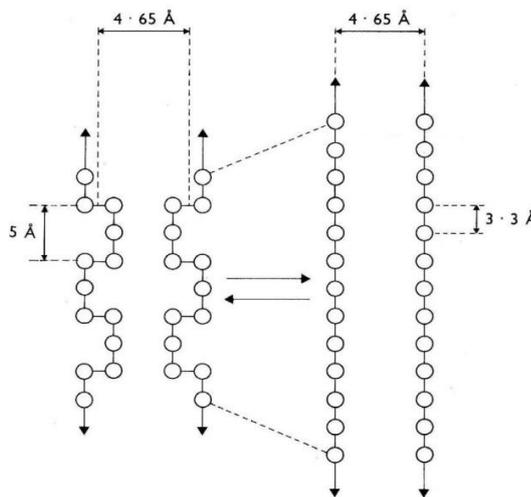


Figure 1.6 - Transition between alpha (on the left) and beta (on the right) keratin.

At the same time, the two-phases structure of the macrofibril has a remarkable effect on the physical properties of the fiber, as it will be shown in the following section. A macrofibril scheme can be seen in Figure 1.7, with the presence of two components: microfibrils, a crystalline regions with elastic behavior, and the matrix, an amorphous region with viscoelastic behavior.

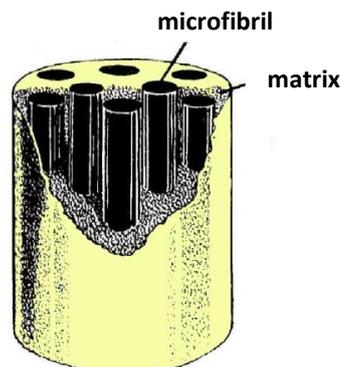
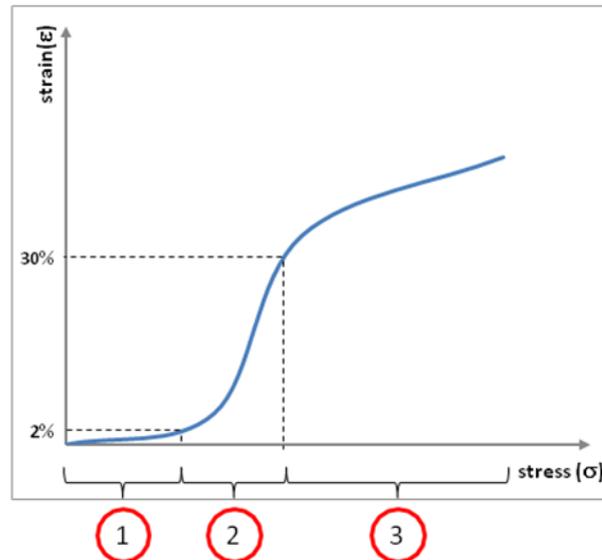


Figure 1.7 - Macrofibril two-phase structure.

### 1.3.3 – Physical properties

The stress-strain curve of a wool fiber shows three different zones (Figure 1.8):



**Figure 1.8** - Stress-strain curve of a wool fiber.

Zone 1: the Hooke's Law is valid within 2% elongation. Thus, the Young modulus ( $E$ ) can be defined by the well known relationship:

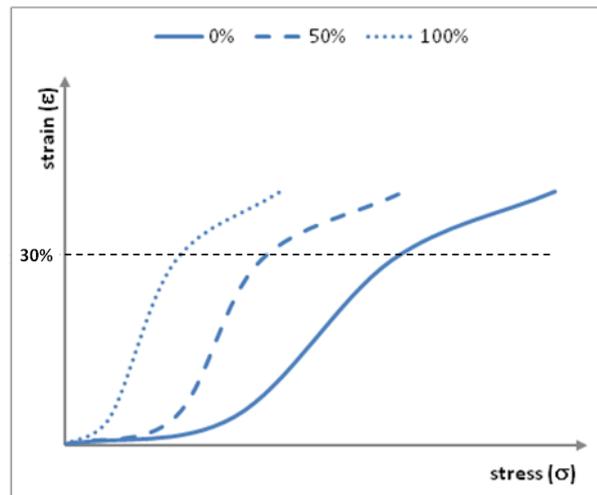
$$E = \frac{\sigma}{\epsilon}$$

Zone 2: little stresses cause high strain.

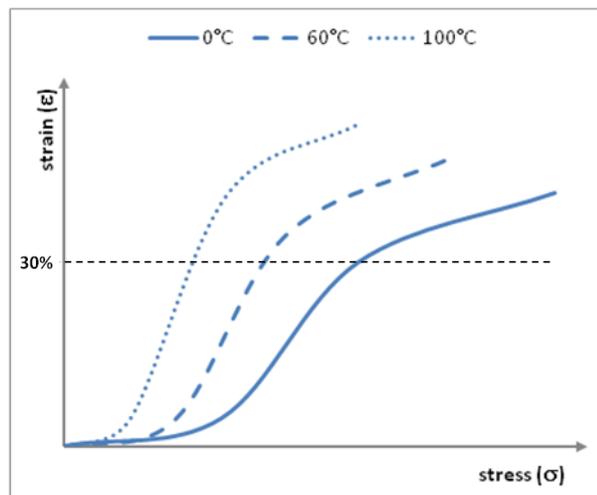
Zone 3: wool fiber stiffness increases as far as the breaking point is reached.

As far as temperature and moisture content are concerned, it can be observed that they both considerably influence the stress-strain curve.

In particular, the stiffness decreases with increasing the moisture content at room temperature (Figure 1.9), whereas, keeping constant the moisture content, a temperature increase causes an increase of the fiber stiffness associated with an upwards shift of the transition point between the second and the third zone (Figure 1.10).



**Figure 1.9** - Effect of the moisture content on the stress-strain curve of a wool fiber.



**Figure 1.10** - Effect of the temperature on the stress-strain curve of a wool fiber.

This behavior can be explained considering the two main bonds (hydrogen and disulphide), which stabilize the macromolecular structure of keratin.

Within the 2% of elongation, only the elongation of such bonds takes place, while beyond this value (if the temperature is kept under 65°C) hydrogen bonds start breaking, with a consequent transition from the alpha to beta keratin secondary structure. Hydrolysis of hydrogen bonds is promoted by the moisture content, thus at higher moisture content values the load necessary to “unfold” the structure is lower. The elastic strain recovery is complete because the reactions concerning the hydrogen bonds

are totally reversible. When the fiber reaches 30% strain, the keratin configuration is totally of beta type and a further strain causes the irreversible break of other bonds.

The complete loss of elasticity, with a certain amount of setting, is reached also if the temperature of the fiber is higher than 65°C. In these conditions not only hydrogen bonds but also the disulphide ones are involved.

## 1.4 Theory of practical wool setting

Many wool finishing processes are responsible of setting phenomena of fabrics, therefore the understanding of such mechanisms is indispensable to effective processing. Until now, we have frequently remarked the fundamental role of the temperature and moisture content. However, as far as finishing operations are concerned, the term “regain”, which it is actually the mass ratio of water to the oven-dry wool mass, expressed as a percentage [5], is often used. This indicates the amount of moisture that the oven dry wool has regained at the time of testing.

“Set” is generally defined as the degree of retention of strain that is imposed during a setting process. Strain is a change in a fiber or fabric shape and the degree of retention of any strain depends on the conditions to which the fiber is exposed after the setting operation. This chapter explains the theory behind the two common types of set, cohesive and permanent, which are related to practical situations.

When a wool fiber is stretched in an aqueous medium, or in a high humidity environment, beyond the first transition point (2% of strain), the breakage and the reformation of the hydrogen bonds will take place. When the fiber is dried, these new bonds will impede the return of the fiber to its initial dimension. However, the degree of set that has been imparted will be completely lost if humidity will be absorbed again by the fiber. Once the fiber has come back to its initial length, the broken bonds are reformed and the fiber gets again its original physical properties.

Also the temperature plays an important role, thus, if the fiber is stretched at temperatures above 65°C, the mechanical properties of the fiber will be permanently modified and a certain amount of set will be maintained.

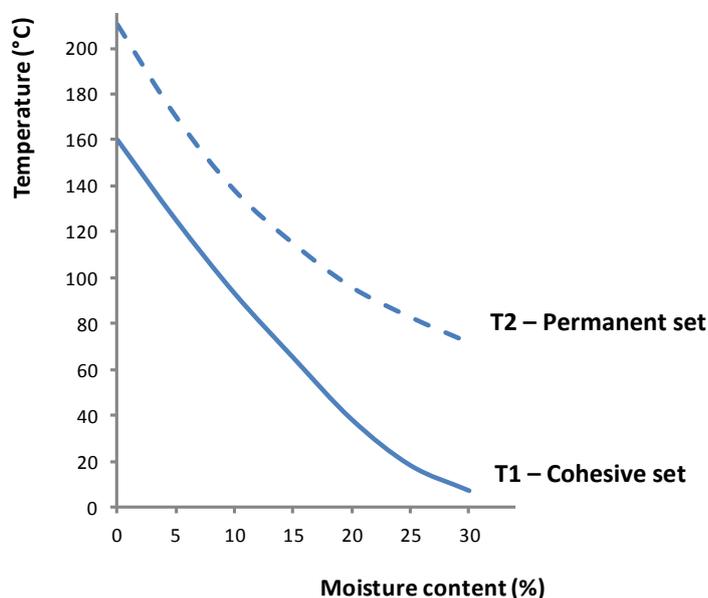
Besides temperature and regain, the degree of set depends also on the duration for which the fiber has been stretched. From a practical point of view, focusing on the operative finishing conditions, three types of set are usually defined:

- *cohesive set*: removed if the fiber is relaxed in water at room temperature (20°C);
- *temporary set*: it is maintained if the fiber is relaxed at 20°C but completely removed at 100°C.
- *permanent set*: it is maintained even if the fiber is relaxed at 100°C.

Considering the common finishing operations, the temporary set has a poor practical interest, thus only cohesive and permanent set are contemplated, and connected respectively to the behavior of hydrogen and disulphide bonds.

The setting of wool can be understood in terms of modern polymer theory. Chemically, wool is composed of long polypeptide protein molecules. Approximately 25% to 30% of the wool protein is crystalline and well structured, and the rest is amorphous. Thus, the fiber can be considered made up of tiny elongated protein crystals, embedded in a highly disulphide-crosslinked unstructured matrix. The structured protein apparently stiffens the fibers and provides strength, while the setting behavior is largely a property of the unstructured matrix.

The previous statements allow introducing the concept of glass transition temperature also for the wool fiber. As can be seen from Figure 1.11, two transition temperature, T1 and T2, exist and correspond respectively to the redistribution of hydrogen bonds and disulphide bonds.



**Figure 1.11** - Wool glass transition temperatures as a function of the moisture content.

When a wool fabric is set between T1 and T2 and then cooled to room temperature keeping it under a mechanical constraint, the new arrangement will be kept until the fabric temperature is brought again to values greater than T1 (cohesive set).

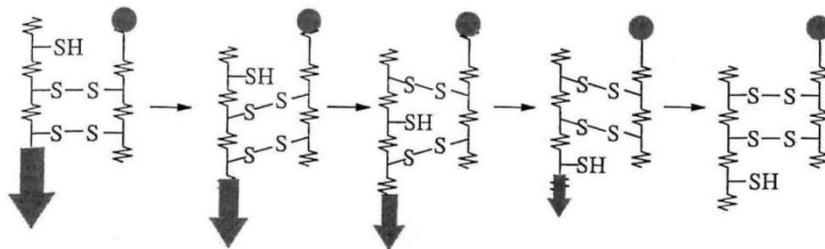
If T2 is reached, the new arrangement remains stable to the traditional tailoring operation and domestic use, in which T2 is not overcome (permanent set). A typical finishing operation of this type is pressure decatizing (KD) in which the moisture

content is a critical factor because it can't be controlled during the treatment and, as a consequence, there is no absolute certainty that T2 is reached.

### 1.4.1 – Permanent set

Permanent setting is surely one of the fundamental goals that must be achieved in wool fabric finishing.

Permanent set takes place because of the rearrangement of disulphide bond crosslinks that stabilize the protein matrix (breakage of preexisting bonds and formation of new bonds). The chemical bases for rearrangement of disulphide crosslinks is the thiolate-disulphide exchange reaction, whose graphical representation can be seen in Figure 1.12.



**Figure 1.12** - Rearrangement of disulphide crosslinks (permanent setting).

The rate at which disulphide bonds rearrange depends on the temperature and the thiolate ion concentration. The last one can vary with the previous history of the wool and the pH of the fabric.

Under practical conditions, permanent setting is always less than 100%, because stress relaxation is never complete. Complete relaxation is prevented by the rigidity of the protein crystals in the matrix, the inability of some crosslinks to rearrange and the introduction of more non-labile crosslinks while disulphide bond rearrangement is taking place. On the contrary, the 50% of permanent set represents approximately the minimum conditions for batch treatments.

### **1.4.2 – Influence of permanent setting on the fabric dimensional stability**

When wool fabrics are subjected to water and steam treatments, as it is during finishing and tailoring operations, their dimensions change, due to two different phenomena: relaxation shrinkage and hygral expansion.

#### *Relaxation shrinkage*

Within the production chain, fibers, yarns and fabrics are often subjected to stresses and tensions that can be set (with various setting degrees) depending on the mechanisms that have been previously described. As an example, after the weaving step, a fabric could become shorter during a washing operation, even at room temperature (cohesive and temporary set).

On a woven fabric, water and humidity cause a dimensional variation, which is called relaxation shrinkage. This is an irreversible phenomenon that could create great defects during tailoring or dressing. One of the possible solution for this problem is to generate a permanent set (pressure decatizing).

#### *Hygral expansion*

Hygral behavior can be explained in terms of changes in fibers diameter and fibers curvature with regain, due to the expansion of wool fibers when absorbing water. Going from dry to wet saturated, the fibers increase of about 17% their diameter but the length increases only of about 1%. As the fibers swell they tend to straighten, therefore the more a fiber bents, the greater is its tendency to straighten as regain increases. Permanent setting in a fabric readily alters fiber curvature and this links the process of setting to the phenomenon of hygral expansion.

Permanent setting processes are usually carried out either at high regains or at saturation. Under these conditions, the fibers and yarns are more swollen than at ambient conditions, and they become permanently set in curved weave crimp shapes determined by the fabric construction. Stress relaxation during permanent set reduces the inter-yam forces as the fibers become stabilized in their new shapes corresponding to the regains at which they are set.

## **1.5 Setting in finishing processes**

In the following sections, various setting processes are discussed in terms of chemical and physical processes involved. Diagrams of fabric temperature and regain are used to show how changes in these parameters affect the type of set introduced [6].

### 1.5.1 – Drying

As the fabric temperature rises during drying, water is first lost from the capillary spaces between the fibers. While the capillary water is evaporating, the temperature of the fabric remains relatively constant. The actual value is determined by the operating parameters that affect heat and mass transfer. When all the capillary water has been removed, absorbed water will be lost from within the fibers and the temperature of the fabric will increase. Eventually, the fabric temperature will reach the temperature of the hot air in the equipment. If the drying is sufficiently prolonged, the regain may fall to zero.

Only cohesive set can be introduced into a fabric during drying, influencing only the relaxation shrinkage. The wet relaxed dimensions of the fabric remain substantially unchanged, and the hygral expansion is not altered. Figure 1.13 illustrates typical changes in the fabric temperature and regain that may occur during drying.

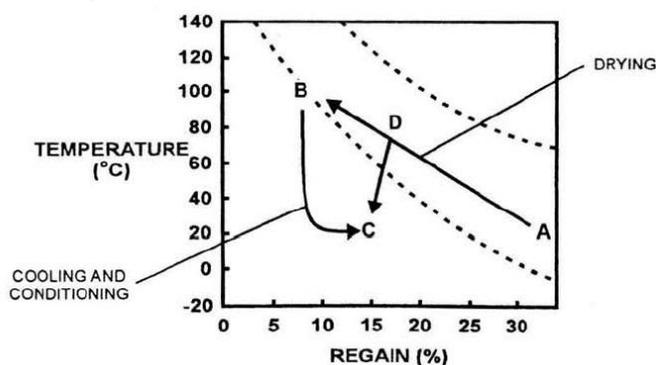


Figure 1.13 - Variation of temperature and regain during wool drying.

The position of a wet fabric (saturated with water) at room temperature is shown at point A on the diagram. As the fabric dries, the temperature increases and regain falls until the fabric exits from the heating zone of the equipment (point B), after which the fabric cools and conditions to point C. In practice, the wool fabric is almost always over-dried. This means that after drying, the regain is less than the value of 14%, which is considered optimal for further dry finishing processes.

If drying would be optimal, the fabric would be delivered from the equipment at about room temperature and 14% regain (or slightly higher). The fabric would be close to point D on the diagram in Figure 1.13 and would still be above its glass transition temperature. Controlled cohesive setting of the fabric dimensions would take place, provided the fabric was cooled to below about 60°C before removal.

When a wet fabric is placed on the machine pins it is usually stretched slightly in the weft direction (to assist in keeping it on the pins). Once the regain of the wool falls

below its saturation value, the fabric will try to contract due to hygral effects and the resulting strains add to the strains already introduced when the fabric was stretched as it was put onto the pins. This results in the introduction of relaxation shrinkage in the weft direction.

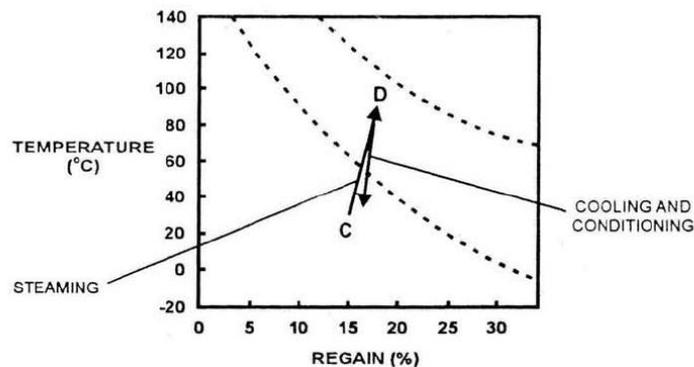
The relaxation shrinkage introduced during drying in any particular practical situation is difficult to predict exactly because it depends on a number of parameters:

- the weft extension and warp overfeed of the wet fabric on the pins;
- the regain at the end of the drying process;
- the cooling of the fabric;
- the relaxation of the fabric as it comes off the pins;
- the hygral behavior of the fabric.

In practice, process settings (of width and underfeed/overfeed), required to obtain desired values of relaxation shrinkage, are usually found by trial and error, while the other variables are kept constant.

### 1.5.2 – Decatizing

The purpose of decatizing is to cohesively set fabric flat. When fabric at 20°C and 14% regain (point C in Figure 1.14) is interleaved with a wrapper, placed in a batch decatizer and heated with steam to 100°C, condensation of steam during heating of the fabric will increase the regain to about 20% (point D). Under these conditions, the wool is above its glass transition temperature and subsequently the fabric will be rapidly cohesively set when the fabric is cooled while still being held by the wrapper.



**Figure 1.14** - Variation of temperature and regain during decatizing of wool fabrics.

Cooling is achieved by drawing ambient air through the batch. While some loss of heat may occur by radiation or conduction, evaporative cooling is assumed to be the major cooling process and results in the loss of about 4-5% moisture; so the regain of the wool returns to a little higher than its original value, at about 15-16% (near point C). Under these conditions, the relaxation shrinkage of the fabric increases only slightly.

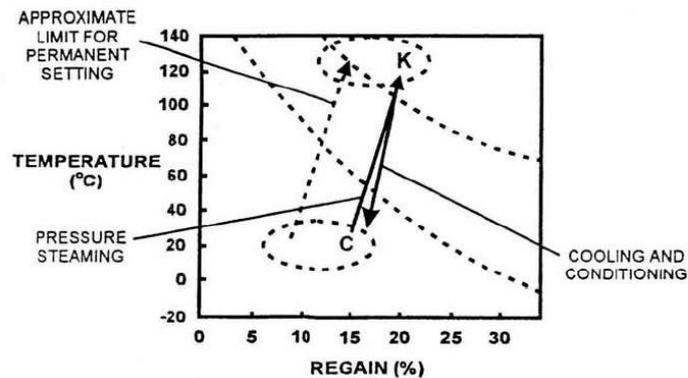
At about 100°C and 20% regain, wool can be permanently set, but the rate is relatively slow. Depending on the fabric pH, approximately 10 minutes steaming is required before permanent setting becomes significant (about 50%).

### **1.5.3 – Steaming**

By steaming on a pin frame, the dimensions of a fabric may be changed and cohesively set with greater accuracy than in decatizing. As in drying, the dimensions are controlled by feeding the fabric onto a pin frame at a predetermined width and with a desired amount of underfeed or overfeed in the warp direction. After framing, the fabric is heated for a short time (between 20 and 60 seconds) using steam at atmospheric pressure and is then cooled by drawing ambient air through the fabric. From the point of view of setting, the situation is similar to that already described for decatizing (see Figure 1.14). Fabric at point C should move to point D on steaming and return to near point C when the fabric cools. As in drying, the fabric may relax slightly as it is removed from the frame, because the degree of cohesive set is always less than 100%. High levels of cohesive set can be obtained, provided the changes in dimensions are not too large. Figure 1.14 shows that the starting regain of the fabric should not be too low, otherwise the regain during steaming may not be high enough for an effective cohesive set. If the fabric is removed from the pin frame at a regain and temperature higher than ambient, then some relaxation may occur as the fabric returns to ambient conditions.

### **1.5.4 – Pressure decatizing**

In pressure decatizing, the fabric, at a regain usually between 5% and 15%, is interleaved with a technical wrapper, rolled up on a perforated drum and loaded into a pressure vessel. After purging with steam to remove air, the fabric is heated with the steam at temperatures between 100°C and 130°C for several minutes. The actual fabric regain and temperature depends on a number of factors that will be discussed in detail in Chapter 2. Generally, the regain can be expected to increase by a maximum of about 6-8%. After pressure steaming, the fabric is cooled, sometimes by blowing air through the fabric, and this can result in evaporation of some absorbed moisture.



**Figure 1.15** - Variation of temperature and regain during pressure decatizing of wool fabrics.

A typical processing cycle is illustrated in Figure 1.15 in which fabric initially at 20°C and 14% regain (point C) is pressure steamed at 120°C and 20% regain (point K). Appreciable permanent setting can occur under these conditions within a few minutes. On cooling, the temperature and regain of the fabric will return to near point C.

The dotted ellipses in Figure 1.15 indicate the approximate ranges of the parameters that may be encountered in practice. As indicated by the dotted arrow, fabric with an initial regain of about 8% may only just take up sufficient moisture for appreciable permanent setting to occur. Fabrics at lower initial regains are unlikely to be effectively permanently set.

The relaxation shrinkage after pressure decatizing will depend on how the fabric is constrained during cooling and conditioning to ambient regain. If the batch is unwrapped at room temperature and 14% regain, a small amount of relaxation shrinkage will take place. This relaxation shrinkage is caused by cohesive setting of the fabric in the batch and the magnitude depends on the regain increase during the pressure steaming process and on the hygral expansion before and after the process.

Generally, the value of relaxation shrinkage introduced with this operation is very low, considering the ideal situations in which 100% permanent set is assumed to have been achieved. In practice, it has been found that this is approximately correct if more than 70% permanent set is introduced.

If levels of permanent set are not very high (below 50%) then the behavior will be intermediate between that described above and what would be expected if no permanent set would had taken place. In the absence of any permanent set, only cohesive set will occur and the situation will be similar to steaming on a pin frame.

In practice, the magnitude of the changes in dimensional properties cannot be predicted precisely because the critical factors involved (namely temperature and moisture content) are neither measured or effectively controlled during the process.

The qualitative effects of pressure decatizing on the dimensional properties of fabrics can be summarized as follows:

- relaxation shrinkage after pressure decatizing is not related to the initial relaxation shrinkage;
- only a small amount of relaxation shrinkage is introduced during cooling and conditioning of the fabric after it has been steamed under pressure;
- hygral expansion of previously permanently set fabric may be reduced, if the fabric initially contains relaxation shrinkage or if the fabric is stretched during batching up.

