

## ENGINEERING PROPERTIES OF SUGARCANE FIBRES

By

J. RODRIGUEZ RAMIREZ and L. MENDEZ LAGUNAS  
*Instituto Politécnico Nacional, CIIDIR Unidad Oaxaca,  
Hornos 1003 Sta. Cruz Xoxocotlan, Oaxaca Mexico*  
[jrodrigr@ipn.mx](mailto:jrodrigr@ipn.mx)

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### Abstract

THE PHYSICAL properties and the mass and heat transfer coefficients for sugarcane bagasse were determined to provide information for process design and manufacturing of products. In this report, true density ( $\rho_s$ ) and apparent density ( $\rho$ ) were measured by the pycnometer method. Superficial area ( $A_s$ ) and pore size distribution of fibres were determined by nitrogen adsorption and mercury porosimetry. Equilibration cells were used in order to obtain sorption isotherms. Water content and surface temperature of the sugarcane fibres were monitored using a modified Thermal Gravimetric Analyzer (TGA). The method of slope was used to calculate the effective water diffusion coefficient. The mass ( $h_M$ ) and heat coefficients ( $h_H$ ) were determined by experimental data, and then compared with one convective transfer correlation. The results show  $\rho_s$  values of  $1231 \text{ kg/m}^3$ ,  $\rho$  of  $466 \text{ kg/m}^3$  and  $A_s$  of  $1300 \text{ m}^2/\text{kg}$ . The sugarcane fibre materials are formed mainly by macropores with an average diameter of  $0.0385 \text{ }\mu\text{m}$ . Sorption isotherms are type II sigmoid form, a form which is consistent with macroporous structures. The results showed that the parameters of the GAB equation adequately represent the experimental data. The order of magnitude of  $D_e$  of fibres was  $10^{-10} \text{ m}^2/\text{s}$ . The value of  $h_H$  was  $40 \text{ W}/(\text{m}^2 \cdot ^\circ\text{K})$  and  $h_M$  was  $0.045 \text{ kg}/(\text{m}^2 \cdot \text{s})$ . The fibre is a porous material consisting of macropores and its internal structure differs from that of the pith. The experimental values of  $h_H$  were more elevated than those calculated with correlations due to the effects of conduction and radiation. The principal mass transfer mechanism was the internal resistance,  $D_e$  increased with temperature in an Arrhenius type function.

### Introduction

Bagasse is the residue left after the crushing of sugarcane for juice extraction. The largest and most traditional use of bagasse is burning it in boilers to generate process steam (Nassar *et al.*, 1996).

A revision of the published results and industrial experience realised by Atchison (1971, 1974) and Pilgrim (1989) has shown the viability of satisfying the energy needs of a sugar factory with half of its residual bagasse. Then, the remainder can be used in more than 40 applications; the most important are paper pulp and cellulose pulp production, animal food, ethanol, and furfural.

In order to expand the use of bagasse, it is essential that information on fibre characteristics and the factors which affect the performance of that fibre be available.

Specific knowledge of the bagasse material is useful to predict its behaviour during transformation processes. Physical properties involved in the heat and mass transfer, such as density and porosity, play an important role in the design, the estimation of other properties, the characterisation of materials, and the prediction of heat transfer operations during processing and handling.

The engineering properties are important in the process design and manufacturing of products. The mathematical models are fitted using data as a function of one or more experimental parameters, such as temperature, water content, porosity, heat, and mass transfer coefficients or others. In order to do this, the aim of the present work is to describe physical characteristics, adsorption capacity, mass and heat transfer coefficient and water diffusivity of bagasse.

## Materials and methods

### Material preparation

The sugarcane bagasse provided by sugarcane factories in Zacatepec, Morelos, Mexico was depithed while wet, dried, sieved, and classified by size manually using a stereoscopic microscope. The highest frequency fractions (9.62% and 7.53%) of fibre (12 to 14 and 20 to 24 mesh screen/sieve, respectively) were used for all tests. A vernier caliper was used for measuring the length and diameter of the selected fibres. Volume and area were calculated using these data. Physical characteristics are shown in Table 1.

