Equilibrium moisture isotherms of textiles materials

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ABSTRACT. Knowledge on thermal characteristics of materials is very important for developing of a drying process in a more economic and viable way. The literature presents isotherms of several natural fibers, as cotton, wool, hemp, jute, sisal and silk (Foust *et al*., 1982; Gomide, 1991), and these isotherms have a very similar and evident behavior. This work presents a reliable database of textile materials isotherms, besides experimental cotton sarja data, obtained by the static method and using saline solutions, at the temperatures of 28, 35 and 70ºC. The samples' equilibrium moisture was obtained after 21 days and dry basis humidity was determined by the stove method. Results were appraised by means of models given in the literature. Henderson's model seems to be the most representative for isotherms of the natural fibers under analysis.

Key words: drying, textile isotherms, isotherms equilibrium, cotton.

RESUMO. Isotermas de umidade de equilíbrio de materiais têxteis. Conhecer as características térmicas dos materiais é extremamente importante para o desenvolvimento de um processo de secagem, pois propicia melhor eficiência operacional, além de melhorar a qualidade do produto final. A literatura fornece isotermas de várias fibras naturais de algodão, lã, cânhamo, juta, sizal e seda, (Foust *et al*. 1982; Gomide 1991), apresentando semelhanças de comportamento bastante evidentes entre si. Este trabalho apresenta um banco de dados de isotermas de materiais têxteis obtidas da literatura, além de dados obtidos experimentalmente para a sarja de algodão. Os dados experimentais da sarja foram obtidos pelo método estático, com o auxílio de soluções salinas, nas temperaturas de 28, 35 e 70 ºC. O equilíbrio das amostras foi obtido, em média, após 21 dias e sua umidade base seca foi determinada pelo método da estufa. Os resultados foram avaliados por meio de modelos existentes na literatura, e, para as condições estudadas, o modelo de Henderson parece ser o mais representativo para as isotermas das fibras naturais estudadas.

Palavras chave: secagem, isotermas têxteis, isotermas de equilíbrio, algodão.

Comfort and good form is all that is needed in clothes, from the simplest to the most sophisticated ones. The thermal comfort is directly linked to the material characteristics. The study of the adsorption and desorption of humidity for these materials is very important to guarantee the control of the finished product's humidity.

The best method to determine patterns of moisture equilibrium isotherms for a wide strip of values is the use of saturated saline solutions conditioned in small closed flasks (Young, 1967). Saline solutions, in a certain concentration and at constant temperature, are in equilibrium with the partial pressure of water vapor and thus define a certain relative humidity.

This work refers to the experimental obtaining of some humidity equilibrium isotherms for an industrial woven fabric (sarja) (Textilpar, state of Paraná, Brazil), and to compile a group of known moisture equilibrium isotherm data for some finished textiles, which were organized and graphically disposed, so that their behavior could be verified.

Furthermore, the mathematical models from isotherm literature that might represent the data presented in this work will be verified.

Cotton

The use of cotton goes back beyond the records of history. As early as 3000 BC, cotton was grown and used in the Indus Valley of India. Ancient Egypt and China also spun and wove it.

Cotton is the most important natural fiber. It provides about fifty percent of the natural fibers consumption in the United States and all around the world. People use cotton in some form or other every day. In summer, cotton clothes are worn because they are cool and easy to clean. At all seasons, there are cotton towels, sheets, rugs, draperies, gloves and any other products ranging from sewing thread to oil for cooking.

In ancient times, cotton had an important cultural and economic role. In modern times, cotton was reintroduced in Europe and America, starting from the discovery of Brazil in the XVI century, with the development of more than 300 types of cotton.

Structure, properties and classification of cotton

Cotton fibers have a monocellular structure. The fibers' development cycle begins 3 days after their prosper and it takes about one month to be complete. During the first phase, the fiber reaches maximum length, coming as a lightly hollow cylinder whose internal wall is formed by cellulose and receives the name of "primary wall", while the external wall is formed by a cuticle covered by wax. In the second phase of growth, that corresponds to the maturation of the capsule (20 to 35 days), a second wall is formed inwardly, called "secondary wall", that increases quickly by cellulose deposits in concentric layers.