## 1.6 Evaluation methods

Still nowadays, when the results obtained by finishing operations have to be quickly evaluated, the most important method is based on the workers' experience. These subjective measurements are generally used to evaluate changes in fabric properties even when objective tests have been used but the data obtained have sometimes been considered inappropriate and questionable.

The currently available objective tests are not sufficiently comprehensive to completely replace traditional subjective assessments of properties, such as "handle", defined as the global feeling which is perceived when touching a fabric.

However, accurate and objective measurement of changes in fabric properties can enhance the quality of information available on the operation of processing equipment.

Each different fabric finishing machine is designed to achieve one or more specific effects. In Table 1.2 the major finishing processes carried out on wool and wool/synthetic blend fabrics are listed, together with the primary results of these operations and appropriate test methods. This table includes all the processes that are critical in changing fabric properties.

**Table 1.2** – Methods for the quantitative evaluation of the effectiveness of finishing processes.

Process	Purpose	Test
Wet setting	Permanent setting	Crease angle Fabric wet dimensions Shear properties (SiroFAST / KES-F)
	Handle modification	Shear properties (SiroFAST / KES-F)
Milling	Controlled felting	Fabric dimensions Fabric thickness (SiroFAST / KES-F)
	Stiffening	Shear properties (SiroFAST / KES-F)
	Surface modification	Surface thickness (SiroFAST / KES-F) Surface contour
	Handle modification	Fabric specific volume
	Reduction in hygral expansion	Surface thickness (SiroFAST / KES-F)

Scouring	Cleaning Handle modification	Determination of residual grease/oils Fabric thickness (SiroFAST / KES-F)
Drying	Moisture reduction Temporary setting of dimensions Control of relaxation shrinkage	Fabric regain Fabric dimensions Relaxation shrinkage
Conditioning	Increase regain moisture	Mass of fabric
Decatizing (including pressure decatizing)	Permanent setting of fabric dimensions  Change dimensional properties Handle modification	Fabric relaxed dimensions Crease angle Shear properties (SiroFAST / KES-F) Relaxed surface thickness Relaxation shrinkage Surface thickness (SiroFAST / KES-F) Shear properties (SiroFAST / KES-F)

### **1.6.1 – Instruments for fabric properties measurement**

The basic concept underlying fabric objective measurement technology is that a necessary and sufficient number of fabric properties must be measured in order to control the quality and predict performances in garment construction and during wear. The following is a summary of the instruments that measure the most important physical and mechanical properties of fabrics.

A number of simple instruments, which can be used manually, have been developed. Other devices can be attached to standard textile tensile test machines and enable measurements to be made automatically. Stand-alone instruments usually measure properties that are characteristic of one type of deformation.

Two sets of instruments and test methods have been developed specifically to measure low stress properties of textiles: the KES-F and SiroFAST systems.

The KES-F (Kawabata's Evaluation System - Fabric) system was developed in Japan. It is rather complex and expensive but is widely used by research workers around the world and particularly in Japan.

The SiroFAST (Fabric Assurance by Simple Testing) system was specifically designed at the CSIRO Division of Wool Technology, Australia, to fulfill the measurement requirements of manufacturers and users, at a relatively low price.

Both the SiroFAST and KES-F systems measure compression, bending, extension and shear properties. The KES-F system also includes measurement of surface characteristics and recovery properties. The SiroFAST system includes a test method for relaxation shrinkage and hygral expansion.

Control charts, sometimes called "fingerprints", have been developed for both SiroFAST and KES-F systems. The results of the fabric measurements are plotted on these charts. Comparisons between fabrics and diagnosis of tailoring problems can be made more easily when the information are presented in this way. Charts also assist

with the storage of data. Generally the results obtained with the SiroFAST and KES-F systems are in good agreement.

While it is possible to assemble a collection of instruments from different sources, there are advantages in using an integrated system. With an integrated system, fabric measurements can be carried out on standard sized samples, which can be used for more than one measurement. This reduces both the required quantity of fabric and the sample preparation time.

Another advantage of using a standard system is that the results obtained by different users can be readily compared. Extensive trials have been carried out using both KES-F and SiroFAST, showing that the reproducibility and repeatability of most results is within the limits required for effective quality control. Large amounts of information are available to users of the SiroFAST and KES-F systems to assist in the interpretation of results. The properties measured have recommended limits and the problems associated with fabrics lying outside the limits have been identified. This information can form the basis of a fabric quality control program.

## **1.6.2 – Measurement of permanent set**

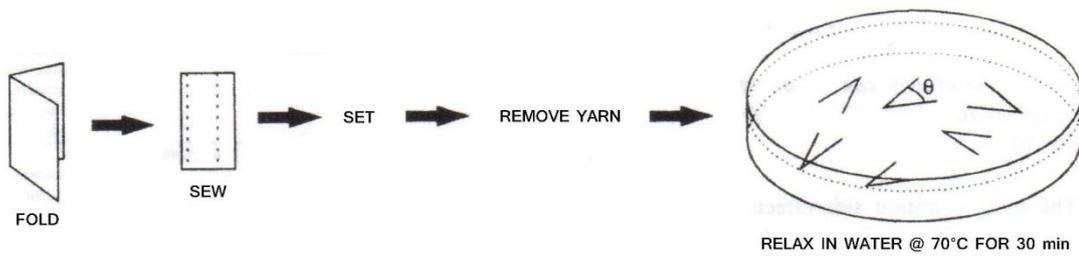
The measurement of permanent set is critical in the evaluation of different processes and machines where permanent set is introduced into fabrics. These processes include crabbing, decatizing (including both atmospheric and pressure decatizing), steaming and chemical setting.

Among the methods normally used to determine the permanent set, SiroFAST and KES-F are surely the most precise but at the same time quite long to perform. The equipments used for assessing the two methods are pretty fragile and can be used only in a quality control laboratory, often far from the production area.

Thus, some other test methods, simpler but effective, may be used for directly measuring permanent set in these types of processes.

### **1.6.2.1 – Crease angle test**

This is perhaps the most useful and generally applicable test. The procedure is illustrated in Figure 1.16.



**Figure 1.16** - Crease angle test procedure.

A sample of a standard test fabric is folded and held flat with one or two rows of stitches sewn parallel to the fold. The prepared sample is then included in a full-scale trial of the setting process. After the treatment, yarn snippets (at least 10 mm long) are extracted from the fold and relaxed in water under the required conditions (70°C for 30 min). The angle  $\theta$  (measured in degrees), formed by the legs of the yarn snippets, is a measure of the amount of permanent set imparted in the process:

$$\text{Permanent set (\%)} = \left(1 - \frac{\theta}{180}\right) * 100$$

### 1.6.2.2 – Permanent set from fabric dimensions

Permanent set can be determined from the residual strain present in a relaxed fabric treated at different dimensions from its relaxed dimensions before treatment. In this case:

$$\text{Permanent set (\%)} = \frac{RD_{bs} - RD_{as}}{RD_{bs} - D_{as}} * 100$$

where:

$RD_{bs}$  is the dimension of the relaxed fabric before setting,

$RD_{as}$  is the dimension of the relaxed fabric after setting,

$D_{as}$  is the actual dimension during setting.

### 1.6.2.3 – Permanent set from fabric thickness measurements

Fabric or surface thickness can also be used to measure the amount of permanent set imparted by operations such as pressure decatizing. This is done by comparing the final thickness of the fabric with the relaxed thickness, both before and after the setting operation. Relaxation can be carried out in water at 20°C, in steam for 30 seconds or any other appropriate conditions.

$$\text{Permanent set (\%)} = \frac{RT_{bs} - RT_{as}}{RT_{bs} - T_{as}} * 100$$

where:

$RT_{bs}$  is the thickness of the relaxed fabric before setting (or the relaxed surface thickness if the SiroFAST system is used),

$RT_{as}$  is the thickness of the relaxed fabric after setting,

$T_{as}$  is the (unrelaxed) thickness after setting.

Measurements along the length of a fabric can reveal end-to-end variations in the amount of permanent set introduced in batch pressure decatizing.

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## **Chapter 2**

### **2. Industrial processes and machinery**

#### **2.1 Introduction**

At the end of the finishing cycle, wool fabrics undergo a series of steam treatments to ensure proper handle characteristics, set fibers and yarns, and stabilize fabrics dimensions.

As already seen in Chapter 1, these treatments are based on the fundamental concept of “setting”, cohesive or permanent, whose intensity depends on process parameters such as temperature, moisture content and mechanical action. As a consequence, the main distinction can be given by:

- *steaming*, in which the fabric has no mechanical constrains and therefore can be relaxed by varying its dimensions;
- *decatizing*, in various forms, in which the fabric is also subjected to a mechanical action.

Before treating separately the two processes, a brief description of the common aspects will be done in the following section, with a particular attention to the steam properties and how they influence processes and machines.

## 2.2 Steam properties in steaming and decatizing equipments

While evaluating steam properties, three different steam conditions can be defined:

- wet steam: mixture of liquid water droplets and steam in which both of them are at the saturation temperature;
- dry saturated steam: steam at its saturation temperature without liquid;
- superheated steam: the steam temperature is higher than the saturation one, at the same pressure.

Steam properties during finishing operations can be besides described by the Mollier's diagram (Figure 2.1).

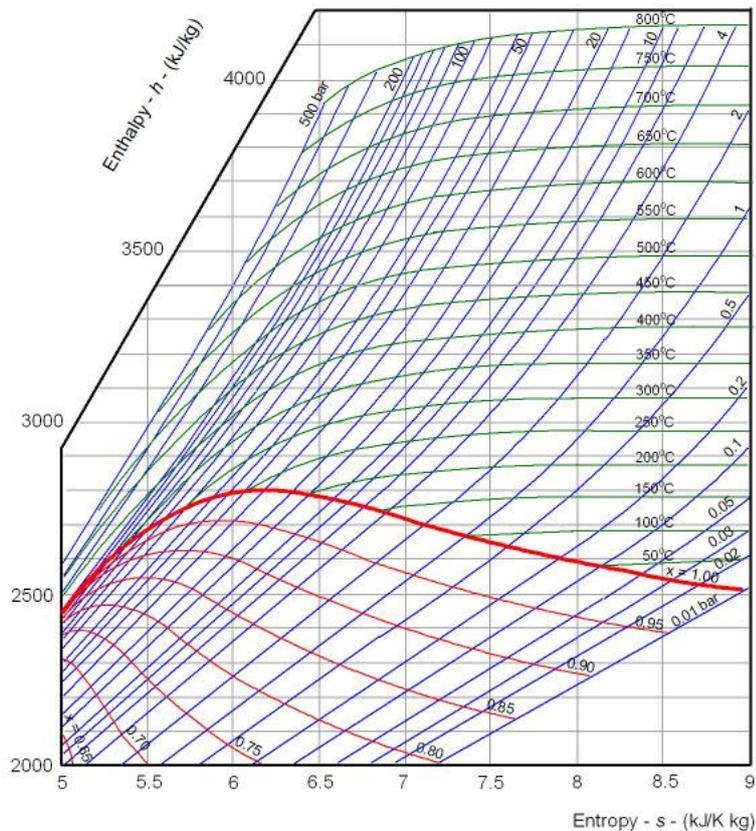


Figure 2.1 – Mollier's diagram.

The Mollier's diagram is widely used for evaluations on steam engine machines, but it can be useful in the study of steaming and decatizing machines.

Steam used in finishing processes is supplied from the boiler as dry saturated steam at a pressure of 8 atm (gauge). Later, steam is expanded or brought to a lower pressure, but always without making any kind of work, thus the heat content does not change.

As an example, considering an initial steam pressure of 8 atm, the corresponding saturation temperature is about 176°C, and, when arriving in a steaming machine the steam is expanded in atmosphere (0 atm) and the superheating temperature will be about 147°C. From this moment on, the steam is spread into the machine, thus its temperature and pressure will change depending on the process parameters.

It is noteworthy that besides steam conditions, it is interesting to follow the evolution of the moisture content within the fabric (which could absorb moisture from steam or vice versa), as this factor plays an important role in all setting processes [1].

### **2.2.1 – Steaming**

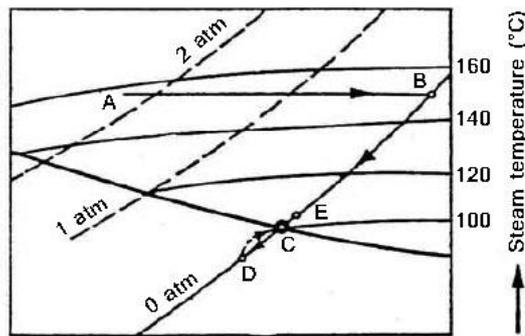
In steaming machines, experimental measures indicate that the operative temperature is around 99°C. If heat losses through the machine are high, steam conditions go towards the wet steam region. If steaming operation is performed for a quite long time, equilibrium between heat of the incoming steam and heat losses will take place. Thus steam comes back towards its saturation condition and could even get into the superheated region. In this way the fabric does not absorb moisture anymore but it is dried instead. In common practice, treatment times are usually around 10 – 20 s, in order to remain in the absorbing phase.

The steam pressure influences also the treatment conditions because, as it increases, the previous phenomena take place quickly and the moisture absorption decreases.

### **2.2.2 – “Finish” decatizing**

In this kind of equipment the steam passes through a relative big perforated cylinder (900 mm diameter) on which the fabric is rolled up but with relative low wrapping thickness. Therefore the excess pressure necessary for the steam to pass through the textile material is negligible, as well as different steam conditions between inner and outer part of the roll.

From experimental measures, as can be seen from Figure 2.2, the incoming steam conditions follow the AB line until the 0 atm pressure are reached. Then the region of wet steam, at first, and superheated steam is reached. In these final conditions the steam reaches a temperature of about 104°C (in about 2 min) whereas the temperature of the fabric does not exceed 100°C.

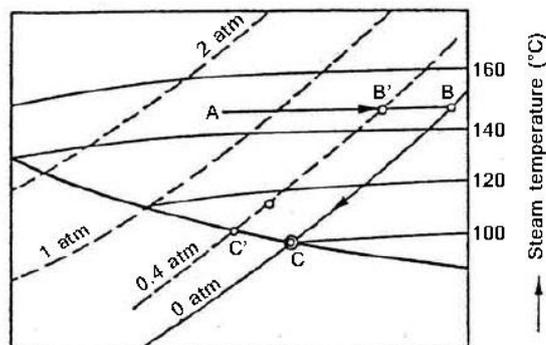


**Figure 2.2** - Evolution of the steam conditions during a finish decatizing.

In the current treatment cycles, the increase in moisture content during the treatment is very low (2%); as a consequence the fundamental parameter for an effective setting operation is the initial moisture content of the fabric.

### 2.2.3 – “Lustre” decatizing

This is the typical atmospheric decatizing, characterized by a smaller cylinder (300 mm diameter), with respect to “finish” decatizing. The steam is introduced in the equipment with two senses of circulation: from inside to outside the rolled fabric or vice versa. It has to pass through a high thickness of textile material, thus it needs an excess pressure of about 0.4 atm. Looking at Figure 2.3, it can be seen that initially the steam conditions moves from A to B and B to C, but the increase in pressure causes a quick moving from BC to B’C’.



**Figure 2.3** - Evolution of the steam conditions during lustre decatizing.

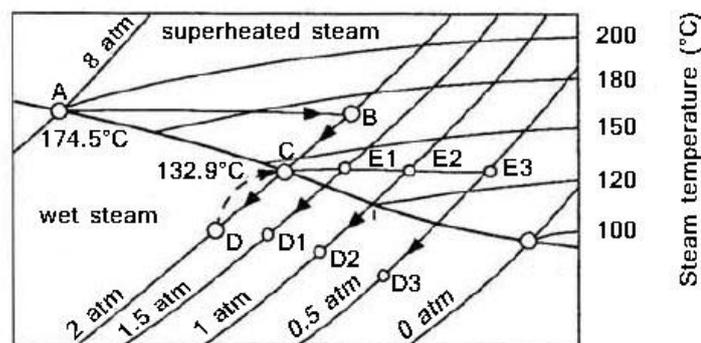
After 4 min the temperature measured inside the cylinder is about 116°C. Considering that the 0.4 atm dry saturated steam temperature is 109.7°C, at this condition the presence of superheated steam causes the fabric drying.

From a technological point of view, in this kind of decatizing the differences of treatment from inner to outer layers of fabrics increases (end-to-end variations within the same batch).

#### 2.2.4 – Pressure decatizing (KD)

In this case the equipment configuration allows to operate in a pressurized autoclave and to use steam with saturation temperatures higher than 100°C.

Before entering the treating chamber, steam passes through a jacket where a certain amount of condensation occurs, due to heat losses. Generally, in the jacket the steam is like the dry saturated one coming from the boiler, at a saturation temperature corresponding to the selected pressure.



**Figure 2.4** - Evolution of the steam conditions during pressure decatizing.

Starting from a steam pressure of 8 atm, reduced at 2 atm in the jacket, the variation of steam conditions are from A to B and from B to C (Figure 2.4). The saturation steam temperature, as far as it is in the jacket in contact with the condensing water, is equal to 132.9°C.

After that, at the inlet of the autoclave, the steam pressure is still reduced, depending on the type of treatment, to 1.5 – 1 – 0.5 atm, thus steam condition moves respectively to points E1 (130°C), E2 (128°C), E3 (125°C) into the superheating region.

At this point the steam comes in contact with the cold rolled fabric, losing heat, reaching the saturation temperature (respectively 126.8°C, 119.6°C, 110.8°C) and entering into the wet steam region, reaching points D1, D2 or D3.

Experimental measurements indicate that temperature differences of 2 – 4°C between inner and outer layers of fabric are quite common. Such differences affect the moisture absorption rates, generating different treatment efficiencies between inner and outer layers. One of the possible solutions which has been found is to increase the cylinder diameter, in order to decrease the thickness of the textile material.

## **2.3 Finishing equipments: description and operating principles**

### **2.3.1 – Steaming**

The tensionless steaming process of wool fabrics is the most widely used technique to obtain a good dimensional stability to ironing with steam press.

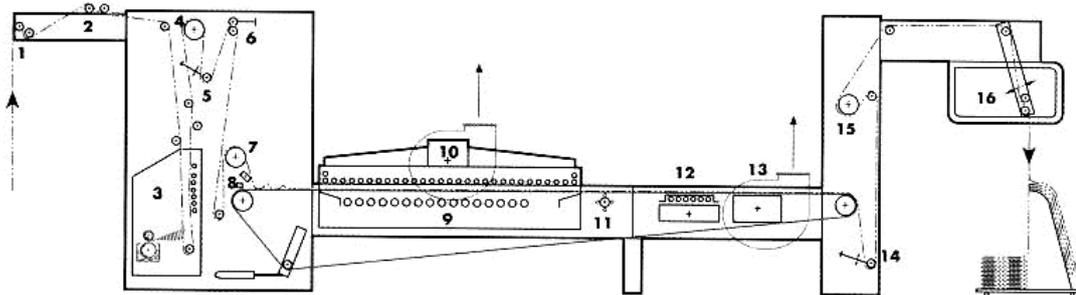
The steam action involves the hygroscopic swelling of the fibers with a subsequent relaxation or shrinkage of the fabric, which recovers its "natural" shape.

The steaming process eliminates also all the residual tensions. The machines used to carry out this treatment are called tensionless steaming machines (tensionless steaming) or steaming-shrinking machines.

The tensionless steaming units can be divided into four main sections:

- 1) feeding section where the fabric is laid on a continuous conveyor belt by means of an overfeeding system, coated with a technical fabric made of synthetic material, stable with regards to the action of heat, featuring an ease passage of steam. It generally vibrates for a better relaxation of the fabric and keeps it quite suspended inside the steaming tunnel;
- 2) steaming area with one or two steaming tunnels with a suction system;
- 3) cooling area equipped with a suction unit assembled under the conveyor belt to eliminate the residual moisture;
- 4) fabric take up area, where an optical control system adjusts the speed to prevent any stretching of the rolled or folded fabric.

Technical innovations applied to the steaming process aim at obtaining a better final relaxation of the fabric and a reduction of the steaming stage, which requires a great quantity of steam (mostly dispersed outside through vents) and long processing times, since good results can be obtained only by keeping the fabric in contact with steam for a long time. The various machine manufactures have developed special systems to cut processing times and steam consumption and obtain an optimum relaxation of the fabric. The system shown in Figure 2.5 is characterized by a programmed and controlled dampening system assembled before the steaming tunnel [2].



**Figure 2.5** - Steaming unit: 1) braking bar; 2) fabric centering device; 3) dampener; 4) adjusting cylinder; 5) compensating cylinder; 6) moisture sensor; 7) feeding cylinder; 8) feeding sensor; 9) steam application field; 10) suction hood; 11) vibrating device; 12) blowing unit; 13) suction unit; 14) fabric unloading regulator; 15) fabric unloading cylinder; 16) variable folding device.

The dampening system has been introduced into the steaming unit for the reasons detailed below:

- steaming generally tends to reduce the moisture percentage dispersed in the fabric and therefore the pre-dampening operation grants a recovery ratio of the fabric after the treatment certainly better than the one obtained with a standard system;
- the moisture dispersed in the dampened fabric fed into the steaming system is transformed into steam, thus providing better shrinkage and relaxation results;
- commercial tests have shown a remarkable steam saving, thanks to the vaporization of water previously sprayed on the fabric.

### 2.3.2 – Decatizing

The process variables of all types of decatizing equipments can be classified in three groups:

- 1) fundamental physical variables: time, temperature and moisture content (regain) of the fabric;
- 2) mechanical pressure;
- 3) operating procedures: composition of the technical undercloth, sense of circulation of the steam (inside-outside, outside-inside, alternated), final thermal shock.

Time, steam temperature and moisture content are strictly correlated, meaning that for some aspects, if the intensity of one of these variables is reduced, the remaining two can be increased in order to compensate the first one.

Nowadays, the main issue is related to the effective evaluation of the moisture content during the process and, at the same time, the lack of suitable dampener devices, which can give a well defined moisture content to the incoming fabric.

Some devices have been already developed to overcome this problem, such as Hygrocor® and Weko® systems, which spray water droplets on the incoming fabric. Clearly, the critical factor is related to the need of a controlled and uniform penetration inside the fibers and not only on their surfaces.

One of the effects obtained with a decatizing treatment is connected to the reduction of the fabric thickness and the geometrical irregularities of the surface. Such reduction has indirect consequences on other physical properties and, more precisely, on the handle and the tailorability of the fabric.

Apart from these effects, the mechanical pressure given to the fabric when it is rolled up on the cylinder has a direct influence on the steam flow and on its properties, causing end-to-end variations between inner and outer layers of the fabric.

The radial mechanical pressure on the fabric ( $P$ ) depends on the wrapping tension ( $S$ ), the fabric length ( $H$ ) and the radius of the roll ( $r$ ) which increases as new layers of the fabric are added:

$$P = \frac{S}{H * r}$$

It is clear that non-uniform decatizing treatments (end-to-end effects) are much more consistent while using small decatizing cylinders [3].

The technical underclothes, necessary to generate mechanical pressure on the fabric, can be generally divided in two types: satins, compact and smooth, and molletons, with a swollen and soft surface. As a consequence, different effects will result on the fabric surface.

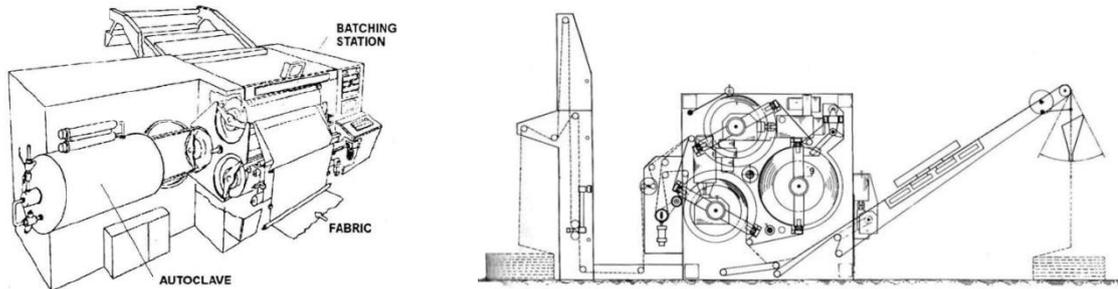
The sense of circulation of the steam is relevant mostly when small decatizing cylinders are used in order to obtain a homogeneous treatment.