**Table 1**—Sample single fibre physical characteristics.

Number of fibres measured	Average diameter	Average length	Average area	Average volume
	mm	mm	mm <sup>2</sup>	mm <sup>3</sup>
40	0.362 ± 0.01	7.492±0.14	8.52	0.970
14	0.5483 ±0.03	10.186±0.19	17.55	2.40

### Heat and mass transfer convective coefficient

A heat and mass balance expressed by equation 1 (Vaccarezza *et al.*, 1974) was used to determine the experimental convective heat and mass coefficients. All symbols are described in the *Notation* section at the end of this paper.

**Equation 1**—Heat balance equation.

$$\Delta H_v \cdot \frac{dX}{dt} = h_H \cdot A \cdot \Delta T$$

Experiments were conducted to measure the moisture lost during drying. The rate of moisture lost ( $dX/dt$ ), determined in the period of constant-rate drying, and fibre surface temperature data were used for determine the convective coefficients of heat and mass transfer. It is assumed the heat of water vaporisation is constant and equal to the heat of water vapour condensation.

A correlation presented by Eckert and Drake (1959) was used for the calculation of the local heat transfer coefficient around the periphery of thin cylinders in the laminar region for flow of a fluid with constant thermophysical properties. For Reynolds numbers 0.1 to  $10^5$  and Prandtl numbers of 0.7 to 1500, the heat transfer coefficient correlation is expressed by equation 2.

**Equation 2**—Heat transfer coefficient correlation,

$$Nu = 0.43 + 0.532 \cdot Re^{0.5} \cdot Pr^{0.31}$$

The Nu and Re numbers were calculated with the fluid properties measured at the mean temperatures of the solid and of the fluid.

An analogous expression for the mass transfer coefficient is shown in equation 3.

**Equation 3**—Mass transfer coefficient correlation.

$$Sh = 0.43 + 0.532 \cdot Re^{0.5} \cdot Sc^{0.31}$$

### Calculation of the effective moisture diffusivity

The effective moisture diffusivity ( $D_e$ ) in solids is a physical property of the system and can be estimated from drying rate data. Assuming that the drying process is entirely controlled by internal mass transfer resistance (falling rate drying period), uniform initial moisture distribution and negligible external resistance, the solution of Fick's diffusion equation developed for particles with cylinder geometry by Crank (1975) for a series of six terms is applicable and is in the form of equation 4.

**Equation 4**—Solution of Fick's diffusion equation for a cylinder.

$$W = 2 \cdot \sum_{i=1}^{\infty} \frac{\int_0^1 J_0(\alpha_i \cdot r) dr}{\alpha_i \cdot J_1(\alpha_i)} \cdot \exp(-F_0 \cdot \alpha_i^2)$$

The effective moisture diffusivity was calculated using the slope method (Perry *et al.* 1984)

### Physical properties

#### True and apparent density

The true density was calculated from the volume measured by a gas pycnometer. A dried, pre-weighed sample was placed in an autopycnometer (MicroMeritics AccuPyc 1330). Helium was used as the displacement fluid. The apparent density of the totally-dried fibres was determined by measuring their dimensions and weight.

#### Surface area and pore size

The size, area and pores distribution were measured by nitrogen adsorption and mercury porosimetry methods, respectively. A nitrogen adsorption surface area analyser (Micromeritics, ASAP-2000) and standard methods ASTM D 3663-92 and ASTM D 4222-91 were used to evaluate the surface area and pore size, and adsorption and desorption by nitrogen isotherms. A mercury porosimeter (Poromaster, Quantachrome) was used between 0 and 60 000 psi for measured macropores. The pore volume distribution over pore diameter is expressed in terms of the distribution function  $F_v$  (eq. 5):

**Equation 5**—Pore volume distribution function.

$$F_v = \left[ \frac{dV}{d \log D} \right]$$

where  $V$  is pore volume. The function is such that area under the function in any pore diameter range yields volume of pores in that range.

#### Sorption isotherms

Sorption isotherms were determined gravimetrically at 25°C and 70°C. Triplicate samples of fibres dried at 90°C, sieved on sieves mesh number 16–14 (1.19–1.41 mm) and weighed, were transferred to vacuum desiccators.

Sulfuric acid solutions at different concentrations were used to achieve the internal, relative humidity in desiccators (Iglesias and Chirife, 1982; Molnár, 1995) over the range of 4% to 80% water activity ( $a_w$ ). The criterion for the stable state was that water content of the samples (dry basis) did not change more than 2 mg/g during three consecutive days.

