Regular Regime analysis and moisture diffusivity in wood

Citation for published version (APA):

Liu, T., & Coumans, W. J. (1993). Regular Regime analysis and moisture diffusivity in wood. *Drying Technology*, 11(5), 977-1003. <https://doi.org/10.1080/07373939308916879>

DOI:

[10.1080/07373939308916879](https://doi.org/10.1080/07373939308916879)

Document status and date:

Published: 01/01/1993

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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- The final published version features the final layout of the paper including the volume, issue and page numbers.

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REGULAR REGIME ANALYSIS
AND MOISTURE DIFFUSIVITY IN WOOD

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Key Words and Phrases:

drying; sorption; desorption; regular regime; diffusion; diffusivity; drying curve; wood;

ABSTRACT

The Regular Regime analysis, introduced by Schoeber in 1976, enables the determination of concentration dependent diffusivities from a single desorption experiment. A study on theoretical and practical aspects of this analysis is presented here. The theoretical background of the method is treated. Efforts have been made to simplify the calculation procedures by compacting and clarifying some complicated relationships. The calculation has become simple, straightforward and easy to use in practice. A stepwise procedure is given. The Regular Regime analysis has been applied to wood specimens (Norway spruce). The moisture diffusivities are compared with those obtained from a Stationary Flux method. The observed differences are discussed. Also attention is paid to some problems in the application of the Regular Regime analysis.

INTRODUCTION

For wood and other hygroscopic construction materials a good understanding of internal moisture transport is important for adequate processing and utilization. Especially for wood this is extremely imperative because a freshly felled tree with a relatively high initial moisture content has to be dried to a low moisture content. Lack of knowledge in this area still causes every year large damage during drying processes. Moreover, moisture movement and accumulation in wooden parts of constructions brings rot and mould growth. These problems might be avoided to a great extent by a better design of drying kilns and storehouses and this requires a good knowledge of moisture transport in wood based materials.

Because of its porous structure several mechanisms are involved in moisture transport in wood (Siau, 1984). In most practical drying conditions no substantial temperature and pressure gradients will develop inside the wood and for all mechanisms the driving forces for mass transfer can be expressed in terms of a moisture concentration gradient. This means that lumping all mechanisms leads to an effective diffusion coefficient and the drying process of wood can be described as a diffusivity process in a pseudo homogeneous medium. Effective diffusivities can be determined from sorption processes in well conditioned experiments. In general a well shaped specimen is conditioned to a well defined and homogeneous initial moisture content and then put into an environment with a different relative humidity of the surrounding air. Usually the air conditions, humidity and temperature, are kept constant and the weight of the specimen is determined as a function of

time. Under such simple conditions the diffusion equation has analytical solutions if the diffusivity is constant (Carslaw, 1959; Crank, 1975). From the experimental sorption data and the analytical solutions the constant diffusivity can be calculated. Unfortunately, in general the diffusivity is not constant but depends, more or less strongly, on the moisture concentration. In most cases no analytical solutions of the diffusion equation are available, even if the type of concentration dependence would be known (e.g. power law, exponential, linear, etc.). The determination of the diffusivity now becomes much more complicated.

In this paper a practical method will be elucidated to determine the concentration dependent diffusivity from a single desorption experiment. This method is based on the so called Regular Regime analysis, which was first introduced by Schoeber (1976). In the falling rate period of a drying process the surface concentration approaches the equilibrium value rather quickly. In this period with nearly constant surface concentration two substages can be distinguished: first, the Penetration Period as long as the centre concentration has not yet changed significantly and second, the Regular Regime where the centre concentration has decreased significantly from its initial value.

The study reported in this paper is limited to unidirectional mass transfer in non-shrinking slabs. First the basic concepts and relations will be introduced. Next procedures will be described how to handle desorption data for several types of concentration dependence of the diffusivity. Finally, the approach presented here will be applied to experimental desorption data of wood.