### 2.3.3 – Pressure decatizing

Pressure decatizing is one of the finishing processes, which permanently set the thickness and relaxed dimensions of a fabrics. It also usually permanently increases surface smoothness and can change fabric suppleness.

In the pressure decatizing process, wool fabric is treated in an autoclave (pressurized vessel) with steam at a pressure greater than the atmospheric one. This occurs while the fabric is interleaved with a wrapper and wound into a batch on a hollow perforated

cylinder. Figure 2.6 shows the principal components of a typical batch pressure decatizing machine.



**Figure 2.6** - General view (left) and side view (right) of a batch pressure decatizing machine.

Although there are many different designs, the most common basic components are as follows:

- 1) a station to prepare the fabric/wrapper batch and to unroll the batch after steaming;
- 2) a transfer system to move the batches to and from the autoclave;
- 3) an autoclave with heated walls, preferably with connection to a vacuum pump;
- 4) provision for cooling the fabric after treatment.

Once that the textile roll is placed in the autoclave, steam is forced through the layers of fabric and wrapper. The direction of the steam flow can usually be varied from outside to inside or alternatively from inside to outside. Before the fabric is steamed under pressure, the air within the autoclave and fabric/wrapper assembly must be removed and replaced with steam. This is achieved by purging the system with steam. Steam can be blown through the batch under relatively high pressure. Alternatively, a vacuum pump can be used to remove most of the air before steam is introduced at a lower pressure. Purging is necessary to ensure that the temperature inside the pressure vessel reaches the desired value. At a pressure of 2 atm the presence of 20% (by volume) of air in saturated steam can lower the temperature by 7°C.

After purging, the steam pressure is rapidly raised to the desired level and maintained for a period of time, usually less than 5 minutes. Then the pressure is released by venting the autoclave to the atmosphere. The fabric/wrapper package is removed from the autoclave and is usually unrolled while still warm. Sometimes the fabric is cooled before unwrapping by sucking room air through the package or, alternatively, ambient air may be blown over, or sucked through, the fabric as the batch is unrolled.

As previously said, wrappers are available in a variety of fiber compositions, thickness and densities. The most common type of wrapper is formerly a heavy-weight cotton

woven fabric but is now usually made from wrap-spun yarn with cotton around a core of filament synthetic fibers.

During the total process of pressure decatizing, both cohesive and permanent set are introduced into fabric. The amount of permanent set imparted increases with increasing temperature (above 100°C), treatment time, moisture content and pH of the fabric. Practical limits on temperature, time and pH are set to avoid yellowing and excessive damage to wool. Figure 2.7 illustrates the relationship between initial regain and steam temperature for one particular fabric.

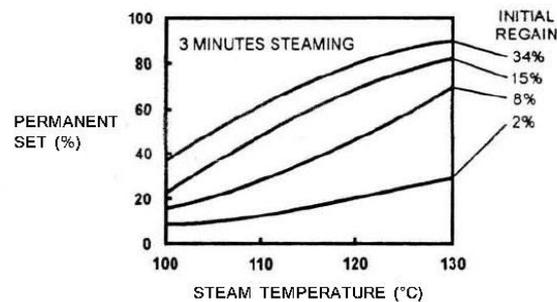


Figure 2.7 - Permanent set and process variables.

The pressure decatizing process is primarily a batch process. Most of the developments and improvements incorporated into commercial pressure decatizing machines have been aimed at improving three aspects of the process:

- to increase the production rate;
- to reduce the variation within the same batch;
- to reduce the variations between batches.

Enlarging the pressure vessel has increased production rates. Machines which can treat more than 800 meters of fabric are now available, giving an effective production rate between 10 and 30 meters per minute. The use of "carousels" for simultaneous winding and unwinding of batches and multiple batching stations with one autoclave has given a further increase in productivity.

The diameter of the perforated cylinder, on which fabric and wrapper are wound, is being continually increased. Increasing the diameter of the cylinder means a reduction in the number of fabric layers in a treatment batch. This minimizes both the difference in lateral pressure imposed on the inner and outer layers of fabric, and the time taken for steam to penetrate the package. This decreases two causes of end-to-end variation within batches.

Improving the control of wrapper tension has increased the consistency of mechanical pressure applied to the fabric. To minimize the effect of excessive compression on fabric layers at the centre of a batch, tension on the wrapper is reduced as the batch is formed.

There have been continual developments in wrapper design in order to improve wrapper life and keep pace with the requirements in pressure decatizing of very lightweight wool fabrics.

Automation and control have been continually improved to ensure good repeatability of machine conditions. These advances are usually confined to machine parameters such as purging time, purging temperature, steam pressure, steam temperature, wrapper tension, treatment time and post treatment cooling. However, for identical treatments, the fabric temperature and regains also need to be controlled.

Further improvements to the batch pressure decatizing process will come mainly from advances in control of process parameters, especially fabric and wrapper regain. Nevertheless, complete removal end-to-end variations are unlikely to succeed while pressure decatizing remains a batch process.

A versatile and efficient continuous machine would be the ultimate development in pressure decatizing. This would alleviate many of the previously mentioned problems associated with batch processing. The Ekofast® decatizing machine was the first commercial continuous machine to offer a finish similar in some respects to that of batch pressure decatizing. From then on, machinery manufacturers have developed prototype continuous machines. However, continuous machines have been unable to produce as a wide range of finishes as batch machines.

### **2.3.3.1 – Purging**

During purging, steam penetrates the package as a fairly discrete front. Condensation of steam occurs at the front and the fabric temperature rapidly rises. Air is displaced from the fabric with the propagation of the front. The condensed steam increases the regain of the fabric, facilitating the permanent setting of the wool.

When a number of materials are heated together, the amount of heat required to raise the temperature of the composite by a specified number of degrees is the sum of the heat requirements of the components. As an example, for a wrapper and fabric initially conditioned at 20°C and 65% relative humidity, about 6% by weight of water will be condensed on the fabric and wrapper to raise the temperature to 100°C.

If a vacuum pump is used to assist purging by removing much of the air from inside the batch before the steam is turned on, lower steam pressures can then be used. An advantage of this method is that less permanent setting takes place during purging. If high-pressure steam is used, permanent setting of the wool can begin before the steam

has fully penetrated the package. This leads to uneven treatment. The passage of the steam front through the fabric and wrapper package may take more than 5 minutes, depending on the size and porosity of the package and the pressure of the steam.

An important function of purging is the removal of air from the wool. The oxygen in the air can react with wool causing yellowing and lowering the permanent setting effect. Also, some dyes are not stable to oxidation and dyed colors can be affected by a greater or lesser extent.

### 2.3.3.2 – Effect of initial moisture content of the wool

As the steam front reaches a particular layer of fabric and condensation occurs, the condensed water is available for absorption by the fibers of both the wool fabric and the wrapper. The absorption of water by the wool and cotton results in the liberation of energy, known as "heat of sorption", which increases the temperature of the fabric and wrapper above the steam temperature. The amount of heat released per unit mass of wool depends on the initial and final regains of the fabric and wrapper and is greatest when the regain is lowest.

The regain of cotton at any relative humidity is about one third that of wool and its heat of sorption is about one fifth that of wool. It has been found that pressure decatizing on wool fabric that has not been adequately conditioned will not only result in a lower level of permanent set, but a greater probability of yellowing due to the temperature of the batch being considerably above the steam temperature.

Figure 2.8 shows temperatures during a pressure decatizing cycle when the initial regain of the wool fabric was about 4%. The temperature outside the batch is shown by trace 1, and the temperatures of the fabric near the outside and centre of the batch are shown by traces 2 and 3 respectively. The direction of steam flow was from outside to inside. The temperatures inside the batch reach a maximum of about 10°C higher than the steam temperature of 130°C.

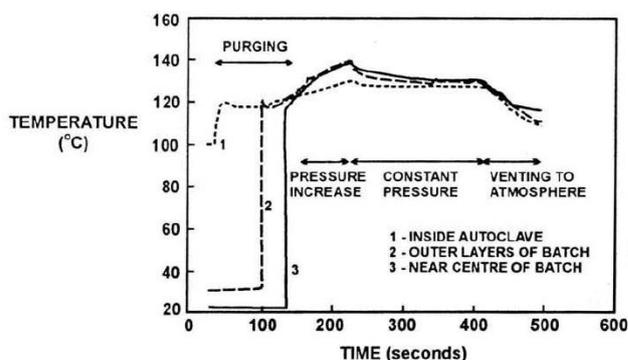


Figure 2.8 - Temperature evolution in different positions inside a pressure decatizer.

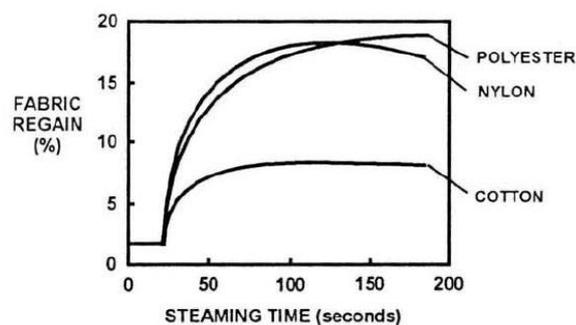
As it will be seen in the following chapters, temperature differences established when the steam front initially moved through the batch, can persist to some extent throughout the decatizing process. These temperature variations can produce uneven treatment in a batch.

Processes usually carried out before pressure decatizing include drying and rotary pressing. Immediately after these processes, fabrics are likely to have regains between 2% and 8%. This range of values is less than optimal for pressure decatizing. It is difficult that fabric will increase its regain significantly while standing in a dry finishing area. The air in that part of the mill tends to be at low relative humidity and is unable to provide significant amounts of moisture to the wool. Also, fabric conditioning while it is stored on carts or in rolls, is very slow and may take several weeks. A conditioning process to increase the regain of fabric to at least 15% is highly desirable if efficient permanent setting has to be achieved.

### 2.3.3.3 – Effect of the wrapper

The variables associated with different wrappers, such as thickness, density, weave, and fiber composition, all affect the outcome of the process. However, with a particular wrapper, the main variables are wrapper tension, temperature and regain.

The moisture that condenses in the batch of fabric during the heating phase may exceed the absorption capacity of the wrapper. Excess condensed water may remain as free water in the wrapper, or the wool fabric being treated may absorb it. The transfer of free water from the wrapper to the wool fabric can further increase the fabric regain. Absorption of the extra water will further raise the fabric temperature due to the evolution of extra heat of sorption. Figure 2.9 shows the calculated changes in regain that may be expected when fabric, initially at a low regain, is steamed with wrappers made from cotton, polyester or nylon.



**Figure 2.9** – Relation between wrapper composition and fabric regain.

The expected increase in regain of wool steamed with a cotton wrapper, is much smaller than with a polyester or nylon wrapper. The different effects are due to the varying amounts of moisture absorbed by the cotton, nylon and polyester fibers and the subsequent transfer of excess moisture from the wrapper to the wool fibers. With wrappers which are unable to absorb all the condensed water, the regain achieved by the wool during steaming can be expected to increase as the proportion of the wrapper mass to wool fabric mass in the batch increases.

Also the wrapper tension needs to be carefully controlled. Fabric needs to be restrained under enough pressure to produce the desired changes in surface texture and fabric thickness. Sometimes the wrapper pressure alone reduces the fabric thickness to the required level.

If the wrapper tension is too high, very dense packages may be formed which result in undesirable effects. High wrapper tension results in a package that is less permeable to the steam flow and high-pressure differences across the package must be used in purging. This means that the pressure and temperature on the inlet side of the package may be high enough to introduce permanent set before the package has been properly preheated. In these circumstances, it is almost impossible to obtain an even degree of permanent setting through a batch, even when the steam flow direction is alternated. Vacuum-assisted purging can reduce the steam pressure required for purging and unwanted permanent setting at this stage of the process can be reduced.

#### **2.3.3.4 – Steaming under pressure**

The steam temperature inside the decatizer is usually controlled by varying its pressure. Steam is normally supplied to the decatizer at pressures between 6 and 8 atm. For consistent results, the steam pressure, temperature and relative humidity should be constant. It is highly desirable that the steam which comes in contact with the fabric should be saturated.

Saturated steam is in thermodynamic equilibrium with water but very little free water may be present. Saturated steam is referred to as being wet if appreciable amounts of free water are suspended in the steam as small droplets or a fine mist. If the temperature of steam is higher than that of saturated steam at the same pressure, (i.e. its relative humidity is less than 100%) the steam is superheated and contains no free water. Superheating occurs when steam loses pressure without losing heat. The most common cause of superheating results from the reduction in pressure between the steam supply line and the interior of the pressure vessel. Not only the temperature of the steam at a given pressure will be higher than desired but the regain of the wool during decatizing will be lower than expected. If superheated steam comes in contact with water it will

evaporate the water until the temperature of the steam drops to the saturation temperature (or all the water has been evaporated).

The high-pressure steam supply is often wet. If the steam contains about 4.5% moisture, saturation will be maintained as the pressure is reduced to atmospheric. In textile mills, steam is often wet, particularly when it is piped appreciable distances from a boiler, even if water separators are fitted.

Superheated high-pressure steam can become saturated if it passes through the outer jacket of the decatizer pressure vessel before passing into the pressure vessel. Condensation of water in the jacket due to heat losses from the decatizer can provide free water to saturate the steam. The effectiveness of this approach may depend on the design of the machine, the ambient temperature and the preheating conditions.

### **2.3.3.5 – Fabric handle and yellowing**

Another important result of pressure decatizing is a change in the fabric flexibility. However, there is little quantitative information available on the relationship between subjective handle and the operating parameters of the process.

Reductions in bending stiffness and shear rigidity can be observed, but the effect of these changes on subjective handle is complicated by concurrent changes in surface smoothness and fabric thickness.

The requirement for permanent setting has to be balanced against the yellowing of wool which occurs at high temperatures. Fabric temperature is more critical than steam temperature as far as yellowing is concerned. It is known that fabric yellowing during pressure decatizing increases with the temperature at which fabric is steamed. Yellowing can be affected by the initial regain of the fabric. With fabrics at low regain, their temperature can be significantly higher than the steam one because of the heat of sorption released when water is absorbed by wool.

Consequently, fabrics at low initial regain can become more yellow than fabrics at high regain. Hence, to achieve a given level of permanent set with minimum yellowing, pressure decatizing should be carried out at the lowest practicable temperature and highest practicable regain.

## **References**

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- [2] P. Bellini, F. Bonetti, E. Franzetti, G. Rosace, S. Vago, *Finishing*, Fondazione ACIMIT, 2006.
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## **Chapter 3**

### **3. Experimental evaluation of heat and moisture transfer in steam treated wool fabrics**

#### **3.1 Introduction**

In the previous chapters, finishing steam treatments and the resulting modifications on fabrics and fibers have been described.

The importance of setting is strictly connected to the type of treatment that is realized and, therefore, on the steam conditions.

Time, temperature, moisture content and mechanical pressure are the four fundamental parameters which affect directly the finishing process and the setting itself, but if the mechanical pressure effects are already well known, temperature and moisture content vary continuously during the process, interacting each other.

The effect of these variables is remarkable especially during pressure decatizing (KD), as it is carried out in a batch and both steam properties and fiber modifications within the autoclave are not monitored.

In this view, the pressurized vessel is considered as a black box. Only the workers' experience, based on previous tests, allows defining a set of initial conditions in order to obtain the desired final result.

It is clear that, as long as these phenomena are not fully understood, an improvement of this process will be extremely difficult. It has been said that the main difficulties related

to a KD treatment lie in the process itself, carried out in a batch, which often causes non homogeneous treatments, not only between different batches, but even within the same batch.

In this view, an analysis of the current problems related to KD treatments has been carried out directly in a well-known textile industry located in the Biella District, which has confirmed the critical issues that still nowadays arise from this process.

Once defined these critical factors, a fundamental study has been carried out on bench scale and prototypal apparatuses, due to the difficulties to perform an experimental campaign on a full scale KD equipment.

The present chapter shows the results obtained from an experimental research activity aimed at analyzing the effects of different steam treatment conditions on wool fabrics. Both temperature and moisture content variables are considered, whereas two different bench scale equipments have been used. Each of them was suitable to analyze a specific variable.

### **3.2 Identification of the current problems in industrial KD treatments**

The analysis of the current problems arising during KD treatments has been carried out directly on a full-scale equipment, located in a textile industry of the Biella District, with the support of the machine manufacturer.

In their current production, the critical factors in the finishing processes arises especially from the difficulties in the treatment of two kind of items: a 100% wool fabric and a 90% wool – 10% polyester fabric.

The KD treatment on the 100% lightweight wool fabric always causes end-to-end variations within the same batch. Often these variations concern not only the difference between inner part and outer part of the textile roll, but also between inner part and central part or between central part and outer part.

These variations are clearly visible and determined by different brightness along the length of the fabric. Besides the visual analysis, the problems have been confirmed also by a colorimetric analysis using a UV-Vis reflectance spectrophotometer. With this instrument, the color differences between a standard and a batch samples can be analyzed.

A first problem has been found in the technical undercloth (wrapper). Usually on the perforated drum several meters of wrapper have to be rolled up before starting to roll up the wool fabric. This is due especially to avoid the shiny effect which could be caused by the stainless steel drum. Therefore, brightness problems in the inner part of the fabric

have been solved by doubling the length of the wrapper on the drum (from 40 m to 80 m).

The resulting decatizing treatment showed again irregularities between the center part of the roll and the two ends, while inner and outer parts were almost good.

A further modification has been done by varying the tension curve of the wrapper in the central part of the roll, in order to apply a lower mechanical pressure. This solution, together with the use of stronger final clamps (to hold the outer part of the textiles at the end of the wrapping process), brought to the best results, confirmed also by colorimetric analysis.

As far as the other type of item is concerned, a different evaluation has been done. The 90% wool – 10% polyester fabric did not show brightness or shade differences but a strange behavior, which it is correlated to the different properties of the two fibers.

In particular, the polyester is weaved in the form of continuous filament yarns, which cover the entire length of the wool fabric (warp direction).

When the fabric undergoes a KD treatment and is subsequently dried and relaxed, its surface becomes wavy and the fabric loosed its traditional flat appearance.

This problem has only been reduced, but not completely solved, by another KD treatment. Different configurations of the decatizing cycles have been applied, but each trial has not been considered satisfactory.

The actual problem has been found in the initial conditions of the fabric and in the different properties of the two fibers. Indeed, the evaluation of the initial moisture content, carried out with a portable moisture meter, showed moisture content lower than 5%. In these conditions, it is possible that a sufficient degree of permanent setting has not been achieved in wool fibers.

Therefore, the structure of the fabric is not fully stabilized and the relaxation shrinkage occurring when the fabric is relaxed, causes the fabric to become shorter. This is valid for the wool fiber but not for polyester, which is a synthetic fiber with a completely different behavior.

The result of a non homogeneous (and permanent) set is a different stress induced in the two fibers: the wool will tend to become shorter but it can't be followed by the polyester, thus causing the wavy effect already mentioned.

It is evident that a second KD treatment on a fabric which is no more plain can only reduce the problem, due to the mechanical pressure applied in the wrapping phase, especially if, also in this case, the initial moisture content is low.

In conclusion, the two examples represents only a small case study but demonstrate the importance of this kind of treatment and the need of a precise set up when starting a new batch.

The applied mechanical pressure is well controlled during the wrapping phase and is always constant during the treatment. On the contrary, no practical information exists on the textile roll during the treatment as far as temperature and moisture content are

concerned. For this reason, a basic study on heat and moisture transfer during the treatment should be carried out in order to evaluate the phenomena and try to find out possible solutions to the current problems.

### 3.3 Heat transfer analyses

#### 3.3.1 – Experimental apparatus

The Vapotest equipment, made by Officine Bisio S.a.s. and located in the CNR-ISMAL laboratories in Biella, has been used to carry out bench scale trials, in order to analyze heat transfer and temperature evolution during steam treatments of wool fabrics.

The apparatus (shown in Figure 3.1) reproduces the same conditions to which the fabric is subjected during the finishing phases and, in particular, during calendaring and decatizing. The machine consists of a small autoclave, containing two perforated plates (200x200 mm) between which the fabrics to be tested are placed while being steamed and pressed at the same time.



**Figure 3.1** - Bisio Vapotest: front view (left) and detail of the treating chamber (right).

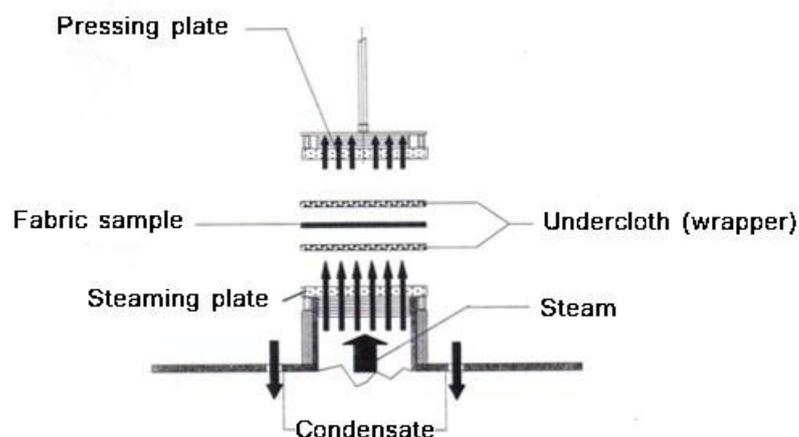
An external boiler, with a volume capacity of 28 liter, equipped with a 5 kW electrical resistance, supplies a maximum steam flow rate of 7 kg/h directly to the pressurized vessel. The autoclave is also equipped with a regulating valve of steam pressure, a digital indicator of the internal temperature, a squeezing pressure regulator for the plates and a process timer.

The flexibility of the equipment allows to operate with different conditions and to set independently several parameters:

- steam conditions (dry saturated or superheated);
- steam pressure and temperature;
- treatment time;
- mechanical pressure.

The last variable is useful to define the conditions currently adopted in an industrial KD treatment, whereas when the mechanical pressure is set to zero, the conditions of a steaming treatment will be recreated.

The scheme reported in Figure 3.2 shows the operating principle of the equipment. Fabric samples (one or more) are placed with the technical undercloth (eventually) on the steaming plate and then pressed with the upper plate thanks to a pneumatic cylinder. The decatizing treatment takes place when, from the steaming plate, the steam is forced through the textile material, replacing air that is vented to the atmosphere. At the end of the treatment time, condensate outlets are opened and cooling air is introduced into the autoclave.



**Figure 3.2** - Bisio Vapotest operating principle.

### 3.3.2 – Samples preparation

The tests were carried out using a 100% wool, plain worsted fabric, 150 g/m<sup>2</sup> specific weight and average fiber diameter of 18 μm. It is a typical lightweight fabric used for dresses, which was not subjected to any kind of finishing treatments.

The fabric was withdrawn directly from a weaving process, thus it still contains oils and waxes that have been applied to perform the previous processes (e.g. spinning and weaving). Steam treatments are regularly carried out on “clean”, often dyed fabrics; therefore a washing step is necessary to remove undesirable substances from the textile material.

Before any other operation, the wool fabric used in these tests was washed at 40°C with a standard surfactant (ECE) at 1 g/l concentration. The fabric was then rinsed with warm and cold water in order to ensure a complete removal of detergent.

The wet fabric was then dried in an oven at 60°C until dry weight (0% moisture content). A further operation was carried out by placing the fabric in the oven at 105°C and weighting it after 10 min. The fabric is considered dry when the difference between two weightings is less than 0.03%.

The fabric is then conditioned to achieve the desired initial moisture content, which is one of the variables that have been selected for our tests.

Moisture content (MC) is calculated as follows:

$$MC = \frac{W_1 - W_0}{W_0}$$

where:

$W_0$  = weight of the dry fabric;

$W_1$  = weight of the conditioned fabric.

Fabric samples of 200 x 200 mm are then cut and stored into polyethylene bottles (Figure 3.3) in order to avoid moisture absorption / desorption from the environment before starting a new test.