The Guggenheim-Anderson-DeBoer (GAB) equation (eq. 6) was used in modelling water sorption (van den Berg and Bruin, 1981):

**Equation 6**—The Guggenheim-Anderson-DeBoer (GAB) equation

$$X = \frac{X_M \cdot C \cdot K \cdot a_w}{(1 - K \cdot a_w) \cdot (1 - K \cdot a_w + C \cdot K \cdot a_w)}$$

The water activity,  $a_w$  is defined as the ratio of the partial pressure,  $p_w$ , to the vapour pressure of water  $p_w(0)$  at equilibrium (Rao and Rizvi, 1986). Temperature dependent GAB constants  $C$  and  $K$  were calculated with the following equations:

**Equation 7**—Temperature dependent GAB constant.

$$C = C_0 \cdot \exp\left[\frac{\Delta H_C}{R \cdot T}\right]$$

$$K = K_0 \cdot \exp\left[\frac{\Delta H_K}{R \cdot T}\right]$$

## Results

### Fibre dimensions

Surface area, pore and diameter volume measured by nitrogen adsorption and mercury porosimetry are shown in Table 2. True density of fibres was  $1.331 \text{ g/cm}^3$ . The order of magnitude is consistent with those of some natural fibres and similar to jute, banana, kenaf, coconut, and sisal (Eichhorn *et al.*, 2001; Biagiotti *et al.*, 2004). Porosity, calculated from true density and pore volume was 0.714. The pore distribution is shown in Figures 1 and 2 for the two measurement methods used.

**Table 2**—Measured fibre properties

Properties	Nitrogen adsorption	Mercury porosimetry
Superficial area ( $\text{m}^2/\text{g}$ )	1.300	5.8267
Pore volume ( $\text{cm}^3/\text{g}$ )	0.0426	1.8733
Pore average diameter ( $\mu\text{m}$ )	0.0385	1.285

