

A KNOWLEDGE BASE FOR THE APPARENT MASS DIFFUSION COEFFICIENT (D_{EFF}) OF FOODS

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ABSTRACT

A Database of Physical Properties of Foods is to be created in the frame of the European Concerted action project (DOPPOF). Among the various properties, the diffusion properties of foods with respect to moisture, salt and other solute components are to be covered. The aim of the Database is to provide data which were carefully selected, evaluated and entered the under construction database shell.

The effective or apparent diffusion property is an important mass transfer property. Values of effective or apparent diffusivities of foods are abundant in the literature and their derivation is the outcome of the application of the Fickian approximation model for mass transfer in foods. The use of chemical potential to be considered as the driving force and the approach "on cell level" is compared to the Fickian approximation approach. The modern alternative has already started to be applied and it is expected to gain increasing importance in the near future.

The purpose of this paper is to provide a "knowledge base" for the use of the effective diffusivity data reported in the literature. The Food scientist or Food engineer is warned of pitfalls observed when using such data. Suggestions are also given for the kind of usage or the applicability extent of the data. A description of the main diffusivity measurement methods in both liquid and solid products is, also, given. In addition, measurement methods of activity coefficients are discussed.

INTRODUCTION

Mass transfer in food systems is described by Fick's second law, which in many cases can be analytically solved if experimental data, as well as initial and boundary conditions are provided, in order to yield an effective mass transfer coefficient. The latter describes the transfer of a given component within the system under study, often a cellular tissue of food product.

Inversely, when the value of this coefficient is known, a mass transfer simulation can be performed and the distribution of concentration in time and space in the food can be obtained by solving Fick's equation. Analytical solutions covering on varying specimen geometry are found in the most well known book by Crank (1975). Numerical solutions are provided by computer programs which deal with solution of the partial differential

equations (PDE's) for momentum, heat and mass transfer, such as NAVIER-STOKES, FOURIER and FICK. An advantage of the numerical solutions is that, also, non-linear terms of the PDE's can be solved covering presence of various mechanisms and source terms. As an example the case of simultaneous mass transfer–chemical reaction could be mentioned.

The so-called effective diffusion coefficient has been used and also misused in the Food literature, since foods are characterized by a complicated structure, making the media involved and hence-to-forth the mass transfer phenomena involved multiphase and multi-component. Then the aim of the present paper is to help the Food Scientist or Engineer, working in both the industry and academy to understand better and to avoid misuse of this important mass transfer property.

METHODS OF DIFFUSIVITY DETERMINATION

Methods for Moisture Diffusivity

There is no standard method of diffusivity estimation, although most of the available methods are based on Fick's laws of diffusion. The differences among the methods include the kind and the conditions of experiments used (simple or sophisticated setups, permeation, sorption or drying operation, various specimen geometries) and the way of treatment of experimental data (analytical or numerical solutions, various statistical data evaluation methods). We distinguish methods for moisture diffusivity in liquid foods and in solid foods/gels.

Liquid Foods

There are many methods available for diffusion coefficient measurement and, among them, there are two main approaches that have been most frequently used for the determination of binary (and even multi-component) liquid diffusivities.

Pseudo-steady-state diffusion through a porous diaphragm using the Stokes type of diaphragm cell has been the one method. The diaphragm cell is shown in Fig.1. It is inexpensive to build, rugged enough to use and yet capable of accuracy as high as 0.2%. In such cells two well stirred volumes are separated by a thin porous barrier or diaphragm. In the more accurate experiments is often sintered glass frit or simply a piece of filter paper. To measure a diffusion coefficient with this cell, the lower compartment is filled with a solution of a known concentration and the upper compartment with solvent. After a known time, both upper and lower compartments are sampled and their concentrations are measured (Cussler, 1984).

Measurement of diffusivities by interferometers is the second method on which an unsteady state refractive profile in a transparent system is used, thus making the method particularly useful for liquids. Gouy interferometer measures the refractive-index gradient between two solutions that are diffusing into each other and it was recognised earlier as valuable tool for diffusimetry due to its high precision, less than 0.1% It is simple to build, easy to align, very reliable and the most highly developed among the other interferometers (Cussler, 1984).