By the end of maturation, the plasma of the fiber cells dies. The fiber begins to evaporate, losing the cylindrical form, then flattens and twists on its own axis. The fiber acquires a form like this typical microscopic image, showed in Figure 1; a tube flattening with numerous torsions on itself, in an average number of 5 for millimeter of fiber.

Cotton fibers are constituted of pure cellulose - long chains of molecules joined by OH groups -, arranged in a spiral form. This arrangement gives to the cotton fibers great resistance and great stability. Figure 1 shows cotton morphology.

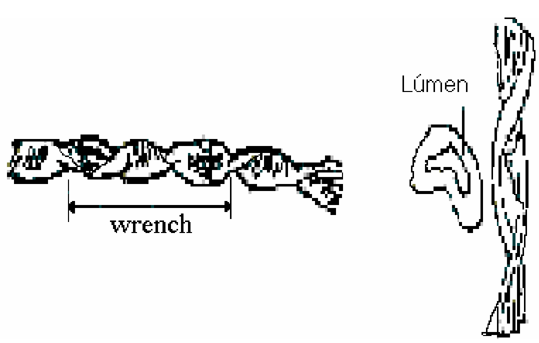

Figure 1. Cotton morphology

Wall thickness may vary from 0.35 to 15.5 μm and the largest diameter of the lumen, from 11.9 to 21.5 μm. For a relative humidity of 65%, its density is about 1.52 g/cm^3. Cotton composition is shown in Table.1.

Table 1. Cotton composition

Compounds	%
Cellulose	85.5
Oil and wax	0.5
Protein, pectoses and color material	5.0
Minerals	1.0
Water	8.0

All textile of natural fibers are hygroscopic, and this is a very notable property from the point of view of hygiene, thermal isolation and comfort.

Woven fabric

Woven fabrics are made of yarns interlaced in a regular order, called a binding system, or weave.

Weaving is widely used because it is cheap, fairly simple, and adaptable. Woven cloth is normally longer than wide. The lengthwise threads are called the warp. The crosswise threads combined with the warp (2) make fabric. The width of the cloth is called the weft (1). Figure 2 shows the interlaced woven sarja 3/1.

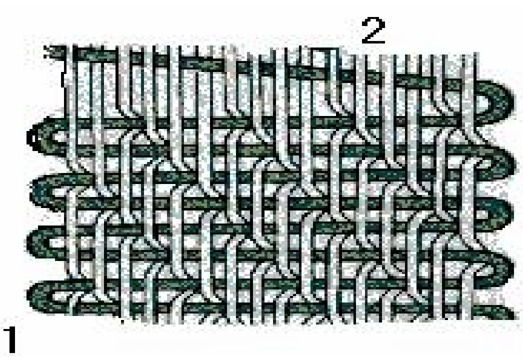

Figure 2. Woven sarja 3/1

Equilibrium moisture isotherms

Equilibrium moisture is the moisture content reached by the material after a sufficient period of time in certain temperature condition and relative environment humidity.

In this condition, the pressure of the water vapor on the product surface is equal to the one contained in the air (Almeida *et al*., 1997).

Consequently, when a solid is exposed to a moist gas, at a certain temperature and moisture content, it will accept or release moisture until equilibrium is established. Solid equilibrium (Xe) is a function of the gas's relative moisture content (RH), temperature and the nature of the solid and liquid. The variation of Xe with the relative humidity of the gas, at constant temperature, is called moisture equilibrium isotherm.

Two methods are normally used in the determination of equilibrium moisture isotherms: the static and the dynamic one.

In the first method, saturated aqueous solutions of several salts or of different acid concentrations are used. As a result, different values of relative air humidity are obtained over the surface of the solutions. To control the air temperature, flasks are placed in a stove or in a refrigerated camera.

In the second method, airflow at a certain humidity is used and the temperature is controlled throughout the sample, until its moisture reaches equilibrium with the air humidity. Moisture equilibrium is reached faster than in the previous method (Almeida *et al.,* 1997).

Adsorption theories offer equations to predict the relationships among Xe, RH and T. However, these equations are valid only within a range of relative humidity. Equations usually involve more than two adjustable parameters and temperature dependence is frequently not included explicitly. Temperature influences on the sorption isotherm are important, because product's temperature might increase during drying processes (Papadakis *et al.,* 1993).