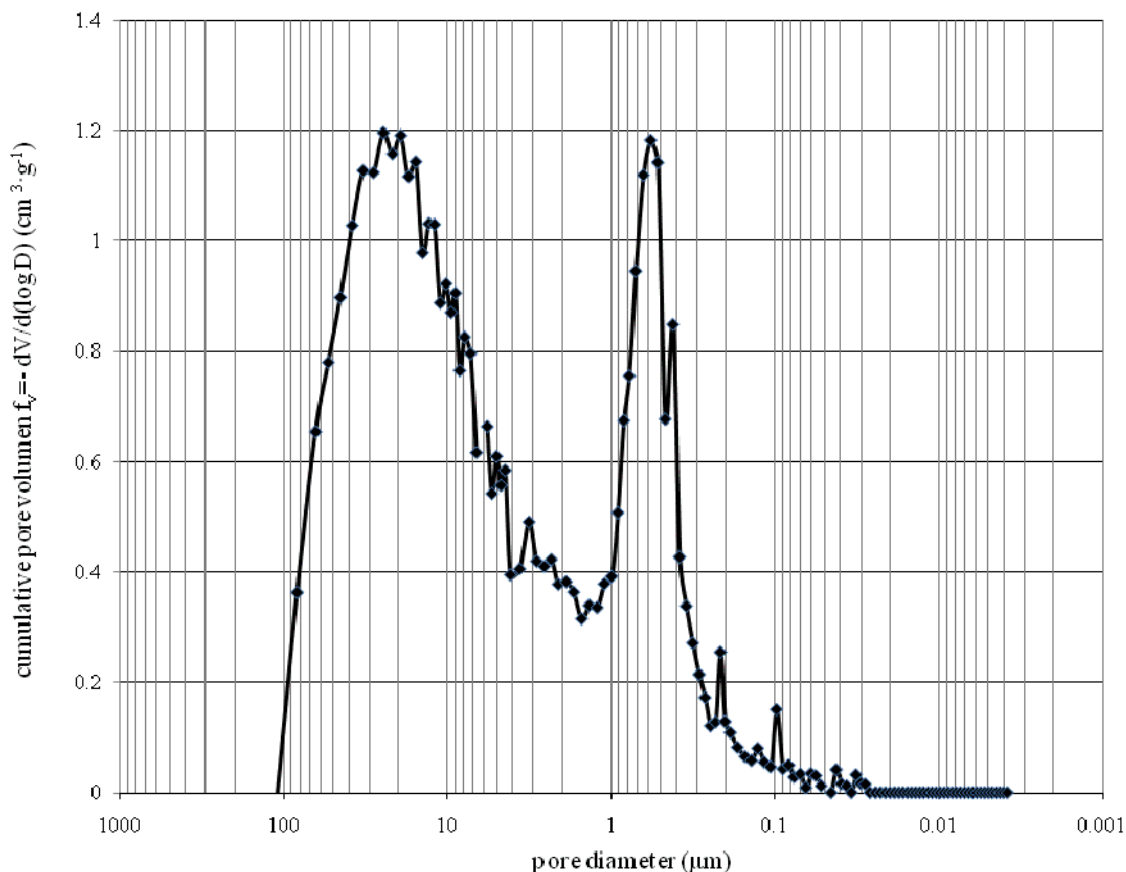


Fig. 1—Fibre pore distribution (mercury porosimetry).

The distribution of pore sizes was represented by the logarithmic derivative of the cumulative intrusion of mercury volume  $V$  ( $dV/d\log D$ ) vs pore diameter ( $D$ ). The nitrogen absorption method shows lower results than the mercury porosimetry method. The difference is explained by the measurement range of each method. The first method has a range of micropores to mesopores of between 10–500 Å while the second method has a range of mesopores to macropores greater than 500 Å.

The pore volume distribution over pore diameter is expressed in terms of the distribution function  $F_v$ . The fibres reveal two pore distributions, one in the range of 0.1 at 1 µm and one in the range 4–100 µm with pore diameter maxima of 0.5774, 5.387 and 29.85 µm. This material mainly contains macropores >0.05 µm.

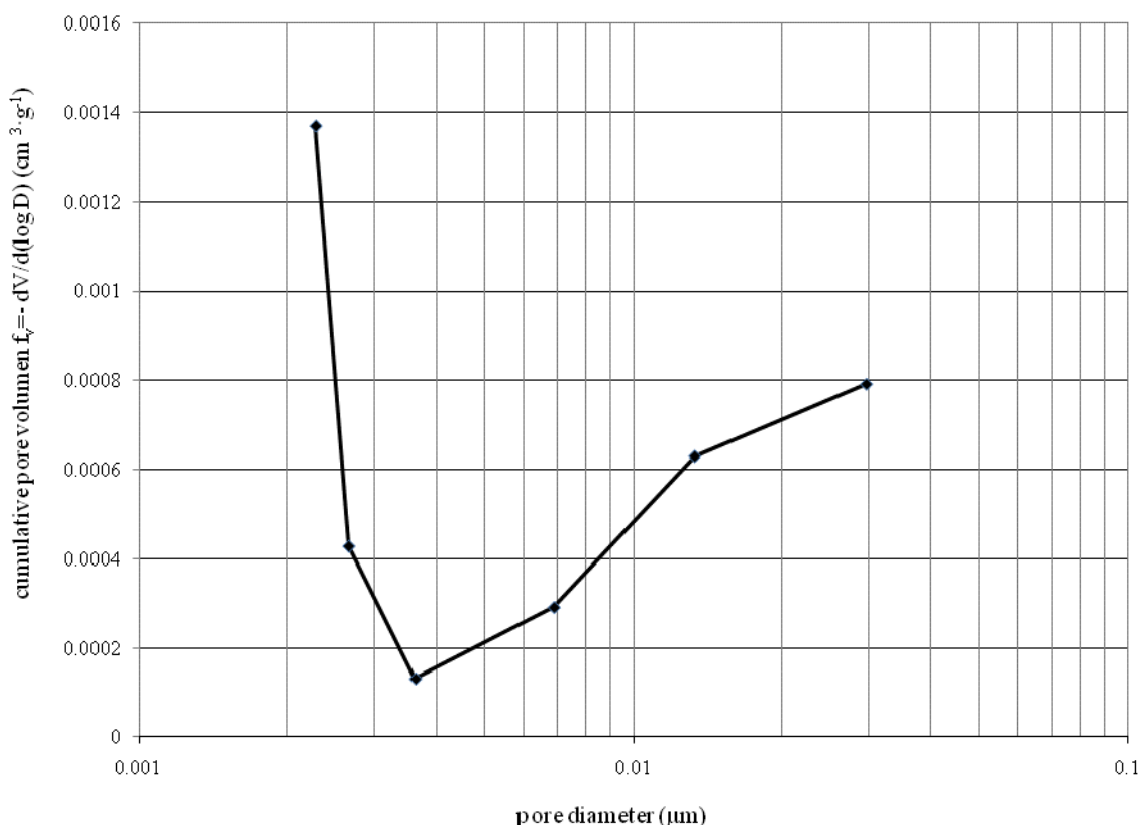


Fig. 2—Fibre pore distribution (nitrogen adsorption method).