**Figure 3.3** - Fabric samples and storage bottles.

### **3.3.3 – Operative conditions**

Different variables can be considered in order to analyze the operative conditions for steaming and decatizing.

- Steam condition: although both dry saturated and superheated steam can be supplied, only the dry saturated one has been taken into account since it is most used in finishing treatments.
- Steam temperature: 100°C and 120°C have been evaluated in order to study steaming, atmospheric decatizing and pressure decatizing. Actually, steam temperatures for industrial pressure decatizing are a little bit higher (125 – 130°C), but, because of boiler limitations, these steam temperatures can't be maintained for a sufficient period of time.
- Treatment time: up to 12 min.
- Initial fabric moisture content: as already seen in Chapter 2, for a KD treatment an optimal initial moisture content value should be around 15%. However, industrial practice shows that fabrics which have to undergo KD treatments, often come from a drying step or have been stored in low humidity areas. Therefore, the moisture content of these fabrics is lower than the optimal one, with average values around 8%. In order to evaluate both cases, the two moisture contents, 15% and 8%, were selected as initial values for our tests.

- Thickness of fabrics bed: the equipment allows to operate with a maximum thickness bed of 50 mm, which corresponds to a stack of 40 layers (samples) of fabric (Figure 3.4). Since the stack of samples is used to simulate a KD treatment, mechanical pressure is also applied, thus reducing the thickness of the stack to an average value of 10 mm.



**Figure 3.4** - Stack of fabrics constituting a 50 mm thickness bed.

With respect to an industrial KD treatment, the system has been simplified avoiding the use of the wrapper, thus to have a homogeneous bed and study the behavior of wool fabrics only.

Thermal evaluations have been carried out by means of copper-constantan thermocouples (T type), 0.4 mm diameter, interleaved between the layers of fabric samples. The temperature sensed by the thermocouples were recorded by a datalogger at 1 s intervals and  $\pm 0.1$  resolution, sent and stored on a pc.

The thermocouples were introduced inside the autoclave thanks to a special seal which impede possible leakage of steam. A global view of the equipment and the monitoring system can be seen in Figure 3.5.



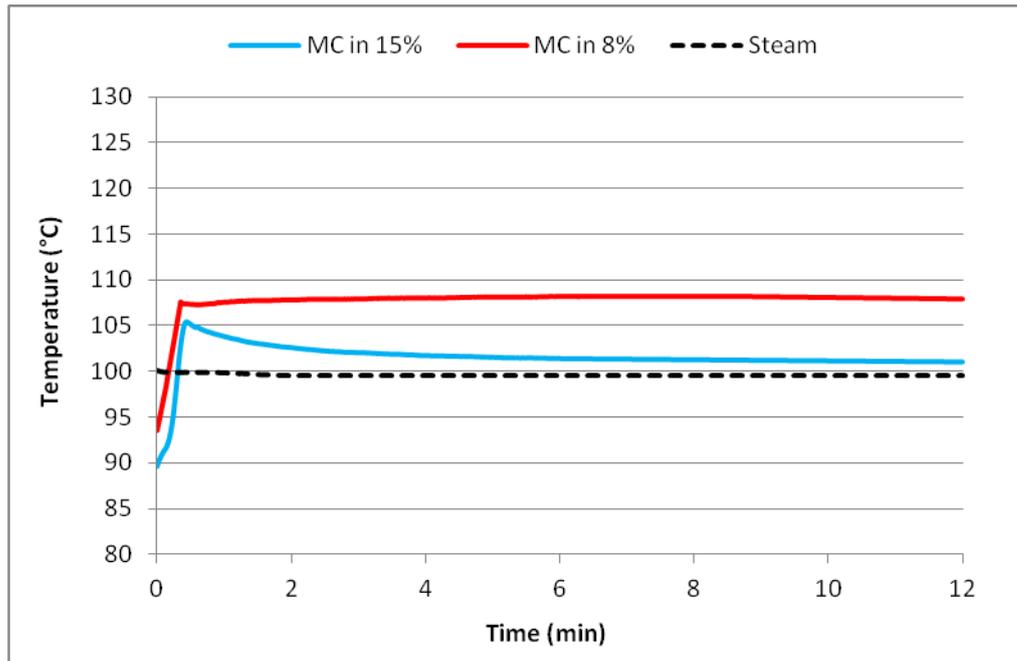
**Figure 3.5** - Global view of the Bisio Vapotest equipment and the monitoring system.

As usually performed in the industrial practice, two treatment cycles of 12 min without textile material (empty autoclave) were done before starting the first test of the series (start up of the equipment), in order to warm up all the components and particularly the autoclave. To ensure the repeatability of the treatment, every test has been replicated three times.

### **3.3.4 – Results and discussion**

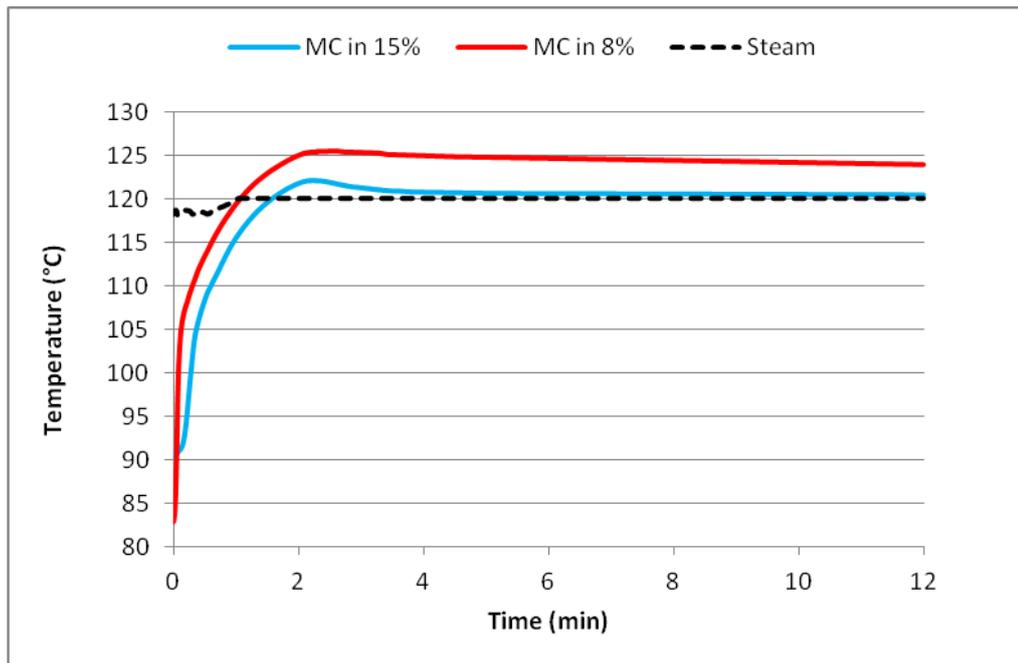
The tests carried out during this part of the work are going to be explained in this section in the attempt of focusing the attention on the most influent variables of the process. Therefore, results obtained with two steam temperatures (100°C and 120°C) on treated material with two different initial moisture contents (8% and 15%) are reported. Dry saturated steam conditions have been selected for both temperatures, whereas the steam flow rate has been regulated in order to achieve steam velocities comparable to those obtained during industrial processes. This choice is important especially when considering KD treatments, in which steam flow rates depend on the perforated drum dimensions, the amount of rolled fabric, the sense of circulation (outside-inside or the

opposite), and the finishing effect. Generally, modern KD equipments allow to use steam flow rates between 100 kg/h and 150 kg/h, or even higher if necessary. For typical treatments this means a range of steam velocities between 0.25 cm/s and 1 cm/s. In Figure 3.6 the behavior of two steaming-like treatments have been compared; the fabrics were treated with steam at atmospheric pressure (1 atm absolute, 100°C).



**Figure 3.6** - Temperature profiles for 8% and 15% initial moisture content fabrics treated with steam at atmospheric pressure and 100°C.

Figure 3.7 represents the comparison of two KD-like treatments, carried out at 120°C and 1.98 ata.



**Figure 3.7** - Temperature profiles for 8% and 15% initial moisture content fabrics treated with steam at 1.98 ata and 120°C.

The black dashed lines represent the steam temperature at the inlet of the autoclave, which is kept constant during the whole treatments. The blue and the red lines represent respectively the temperature evolution of a 15% and a 8% initial moisture content fabrics.

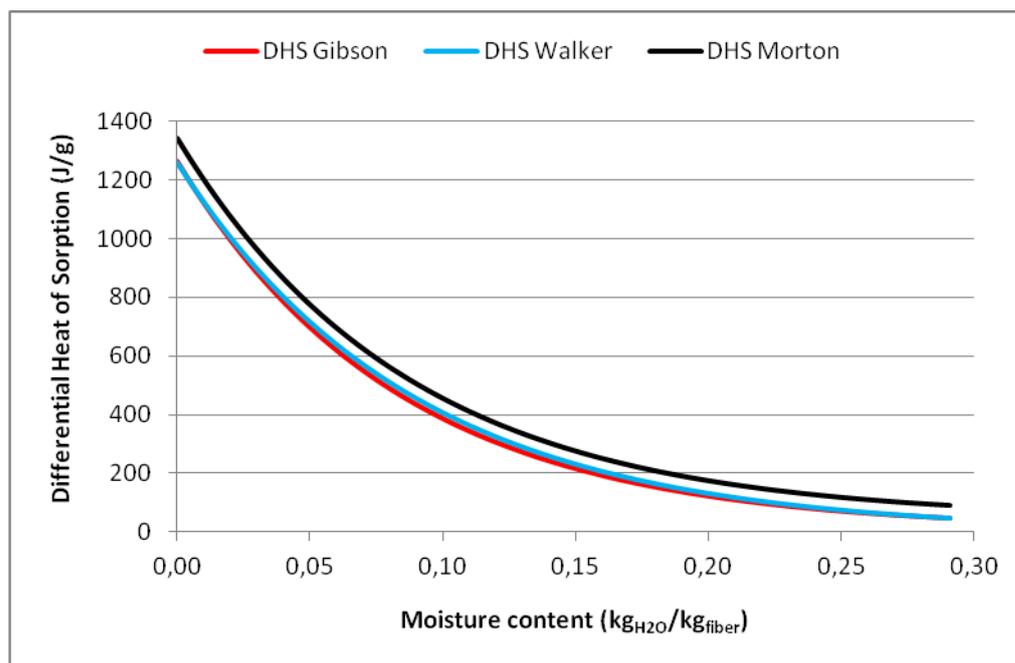
The initial fabric temperature is approximately around 90°C. Actually, before introducing the fabrics into the autoclave, they all have the room temperature. However, when they are introduced in the autoclave, they quickly reach the autoclave temperature, which is quite high because of the previous warm up.

It can be seen that all the fabrics reach and exceed the steam temperature in a short time, less than 1 min for fabrics treated at 100°C and about 2 min for fabrics treated at 120°C. The fabric temperature is always higher than that of the steam, due to the heat released as the wool absorbs moisture.

This behavior can be explained considering that when a fiber absorbs water, heat is released, as a result from the attractive forces between fiber molecules and water molecules.

The differential heat of sorption (sometimes called heat of sorption or heat of absorption) is the heat released when 1 g of water is absorbed by an infinite mass of the material at given moisture content. It is expressed in joules per gram (of water absorbed).

As far as our tests are concerned, it is noteworthy that the amount of heat released depends on the moisture content of the fiber. At zero moisture content, the differential heat of sorption is about 1250 J/g and strong bonds are created. As absorption continues, the water is more loosely attached, and consequently less heat is evolved. The relation between the actual moisture content of the fiber and the heat released when absorbing water at that moisture content, has been described by several authors, namely Walker [1], Morton [2], and Gibson [3]. Their studies brought to similar results that are shown in Figure 3.8.



**Figure 3.8** - Differential Heat of Sorption (DHS) with respect to the fiber moisture content. Comparison among Gibson, Walker and Morton studies.

Our results show that in both the treatment conditions (100°C and 120°C) the initial moisture content plays an important role in the actual fabric temperature evolution. Fabrics conditioned at 15% initial moisture content show only a small increase in the fabric temperature which drops after few minutes, reaching a value close to that of the steam. Low regain fabrics, at 8% initial moisture content, are more affected by the heat of sorption, thus allowing to maintain the fabric temperatures higher than that of the steam for longer times.

### 3.4 Moisture transfer analyses

#### 3.4.1 – Experimental apparatus

Concerning the moisture content evaluation, another type of equipment has been developed and used. The reason is due to preliminary tests carried out with the Bisio Vapotest apparatus which demonstrated that the moisture content evolution during the treatment is characterized by slow kinetics. As a consequence, the maximum treatment time achievable in the Bisio Vapotest (12 min) allowed obtaining only partial results, which could not be sufficient for a complete study.

The new equipment has been developed and built in order to treat fabric samples at different steam conditions and for long times, up to 4 h, in order to evaluate the fibers moisture absorption until equilibrium is reached.

The scheme can be seen in Figure 3.9.

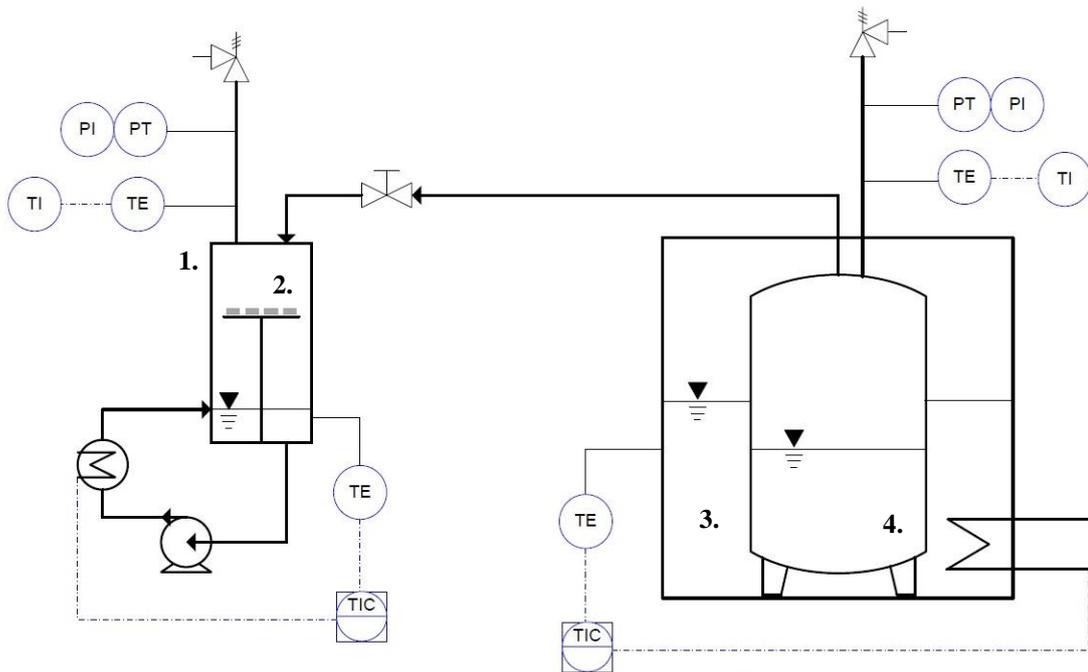


Figure 3.9 - Scheme of the equipment used for moisture transfer evaluation: 1. treating chamber; 2. fabric sample; 3. glycerin bath; 4. tank for steam generation.

The equipment consists of a 36 liter glycerin bath that can be heated thanks to a 6 kW electrical resistance. The glycerin bath temperature is controlled and on-line monitored using a PLC, which allows setting up temperature gradients and maintenances as well.

A 10 liter capacity stainless steel tank is immersed in the glycerin bath. The tank has been selected in order to hold an internal pressure higher than 10 ata in order to generate saturated steam at various temperatures.

An insulated pipe connects the tank directly to the pressurized chamber, in which the steam, regulated by a needle valve, flows and condenses on the wall.

The 1.5 liter Pyrex glass chamber, is equipped with a recirculation and a heating systems for the liquid phase being generated by the condensing steam. Similarly to the glycerin bath, the temperature is controlled and monitored using a PLC in the treating chamber too.

Temperature and pressure monitoring systems have been adopted both in the steam generation tank and in the treating chamber, thus to evaluate and check the steam conditions during the tests.

Differently from the Bisio Vapotest apparatus, the present one is not equipped with a mechanical pressure device; as a consequence fabric samples are not constrained in any way.

### **3.4.2 – Samples preparation**

The fabric used in these tests is the same used for the heat transfer analysis, thus it has been subjected to the identical washing and conditioning pre-treatment operations.

Fabric samples were then cut in a circular shape, 70 mm diameter, to be adapted to the treating chamber, and stored into polyethylene bottles in order to avoid moisture absorption / desorption from the environment before testing.

### **3.4.3 – Operative conditions**

The variables taken into account for the moisture transfer analysis are almost similar to those considered for the heat transfer analysis, although some particular choices have been made.

- Steam condition: the tests have been carried out considering a saturated steam, since it is the most used in finishing treatments.
- Steam temperature: the equipment allowed to reach temperatures up to 140°C, therefore 100°C, 120°C and 140°C have been selected in order to cover the temperature range usually found during steaming and decatizing.

- Treatment time: up to 4 h. The tests have been carried out in order to evaluate the variation of moisture content within the wool fiber during time. For this reason different treatment times have been selected: 5, 15, 30, 60, 90, 120, 240 min. Although long treatment times are not used in industrial operations, the reason why they have been chosen for our tests is due to the need of performing a complete study on the moisture absorption kinetics of wool. This is why all tests were led until moisture content equilibrium.
- Initial fabric moisture content: following industrial practice, a 8% initial moisture content was chosen to carry out the tests. This is an average value, although a reasonable range could vary from 6% to 10%.
- Thickness of fabrics bed: even if several layers of fabric could be treated at the same time, only one layer at a time undergoes treatment. The fabric sample is therefore immersed in a saturated steam atmosphere and the transport resistances are characterized only by the structure of the fabric, yarns and fibers themselves.

Also in this study, the system has been simplified avoiding the use of the wrapper, thus to have a homogeneous bed and study the behavior of the wool fabrics only.

Fabric samples are placed on a supporting frame (Figure 3.10 on the left) and then put inside the treating chamber only once the desired steam conditions are reached (Figure 3.10 on the right).



**Figure 3.10** - Preparation of a fabric sample (left) and particular of the treating chamber when performing a test (right).

To ensure the repeatability of the treatment, every test was replicated three times.

Moisture content evaluation before and after the treatment were done by weight measurements.

Post treatment operations aimed at removing the condensate fraction formed during the rapid cooling at the end of the treatment, were carried out in a pad mangle machine (Figure 3.11).



**Figure 3.11** - Pad mangle machine used for squeezing fabric samples after the treatment.

The presence of a condensate fraction on the fabric surface gives rise to consistent measurement errors when weighting the treated material. A solution has been found by interleaving the treated fabric sample between two blotting papers and then squeezing the assembly between the machine cylinders set at 1 bar gauge pressure.

After squeezing, the samples were then stored again in the polyethylene bottles and afterwards measured.

This measurement method has been selected because, still nowadays, it is the most accurate one. Electronic sensors based on conductive, resistive or capacitive systems could be suitable to be used on-line, within the equipments and during the treatments, but they are rather fragile and strongly influenced by the condensate fraction.

Capacitive sensors, which actually are the most accurate ones, are not suitable to work in extreme conditions, because they are negatively affected by the combined action of high temperature and humidity. As can be seen from Figure 3.12, this kind of sensors can work in a normal and in a maximum range of temperatures and humidity, but also the last case does not include the conditions used in our tests.

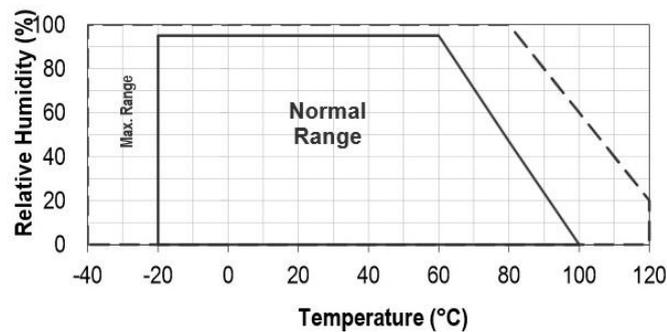


Figure 3.12 - Operating conditions for capacitive sensors.

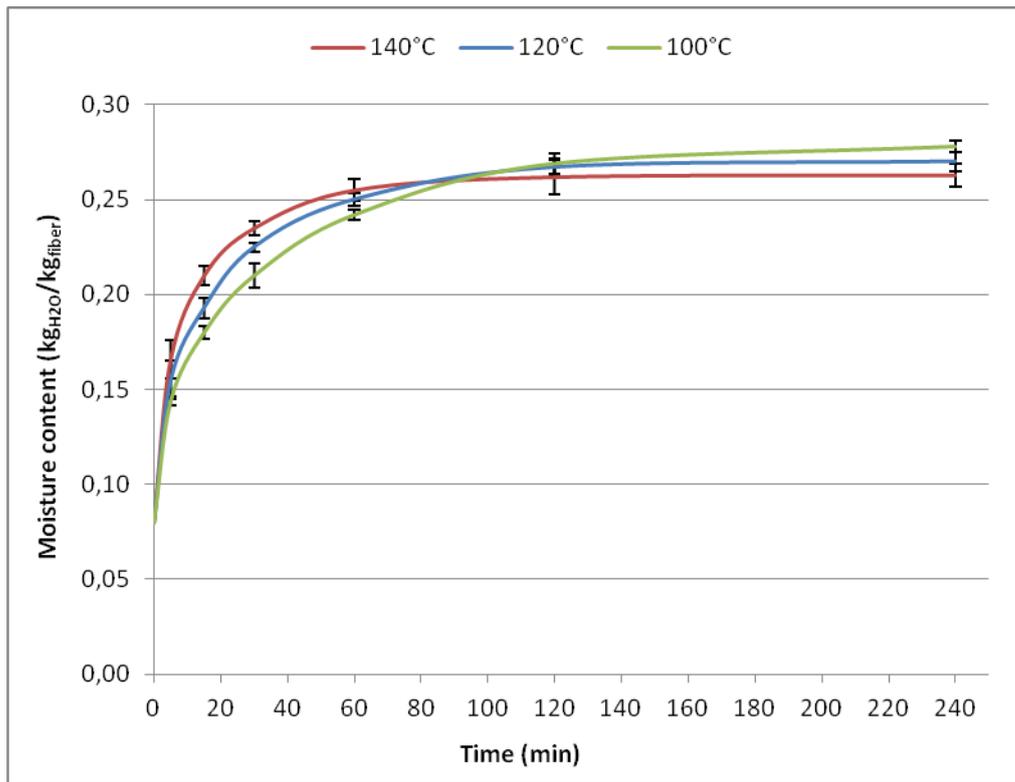
### 3.4.4 – Results and discussion

Since the diffusion of water molecules within the fiber is the limiting factor of the whole process, and considering the geometry of the system and the textile material under treatment, high steam flow rates are not necessary for this kind of study. Therefore the steam flow rate has been set around 0.5 kg/h, considering that the equipment can supply a maximum steam flow rate of 1 kg/h.

The comparison of the results obtained with the three operative steam temperature (120°C, 130°C and 140°C) is reported in Figure 3.13.

The figure shows the variation of the fiber moisture content due to the moisture absorption for different steam temperatures.

The error bars take into account both possible measurement errors and delay times at the beginning of every new test. The delay time represents the time required by the equipment to reach operative testing conditions. This means that when a fabric sample and the supporting frame are placed inside the treating chamber, and the steam starts to flow filling up the chamber, a minimum time is necessary so that the desired operative conditions are reached. The delay time can vary from few seconds when operating with steam at 100°C up to one minute with steam at 140°C. Clearly, this kind of error has much more influence for short treating time, 5 and 15 min, whereas it is almost negligible in the other contemplated cases.



**Figure 3.13** - Evaluation of the fiber moisture content with respect to the treatment time at different steam temperatures.