Material and methods

Raw material

Woven samples of 50 mm diameter and about 0.7 mm thick, constituted of long fiber cotton yarn without load addition, were used. Their moisture content, in room conditions of the Separation Process Laboratory - DEQ/UEM, ranged from 8 to 9 % (d.b).

Methods

The static method with saline solutions (Arnosti, 1997) was used to determine equilibrium isotherms. Tightly closed glass flasks were used to guarantee constant conditions (Figure 3). Eight different salt solutions were used: LiCl, CH_3CO_2K, $MgCl_2.6H_2O$, K_2CO_3, $Mg(NO_3)_2$, $NaNO_2$, NaCl and KCl.

The flasks had a diameter of 86 mm and a height of 125 mm. To avoid contact with the saline solution, a support was placed inside with a perforated stainless steel tray containing the samples. Inside the flask, there was a Teflon magnetic agitator to homogenize the solution.

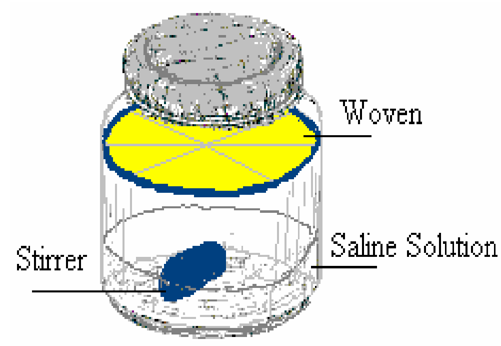

Figure 3. Glass flask for textile samples

Woven samples were washed with water and detergent at 100ºC to remove the gum.

After weighting the samples on a precision scale, they were placed inside the flasks and left inside at constant temperature stove. Samples were weighted every 7 days until equilibrium was reached (about 21 days). Equilibrium moisture content of the woven samples was determined by the stove method (105 ºC for 24 hours).

Results and discussion

Isotherms of sarja

Moisture equilibrium isotherms (RH x Xe) of the woven sarja 3/1 samples are shown in Figure 4.

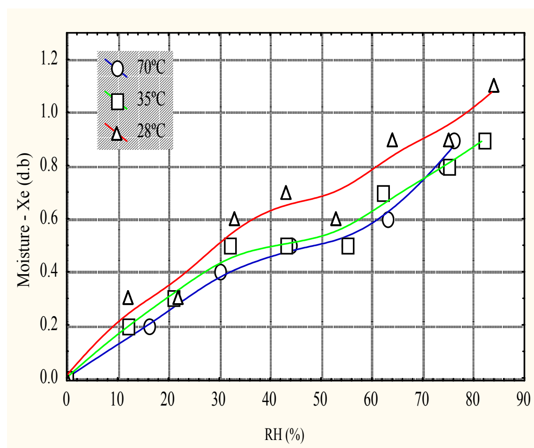

Figure 4. Moisture isotherms of sarja

Figure 4 also presents a minimum square fit of the isotherms, facilitating the comparison among curves behavior. The obtained curves are similar in shape and one may observe that woven moisture equilibrium decreases when temperature increases, confirming the characteristic presented in cellulose materials studied in literature.

Data were compared to Luikov's (Equation 1), Henderson's (Equation 2) and Halsey's (Equation 3) models proposed in isotherm literature (Barrozo, 1995). Table 2 presents their fitting results and Figures 5, 6 and 7 are the residual distributions for these three models, respectively.

$$X_e = A_1 / \left(1 + A_2 T \ln\left(\frac{1}{RH} \right) \right) \tag{1}$$

$$X_e = A_1 \left(\frac{1}{T} \ln\left(\frac{1}{1-RH} \right) \right)^{A_2} \tag{2}$$

$$X_e = A_1 \left(T \ln\left(\frac{1}{RH} \right) \right)^{-A_2} \tag{3}$$

Table 2. Woven sarja - models fitting results

Model	R^2	A1	A2	F
Henderson	0.95	1.564	0.524	74.3
Halsey	0.92	0.862	0.496	54.3
Luikov	0.95	0.132	0.006	69.1