### Sorption isotherm

The values of GAB constant and the correction factors are presented in Table 3. The water adsorption isotherm results plotted for the fibre were carried out at 25°C and 70°C and are presented in Figure 3.

The isotherm presents a sigmoid or S-shape. For the same moisture content, water activity increased with temperature. This behaviour is frequently observed in cellulose-based materials (Jonquière and Fane, 1998).

The high level of moisture adsorption is caused by the high hydrophilic nature of the sugarcane fibre compared to other natural fibres, like the agave fibre which shows a low adsorption of 0.3 g water/g dry fibre at 0.8  $a_w$  (Bessadok, 2009).

Cane fibre has a high cellulose composition of 32–48 % (Rowell *et al.*, 2000) and therefore a number of accessible –OH groups that are responsible for the negative charge and the best characteristics of sorption.

**Table 3**—GAB constants.

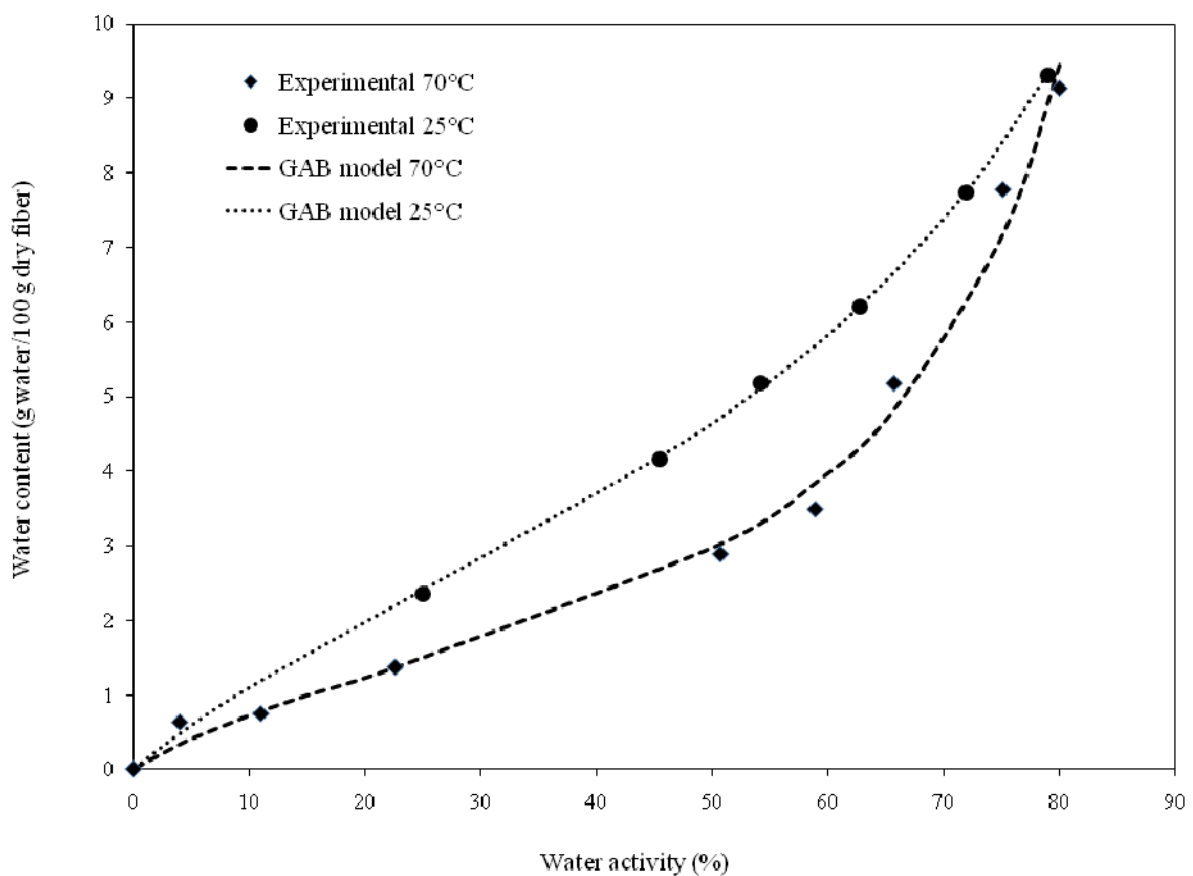
GAB constants	25°C	70°C
$X_m$	3.6511	4.2061
C	4.206	5.4379
K	$82.57 \times 10^{-4}$	$103.73 \times 10^{-4}$
Co	29.8235	29.8235
Ko	0.04702	0.04702