BASIC CONCEPTS AND RELATIONS

The unidimensional mass transfer in nonshrinking slabs with constant boundary concentration can be formulated mathematically by the following partial differential equation:

$$\frac{\partial u}{\partial t} = \frac{\partial}{\partial x} \left(D \frac{\partial u}{\partial x} \right) \quad (1)$$

$$\begin{aligned} t=0 \quad u &= u_0 \quad -L \leq x \leq +L \\ t>0 \quad u &= u_i \quad x = \pm L \end{aligned}$$

in which u is moisture concentration in the material, D is the moisture diffusivity, L is the half thickness of the specimen, u_0 is the initial moisture concentration, u_i is the interface moisture concentration in the specimen, x is the space coordinate and t is the time. From a moisture mass balance over the slab the following expression of the moisture flux j is obtained:

$$j = -L\rho_s \frac{d\bar{u}}{dt} \quad (2)$$

where ρ_s is the density of the dry wood (solid) and $\bar{u}$ is the averaged moisture concentration in the slab. By defining the flux parameter F :

$$F = \frac{jL}{\rho_s} \quad (3)$$

it follows:

$$F = -L^2 \frac{d\bar{u}}{dt} \quad (4)$$

This equation is important for the calculation of the flux parameter F from experimental desorption data $\bar{u}$ versus t .

In the analysis of desorption experiments also the parameter X plays an important role (Schoeber, 1976):

$$X = \frac{d \ln F}{d \ln (\bar{u} - u_i)} \quad (5)$$

The parameter X can be calculated from experimental sorption data by applying equation (5) to equation (4). The resulting expression is:

$$X = \frac{x_1}{x_2} \quad (6)$$

where

$$x_1 = (\bar{u} - u_i) \frac{d^2 \bar{u}}{dt^2} \quad \text{and} \quad x_2 = \left(\frac{d\bar{u}}{dt} \right)^2 \quad (7)$$

According to Schoeber (1976), in a desorption process with constant boundary concentration, two stages can be distinguished viz. Penetration Period and Regular Regime.

Penetration Period

In the Penetration Period the moisture concentration in the centre of the slab has not yet changed and the diffusion process may be regarded as taking place in a semi-infinite medium. Consequently the following relation holds (Schoeber, 1976; Liou, 1982; Liou and Bruin, 1982; Coumans, 1987):

$$F(u_0 - \bar{u}) = \text{constant} \quad (8)$$

and with the aid of equation (5) the parameter X can be simply expressed as:

$$X = \frac{\bar{u} - u_i}{u_0 - \bar{u}} \quad (9)$$

This equation plays an important role in the determination of the onset of the Regular Regime in an experimental sorption process, as will be shown later.

Regular Regime

It is characteristic for the Regular Regime that the moisture concentration profile in the specimen has become independent of the initial moisture concentration and the initial desorption flux. Sooner or later any drying process, *irrespective the initial conditions*, will enter the Regular Regime. Not the absolute time scale is now important but the derivatives of moisture content with time. The Regular Regime appears to be dependent on the material properties governing moisture diffusivity only. Therefore the Regular Regime of a single desorption process provides excellent data for the determination of moisture diffusivities.

Transition Point

The transition from the Penetration Period to the Regular Regime can be established in two ways. Firstly, by finding the following intersection as proposed by Schoeber (1976):

- 1) Calculate from the experimental sorption data, at any value of the averaged moisture concentration $\bar{u}$, the corresponding parameter X with equation (6).
- 2) Calculate the theoretical values of X for the Penetration Period with equation (9) as a function of the averaged moisture content.
- 3) The transition point u_t is found from the intersection point of both equations.