From Figure 3.13 it can be seen that the moisture absorption kinetics increase with increasing the steam temperature. It is also interesting to highlight that the final equilibrium values are slightly different. This is in accordance with previous works [4, 5] where it was experimentally verified that the amount of moisture absorbed at any specified humidity of the external environment decreases with increasing the temperature, but always maintaining a characteristic sigmoid curve. The following equation was proposed to describe the sorption isotherm of wool, which is applicable also for other keratin fibers such as human hair:

$$M_e = Z' \frac{Z \frac{p}{p_{sat}}}{1 + K \frac{p}{p_{sat}}} + W \frac{p}{p_{sat}} + z' \frac{z \frac{p}{p_{sat}}}{1 - k \frac{p}{p_{sat}}}$$

where  $M_e$  is the moisture content (kg/kg) at the equilibrium,  $p/p_{sat}$  is the relative humidity, that is the partial pressure of water vapor ( $p$ ) in the mixture air/vapor to the saturated vapor pressure of water ( $p_{sat}$ ) at a given temperature.  $Z'$ ,  $Z$ ,  $W$ ,  $z'$ , and  $z$

constitute a set of five parameters, which have been defined meanings in the context of the sorption processes and vary with temperature.

The right hand side of the equation contains three components. The first term has the form of a Langmuir isotherm and describes the adsorption onto a variety of molecular sites, summarized into a group classified as “strongly adsorbing.” The second term has the form of Henry’s law of mixing and describes adsorption onto the group of weakly adsorbing sites. The third term describes multilayer formation by water molecules, as described by the modified BET theory [6].

With respect to the range of temperatures used in our study, the previous equation generates three similar curves, as can be seen in Figure 3.14.

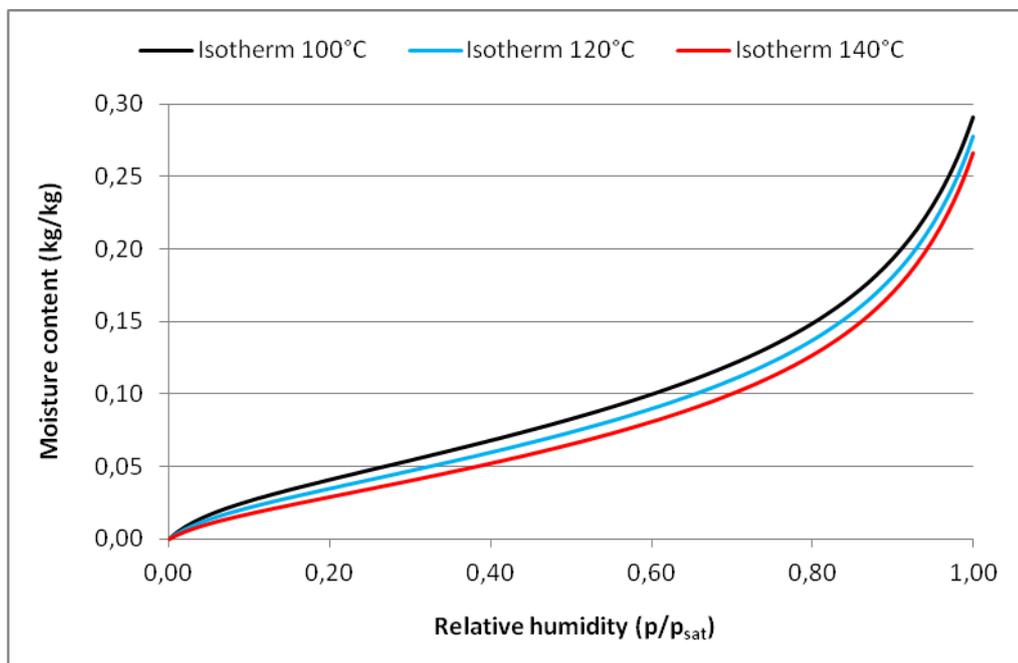


Figure 3.14 - Moisture content equilibrium values with respect to the relative humidity, at different temperatures.

Each point of the curve represents the fiber moisture content at the equilibrium with the corresponding relative humidity, at a determined temperature.

It can be seen that for a relative humidity equal to 1, that is the condition concerning our tests, the moisture contents that should be reached at the equilibrium are approximately 0.28, 0.27 and 0.26, respectively for 100°C, 120°C and 140°C isotherms.

These values are very close to those obtained in our tests, as far as the equilibrium conditions are reached.

The results obtained in our tests, reported in Figure 3.12, demonstrate that moisture absorption is surely the controlling factor of a finishing process, either steaming or decatizing. However, also in the case of pressure decatizing, where a consistent degree

of set should be imparted to the textile material, it is not necessary for the fiber to reach the moisture content equilibrium conditions, as explained in Chapter 1.

### 3.5 Conclusions

Heat and moisture transfer are fundamental phenomena of any finishing process. The degree of setting imparted to the fabric/yarns/fibers system depends on their combined action. The heat transfer is quite rapid, as we saw from experimental measurements; it takes less than 2 min for the fabric to reach the steam temperature. Moreover, thanks to the differential heat of sorption, the fabric temperature rises to values higher than those of the steam.

On the other hand, the moisture transfer is a relatively slow process because it depends on the diffusivity of water molecules inside the wool fiber structure, which is extremely compact and has a certain degree of crystallinity. It is clear that the initial moisture content of the fiber is the fundamental parameter affecting the effect of the steaming or decatizing treatments.

As far as the stabilization (set) phenomena are concerned, it is interesting to analyze again the regions in which cohesive and permanent set take place, taking into account the results obtained from our experimental campaign.

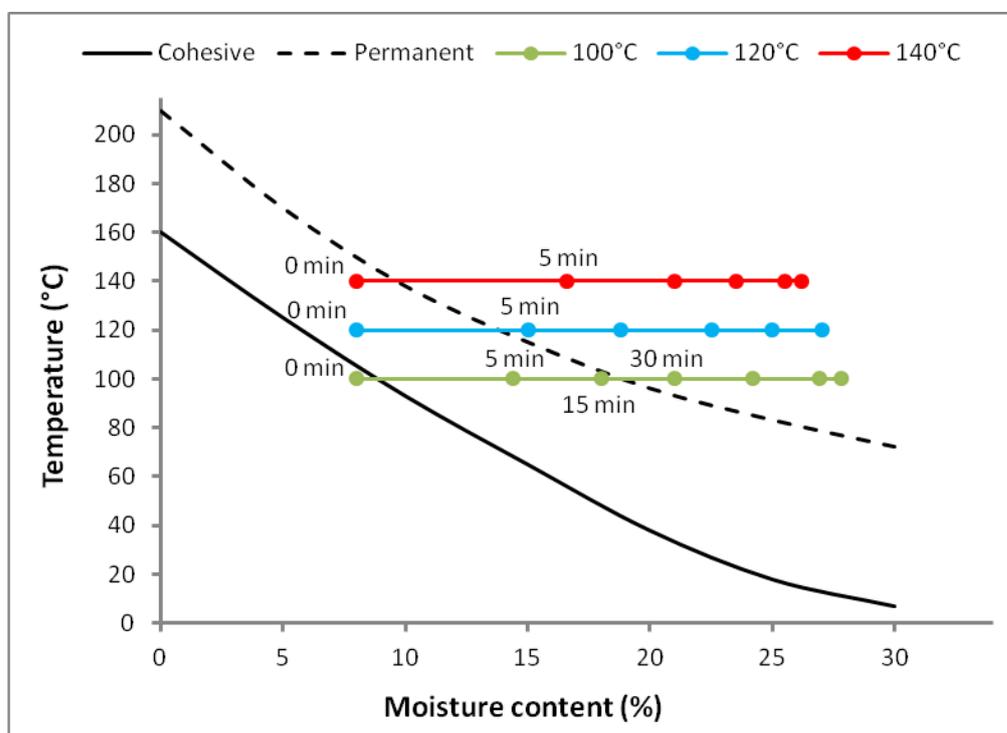


Figure 3.15 - Relation between setting regions and operative conditions for steam treatments.

Figure 3.15 shows the setting regions graph, already seen in Chapter 1, in which the operative conditions considered in our tests have been added. Variables such as time, temperature and moisture content determine the “operating points” of the process.

The graph is divided into three regions in which the stabilization phenomena could happen. Cohesive set region (between the two black lines) and permanent set region (above the dashed black line) are certainly the most important in finishing treatments.

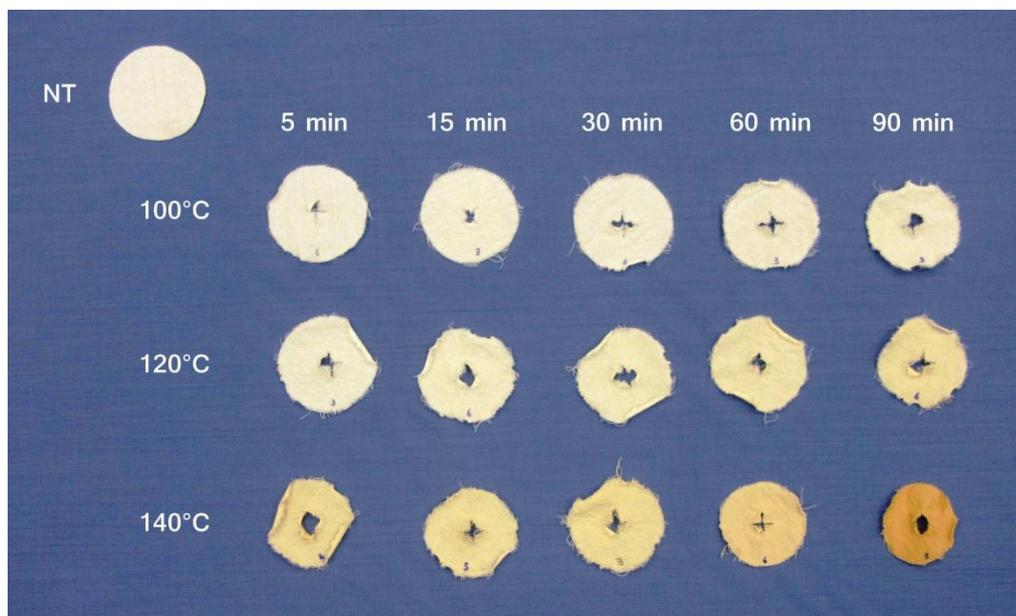
Process such as steaming and atmospheric decatizing, carried out with steam at 100°C, unlikely allow to obtain a permanent set on the treated fabric. This could happens only for long treatment times, i.e. more than 15 minutes if we start from a 8% initial moisture content.

Pressure decatizing allows to work with higher temperatures, between 125° and 130°C, thus reaching conditions to achieve high levels of permanent set in less than 5 minutes treatment.

Our tests carried out at 140°C demonstrated that the time necessary to reach an adequate moisture content, sufficient to give a permanent set to the fabric, is even lower, even if we would use higher steam temperatures.

By using high steam temperatures, a low initial moisture content is required to rapidly bring the fabric into the permanent set region; however another problem could arise from possible damages on the fibers.

Figure 3.16 gives an overview of the samples treated in our experimentations, at the three different temperatures (100, 120 and 140°C) for different treatment times (5, 15, 30, 60, 90 min), compared with the untreated sample (NT).



**Figure 3.16** - Overview of the samples treated at three different temperatures (100, 120 and 140°C) for different treatment times (5, 15, 30, 60, 90 min), compared with the untreated sample (NT).

During steam treatments, fabric yellowing increases with the temperature at which the fabric is steamed. It can be seen that, at 140°C, a treatment time of 5 minutes is enough to damage the fibers.

Generally speaking, fabric yellowing is affected by low initial moisture contents; indeed, in this case the fabric temperature can be significantly higher than the steam temperature because of the heat of sorption released when water is absorbed by wool.

As a consequence, to achieve a given level of permanent set with minimum yellowing, steam processes like pressure decatizing should be carried out at the lowest practicable temperature and highest practicable moisture content.

On the contrary, it has been said that it is quite common that fabrics which undergo KD treatments often own a low moisture content, close to 8% or even lower; therefore they should be brought to higher values before starting the setting treatment.

In this case the easiest solution could be to store the fabrics in a conditioning area, so that they could achieve the desired moisture content. However, as we have seen, this will be an extremely long process, because of the low diffusivity of water molecules inside the wool fiber structure.

Another possible solution could be to find and develop a pre-treatment operation, prior to KD, which could supply a homogeneous humidity on the entire fabric surface and at the same time well-penetrated inside the fiber structure.

In recent years, the problem related to the low moisture content of the fabrics has not been fully understood, as well as the lack of devices which can give a well defined moisture content to the materials that have to be treated.

Devices such as the ones developed by Weko, which can spray tiny liquid droplets on the fabric surface, or make the fabric passing through a confined area filled with a mist of saturated steam, represent only a partial solution. The main problem that has still to be solved is related with the need of a controlled and uniform penetration of water molecules inside the fiber structure, not confined on the fabric surface only.

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## **Chapter 4**

### **4. Modeling of the wool textile finishing processes**

#### **4.1 Introduction**

The results obtained with the experimental campaign demonstrated the importance of the process variables, namely temperature and moisture content, on the setting conditions of wool fabrics.

Despite that, the aim of the present work is also to understand the phenomena which govern the finishing processes, correlating these phenomena with the measured variables.

Therefore the purpose of this chapter is to develop a set of equations which could describe the coupled simultaneous transfer of energy and mass through hygroscopic porous media, to which a wool fiber can be assimilated.

The coupled heat and mass transfer between a penetrating mixture of air and water vapor and an absorbing fibers bed has already been evaluated in many literature works. The first model was proposed by Henry [1], who studied the diffusive penetration of atmospheric moisture into a bale of cotton. This work was soon followed by Cassie [2] who developed a forced convection model for the flow of moist air through a textile fibers assembly.

Various workers [3, 4, 5] have extended Henry and Cassie's approaches over the years, making different assumptions concerning the nature of the sorption process within hygroscopic fibers.

The above mentioned works all focused on woven and nonwoven textiles as the materials of interest, but many more studies have been undertaken considering the textile material as a porous media.

Whitaker [6] introduced for the first time the "local volume average" method, to model heat and mass transfer in a multiphase system consisting of multiple components within the same phase. Whitaker modeled the solid portion of the matrix as a rigid inert material, which only participates in the transport process through its thermal properties. In hygroscopic textile materials the diffusion of water into the solid is a significant part of the total transport process. Therefore, the inclusion of the extra transport terms into and out of the solid matrix necessitate significant modification of the Whitaker's original derivations.

Recent works [7, 8] carried out by Le, Ly and Postle, developed models based on the Whitaker's method applied to a porous fibrous material, which releases heat due to sorption of water vapor and also to the condensation occurring within the porous structure. They showed that the transient nature of the heat flow process in fibrous materials could produce large errors if the heat of sorption is neglected.

In the present study, energy, mass and continuity equations, as well as physical and experimental relationships, will be used to develop a model which can simulate heat and moisture transfers in wool fibers and fabric assemblies.

The development of the model has been achieved following two ways. A first simplified approach using a .NET Framework programming environment, which has brought to the creation of an executable (.exe) file running with Microsoft Windows operative systems. The long-term plan is to develop diagnostic software, which could predict the treatment conditions and the effects on the textile material by varying its own features as input data. In this way this application could be integrated in the equipment software, helping to perform problematic treatments.

The second approach was based on the integration of the above mentioned equations and relationships in a finite elements analysis simulation software, i.e. Comsol Multiphysics. It has been possible to create realistic geometries and to treat the gas phase as a real gas, whose characteristics depends on the fluid dynamics and thermodynamics of the system.

Both approaches brought to valuable results in good agreement with the experimental data, thus succeeding in the modeling of a quite complex system.

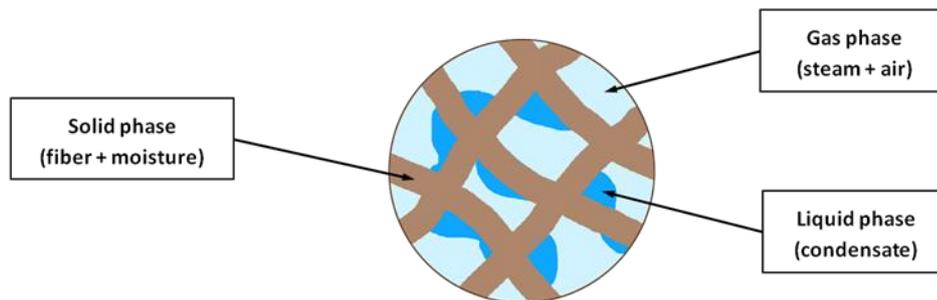
## 4.2 First approach: .NET Framework

### 4.2.1 – Model overview

.NET Framework uses the VB.NET programming language (the old Visual Basic) and a software editor, e.g. Microsoft Visual Studio, for the creation of programs and applications running with Microsoft Windows operative systems.

In the present study, Microsoft Visual Studio 2010 has been used as an equation editor to simulate heat and mass transfer occurring in a textile material when interacting with a steam flow.

The textile material has been assimilated to a hygroscopic porous media, whose generic geometry can be seen in Figure 4.1.



**Figure 4.1** - View of the multiphase system present in hygroscopic porous media.

A typical porous hygroscopic textile material can be described as a mixture of a solid phase, a liquid phase, and a gas phase.

The solid phase consists of the textile material, i.e. wool, plus any bound water absorbed in the solid matrix. The solid phase is thus a mixture of the solid and the liquid. This definition of the solid phase means that the density is dependent on the amount of water contained in the solid phase.

The liquid phase consists of the free liquid water, which may be present within the structure of the porous solid. This would also include the water which is contained within the pore spaces of the solid but is not absorbed into the solid matrix. This liquid phase is a pure component, and we will be able to assume a constant density for it.

The gaseous phase consists of the vapor component of the liquid (water vapor) plus the inert air component (only for the initial transient state). Since it is a mixture of water vapor and air, its density will not be constant, but will be a function of temperature, concentration, etc.

When considering a liquid phase within the system, a remarkable drawback is introduced. This is due to the rate of absorption of the condensed water inside the fiber

(solid phase), which is much slower than the rate of condensation / evaporation. This could also be a problem if we would consider fabrics or multilayer of fabrics constituted by different type of fibers. In this case the condensed water can be absorbed differently depending on the hydrophilicity of the material. A typical example is the case of a pressure decatizing treatment in which the wool fabric (hydrophobic) is rolled up interleaving a wrapper made of a blend of cotton (hydrophilic) and polyester (hydrophobic) fibers.

In order to develop the first theoretical model, a set of simplifying hypothesis has been assumed:

- insulated system;
- textile assembly considered as an isotropic porous media with homogeneous density and porosity;
- technical undercloth (wrapper) not considered;
- ideal gas law assumed for the gas phase;
- gas flow considered to be of Darcian type (laminar flow), one-dimensional and natural convection and gravitational effects are ignored;
- negligible diffusion of moisture in the gas phase;
- liquid phase assumed to be immobile and in thermal equilibrium with the solid phase;
- negligible heat transfer by radiation and conduction between fibers.

In the following sections the formulation of the problem will be taken into account by considering each phase of the system separately. The definitions of the symbols presented in the equations are given in the Nomenclature section.

### 4.2.2 – Solid phase

In order to take into account the variations in the properties of the solid phase due to the absorbed water, the solid phase has been considered as a homogeneous phase, but with properties variations which depend on the moisture content.

The general form of the continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla(\rho v) = 0 \quad (1)$$

with our simplifying hypothesis can be expressed as

$$\frac{\partial}{\partial t}(\theta_s \rho_s) = F_{ls} + F_{gs} \quad (2)$$

where  $F$  are the mass transfer rates between the solid phase and the other phases. As already said, the solid phase can be considered as constituted by the dry fiber plus the absorbed water

$$\theta_s \rho_s = \theta_f \rho_f + \theta_w \rho_w \quad (3)$$

Therefore, considering that both volume fraction and density of the dry fiber do not vary, equation (2) can be simplified as follows

$$\rho_w \frac{\partial}{\partial t} \theta_w = F_{ls} + F_{gs} \quad (4)$$

$F_{ls}$  and  $F_{gs}$  are respectively the mass transfer rate of the liquid water to the absorbing fiber and the mass transfer rate of the water molecules present in the gas phase to the absorbing fiber.

$$F_{ls} = -F_{sl} = h_m \alpha_s \gamma_{ls} \frac{\theta_l}{\theta_l^{cr}} \left( \frac{M_e}{M_s} - 1 \right) \quad (5)$$

$h_m$  is the mass transfer coefficient, which is related to the heat transfer coefficient  $h$  by the heat and mass transfer analogy [1]

$$h_m = \frac{h}{\rho_g C_{p,g} Le} \quad (6)$$

where the Lewis number is given by

$$Le = \frac{\alpha_{tex}}{\theta_g D_a} \quad (7)$$

$\alpha_{tex}$  is the thermal diffusivity of the fabric, linked to the thermal conductivity  $k_{tex}$  by

$$\alpha_{tex} = \frac{k_{tex}}{\rho_v C_{p,v}} \quad (8)$$

With respect to equation 5,  $a_s$  is the specific surface area, which for a bed porosity of  $1-\theta_s$ , and indefinite fibers length, represents the total solid surface compared to the volume of bed that has been considered. Le and Ly [2] confirmed that  $a_s$  can be calculated as:

$$a_s = \frac{4\theta_s}{d} \quad (9)$$

$\theta_i^{cr}$  is the critical value of the volume fraction at which the liquid phase becomes mobile. As explained by Sozen and Vafai [3], for a generic porous bed it can be considered as

$$\theta_i^{cr} = 0.1\theta_g \quad (10)$$

The moisture content at equilibrium  $M_e$  has already been defined in Chapter 3 (3.3.4 – Results and discussion) and expressed as

$$M_e = Z' \frac{Z \frac{p}{p_{sat}}}{1 + K \frac{p}{p_{sat}}} + W \frac{p}{p_{sat}} + z' \frac{z \frac{p}{p_{sat}}}{1 - k \frac{p}{p_{sat}}} \quad (11)$$

which correlates the relative humidity of the gas phase to the moisture content of the wool fiber as a function of the temperature. Indeed  $Z'$ ,  $Z$ ,  $W$ ,  $z'$  and  $z$  are coefficients that vary with temperature.

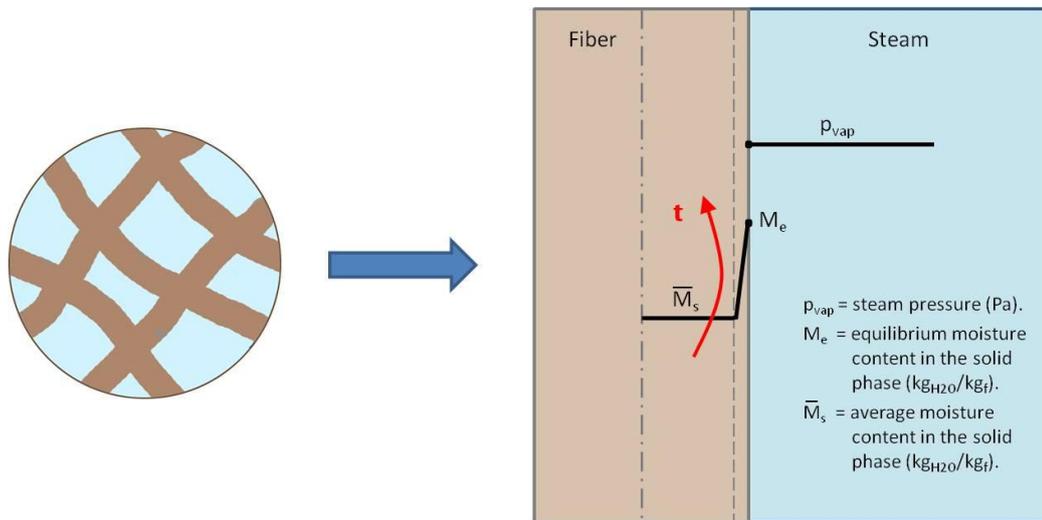
Whereas the last term of equation (4)

$$F_{gs} = h_m a_s \gamma_{gs} (M_e - M_s) \quad (12)$$

$\gamma_{gs}$  is linked to the diffusion coefficient of moisture in wool fiber, as explained by Le [4], by the following expression

$$\gamma_{gs} = \frac{8D_f \rho_f}{h_m a_s d^2} \quad (13)$$

Due to the wool fiber structure, the diffusion coefficient of moisture in the fiber is not constant with the radius. As a first approximation, we developed this model considering a moisture absorption profile almost constant, except for the fiber surface, which generates the highest resistance (Figure 4.2) and an apparent constant diffusion coefficient.