### Mass and heat transfer

The experimental heat and mass transfer coefficients were larger than those typically used in correlations. This could be explained because other factors like thermal conduction and radiation are involved in the experimental tests (Table 4).

The values of effective diffusivity for different experimental conditions are presented in Table 4. These values are within the general range of  $10^{-11}$  for dry food materials and lower than the reported values of  $3.92 \times 10^{-12}$  m<sup>2</sup>/s for sisal at 30% relative humidity (Alvarez *et al.*, 2004).

The mass transfer Biot number values were higher than 50. Therefore, the controlling mechanism of mass transport is the internal resistance to the transfer of humidity. Both internal and external resistance are important for heat transfer (Biot less 50).

**Fig. 3**—Fibre sorption isotherm.

**Table 4**—Mass and heat transfer coefficients

Experimental conditions			$h_H$		$h_M$		$D_e$	$Bi_H$	$Bi_M$
Temp.	Air flow	Fibre diameter	Correlation	Exp.	Correlation	Exp.	$D_e \cdot 10^{-11}$		$Bi_M \cdot 10^6$
°C	m/s	mm	(W/(m <sup>2</sup> °K))		(kg/(m <sup>2</sup> s))		m <sup>2</sup> /s	Dimensionless	Dimensionless
70	0.35	0.552	30.58	46.70	0.034	0.047	2.012	0.347	1.120
70	0.80	0.366	48.99	32.67	0.055	0.033	1.364	0.366	1.734
80	0.35	0.552	30.93	39.80	0.035	0.040	3.621	0.351	0.638
80	0.35	0.552	30.91	41.34	0.035	0.041	2.835	0.351	0.813
90	0.35	0.552	31.43	46.32	0.035	0.046	4.683	0.357	0.509
90	0.80	0.366	50.36	39.39	0.056	0.036	1.662	0.376	1.51
90	0.35	0.552	45.49	40.66	0.051	0.040	2.382	0.340	0.955
90	0.80	0.552	35.61	51.27	0.040	0.057	4.889	0.404	0.556
110	0.35	0.552	32.19	40.53	0.035	0.040	10.20	0.365	0.246
120	0.35	0.552	47.68	44.13	0.052	0.043	4.259	0.356	0.587
120	0.80	0.366	36.63	55.58	0.040	0.054	1.272	0.416	0.227
120	0.35	0.552	32.64	46.92	0.036	0.046	9.814	0.370	0.263
130	0.35	0.552	33.10	53.45	0.036	0.052	9.029	0.376	0.294

## Conclusions

The dimensions of the fibre, physical properties, and mass and heat transfer coefficients of cane fibre bagasse were studied. The fibres are made up mainly of macropores distributed essentially in two pore diameters.

The analysis of the water sorption indicates that the fibre is highly hydrophilic. This behaviour is a result of its high cellulose composition and is consistent with other cellulose fibres. The GAB model gives a good fit to the water adsorption data.

The heat and mass transfer coefficients, determined by experimental tests and correlations, show differences. The explanation of this behaviour would be the effect of thermal conduction and radiation.

The controlling mechanism of mass transport is the internal resistance to humidity transfer and, for heat transfer, internal and external resistance are important.