Secondly, if the foregoing procedure fails (e.g. due to experimental errors) or if one wants to proceed simply and quickly, then only sorption data for which the criterion

$$\frac{u_0 - \bar{u}}{u_0 - u_i} \geq 0.5 \quad (10)$$

applies are taken as Regular Regime data. This criterion is based on the observation that, in case of constant diffusivity, equation (10) holds for all Regular Regime data. In case of lower diffusivities at lower moisture contents the concentration profiles become more rectangular and thus the transition point shifts to higher values of the averaged moisture content. This implies that in general the above simple criterion, is a very severe one.

Diffusivity from Regular Regime Data

The analysis of the Regular Regime starts with the description of the moisture flux based on driving forces inside the specimen:

$$j = k_d \rho_s (\bar{u} - u_i) \quad (11)$$

in which k_d is the so called mass transfer coefficient belonging to a driving force in the dispersed phase. The Sherwood number Sh_d for the dispersed phase is defined as:

$$Sh_d = \frac{2k_d L}{\bar{D}} \quad (12)$$

where the averaged diffusivity is defined according to:

$$\bar{D} = \frac{\int_{u_i}^{\bar{u}} D du}{\bar{u} - u_i} \quad (13)$$

From the above definitions the flux parameter F can also be expressed as:

$$F = \frac{1}{2} Sh_d \bar{D} (\bar{u} - u_i) \quad (14)$$

From equations (13) and (14) it follows that the diffusivity can be calculated from:

$$D = \frac{d}{d\bar{u}} \left(\frac{2F}{Sh_d} \right) \quad \text{at } u = \bar{u} \quad (15)$$

Though the above theoretical description applies to the Penetration Period as well, its great advantage can be found in the Regular Regime where the Sherwood numbers appear to show interesting properties. By numerically solving the diffusion equation (1) Schoeber (1976) calculated the Sherwood numbers for the following types of diffusivities:

$$\begin{aligned} (a) \text{ powerlaw} \quad D &= D_o (u - u_1)^a \\ (b) \text{ exponential} \quad D &= D_o \exp[a(u - u_1)] \\ (c) \text{ linear} \quad D &= D_o [1 + a(u - u_1)] \\ (d) \text{ constant} \quad D &= D_o \end{aligned} \quad (16)$$

where a and D_o are constants. It should be noticed that for $a=0$ in all cases the diffusivity $D=D_o=\text{constant}$. The Sherwood numbers for the Regular Regime of non-shrinking slabs are given by Schoeber (1976). It appears that in case of power law diffusivity in the Regular Regime the Sherwood numbers take on constant values, and thus are independent of the averaged moisture concentration and time. Schoeber (1976) correlated the calculated Sherwood numbers with the parameter X and concluded that this relationship is nearly independent of the type of diffusivity (see Figure 1). The essence of the determination of diffusivities from the experimental sorption data of unknown samples lies in taking advantage of this important observation.

FIGURE 1. Sherwood number versus parameter X for power law, exponential and linear concentration dependent diffusivities (Schoeber, 1976)

Schoeber's Procedure

Schoeber (1976) proposes a general procedure for the determination of the diffusivity as follows:

- (1) Determine experimentally a desorption curve by periodically weighing the specimen during a desorption process and establish the averaged moisture concentration $\bar{u}$ as a function of time t ;
- (2) Calculate the flux parameter F according to equation (4);
- (3) Calculate the parameter X according to both equation (6) and equation (9) in order to find out which data belong to the Regular Regime and proceed with this data only in the remaining steps of this procedure;
- (4) Read the Sherwood number from the graph as shown in Figure 1;
- (5) Calculate the diffusivity from equation (15).

Although this general procedure seems to be clear and simple, it is not very practical to use. It is difficult to read the Sherwood numbers from Figure 1 with sufficient accuracy and the original figure in Schoeber's thesis is even worse. Further, a threefold numerical differentiation is necessary for this procedure: first the flux parameter F has to be calculated with equation (4), secondly the parameter X with equation (6) and thirdly, the diffusivity according to equation (15). Since the experimental data inevitably contain errors and noise, a direct threefold numerical differentiation amplifies the noise a great deal and may cause a violent fluctuation of the computed diffusivities.