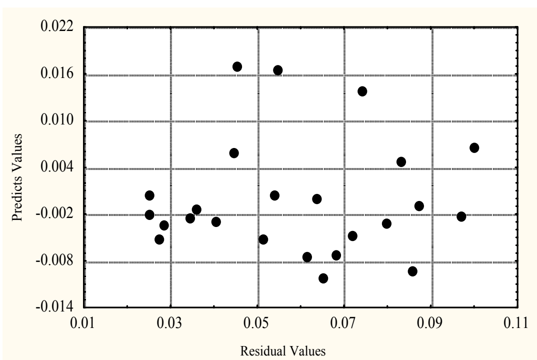

Figure 5. Residual analysis of Henderson's model

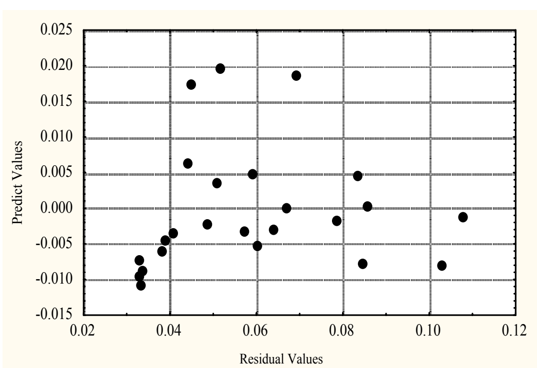

Figure 6. Residual analysis of Halsey's model

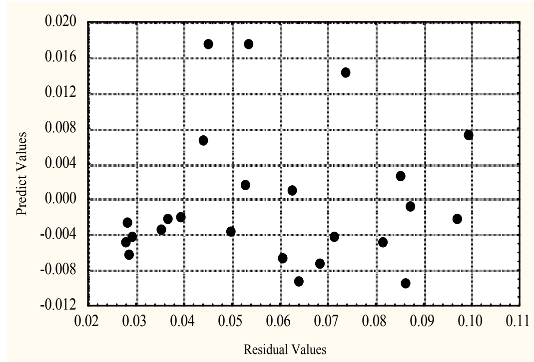

Figure 7. Residual analysis of Luikov's model

The analysis of the R^2 and test F values, and the good residual distributions for the three models show that Henderson's model (Equation 2) had the best performance for the sarja 3/1 woven moisture equilibrium isotherms.

Study of equilibrium isotherms reported in literature

The collected textile isotherm literature data show that natural fibers of cotton, wool, hemp, jute, sisal, and silk present the same characteristics and produce near equilibrium points when exposed to environments at controlled relative humidity.

In this context, Figure 8 shows literature data for raw cotton isotherms reported in Foust *et al*. (1982).

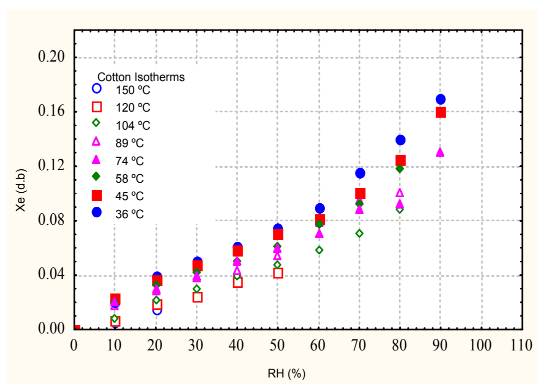

Figure 8. Raw cotton isotherms

Figure 9 for cotton, woven cotton and absorbent cotton, and Figure 10 for other kinds of textile fibers; show the isotherm literature data reported in Gomide (1991).