**Figure 4.2** - Wool fiber moisture absorption profile.

The outer part of the fiber surface is assumed to immediately come into equilibrium with the relative humidity of the gas phase.

Considering the previous approximation and equations (12) and (13), the moisture absorption equation can be calculated by

$$\frac{dM_s}{dt} = \frac{8D_f\rho_f}{d^2} (M_e - M_s) \quad (14)$$

whose solution leads to an exponential form

$$M_s = M_e - (M_e - M_s^0) e^{-jt} \quad (15)$$

where

$$j = \frac{8D_f\rho_f}{d^2} \quad (16)$$

### 4.2.3 – Liquid phase

With liquid phase we consider the condensed water present on the fiber surface before it is absorbed by the fiber or re-evaporate to the gas phase. As already mentioned, the liquid phase is assumed to be immobile, and the continuity equation can be written in this form

$$\frac{\partial}{\partial t}(\theta_l \rho_l) = F_{sl} + F_{gl} \quad (17)$$

We have already seen the meaning of  $F_{sl}$ , whereas  $F_{gl}$  is the condensation rate, proportional to the vapor density difference between the one in the gas phase and the one at the condensing surface

$$F_{lg} = -F_{gl} = h_m a_s (\rho_{v,l} - \rho_v) \quad (18)$$

As far as thermal energy equations are concerned, liquid and solid phases can be combined in the same equation

$$(\theta_s \rho_s C_{p,s} + \theta_l \rho_l C_{p,l}) \frac{\partial T_s}{\partial t} = h a_s (T_g - T_s) + \Delta h_{vap} (F_{gs} + F_{gl}) + DHS (F_{ls} + F_{gs}) \quad (19)$$

Steam table data for the latent heat of evaporation / condensation  $\Delta h_{vap}$  were fitted to a polynomial as a function of temperature [5]

$$\Delta h_{vap} = 2.792 * 10^6 - 160 T - 3.43 T^2 \quad (20)$$

The differential heat of sorption  $DHS$  has already been defined in Chapter 3 (3.2.4 – Results and discussion). Generally speaking, when dry fiber comes into contact with water the differential heat of sorption is liberated. When water is absorbed in dry fiber, the strong bonds will be made first, the weaker indirect bonds are affected only at higher moisture contents. As a consequence, the heat that is associated with the formation of the bonds is high for low moisture contents and then progressively decreases. The equation which correlates the  $DHS$  to the moisture content (or the relative humidity) has been reported for the first time by Walker [6] fitting experimental data.

$$DHS = 4.187 e^{-11.3M_s + 5.7} \quad (21)$$

#### 4.2.4 – Gas phase

If we consider a porous bed of  $N$  layers of fabrics, which determines a thickness equal to  $L$  meters, the pressure difference between inlet side and outlet side of the bed allows the steam to flow through the bed.

The velocity of the steam through the bed in an industrial equipment is small, therefore the flow can be considered of laminar type (a maximum Reynolds number of 1200 has been calculated). Considering a constant pressure drop, the flow velocity depends on the permeability of the bed

$$\frac{(P_{in} - P_{out})}{L} = -\frac{\mu_g}{K} v_g \quad (22)$$

The fabric permeability  $K$  is calculated using the Kozeny-Carman equation, valid for laminar flow

$$K = \frac{\theta_g^3}{k\alpha_s^2(1 - \theta_g)^2} \quad (23)$$

where  $k$  is the Kozeny factor which can be calculated using the Labrecque's correlation [7], valid for beds constituted by fibers with circular cross section

$$k = 5 + e^{[14(\theta_g - 0.8)]} \quad (24)$$

Although in the initial transient state both air and steam are present (the steam flows and displace air as it penetrates the bed), in the mass balance equation only the steam is considered, since the inert air does not exchange mass with the fiber

$$\frac{\partial}{\partial t}(\theta_g \rho_v) + \frac{\partial}{\partial x}(\rho_v v_g) = -F_{gs} - F_{gl} \quad (25)$$

whereas in the thermal energy equation also the presence of air has to be considered

$$(\theta_g \rho_v C_{p,v} + \theta_g \rho_a C_{p,a}) \frac{\partial T_g}{\partial t} + (\rho_v C_{p,v} v_g + \rho_a C_{p,a} v_g) \frac{\partial T_g}{\partial x} = -h\alpha_s(T_g - T_s) \quad (26)$$

#### 4.2.5 – Model implementation

The development of the model takes the cue from a old Visual Basic calculation script, which has been rewritten and made stable using the VB.NET programming language, and upgraded implementing the previous equations.

Clearly equations and correlations have been rewritten to make them compatible with the programming environment, and a finite difference scheme was used to solve them. The numerical solution is obtained by the iterative increasing of time and position, intended as a new level in the porous bed structure, and getting a global solution of the system.

Therefore, before starting any new calculation, time steps and level steps have to be defined as input data, in order to define the “fineness” of the grid, both in time and in space, to ensure the stability of the computations.

For every calculation time, the properties on the same level can be considered constant, due to the simplifying hypothesis that have been stated.

In this way, the spatial evolutions of fabric temperatures and moisture contents were calculated following the thickness of the fibrous bed, and thus the steam penetration.

The main window of the application is showed in Figure 4.3 and allows to type input data, start a new calculation and show the results.

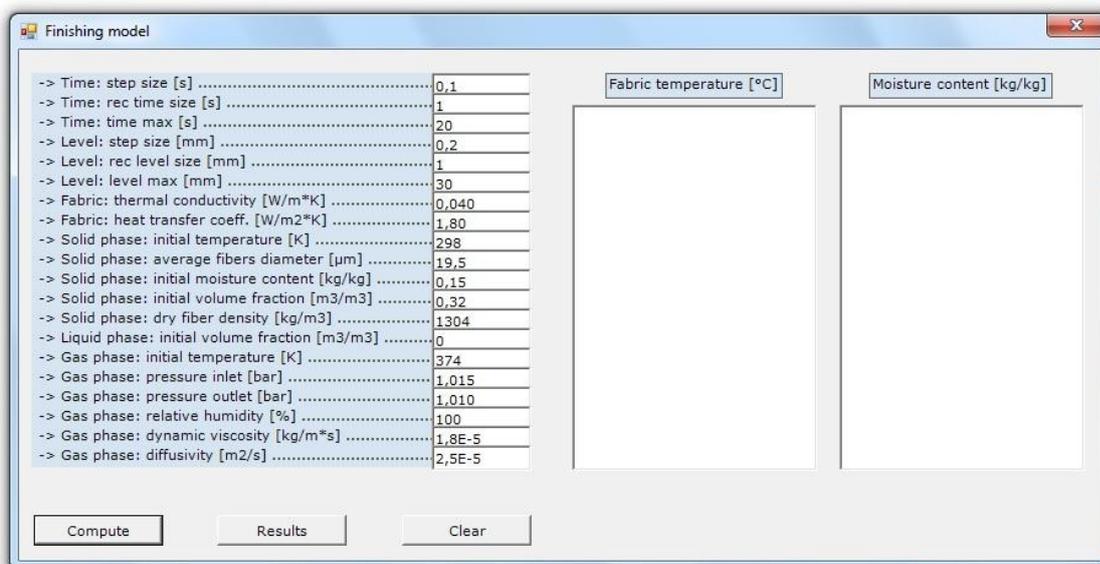


Figure 4.3 - Main window of the finishing simulation model.

Input data can be divided in the following sections:

*Time:*

- Step size: time increase between two calculation cycles. It corresponds to the finite difference used for the numerical solution of the differential equations, with respect to the time. Low values allow to obtain precise results, but require high computation time.
- Rec time size: it indicates how often the data are recorded and stored.

- Time max: maximum time that has to be considered for the calculations.

*Level:*

- Step size: level increase between two calculation cycles. It correspond to the finite difference used for the numerical solution of the differential equations, with respect to the space. Low values allow obtaining precise results, but require high computation time.
- Rec level size: it indicates the spatial distance between two recorded data.
- Level max: maximum thickness of the fibrous bed.

*Fabric:*

- Thermal conductivity: it depends on the fiber type and the fabric structure. It can be experimentally measured. Average values can be found in literature.
- Heat transfer coefficient: coefficient that depends on the heat transfer between steam and textile material. It can be experimentally measured. Average values can be found in literature.

*Solid phase:*

- Initial temperature: initial fibers temperature, before starting the treatment.
- Average fibers diameter: it depends on the fineness of the fibers which form the yarns of the fabric.
- Initial moisture content: moisture content of the fibers before starting the treatment.
- Initial volume fraction: fibers volume, with respect to the total volume.
- Dry fiber density: specific for every type of fiber.

*Liquid phase:*

- Initial volume fraction: volume of liquid water present on the fibers before starting the treatment, with respect to the total volume. Usually this value is equal to zero, but this variable has been introduced to take into account an eventual pre-treatment wetting operation.

*Gas phase:*

- Initial temperature: steam temperature at the inlet of the system.
- Pressure inlet: steam pressure at the inlet of the system. It is directly linked to the steam temperature, depending on the steam conditions (usually dry saturated).
- Pressure outlet: steam pressure at the outlet of the system. Often equal to the atmospheric pressure.
- Relative humidity: relative humidity of the steam at the inlet of the system. If the steam is in a saturated condition, the relative humidity is equal to 100%.

- Dynamic viscosity: it varies with temperature. Steam tables can be used to define this value.
- Diffusivity: diffusion coefficient of water vapor in air. Steam tables can be used to define this value.

#### 4.2.6 – Model validation: comparison between experimental and numerical results

The model has been validated using different data coming from the existing scientific literature. Particularly, a detailed study has been realized by Le et al. [8], and the results that they obtained have been taken as benchmarks to validate our model.

With the support of the CSIRO Division of Wool Technology, Le studied the propagation of a steam flow through a textile assembly made of different layers of wool fabrics. Experimental tests have been done on lab scale equipment made of a vertical cylinder sealed at the bottom and open to atmospheric pressure at the top. The side wall of the chamber is wrapped by an heating element to pre-heat it to the steam temperature, in order to prevent condensation. The fabric, made up of 24  $\mu\text{m}$  fibers at a 2% initial moisture content, is stacked one layer after the other vertically on the top of a perforated plate, reaching a total thickness of 50 mm. The saturated steam, relative humidity equal to 100%, at 100.9°C and 1.03 ata, flows from the bottom to the top. A schematic sketch has been reported in Figure 4.4.

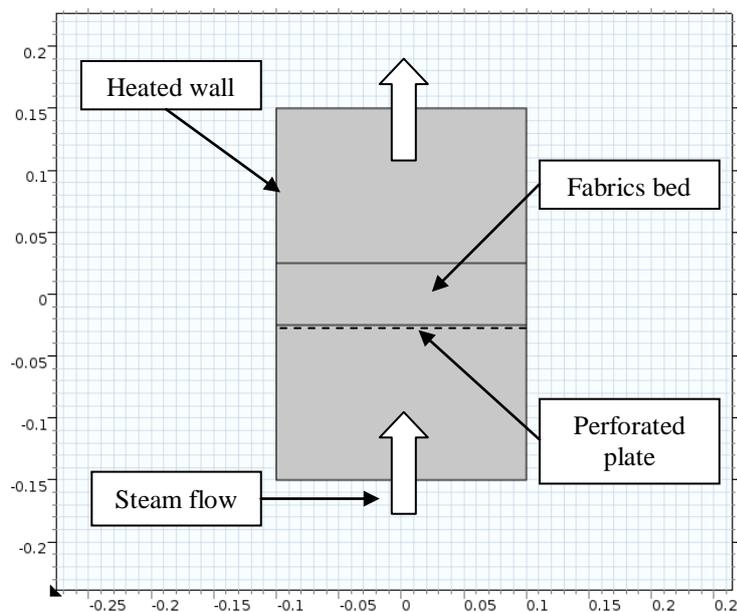


Figure 4.4 - Schematic sketch of the CSIRO experimental equipment.

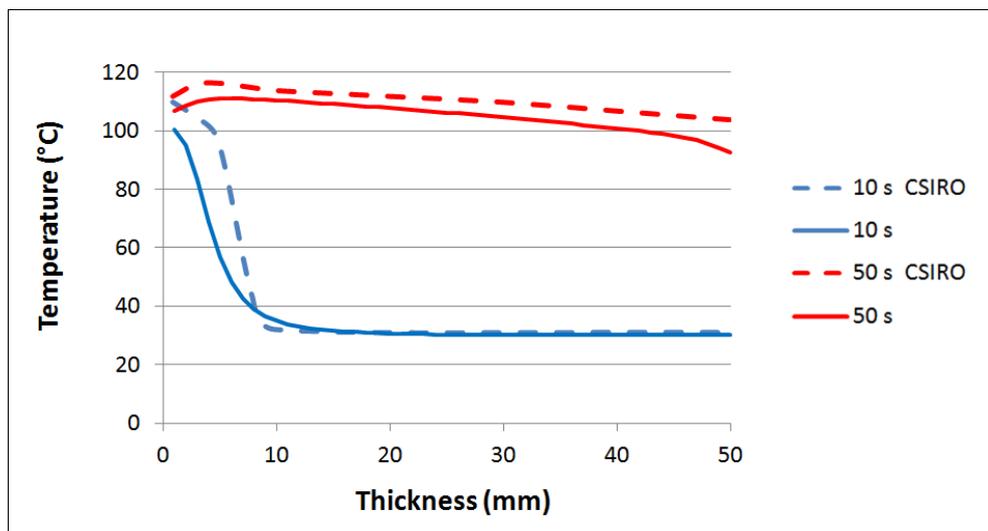
The evaluation of the steam front penetrating the layers of fabric has been done by using thermocouples positioned between the layers of the fabric.

Le stated that the early stage of the steaming process is marked by a very distinctive heat transfer front, which propagates through the fabrics bed. With the heat transfer front the bed temperature is first brought up to the steam temperature and then it reaches higher temperatures due to the simultaneous condensation and absorption. Particularly the moisture absorption releases a large amount of energy and quickly raises the fiber temperature. He demonstrated that the steam front takes about 50 seconds to move through a 50 mm bed.

Using the variables of the Le's work as input data, a simulation has been done with the VB.NET model. The results of the thermal analysis on the propagation of the steam front through a packed fibrous bed can be seen in Figure 4.5.

*Initial conditions:*

- Fiber type: 100% wool.
- Average fibers diameter: 24  $\mu\text{m}$ .
- Initial moisture content: 2%.
- Initial fabric temperature: 30°C.
- Packed bed thickness: 50 mm.
- Steam conditions: saturated, relative humidity 100%, temperature 100°C.



**Figure 4.5** - Evolution of the heat transfer front due to the steam propagation through a 50 mm thick packed fibrous bed.

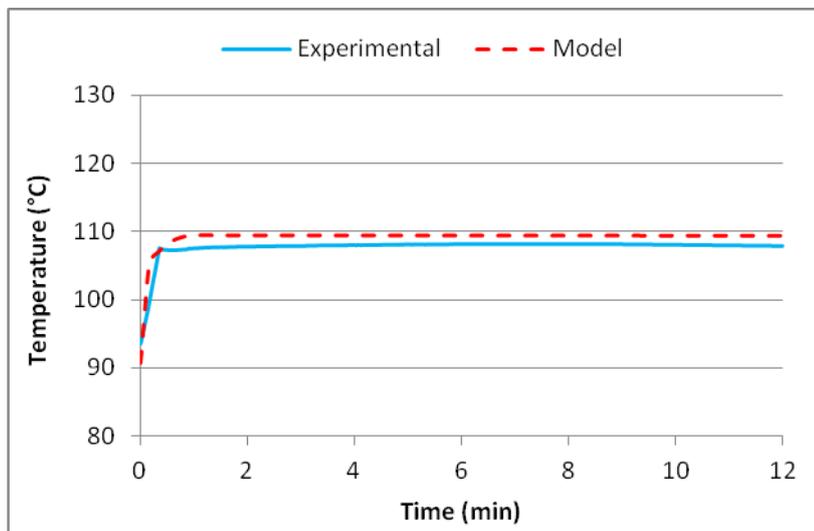
The VB.NET model brought to similar results as Le's work, demonstrating that a treatment time of 50 seconds is enough for the steam front to move through the 50 mm thick fibrous bed.

However, such results were obtained hypothesizing some input data, since they were missing, and have been chosen using average values, typical of the considered type of fabric.

Therefore, in order to have a more complete validation of the process and verify if the results obtained with the theoretical model fit actual experimental data, a series of simulations have been carried out using as input data the initial values and physical properties of the experimental campaign described in Chapter 3. Both temperature and moisture content have been evaluated and the results obtained from the simulation have been compared to the experimental ones and presented in Figures from 4.6 to 4.12.

#### *Test 1*

- Initial moisture content: 8%.
- Steam temperature: 100°C.



**Figure 4.6** - Comparison between experimental results and numerical simulations for fabrics at 8% initial moisture content treated with steam at 100°C.

#### *Test 2*

- Initial moisture content: 15%.
- Steam temperature: 100°C.

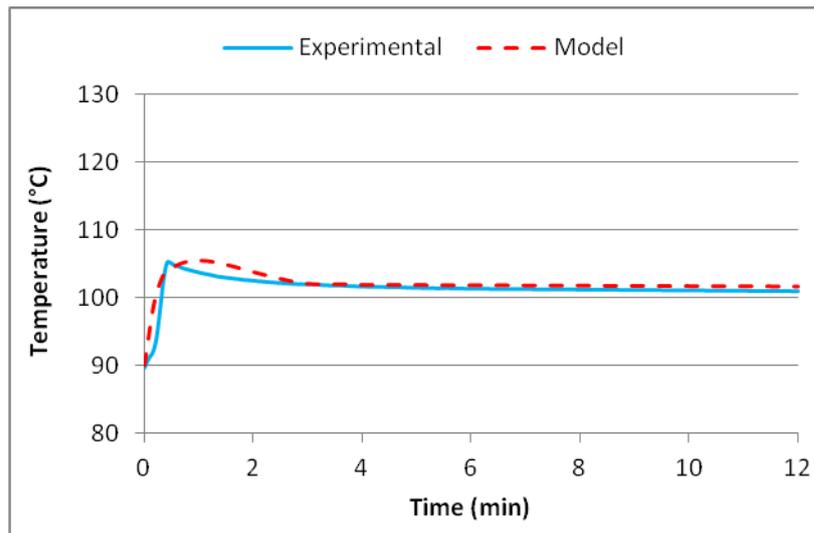


Figure 4.7 - Comparison between experimental results and numerical simulations for fabrics at 15% initial moisture content treated with steam at 100°C.

Test 3

- Initial moisture content: 8%.
- Steam temperature: 120°C.

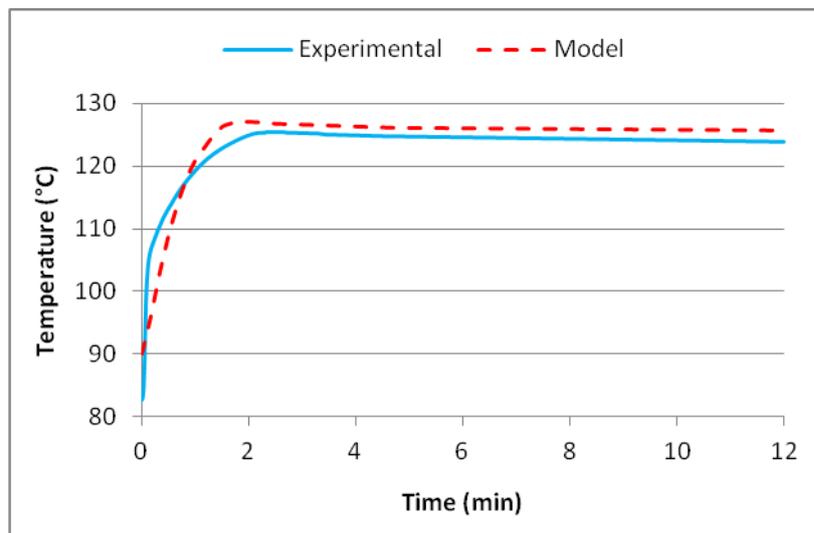
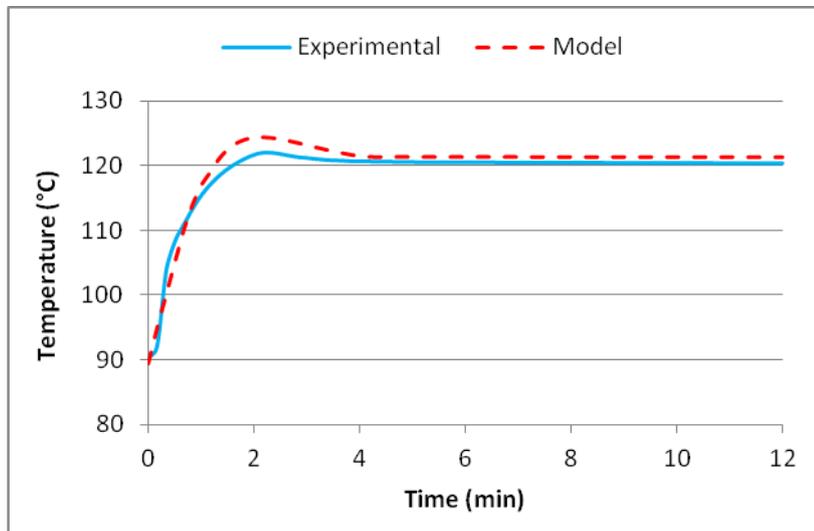


Figure 4.8 - Comparison between experimental results and numerical simulations for fabrics at 8% initial moisture content treated with steam at 120°C.

Test 3

- Initial moisture content: 15%.
- Steam temperature: 120°C.

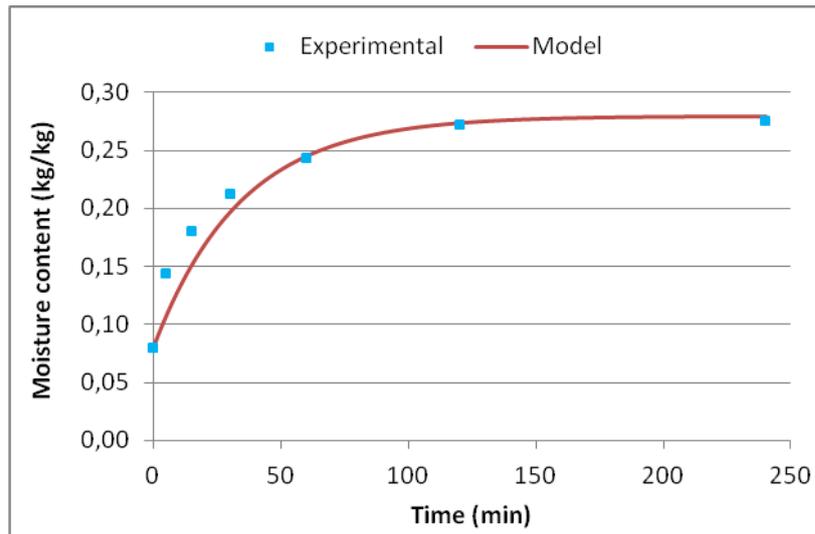


**Figure 4.9** - Comparison between experimental results and numerical simulations for fabrics at 15% initial moisture content treated with steam at 120°C.