Liou (1982) and Coumans (1987) improved the calculation procedures for the case of power law diffusivity. In this paper the authors have made endeavours to improve also the calculation for exponential diffusivity. Both for power law diffusivity and for exponential diffusivity correlations are given for the Sherwood number as a function of the parameter X . Furthermore, a procedure is introduced to ensure the stability of the derivatives. As a final result the application of the Regular Regime analysis for evaluating diffusivities has become more practical. This will be shown below.

POWER LAW DIFFUSIVITY

From equations (16a), (13) and (14) the following expression for the flux parameter can be derived in case of power law diffusivity:

$$F = \frac{1}{2} \frac{Sh_d}{a+1} D_o (\bar{u} - u_i)^{a+1} \quad (17)$$

Combining this equation with equation (4) gives:

$$-\frac{d\bar{u}}{dt} = \frac{1}{2} \frac{Sh_d}{a+1} \frac{D_o}{L^2} (\bar{u}-u_i)^{a+1}$$

According to Schoeber (1976) the Sherwood numbers in the Regular Regime are not dependent on $\bar{u}$ but only on the power a . A very accurate correlation has been given by Liou (1982) and Liou & Bruin (1982):

$$Sh_d = 4.935 + 2.456 \frac{a}{a+2} \quad (19)$$

Similar correlations were given by Coumans (1987) for massive and hollow cylinders and spheres.

Evaluating the experimental Regular Regime data $\bar{u}$ versus t according to equation (18) values for a and D_o are obtained. Two types of calculation are possible: nonlinear regression based on equation (18) or linear regression based on:

$$\ln\left(-\frac{d\bar{u}}{dt}\right) = \ln\left(\frac{1}{2} \frac{Sh_d}{a+1} \frac{D_o}{L^2}\right) + (a+1) \ln(\bar{u}-u_i) \quad (20)$$

A plot of $\ln(-d\bar{u}/dt)$ versus $\ln(\bar{u}-u_i)$ will show a straight line for all Regular Regime data. From the slope and the intercept of this line the parameters a and D_o can be calculated.

DIFFUSIVITY WITH ANY MOISTURE CONCENTRATION DEPENDENCE

If linear regression of all Regular Regime data fails, Coumans (1987) suggested to apply linear regression to small intervals of the sorption data. Such a local linear regression is a first approximation of a smoothed numerical differentiation. In this way, a series of pairs (a, D_o) are obtained and the diffusi-

vity can be calculated by:

$$D(u) = D_0 (\bar{u} - u_i)^a \quad \text{at } u = \bar{u} \quad (21)$$

where both a and D_0 are dependent on $\bar{u}$.

In this study the authors have improved this calculation method. The starting point is equation (15), which is modified by first substituting equation (4) and next by taking the time derivatives:

$$D = 2L^2 \left[\frac{\frac{d\bar{u}}{dt} \frac{dSh_d}{dt} - \frac{d^2\bar{u}}{dt^2} Sh_d}{\frac{d\bar{u}}{dt} Sh_d^2} \right] \quad (22)$$

It should be noticed that this equation has been derived without any assumption about the type of diffusivity; therefore this equation will be the *basic equation for the calculation of the diffusivity in the improved calculation procedure*.