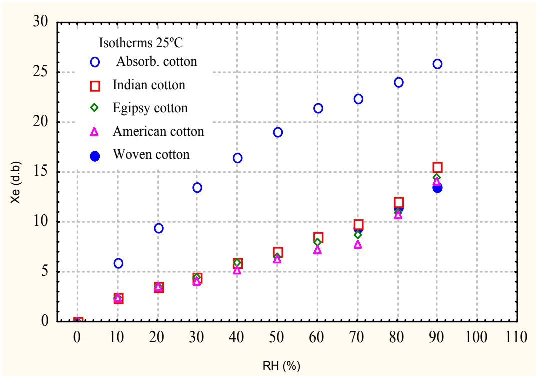

Figure 9. Cotton, woven cotton and absorbent cotton isotherms

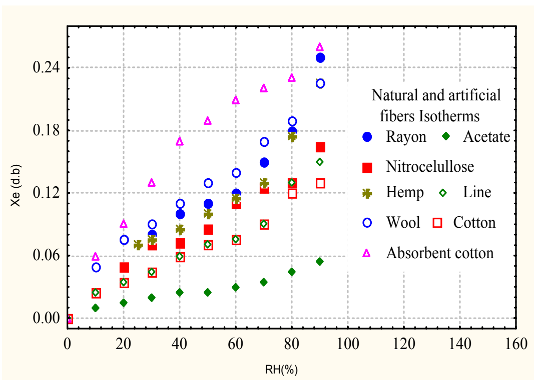

Figure 10. Isotherms of some various natural and artificial fibers

All these data were compared to the three models proposed in literature. The fitting results may be seen in Tables 3 to 7.

Table 3. Raw cotton - models fitting results

Modelo	R^2	A1	A2	F
Halsey	0.90	0.15	0.004	34.0
Henderson	0.94	5.96	0.74	54.0
Luikov	0.93	0.22	0.01	45.0

The best fitting results were obtained with Henderson's model (Equation 2).

Table 4. Cotton, woven cotton and absorbent cotton - Model's fitting results

		Cotton and Woven Cotton Fabrics		
Model	R^2	A1	A2	F
Henderson	0.94	773.5	0.88	82.0
Luikov	0.63	29828	698	12.0
		Absorbent cotton		
Model	R^2	A1	A2	F
Henderson	0.99	25420	1.49	658.0
Luikov	0.66	28512	1040	160.0

In both cases, the best fitting results were obtained with Henderson's model (Equation 2).

Table 5. Natural hemp fibers - Model's fitting results

Model	R^2	A1	A2	F
Halsey	0.99	1.091	0.448	1999
Luikov	0.98	0.279	0.008	386

Halsey's model (Equation 3) may represent hemp isotherms.

Table 6. Natural wool fibers - Model's fitting results

Model	R^2	A1	A2	F
Halsey	0.94	0.90	0.378	109
Henderson	0.99	2.38	0.481	2730
Luikov	0.99	0.26	0.261	1496

Henderson's model may represent natural wool fiber isotherms.

Table 7. Artificial acetate fiber - Model's fitting results

Modelo	R^2	A1	A2	F
Halsey	0.97	0.270	0.443	165
Henderson	0.99	0.895	0.574	457
Luikov	0.99	0.672	0.007	520

Luikov's model (Equation 1) may represent artificial acetate fibers isotherms.

Conclusion

For each of the tested textile materials, at least one of the studied correlations gave a good fit over the range of relative humidity employed. Furthermore, it is unwise to extrapolate the results obtained here to very low or very high relative humidity. Otherwise, experimental data should be taken over the whole range of relative humidity. New temperatures are being studied, together with desorption tests where textile initial moisture contents are about 100 % (d.b.).

The sarja results shows a range of relative humidity (0.3 to 0.6) in which equilibrium moisture of the material tends to be constant. Within this range it is not recommended to use some kind of equipment to alter the relative humidity of air that will be used for drying.

For the raw cotton isotherms, as for the woven sarja 3/1 samples, the material equilibrium moisture content decreases with increase of temperature.

For the absorbent cotton, an inversion may be observed in the equilibrium moisture content behavior, when compared with the other studied isotherms, due to its great capacity of humidity absorption.

Observing the natural and artificial fiber data (Figure 10), it may be easily verified that fitting analysis might be done individually for each type of fabric to obtain satisfactory results. This fact shows that the individual characteristics of the studied textiles influence their equilibrium moisture isotherms behavior.

Literature models could be employed for predicting the equilibrium moisture isotherms of different textile materials studied in this work at different operational conditions. Owing to the above fitting results, Henderson's Model might be a good choice to characterize those isotherms.

Notation

A1 and A2 - Constants
T - Absolute temperature (K)
R^2 - Correlation coefficient
Xe - Equilibrium moisture content
RH - Relative humidity
% d.b - Concentration in dry basis
F = Ratio between the mean of the square of the predicted values and the mean of the square of estimated residuals

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