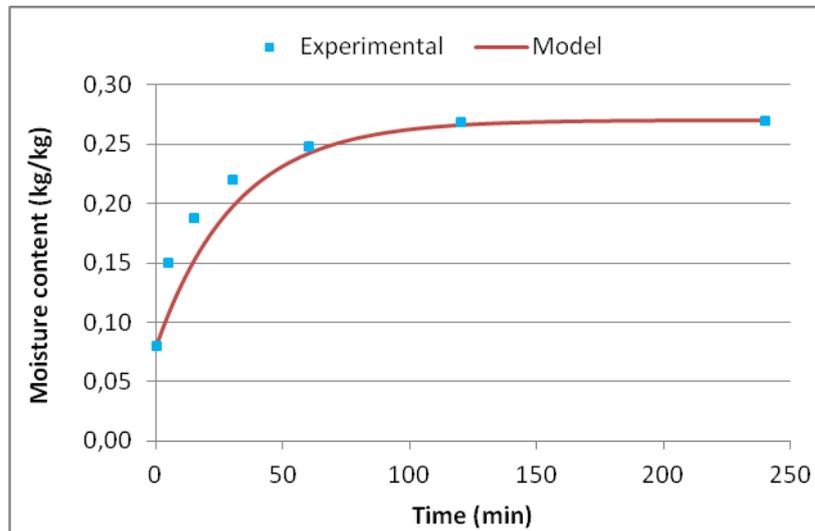
As can be seen from Figures 4.6 – 4.9, all experimental tests start with initial fabric temperatures around 90°C, for the reason discussed in Chapter 3; therefore an initial solid phase temperature of 90°C has been selected also for numerical simulations.

The good approximation between experimental and simulated data demonstrates the efficiency of the model. The widest gap can be found in the initial instants of the process, where the effect of the differential heat of sorption is more pronounced.

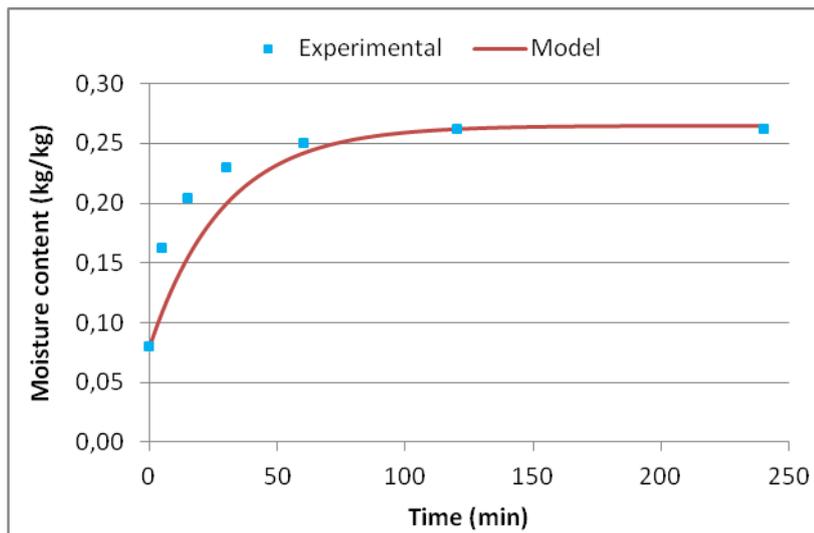
As far as moisture absorption is concerned, Figures 4.10, 4.11 and 4.12 show the comparison between experimental and simulated results for the tests carried out respectively at 100°C, 120°C and 140°C, with 8% initial moisture content.



**Figure 4.10** - Comparison between experimental results and numerical simulations for fabrics at 8% initial moisture content treated with steam at 100°C.



**Figure 4.11** - Comparison between experimental results and numerical simulations for fabrics at 8% initial moisture content treated with steam at 120°C.



**Figure 4.12** - Comparison between experimental results and numerical simulations for fabrics at 8% initial moisture content treated with steam at 140°C.

The results demonstrate that the simplified model that we have assumed can't accurately evaluate the early stage of the treatment, which is actually the most important in finishing treatments.

In the first 60 min the real kinetics is higher than the simulated one, as fast and consistent initial moisture absorption takes place. Thus the kinetics do not depends only by the driving force generated by the difference in moisture content between the one at the fiber surface (considered at the equilibrium) and the one within the fiber. Moreover the effective diffusivity of water vapor within the fiber can't be considered constant, as well as the fiber porosity.

In conclusion, the VB.NET model can estimate with a quite good approximation the fundamental process variables of a steam treatment. The numerical simulations brought to good results especially concerning the heat transfer analysis, whereas an improvement could be achieved in the modeling of the moisture absorption.

The last issue becomes even more relevant if industrial KD treatments are considered, especially in the view of a reduction of the treatment times.

## 4.3 Second approach: Comsol Multiphysics

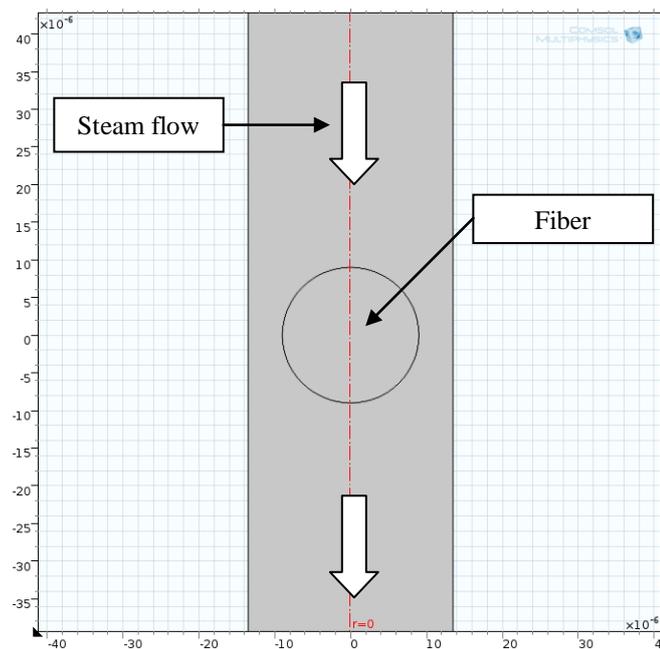
### 4.3.1 – Model overview and implementation: fiber geometry

Comsol Multiphysics is a finite elements analysis simulation software which allows the user to perform numerical simulations either with its built-in modules or manually implementing PDEs (Partial Differential Equations), ODEs (Ordinary Differential Equations) and other equations.

The advantage of using this kind of software lies on the possibility of simulating realistic systems, with specific geometries.

In our study, two different geometries have been analyzed, with the main aim to improve the moisture transfer analysis which was the weakness of the .NET Framework model.

From the experimental part it has been seen that the moisture transfer is a relatively slow process because it depends on the diffusivity of water molecules inside the wool fiber structure. Therefore the first geometry that has been created is the fiber one, represented in Figure 4.13.



**Figure 4.13** - Schematic view of the fiber-steam geometry system. Homogeneous fiber.

The model presented in Figure 4.13 represents the evolution of the VB.NET model in which the fiber, represented in a cross sectional view, has a uniform structure and, as a consequence, uniform properties and absorption behavior.

The fiber, with 18  $\mu\text{m}$  diameter, is placed in the middle of an ideal channel in which the steam flows from the top to the bottom. A pressure difference is applied between inlet and outlet in order to achieve a laminar steam flow.

The distances between the outer part of the fiber and the two side walls of the channel are approximately the half average distances between wool fibers in a yarn.

The fiber structure is considered as a porous media in which only two phases are present: solid (fiber + absorbed moisture) and gas (saturated steam).

Thus, respect to the VB.NET model, the present one has been simplified by neglecting the liquid phase (condensate). This assumption has been done on the basis of Le's work [8], who analyzed the evolution of the condensate volume fraction of a condensing flow of saturated steam through a 50 mm thick fibrous bed. He demonstrated that the condensed water forms and rapidly disappears in few seconds as it is evaporated back in the gas phase. Only an infinitesimal part is absorbed by the solid phase.

Moreover the condensation takes place only until the solid phase has a surface temperature lower than the steam one. In our model, with the presence of a single fiber, the solid phase temperature reaches the steam one almost instantaneously.

The saturated steam, with a relative humidity of 100%, flows continuously following the classical model of a laminar flow.

The fiber has been defined as a porous media, therefore differential equations and empirical relations are same used in the VB.NET model, but in this case also the spatial components have been considered.

On the contrary, not all the simplifying hypothesis have been assumed anymore. In particular:

- the system is no more considered as insulated;
- only a single fiber is considered;
- gas phase treated as a real gas;
- gravitational effects are ignored;
- the liquid phase (condensate) has been neglected.

In this case, input properties depend only on the solid and gas phase:

*Solid phase:*

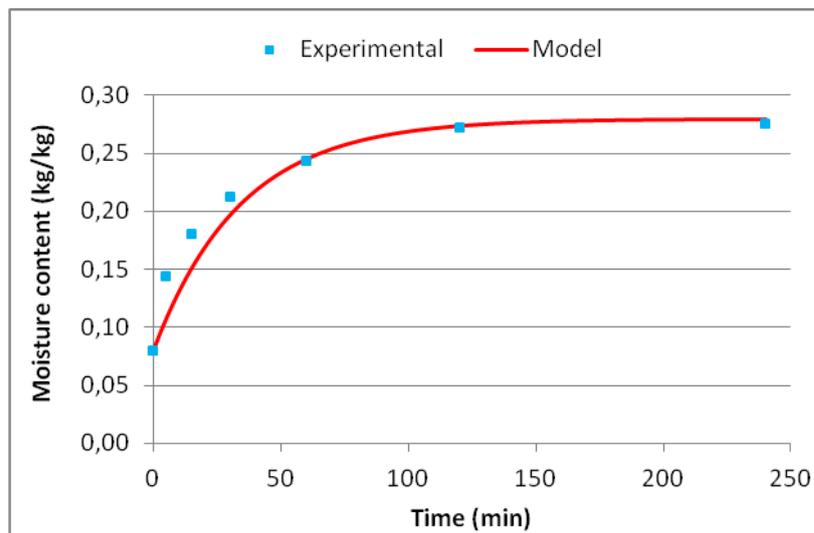
- Porosity and permeability: average values can be found in literature.
- Thermal conductivity: average values can be found in literature.
- Initial temperature: initial fiber temperature, before starting the treatment.

- Fiber diameter: the fiber diameter of 18  $\mu\text{m}$  has been selected in agreement with the average fibers diameter of the wool used in our experimental tests.
- Initial moisture content: moisture content of the fibers before starting the treatment.
- Dry fiber density: average values can be found in literature.

*Gas phase:*

- Initial temperature: steam temperature at the inlet of the system.
- Pressure inlet: steam pressure at the inlet of the system. It is directly linked to the steam temperature, depending on the steam conditions (usually dry saturated).
- Pressure outlet: steam pressure at the outlet of the system.
- Relative humidity: relative humidity of the steam at the inlet of the system. If the steam is in a saturated condition, the relative humidity is equal to 100%.
- Diffusivity: diffusion coefficient of water vapor in air. Steam tables can be used to define this value.

The data of the experimental campaign on the moisture absorption evaluation have been used again to validate the model. The numerical simulations have been carried out using as input data the initial values and physical properties characterizing the experimental tests. The results obtained from the simulation are quite similar to the VB.NET model. As an example, the comparison between experimental data and numerical simulation for the 100°C steam temperature is reported in Figure 4.14.

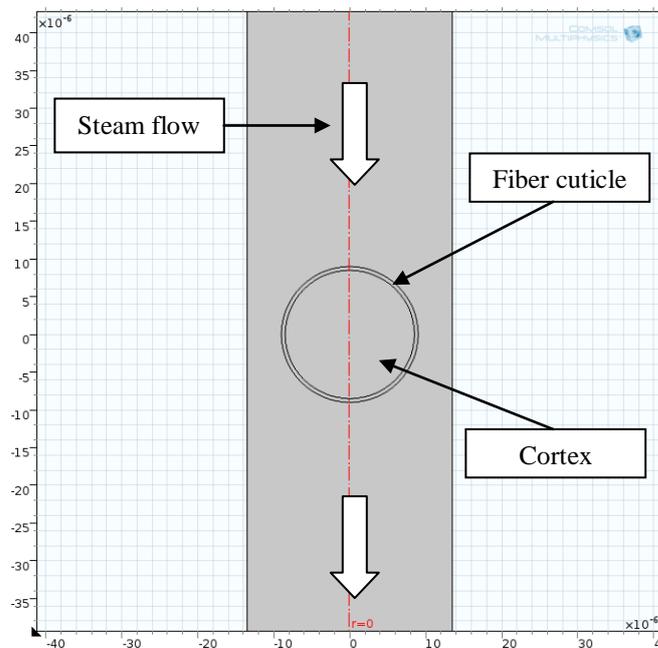


**Figure 4.14** - Comparison between experimental results and numerical simulations for wool fibers at 8% initial moisture content treated with steam at 100°C.

The surface values of the fiber cross section have been averaged with respect to the considered area in order to obtain mean values which could be compared with the experimental ones.

The great similarity with the data obtained from the VB.NET model is not surprising, considering that values of fiber porosity and water-vapor diffusivity within the fiber structure are the same.

The refinement of the model has been achieved considering the wool fiber structure (see Chapter 1) with the presence of the external part (cuticle) which could describe the quick absorption of moisture in the early stage of the process. The new geometry has been shown in Figure 4.15.



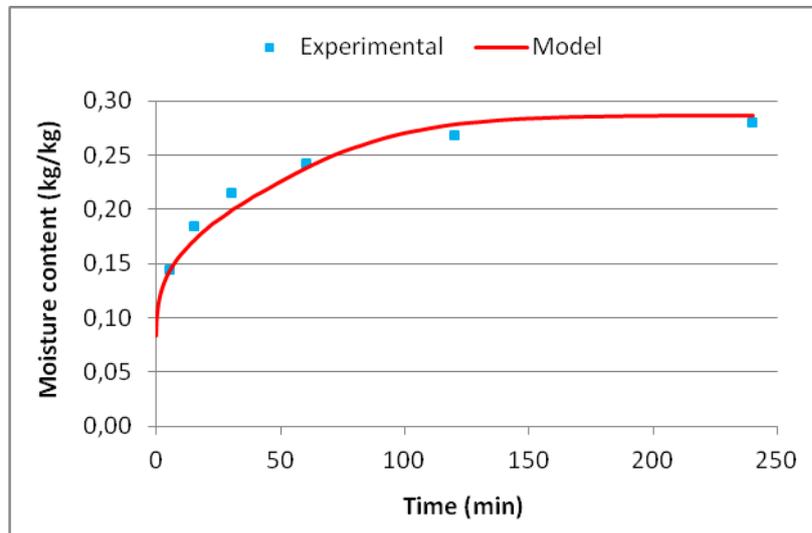
**Figure 4.15** - Schematic view of the fiber-steam geometry system. Cuticle and cortex geometry.

The fiber cuticle is a very thin layer (approximately  $0.5 \mu\text{m}$ ) constituted by overlapping scales, which usually acts as a barrier with respect to external agents. It can be supposed that the swelling of the wool fiber, above its glass transition temperature, is fully reached at  $100^\circ\text{C}$ , thus facilitating diffusion of water molecules between the cuticle scales. This behavior, together with possible phenomena of capillary condensation and surface absorption, as explained by Morton [9], can explain the quick initial moisture absorption.

Moreover, water absorption is possible only in the amorphous regions of the fiber and the cuticle is completely amorphous.

The internal part of the fiber (cortex) has been modeled with a uniform structure, considering average values of porosity and vapor diffusivity.

The results of the numerical simulation, compared with experimental data, for the 100°C steam temperature is reported in Figure 4.16.



**Figure 4.16** - Comparison between experimental results and numerical simulations for wool fibers at 8% initial moisture content treated with steam at 100°C.

The simulated results now appear to be in good agreement with experimental data especially in the initial part of the treatment, whereas they appear to be slightly underestimated when considering the second (15 min) and third (30 min) experimental points. It is clear that an higher absorption of the cuticule layer represents a good explanation for the fast initial absorption, but the fitting with the average values of porosity and vapor diffusivity can't explain in a detailed way what happens to the water molecules when they reach the cortex part of the fiber.

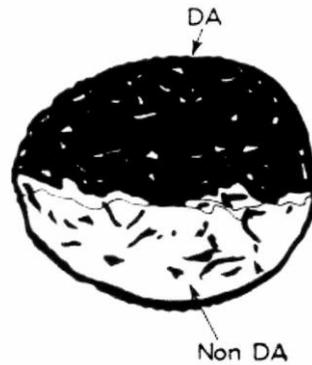
A truthful explanation can be given considering also the cortex part of the fiber, which is not uniform but made of two distinct parts: ortho-cortex and para-cortex.

In a Merino wool, like the one used for our tests, the distinction between the two parts is evident and the two parts constitute a bilateral structure along the entire length of the fiber.

The two parts have a different behavior and different properties, due to the different composition of the amorphous regions. The para-cortex is more cross-linked (disulphide bonds) than the ortho-cortex, that, on the contrary represents a more accessible region.

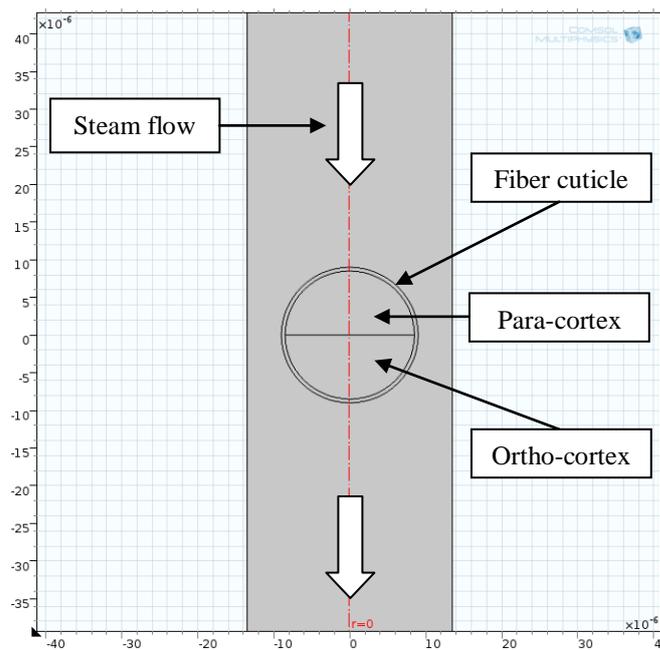
A proof of this behavior is given by a test made with a disperse dye, which has no affinity and do not make bonds with the wool fiber [10]. This test is useful to define the behavior wool fibers with respect to the dye accessibility. As can be seen from Figure

4.17, a Merino wool fiber has been dyed with a disperse dye, demonstrating the accessibility of the dye molecules only in a specific region (ortho-cortex), which has been defined with “DA” (Dye-Accessible). The other part (para-cortex) is only poorly accessible, therefore it has been defined as “Non DA” (Non Dye-Accessible).



**Figure 4.17** - Merino wool fiber cross-section. The fiber has been treated with a disperse dye in order to highlight the asymmetric dye absorption in the different parts of the fiber.

The new geometry that has been developed (Figure 4.18) takes into account these characteristics.

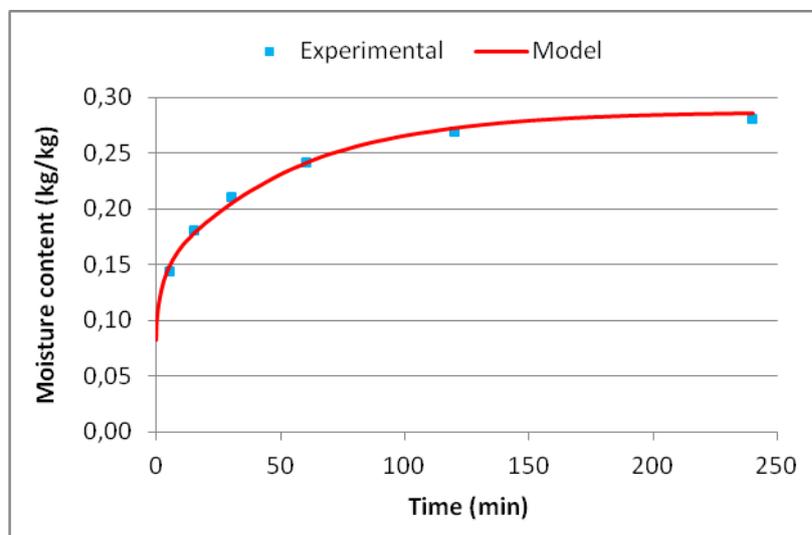


**Figure 4.18** - Schematic view of the fiber-steam geometry system. Cuticle, para-cortex and ortho cortex geometry.

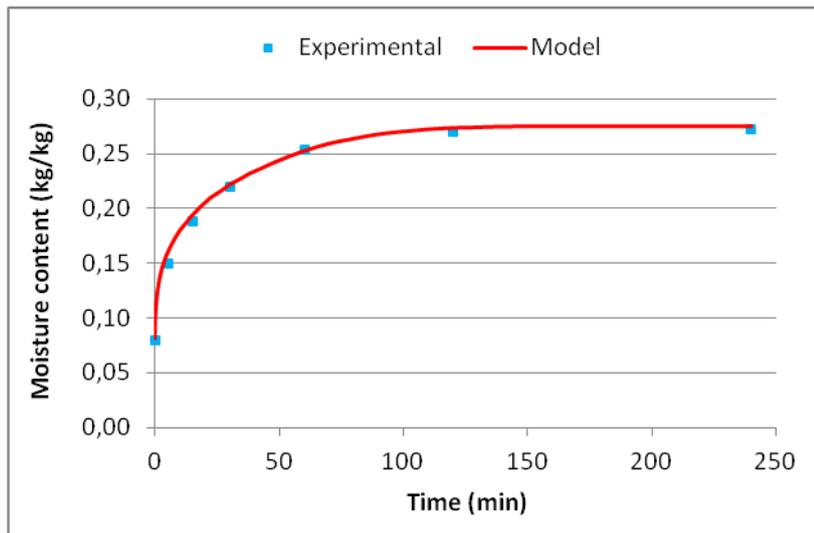
Water molecules are much smaller than the dye ones and during a steam treatment they will be able to penetrate also in the para-cortex, but it is clear that the most accessible and amorphous region is the ortho-cortex one. As a consequence, porosities and diffusivities will be higher for ortho-cortex than for para-cortex.

Among the average values, porosities and diffusivities have been selected with a parametric analysis of the model, aimed at optimizing the fitting with the experimental data. Figures 4.19, 4.20 and 4.21 show the comparison between experimental and simulated results for the tests carried out respectively at 100°C, 120°C and 140°C, with 8% initial moisture content. During the simulations the porosities of the different regions have been kept constant. Water-vapor diffusivities inside the wool fiber slightly change as the temperature increase.

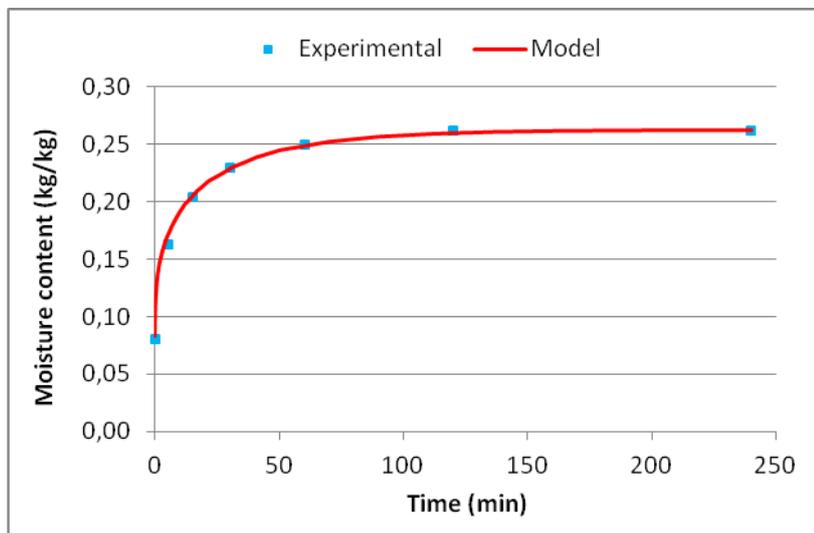
From the Figures it is clear that the new geometry is more suitable to estimate the fiber moisture absorption, independently from the steam temperature and generally from the treatment conditions.



**Figure 4.19** - Comparison between experimental results and numerical simulations for fabrics at 8% initial moisture content treated with steam at 100°C.



**Figure 4.20** - Comparison between experimental results and numerical simulations for fabrics at 8% initial moisture content treated with steam at 120°C.



**Figure 4.21** - Comparison between experimental results and numerical simulations for fabrics at 8% initial moisture content treated with steam at 140°C.