For power law diffusivity the parameter X follows by applying its definition to equation (17):

$$X = a + 1 \quad (23)$$

and the Sherwood number given by correlation (19) can now be expressed as:

$$Sh_d = 4.935 + 2.456 \frac{X-1}{X+1} \quad (24)$$

From equations (24), (6,) and (7) the time derivative of Sh_d can be derived:

$$\frac{dSh_d}{dt} = 4.912 \frac{x_2 x_3 - x_1 x_4}{(x_1 + x_2)^2} \quad (25)$$

where

$$x_3 = \frac{d\bar{u}}{dt} \frac{d^2\bar{u}}{dt^2} + (\bar{u} - u_i) \frac{d^3\bar{u}}{dt^3} \quad \text{and} \quad x_4 = 2 \frac{d\bar{u}}{dt} \frac{d^2\bar{u}}{dt^2} \quad (26)$$

TABLE 1
Spreadsheet calculation procedure for diffusivity

t	$\bar{u}$	$\frac{d\bar{u}}{dt}$	$\frac{d^2\bar{u}}{dt^2}$	$\frac{d^3\bar{u}}{dt^3}$	x_1	x_2	x_3	x_4	X	Sh_d	$\frac{dSh_d}{dt}$	D
experimental data		numerical differentiation			equation 7	equation 7	equation 26	equation 26	equation 6	equation 24	equation 25	equation 22
<div> <div></div> <div>This part of spreadsheet has to be done in any case</div> <div></div> </div>										<div> <div></div> <div>specific to concentration dependence</div> <div></div> </div>		

Now all the quantities in the basic equation (22) are expressed in terms of the averaged moisture concentration and its 1st, 2nd and 3rd time derivatives.

Improved Procedure

In a desorption experiment the averaged moisture concentration can be directly measured as a function of time by weighing the specimens at different time intervals. Next the time derivatives can be calculated numerically. To secure the stability of the derivatives proper smoothing techniques should be used (see section DATA PROCESSING). Eventually, the diffusivity can be calculated with the basic equation (22).

The evaluation of the diffusivity from a sorption experiment might be performed very well by means of a spreadsheet program (see Table 1).

EXPONENTIAL DIFFUSIVITY

The moisture diffusivity in wood is generally regarded to be approximately exponentially dependent on the moisture concentration (Rosen, 1976; Siau, 1984 and Liu, 1989). For this reason the foregoing approach based on power law diffusivity, which is claimed to be a good approximation for any type of diffusivity, will be refined here for exponential diffusivity. The diffusivity again follows from the basic equation (22) and this adaptation will only affect the calculation of the Sherwood numbers and there time derivatives (see last 3 columns in the spreadsheet of Table 1).

By substitution the exponential relation (16b) into equations (13) and (14) the following expression for the flux can be derived straightforward:

$$F = \frac{Sh_d}{2a} D_o (e^{a(\bar{u}-u_i)} - 1) \quad (27)$$

The Sherwood numbers as given by Schoeber (1976) for exponential diffusivity can be fitted very well (deviations less than 3.5%) by the following correlation:

$$Sh_d = 7.39 - 2.456 \cdot e^{-0.625a(\bar{u}-u_i)} \quad (28)$$

By applying its definition to equation (27) the parameter X now becomes:

$$X = a(\bar{u}-u_i) \left[0.625 \frac{7.39 - Sh_d}{Sh_d} + \frac{e^{a(\bar{u}-u_i)}}{e^{a(\bar{u}-u_i)} - 1} \right] \quad (29)$$

Now it is possible to correlate the Sherwood number with the parameter X by calculating both quantities at the same values of $a(\bar{u}-u_i)$. This yields the following correlation (deviations less than 2.5%):

$$Sh_d = 7.39 - 2.456 \cdot e^{-0.774(X-1)} \quad (30)$$

This expression has to be used now in the basic equation (22) for the calculation of the diffusivity. However the time derivative of the Sherwood number can best be splitted according to:

$$\frac{dSh_d}{dt} = \frac{dSh_d}{dX} \frac{dX}{dt} \quad (31)$$

where the derative of Sherwood number with respect to parameter X can be evaluated straightforward from equation (30):

$$\frac{dSh_d}{dX} = 1.900 e^{-0.774(X-1)} \quad (32)$$

and the time derivative of parameter X can be derived from equations (6) and (7):

$$\frac{dX}{dt} = \frac{x_3 - x_4 X}{x_2} \quad (33)$$

EXPERIMENTAL

Unidirectional desorption experiments have been performed with wood slabs and the moisture diffusivities were calculated according to the procedures presented in the foregoing sections. Recently the diffusivities of wood have also been measured (Liu, 1989) with the stationary flux method (also called vapometer method). The diffusivities from both approaches are compared here.