## Acknowledgments

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## Notation

A	Area [m <sup>2</sup> ]
As	Superficial area [m <sup>2</sup> /kg]
$a_w$	Water $\left[ \frac{p_w}{p_w^0} \right]$ activity
$Bi_H$	Biot number (heat) $\left[ \frac{h_H \cdot d}{k_f} \right]$
$Bi_M$	Biot number (mass) $\left[ \frac{h_M \cdot R \cdot T \cdot d}{F \cdot P \cdot M_s \cdot D} \right]$
C	GAB parameter
$C_0$	GAB parameter
$cp_a$	Specific heat capacity [J/kg°K]

d	Particle diameter [m]
D	Pore diameter [cm]
$D_{AB}$	Molecular diffusivity [m <sup>2</sup> /s]
$D_e$	Effective moisture diffusivity [m <sup>2</sup> /s]
Fo	Fourier number $\left[ \frac{D_e \cdot t}{r_0^2} \right]$
$h_H$	Heat transfer coefficient [W/m <sup>2</sup> °K]
$h_M$	Mass transfer coefficient [kg/m <sup>2</sup> s]
$J_0$	Bessel function of the first kind of order 0
$J_1$	Bessel function of the first kind of order 1
$k_a$	Thermal conductivity of air [W/m <sup>2</sup> °K]
$k_s$	Thermal conductivity of solid [W/m <sup>2</sup> °K]
K	GAB parameter
$K_0$	GAB parameter
Nu	Nusselt number $\left[ \frac{h_H \cdot d}{k_s} \right]$
P	Pressure [Pa]
$PM_a$	Air molecular weight [g/mol]
Pr	Prandtl $\left[ \frac{c_{p_s} \cdot \mu_s}{k_s} \right]$ number
$p_w$	Partial pressure of water vapour [Pa]
$p_w(0)$	Vapor pressure of water at equilibrium [Pa]
r	Radial coordinate [m]
$r_0$	Particle radius [m]
R	Universal gas constant [kJ/mol°K]
Re	Reynolds $\left[ \frac{d \cdot v \cdot \rho_s}{\mu_s} \right]$ number
Sc	Schmidt $\left[ \frac{\mu_s}{\rho_s \cdot D_{AB}} \right]$ number
Sh	Sherwood $\left[ \frac{h_M \cdot R \cdot T \cdot d}{P \cdot PM_a \cdot D_{AB}} \right]$ number
T	Temperature [°K]
t	Time [min]
v	Air rate [m/s]
V	Volume [cm <sup>3</sup> ]
W	Water content $\left[ \frac{X - X_e}{X_c - X_e} \right]$ dimensionless
X	Water content (dry base) [kg water/kg dry solid]
$X_c$	Critical water content (dry base) [kg water/kg dry solid]
$X_e$	Equilibrium water content (dry base) [kg water/kg dry solid]
$X_M$	Monolayer water content [kg water/kg dry solid]
$\alpha_1$	Root of the Bessel function of the first kind of order 0
$\Delta H_c$	GAB equation parameter [J/mol°K]
$\Delta H_k$	GAB equation parameter [J/mol°K]



$\Delta H_v$	Latent heat of vaporisation [J/kg]
$\rho$	Apparent density [kg/m <sup>3</sup> ]
$\rho_a$	Air density [kg/m <sup>3</sup> ]
$\rho_s$	True density [kg/m <sup>3</sup> ]

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## PROPRIÉTÉS PHYSIQUES DES FIBRES DE CANNE A SUCRE

Par

J. RODRIGUEZ RAMIREZ et L. MENDEZ LAGUNAS  
*Instituto Nacional de Politécnico, CIIDIR Unidad Oaxaca,  
1003 Hornos Santa Cruz Xoxocotlan, de Oaxaca au Mexique*  
[jrodrigr@ipn.mx](mailto:jrodrigr@ipn.mx)