A graphical view of the results obtained with the last geometry for the 100°C steam temperature can be seen in Figure 4.22.

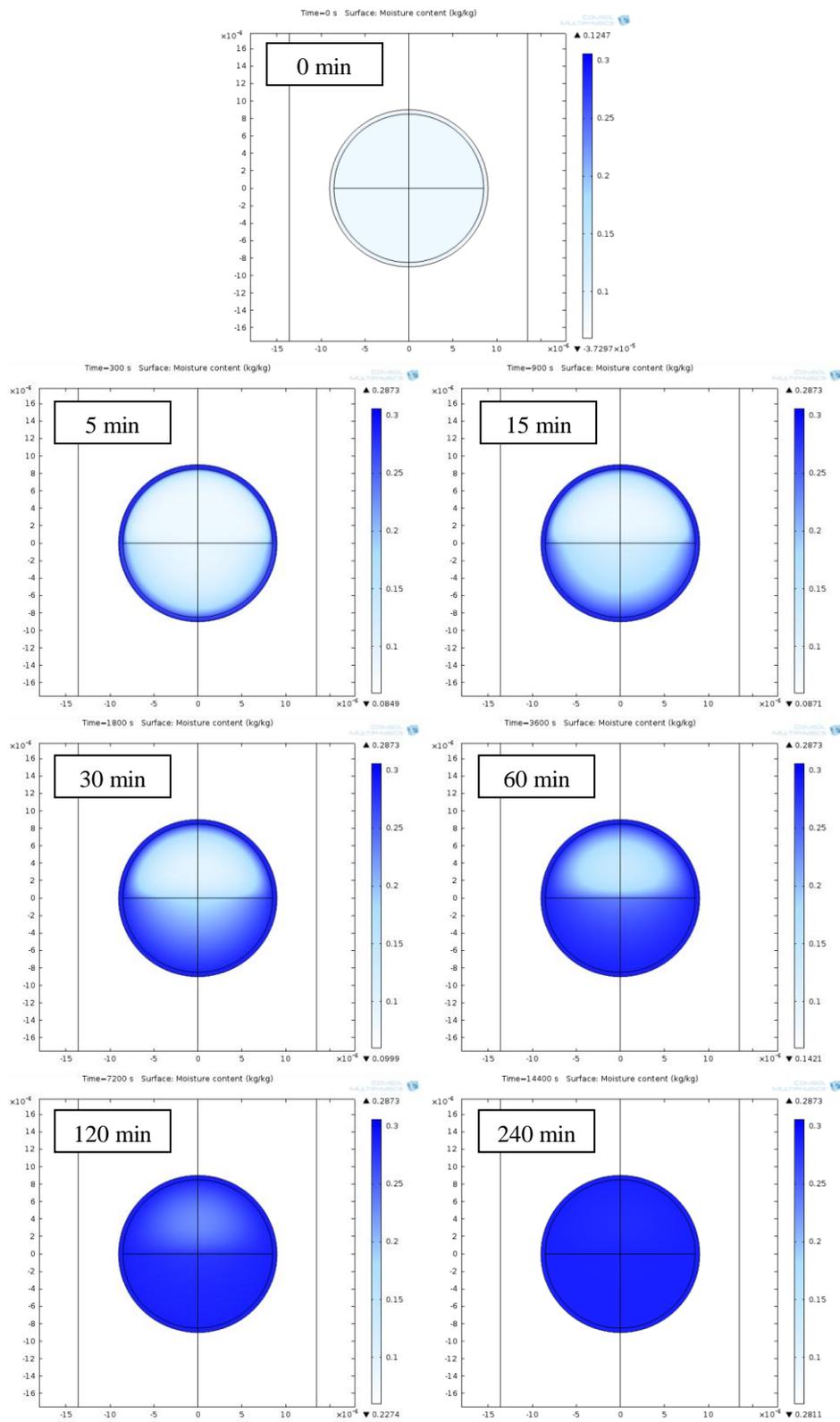


Figure 4.22 - Graphic view of the evolution of the moisture content at the selected times for a wool fiber with 8% initial moisture content, treated with saturated steam at 100°C

Figure 4.22 reports the evolution of the moisture content at the selected times for a wool fiber with 8% initial moisture content, treated with saturated steam (relative humidity equal to 100%) at 100°C. The sampling times correspond to those contemplated in the experimental tests (0, 5, 15, 30, 60, 120 and 240 min), thus this sequence can be correlated to the data reported in Figure 4.19.

Analyzing both Figure 4.19 and Figure 4.22, the sharp and rapid increase in moisture content at the beginning of the treatment is supposed to be due to the absorption of water molecules on the fiber surface (cuticle).

Then water molecules have to penetrate inside the two main zones, ortho and para-cortex, of the wool fiber structure.

The para-cortex has a higher level of cross-links (disulphide bonds) and is more compact than the ortho-cortex. The last one is more accessible to chemicals and has a higher swelling degree. Thus it can be supposed that ortho-cortex cells are more accessible also to water molecules. The last step is the penetration of water molecules as far as the core of the para-cortex zone.

The time needed by the fiber to reach the moisture content equilibrium decreases when increasing the temperature, as the kinetics slightly increases.

### 4.3.2 – Model overview and implementation: yarn geometry

In order to evaluate the diffusion coefficient also in a more complex geometry, a yarn geometry has been created (Figure 4.23).

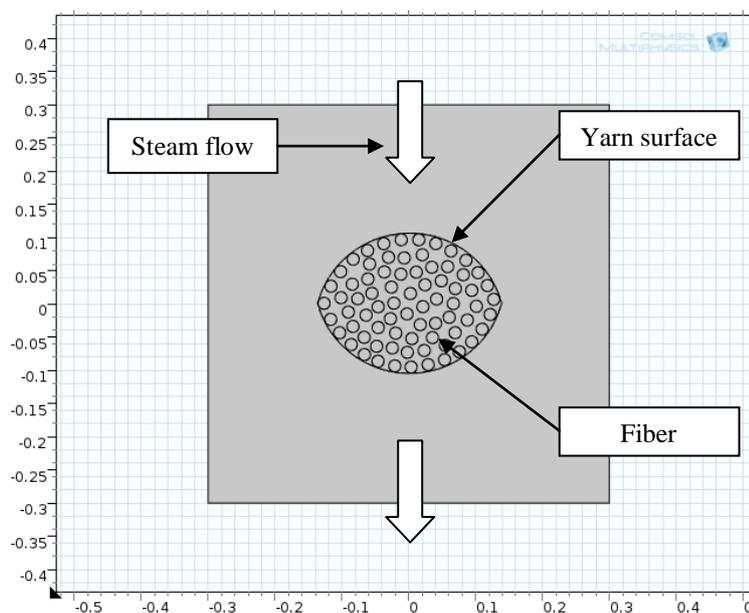


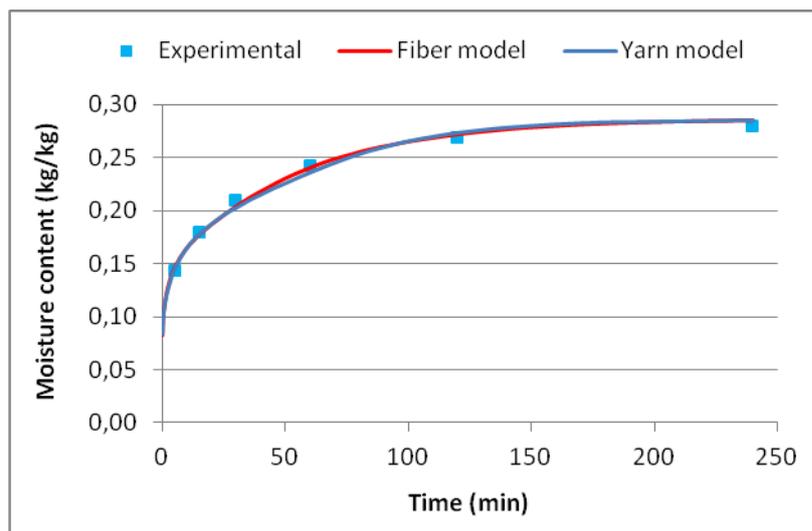
Figure 4.23 - Schematic view of the yarn-steam geometry system.

Figure 4.23 shows the geometry of a yarn cross section which has been recreated as similar as possible to the type of yarn constituting the fabric used in the experimental tests. A single yarn is composed by a variable number of fibers, depending on the average fibers diameter, the weight of a specific length of yarn (count), the twist given to the fibers in the spinning process. By knowing all these parameters it is possible to calculate the actual number of fibers present in a fiber section and to define the shape of the yarn section.

The fibers which form the yarn showed in Figure 4.23 have been created using the three regions division already explained in section 4.3.1 (last fiber geometry), although they have been hidden to facilitate the view of the Figure.

Except for the geometry, all other assumptions, variables, parameters, equations, relationships, input data, etc are the same used for the simulations of the fiber geometry (see section 4.3.1).

The numerical simulations brought to almost identical results to those obtained with the fiber geometry. As an example, the evolution in moisture content for a treatment with saturated steam at 100°C on a 8% initial moisture content fiber has been reported in Figure 4.24. The surfaces values of all fibers cross sections have been averaged with respect to the considered surfaces in order to obtain mean values.



**Figure 4.24** - Comparison between experimental results and numerical simulations of fiber and yarn geometric models for fabrics at 8% initial moisture content treated with steam at 100°C.

As can be seen from Figure 4.24, there is no practical difference between the simulated absorption in the yarn and the one in the fiber, demonstrating that the resistance generated by the yarn structure is almost negligible.

Similar considerations can be done also for the 120°C and 140°C steam temperatures.

## 4.4 Conclusions

The development of a set of governing equations which describes the coupled simultaneous heat and mass transfer in hygroscopic porous media has been carried out by means of two approaches and relative models.

Energy, mass and continuity equations, as well as physical and experimental relationships have been used as a common denominator to develop both models.

The multiphase system modeled by implementing the above mentioned equations and relationships, into a .NET Framework environment, thanks to a VB.NET programming language, allowed to simulate a simplified system, independent from the geometry.

The developed model allows evaluating both temperature and moisture content during a steam treatment, simply by varying steam and fabric characteristics as input data.

The results obtained have been validated both with literature data and with the results of the tests collected during the experimental campaign described in Chapter 3.

Good approximations have been found especially concerning the heat transfer analysis, with simulated temperature profiles very close to the experimental ones. On the contrary, the moisture transfer analysis demonstrated that the simplifying hypothesis introduced within the model, are not enough to simulate the moisture absorption, especially during the initial minutes of the treatments.

The need of a better theoretical model, which could properly simulate the moisture absorption in the initial phase of the processes, is due to the fundamental importance of the moisture content in steaming and decatizing processes.

Indeed, this issue is relevant especially as far as pressure decatizing treatments are concerned, in the view of a reduction of the treatment times.

The study of a new model has been therefore carried out, but the more detailed approach needed to move from the .NET Framework platform to a finite element simulation software: Comsol Multiphysics.

The models developed with Comsol Multiphysics allowed performing simulations without taking into account the great part of simplifying hypothesis introduced with the .NET Framework model. Particularly, the possibility to create and subsequently analyze a realistic geometry of the system is extremely important.

The two models, thought with specific regard to the moisture absorption analyses, have been developed considering the fiber and the yarn geometries.

The results obtained with these models fit and are in good agreement with the experimental data during the entire treatment time. This is due to the more detailed configuration of the fiber structure, with its inner properties depending on the specific region in which the fiber has been divided.

As far as the single wool fiber geometry is concerned, the development of different geometries, based on appropriate studies on the wool fiber structure, highlighted the non-homogeneous behavior of wool.

A wool fiber is made of different components, each one with its own properties and, as a consequence, absorption behavior.

Simulations carried out using the fiber / yarn models, and the validation with the experimental data, confirmed the statements supposed at the end of the experimental campaign, particularly concerning the resistances generated by the fabric / yarns / fibers system to the moisture transport.

Indeed, fabric and yarn structures have a low influence on moisture absorption, whereas the fiber structure, extremely compact and with low porosity, represents the highest resistance to the diffusion of water molecules.

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## **Chapter 5**

### **5. Conclusions and future perspectives**

The first part of the present work has allowed to define wool properties and how they are influenced by external factors. In finishing processes, the coupled action of temperature and moisture content has a remarkable effect on wool fibers from a physico-chemical point of view. Both these variables, often combined with a mechanical action, are necessary to modify the structure of the fiber, especially acting on two main bonds: hydrogen and disulphide.

Indeed, the main goal of finishing is to stabilize the structure of the textile material, with the so-called setting phenomena, and, depending on the values of temperature and moisture content reached during the treatment, two types of set can be imparted to the fabric: cohesive and permanent set.

Cohesive set is linked to the hydrolyses of hydrogen bonds, while the permanent set to the breakage and redistribution of disulphide bonds. The last one is surely the most important, as far as worsted wool fabrics are concerned, and a high degree of permanent set can be achieved only if high temperatures and consistent moisture content are reached during the treatment.

In current industrial equipments, permanent set is introduced with pressure decatizing, also known as KD, which operates with steam under pressure, allowing to reach steam temperatures between 125°C and 130°C.

A KD operation is carried out in a batch, due to the need of operating in a pressurized autoclave. The process variables are known only at the beginning of the process, but not during the treatment, where the setting phenomena take place. As a consequence,

similar fabrics, which have to be treated in the same way but in separate batches, sometimes are characterized by different final effects.

Differences between different batches are often associated with differences within the same batch, as it has been highlighted also from the tests carried out in a textile industry on a full scale KD equipment.

Time, temperature, moisture content and mechanical pressure are the four fundamental variables which determines the final properties and effects in these kind of treatment. The mechanical pressure can be easily set up at the beginning of the process and does not vary during the process, whereas the other three variables are strictly connected.

In order to study the influence of these variables during a steam treatment (either under pressure or not) an experimental campaign has been carried out on bench scale and prototypal equipments.

The heat transfer analysis demonstrated that heat transfer is quite rapid, as we saw from experimental measurements, moreover, thanks to the differential heat of sorption, the fabric temperature quickly rises to values higher than the steam one.

On the other hand, the moisture transfer is a relatively slow process because it depends on the diffusivity of water molecules inside the wool fiber structure, extremely compact and with a certain degree of crystallinity. It is clear that the initial moisture content of the fiber is the fundamental parameter from which the effect of the steaming or decatizing treatment depends.

Heat and moisture transfers have also been analyzed from a scientific point of view, trying to rationalize the phenomena occurring during the steam treatment of wool fabrics. Two different approaches have been considered, which have brought to the development of two models. Both approaches were based on differential equations of continuity, heat and mass transfer, as well as physical and experimental relationships to define the theoretical model.

The first model, based on simplified hypotheses and independent from the geometry of the system, was developed with a VB.NET programming language and has brought to valuable results especially considering the heat transfer analysis, but not so good as far as the moisture transfer is concerned.

In this view, the second approach brought to the development of a second model, thanks to the Comsol Multiphysics finite element simulation software. The moisture transfer analysis have been achieved considering different geometries, aimed at explaining the behavior of wool especially correlating the numerical simulations to the experimental data. The evolution of the different geometries brought to consider the fiber as a non-homogeneous medium, but with properties depending on the specific parts in which the fiber is divided.

The final fiber and yarn geometries allowed to obtain good explanations of the mass transfer and confirmed that the slow moisture transfer depends exclusively on the fiber structure, while the yarn one has a negligible influence.

In the view of a reduction of the current industrial problems, especially in KD treatments, the only upgrade would consist in the development of a new kind of equipment which could work continuously but clearly producing the same effects of a traditional KD.

This aspect can be analyzed looking again to the regions in which cohesive and permanent set take place, taking into account the results obtained from our experimental campaign (Figure 5.1).

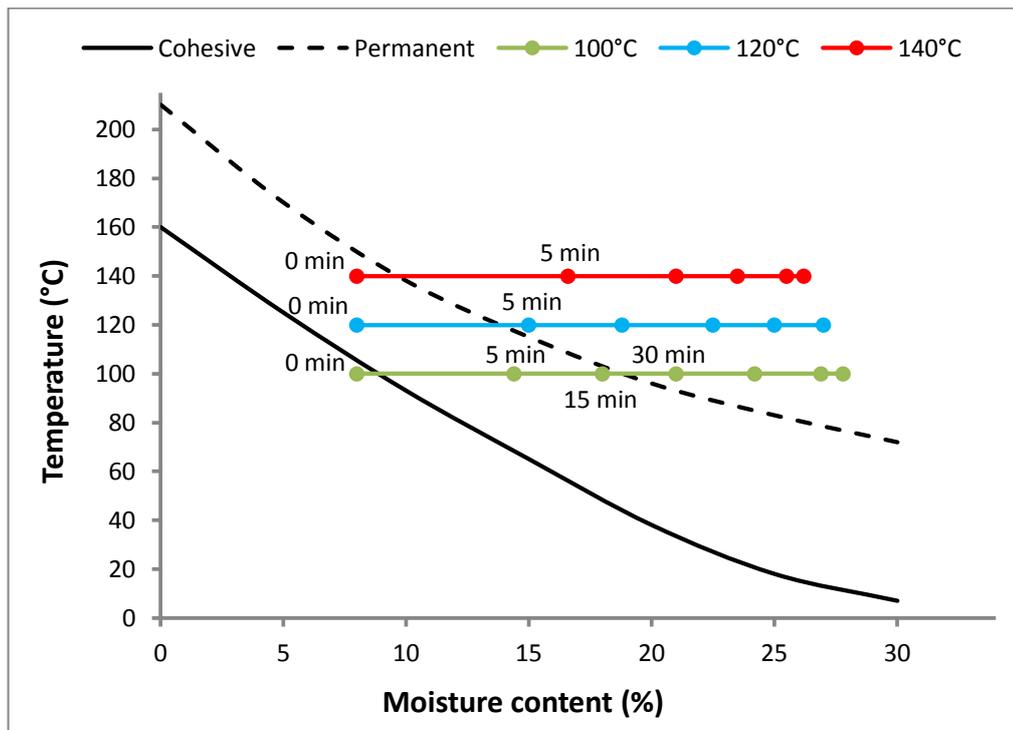


Figure 5.1 - Relation between setting regions and operative conditions for steam treatments.

The possible solutions aimed at developing a continuous KD-like machine move in two different ways: increasing the operating steam temperature (and of course its pressure), and/or increasing the initial moisture content of the fabric.

Considering that for both solutions it will not be possible to maintain the current KD equipment, designed for batch treatments, the development of a new machine, in which the fabrics flows continuously, has to take into account the seals issue. Special seals, which prevent possible steam leakages, with high abrasion resistance, long-lasting and that do not damage the fabrics, have to be specially designed.

Machinery constructors have been tried for years to develop a continuous pressure decatizing equipment and, trying to overcome the problem, different types of

continuous “KD-like” machines have been built, but none of them ensures the same effects of a traditional KD.

Moreover, another critical issue is linked to the fabric conditions and to the thermal stresses to which the fabric is subjected. It has been said that during steam treatments, fabric yellowing increases with the temperature at which the fabric is steamed. Indeed, the experimental evaluation demonstrated that at 140°C a treatment time of 5 minutes is enough to damage the fibers.

However, focusing the attention on a continuous KD-like treatment, in order to achieve at least the same productivity of a traditional KD, the estimated treatment time should be no longer than 1 minute. Therefore, for hypothetical steam temperatures higher than 140°C, an accurate evaluation of the possible fiber damages should be done.

## Nomenclature

$a_s$	specific surface area [ $\text{m}^{-1}$ ]
$C_{p,a}$	constant pressure heat capacity of dry air [ $\text{J kg}^{-1} \text{K}^{-1}$ ]
$C_{p,g}$	constant pressure heat capacity of the gas phase [ $\text{J kg}^{-1} \text{K}^{-1}$ ]
$C_{p,l}$	constant pressure heat capacity of the liquid phase [ $\text{J kg}^{-1} \text{K}^{-1}$ ]
$C_{p,s}$	constant pressure heat capacity of the solid phase [ $\text{J kg}^{-1} \text{K}^{-1}$ ]
$C_{p,v}$	constant pressure heat capacity of water vapor [ $\text{J kg}^{-1} \text{K}^{-1}$ ]
$d$	average fibers diameter [m]
$D_a$	diffusion coefficient of water vapor in air [ $\text{m}^2 \text{s}^{-1}$ ]
$D_f$	diffusion coefficient of water in wool fiber [ $\text{m}^2 \text{s}^{-1}$ ]
DHS	differential heat of sorption [ $\text{J kg}^{-1}$ ]
$F_{gl}$	mass transfer rate between gas phase and liquid phase (condensation rate) [ $\text{kg m}^{-3} \text{s}^{-1}$ ]
$F_{gs}$	mass transfer rate between gas phase and solid phase [ $\text{kg m}^{-3} \text{s}^{-1}$ ]
$F_{ls}$	mass transfer rate between liquid phase and solid phase [ $\text{kg m}^{-3} \text{s}^{-1}$ ]
$\Delta h_{\text{vap}}$	latent heat of evaporation / condensation [ $\text{J kg}^{-1}$ ]
$h$	heat transfer coefficient [ $\text{W m}^{-2} \text{K}^{-1}$ ]
$h_m$	mass transfer coefficient [ $\text{m s}^{-1}$ ]
$k$	Kozeny factor [-]
$k_{\text{tex}}$	thermal conductivity of wool fabric [ $\text{W m}^{-1} \text{K}^{-1}$ ]
$K$	permeability [ $\text{m}^2$ ]
$L$	characteristic length of fabric bed [m]
$Le$	Lewis number [-]
$M_e$	equilibrium moisture content of fibers with respect to the steam [ $\text{kg kg}^{-1}$ ]
$M_s$	moisture content in the fibers [ $\text{kg kg}^{-1}$ ]
$p$	pressure [Pa]
$P_{\text{in}}$	inlet steam pressure [Pa]
$P_{\text{out}}$	outlet steam pressure [Pa]
$p_{\text{sat}}$	saturation vapor pressure [Pa]
$t$	time [s]
$T_g$	temperature of the gas phase [K]
$T_s$	temperature of the solid phase [K]
$v_g$	gas phase velocity [ $\text{m s}^{-1}$ ]

*Greek letters*

$\alpha_{\text{tex}}$	thermal diffusivity of the fabric [ $\text{m}^2 \text{s}^{-1}$ ]
$\gamma_{\text{gs}}$	gas to solid absorption coefficient [ $\text{kg m}^{-3}$ ]
$\gamma_{\text{ls}}$	liquid to solid absorption coefficient [ $\text{kg m}^{-3}$ ]
$\theta_{\text{f}}$	volume fraction of dry fiber [ $\text{m}^3 \text{m}^{-3}$ ]
$\theta_{\text{g}}$	volume fraction of the gas phase [ $\text{m}^3 \text{m}^{-3}$ ]
$\theta_{\text{l}}$	volume fraction of the liquid phase [ $\text{m}^3 \text{m}^{-3}$ ]
$\theta_{\text{l}}^{\text{cr}}$	critical value of the liquid fraction at which the liquid phase becomes mobile [ $\text{m}^3 \text{m}^{-3}$ ]
$\theta_{\text{s}}$	volume fraction of the solid phase [ $\text{m}^3 \text{m}^{-3}$ ]
$\theta_{\text{w}}$	volume fraction of bound water (linked to the moisture content) [ $\text{m}^3 \text{m}^{-3}$ ]
$\rho_{\text{f}}$	density of dry fiber [ $\text{kg m}^{-3}$ ]
$\rho_{\text{g}}$	density of the gas phase [ $\text{kg m}^{-3}$ ]
$\rho_{\text{l}}$	density of the liquid phase [ $\text{kg m}^{-3}$ ]
$\rho_{\text{s}}$	density of the solid phase [ $\text{kg m}^{-3}$ ]
$\rho_{\text{v}}$	density of the vapor [ $\text{kg m}^{-3}$ ]
$\rho_{\text{v,l}}$	density of the vapor at the condensing surface [ $\text{kg m}^{-3}$ ]
$\rho_{\text{w}}$	density of water [ $\text{kg m}^{-3}$ ]
$\mu_{\text{g}}$	dynamic viscosity of water vapor [ $\text{kg m}^{-1} \text{s}^{-1}$ ]

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