The experiments were carried out in a simple and cheap drying system, as shown in Figure 2. The specimens were manufactured as circular slabs (thickness $2L=0.010$ m

FIGURE 2. Experimental drying system

and diameter=0.080 m) and the mass transfer direction coincides with either the longitudinal or the tangential direction of the wood structure. The curved side-walls of the specimens were sealed with two layers of plastic adhesive tape. This was expected to provide an effective vapour-tight seal and consequently to ensure unidirectional desorption. Each specimen was hang up in the drying chamber by means of a wire, which passes the chamber wall via a sealing.

Drying air with zero relative humidity was used in all experiments. This condition was maintained by means of a strong drying agent ($\text{Mg}(\text{ClO}_4)_2$) and a good air circulation inside chambers A and B. Under these air conditions of humidity and mixing a zero boundary concentration ($u_i=0$) may be assumed at the wood surfaces. The temperature of the wood and the air was not controlled particularly, but the drying system was located in the basement of an air-conditioned laborato-

ry. The ambient temperature changed very slowly from 22°C at night to 26°C at day. The average temperature was taken to be 24°C.

Without removing the specimens from chamber A the weighing was performed manually by loosening the wire sealing and by attaching the specimen via the wire to a balance. In this way disturbances of the climate in the chamber were minimized. The sorption data were obtained within a time span of about 100 hours. The constant final weight of the sample was taken as the dry solids weight.

DATA PROCESSING

First the basic experimental data (averaged moisture concentration versus time, see Table 1), are calculated from the specimen weight versus time.

Next the time derivatives are to be calculated. Since the weighing was carried out manually, the sorption data are non-equidistant in time and the number of data is rather limited (about 40 data points in each experiment). In order to obtain correct and stable derivatives the sorption data are first fitted with a proper mathematical expression. This expression has to fit the sorption data quite well and its 1st, 2nd and 3rd time derivatives with respect to time have to be monotoneous functions with time. Though polynomial curve fitting of $\bar{u}$ versus t and $\ln(\bar{u})$ versus t gave a very good fit of the sorption data, they have to be rejected because of unstable derivatives. It was found in this study that the generalized Kelvin element expression in linear viscoelasticity theory (Flügge, 1975) matched the above requirements fully:

$$\frac{u_0 - \bar{u}}{u_0 - u_i} = \sum_{k=1}^n S_k \left[1 - \exp\left(-\frac{t}{\tau_k}\right) \right] \quad (34)$$

where S_k and τ_k are fitting parameters.

It appears to be more convenient to prescribe values for τ_k and to determine only values of S_k by multiple regression. In this study six terms of the exponential series proved to give satisfying results and the following values for τ_k were found to be suitable for all sorption data:

$$(\tau_1, \tau_2, \tau_3, \tau_4, \tau_5, \tau_6) = (0.5, 5, 15, 35, 45, 50)$$

where the values are given in hours.

The derivatives can now be calculated analytically, thus:

$$\frac{d\bar{u}}{dt} = -(u_0 - u_i) \sum_{k=1}^6 \frac{S_k}{\tau_k} \exp\left(-\frac{t}{\tau_k}\right) \quad (35)$$

$$\frac{d^2\bar{u}}{dt^2} = (u_0 - u_i) \sum_{k=1}^6 \frac{S_k}{(\tau_k)^2} \exp\left(-\frac{t}{\tau_k}\right) \quad (36)$$

$$\frac{d^3\bar{u}}{dt^3} = -(u_0 - u_i) \sum_{k=1}^6 \frac{S_k}{(\tau_k)^3} \exp\left(-\frac{t}{\tau_k}\right) \quad (37)$$

In Figure 3 an example is given to show the excellent fitting of the desorption data. The equations (35-37) produced indeed monotoneous time derivatives. It can be concluded that the above described procedure enables a stable evaluation of non-equidistant and noisy desorption data.