**MOTS-CLEFS: Propriétés Physiques, Fibres de Canne a Sucre,  
Coefficients de Transfert Massique et Thermal.**

### Résumé

LES PROPRIÉTÉS physiques de la bagasse et les transferts de masse et de chaleur ont été déterminés afin de fournir des informations pour les processus de conception et pour la fabrication de produits. Dans ce rapport, la densité réelle ( $\rho_s$ ) et la densité apparente ( $\rho$ ) ont été mesurées avec un pycnomètre. La superficie ( $A_s$ ) et la distribution de taille des pores de fibres ont été déterminées par adsorption d'azote et par porosimétrie. Des cellules d'équilibrage ont été utilisées afin d'obtenir des isothermes. La température de surface et la concentration d'eau de la fibre ont été déterminées avec un Thermal Gravimetric Analyzer (TGA). La méthode de pente a été utilisée pour calculer le coefficient de diffusion de l'eau. Les coefficients de masse ( $h_M$ ) et de chaleur ( $h_H$ ) ont été déterminés par les données expérimentales et puis comparées par corrélation. Les résultats montrent des valeurs  $\rho_s$  de  $1231 \text{ kg/m}^3$ ,  $\rho$  de  $466 \text{ kg/m}^3$  et  $A_s$  de  $1300 \text{ m}^2/\text{kg}$ . La fibre de canne est constituée principalement par des macro pores d'un diamètre moyen de  $0.0385 \text{ }\mu\text{m}$ . Les isothermes de sorption sont du type II sigmoïde, un formulaire qui est compatible avec les structures macro pores. Les résultats montrent que les paramètres de l'équation de GAB représentent convenablement les données expérimentales. L'ordre de grandeur pour le  $D_e$  des fibres est  $10^{-10} \text{ m}^2/\text{s}$ . La valeur de  $h_H$  était  $40 \text{ W}/(\text{m}^2 \cdot ^\circ\text{K})$  et celle de  $h_M$   $0.045 \text{ kg}/(\text{m}^2 \cdot \text{s})$ . La fibre est un matériau poreux, composé de macro pores et sa structure interne diffère de celle de la moelle. Les valeurs expérimentales de  $h_H$  étaient plus élevés que celles calculées par corrélations due aux effets de conduction et rayonnement. Le mécanisme principal du transfert de masse était la résistance interne,  $D_e$  a augmenté avec la température en fonction de l'équation d'Arrhenius.

## PROPIEDADES DE INGENIERÍA DE LAS FIBRAS DE LA CAÑA DE AZÚCAR

Por

J. RODRIGUEZ RAMIREZ y L. MENDEZ LAGUNAS

*Instituto Politécnico Nacional, CIIDIR Unidad Oaxaca, Hornos 1003 Sta. Cruz Xoxocotlan,*

*Oaxaca Mexico*

[jrodrigr@ipn.mx](mailto:jrodrigr@ipn.mx)

**PALABRAS CLAVE: Propiedades Físicas, Fibras de Caña de Azúcar,  
Coeficientes de Transferencia de Calor y Masa.**

### Resumen

SE DETERMINARON las propiedades físicas y los coeficientes de transferencia de calor y de masa del bagazo para suministrar información para diseño de proceso y fabricación de productos. En este trabajo se midieron la densidad real ( $\rho_s$ ) y aparente ( $\rho$ ) con el método del picnómetro. El área superficial ( $A_s$ ) y el tamaño y distribución de fibras se determinaron por adsorción de nitrógeno y la distribución de los tamaños de poros de las fibras se determinó por adsorción de Nitrógeno y porometría de Mercurio. Para la obtención de las isothermas de adsorción se usaron celdas de equilibrio. El contenido de agua y la temperatura superficial de las fibras de caña se monitoreó con un Analizador Termogravimétrico modificado (TGA). El coeficiente efectivo de difusión de agua se calculó por el método de la pendiente. El coeficiente de transferencia de masa ( $h_M$ ) y el coeficiente de transferencia de calor ( $h_H$ ) se determinaron con datos experimentales y se compararon con una correlación de transferencia convectiva. Se obtuvieron valores de  $\rho_s$  de 1231 Kg./m<sup>3</sup>,  $\rho$  de 466 kg/m<sup>3</sup> y  $A_s$  de 1300 m<sup>2</sup>/Kg. Las fibras de caña están formadas principalmente por microporos con un diámetro promedio de 0.0385  $\mu$ m. Las isothermas de adsorción son del tipo II de forma sigmoide, consistente con las estructuras macroporosas. Los resultados mostraron que los parámetros de la ecuación GAB representan adecuadamente los datos experimentales. El orden de magnitud para el  $D_e$  de las fibras fue 10<sup>-10</sup> m<sup>2</sup>/s. El valor de  $h_H$  fue 40 W/(m<sup>2</sup>.°K) y  $h_M$  fue 0.045 Kg./(m<sup>2</sup>.s). La fibra es un material poroso formado por macroporos y su estructura interna es diferente de la de la médula. Los valores experimentales de  $h_H$  fueron más elevados que los calculados con correlaciones debido a los efectos de conducción y radiación. El principal mecanismo de transferencia de masa fue la resistencia interna, y  $D_e$  se incrementó con la temperatura en una función del tipo Arrhenius.