RESULTS AND DISCUSSION

According to the Regular Regime analysis (RR-analysis) described in this paper, the moisture diffu-

FIGURE 3. Curve fitting of experimental measured desorption data for specimen 1 and 5 by means of the exponential series equation (34).

sivities of 8 specimens of Norway spruce are determined, both in tangential and longitudinal direction. Both the power law and the exponential approach yield nearly the same results. In general the exponential approach appears to be more sensitive to data noise and errors. It is therefore recommended to use the more stable power law approach. In some experiments no transition point could be detected by the intersection method. In these cases the criterion according to equation (10) has been applied. The experimental moisture diffusivities from the power law approach are represented in Figures 4 and 5. It can be seen that at a given moisture content diffusivities in longitudinal direction are much higher than in tangential direction. It is obvious that this anisotropic behaviour will be related to the orientation of the wood fibres in the longitudinal direction and so causing less resistance to

FIGURE 4. Moisture diffusivity of wood specimens in tangential direction; from RR-analysis (this work) and from SF-method (Liu, 1989).

FIGURE 5. Moisture diffusivity of wood specimens in longitudinal direction, from RR-analysis (this work) and from SF-method (Liu, 1989).

FIGURE 6. Moisture desorption data of two wood specimens. The dots represent experimental data points, whereas the solid curves are from the numerical solution of the diffusion equation (1), using diffusivities from the RR-analysis (Figures 4 and 5).

mass transfer (liquid flow, vapour diffusion,...) in this direction than in the tangential direction.

To have a check on the correctness of the determined diffusivities, the desorption curves were calculated by solving equation (1) numerically with an implicit finite difference scheme using the diffusivities from the RR-analysis. In Figure 6 the calculated desorption data for two specimen are plotted together with the original measured data. Although the calculated curves are somewhat lower than the measured ones the agreement is good.

Liu (1989) has systematically measured the moisture diffusivities of the same wood species by means of

the "Stationary Flux method" (SF-method, also called the "vapometer method"). In the SF-method a constant concentration difference is maintained between the two surfaces of a wood specimen; all specimen were of the same shape and size as those used in the desorption experiments. From the stationary moisture flux through the wood piece the concentration dependent diffusion coefficient can be derived (Crank, 1975). The diffusivities from the SF-method are also represented in Figures 4 and 5.

In an optimistic view one could state, that, considering the difference in measuring methods and the relatively high diversity of the natural material wood, both methods produce diffusivities of the same order of magnitude and the agreement between the two methods is not too bad. Nevertheless, two important deviations may be noticed: the SF-method tends to give lower diffusivities and the shape of the curves is quite different. In most cases the SF-method yields a diffusivity depending *more than linear* on moisture content, whereas the RR-analysis shows a dependence being *less than linear*. How to explain this?

Assuming that no serious experimental errors are involved, and the samples used in both methods do not deviate too much, the explanation for this different behaviour has to be derived from what is happening on the microscopic scale within the wood material. It should be kept in mind, that the wood diffusivities are lump parameters. Microscopic mass- and heat phenomena are leading to some macroscopic drying behaviour, from which the diffusivity is being derived. Microscopic phenomena with respect to mass- and heat transfer might be different in both methods. The following two postulates might be true here:

i) *Effect of moisture concentration profile*

In the RR-analysis the diffusion coefficient is derived at $u=\bar{u}$; in the SF-method the diffusion coefficient is calculated at $u=u_2$, where u_2 is one of the boundary concentrations ($u_1=0$). Comparison of the diffusivity at the same concentration $u=\bar{u}=u_2$, means that in both methods the profiles are different! As can be seen from Figure 7 the averaged moisture concentration in the SF-method is lower than with the RR-analysis. This might explain the lower diffusivities found in the SF-method. Further, because several mechanisms are contributing to mass transfer, it may be expected that the diffusivity will not depend only on the (local and averaged) moisture concentration but also on the concentration profile.

ii) *Effect of local equilibrium inside wood pieces*

The RR-analysis is based on transient behaviour, whereas the SF-method is not. In the latter method it may be expected that local equilibrium between the fluid phase and the solid phase inside the wood will be reached more than in the dynamic RR-analysis. This means that resistances for mass transfer in the solid phase will be more dominant in

the SF-method. It may also be expected that this resistance is more dependent on moisture content than resistances in liquid and vapor phases. The above explanati-

FIGURE 7. Concentration profiles in RR-analysis and SF-method, where the averaged moisture content $\bar{u}$ from profile RR is equal to the boundary moisture content u_2 in profile SF.

ons are tentative however and a further study of the comparison of both methods is needed.

In the RR-analysis the diffusivities are derived from small changes of drying rates. For this reason the RR-analysis, just as any other method, is numerically unstable by nature. Therefore smoothing and regression methods are required to obtain stable results, however this may introduce undesired artefacts. Because of the relatively crude manually operated experiments in this work, the number of data points in a drying experiment is rather low, varying from 30 to 40, and the accuracy can be qualified as being moderate. Some exponential expression (equation 34) has been chosen partially arbitrarily for data smooting. This choice may be questioned. To reduce the instabilities and to minimize the introduction of artefacts one should strive for many data points of high accuracy. This implies the need for a fully automated experimental set up.

CONCLUSIONS

For hygroscopic materials the improved RR-analysis, as suggested in this paper, can be used for the determination of moisture diffusivities in dependence of moisture content. However, it is very hard to check the correctness of the experimentally determined diffusivities in an unambiguous way, because of the lack of standard materials with known diffusivities.

In the RR-analysis the diffusivities as function of moisture content are derived from a single desorption experiment. The calculation procedure has been compacted and streamlined. The procedure is simple, straightforward and easy to use in practice. Because of its higher stability the power law approach is recom-

mended. It is suggested that an increasing stability and reliability of the diffusivities requires a large number of data points with a high resolution, especially at the lower drying rates.

Diffusivities of the same wood species obtained by means of the SF-method are in some views differing from those by the RR-analysis, though the order of magnitude is the same. It is postulated, that the observed differences might be caused by physical phenomena on the microscopic level, however further study will be needed here.

NOTATION

- a constant in diffusivity relations,
 - power law diffusivity: (-/-)
 - exponential and linear diffusivity: (kg solid/kg moisture)
- D diffusivity (m^2/s)
- $\bar{D}$ averaged diffusivity, defined by equation 13
 (m^2/s)
- D_0 constant in diffusivity relations (m^2/s)
- F flux parameter (m^2/s)
- j drying flux ($\text{kg}/\text{m}^2\text{s}$)
- k_d mass transfer coefficient in dispersed phase (m/s)
- L half thickness of slab (m)
- S fitting parameter in equation 34 (-/-)
- Sh_d Sherwood number in dispersed phase (-/-)
- t time (s)
- u moisture concentration (kg moisture/kg dry solid)
- $\bar{u}$ space averaged moisture concentration (kg/kg)
- $\bar{u}_t$ averaged moisture concentration at transition
 from Penetration Period to Regular Regime
 (kg/kg)

- u_0 initial moisture concentration (kg/kg)
 u_i moisture concentration at interface (kg/kg)
 x space coordinate (m)
 x_i with $i=1..4$: help quantities according to equations 7 and 26
 X parameter defined by equation 5 (-/-)
 ρ_s density of dry wood (kg/m³)
 τ characteristic time in equation 34 (s)

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