The method of diaphragm has been applied also for moisture diffusivity with gels, and cellular foods, where the diaphragm is made of the gel or the solid food material. The material is treated as a membrane and by measuring the permeate flux is then possible to deduce the diffusion coefficient (Gekas, 1992)

The sorption method is applied when negligible external mass limitations exist in the system to be studied. Then the moisture uptake or loss will follow a well-known kinetic pattern – penetration depth directly proportional to the square root of time- until equilibrium. The dimensionless time (Fick number) at which the moisture content of the food specimen will reach half of the equilibrium value has a characteristic arithmetic value, from which the apparent diffusion coefficient can be determined (Gekas, 1992).

Most of the moisture diffusivity data available originate from the method of drying curves (Gekas, 1992; Geankoplis, 1993). What is usually meant by a drying curve is the representation of change in moisture content of a food specimen with time or the change in the drying rate with moisture content. Depending on the material and drying conditions, the drying curve may adopt different shapes. Sometimes two, or even three periods may in general be distinguished. With foods, the initial so-called constant rate period, is very rarely observed, due to the high critical moisture content of most of the foods.

The shape of the following falling rate periods may help for the diagnosis of the drying mechanism, and this is a very crucial issue and also a warning point for the user of the diffusion property data (in the literature in general and in the Database of DOPPOF in particular). Thus a falling rate period given by a straight line in the diagram Drying Rate, F , as a function of moisture content, X , does not indicate a diffusion-like mechanism, but a capillary one, thus it is not really appropriate for deduction of any apparent diffusion coefficient. A diffusion mechanism can be recognised from its parabolic shape, reflecting the kinetics of diffusion, e.g. the time needed to obtain a given percentage of reduction of moisture content is related to the square of the thickness of the food specimen (Geankoplis, 1993).

Another method using drying rate curves is the regular regime model (RR). The drying process is divided into three periods, the constant rate, the penetration and the regular regime. The regular regime period corresponds to a stage during the drying process in which the drying kinetics does not depend on the initial moisture content. The model considers the diffusion coefficient not as a constant but as varying with moisture content. The drying curves are given in diagrams with the characteristic flux parameter F plotted against the moisture content (X). Starting at an initial moisture content, various constant-rate period curves are possible, but all terminate at the same penetration curve. All penetration curves terminate at only one regular-regime curve, i.e., the curve containing the equilibrium values of the moisture content, which is thus, a characteristic property of a given food material. The model presupposes homogeneous non porous products, such as glucose gels for example, however it has been applied also to cellular tissue foods such as apples and potatoes (Schoeber, 1976). Schoeber solved the diffusion equation numerically for the regular regime period of an isothermal diffusion process. He used the geometries of slab, sphere or cylinder, at various types diffusivity moisture dependence. He also considered the case of shrinkage

or swelling. The RR method needs laborious experiments and successive interpolations and differentiations of the experimental drying data in order to determine the concentration dependence of diffusivity. A short-cut method is proposed to avoid the rigorous procedure (Schoeber, 1978). The usefulness of this model is that the knowledge of the regular-regime curve permits to go backwards and by calculation follow the whole drying process. The weakness is that isothermal conditions are required, nevertheless the model is applicable even with non-isothermal drying within the accuracy limits set by reality.

Methods for Solute Diffusivity

The concentration profile curve method has often been used for the diffusivity of diverse substances, such as salt, small organic acids, aromas etc, i.e. other than water. It is the method being used and recommended by the COST 90 project to measure the diffusion coefficient of salt in gels, cheese and also aroma in gels.(Gross and Ruegg, 1987). The method is based on the exact solution of the Fick equation for a semi-infinite medium using the method of "combination of variables". The diffusion in a semi infinite slab is shown in Fig. 2. The slab initially contains a uniform concentration of solute. At time zero, the concentration at the interface (at the left) is suddenly increased. Diffusion occurs in the region to the right as the solute penetrates into the slab, producing the time-dependent concentration profile.

$$\frac{C - C_0}{C_\infty - C_0} = \text{erf } \zeta$$

where

$$\text{erf } \zeta = \frac{2}{\pi} \int_0^\zeta e^{-t^2} dt \text{ is the error function of } \zeta$$

C is the concentration of solute in the semi infinite medium

C_0 is the concentration of the surrounding medium

C_∞ is the initial concentration in the semi infinite medium (slab)

$$\zeta = \frac{z}{\sqrt{4Dt}} \text{ is the Boltzman parameter}$$

Warin et al. (1997), have applied a similar method (two semi-infinite media with common interface or in touch with each other or in touch with each other) for the determination of diffusivities of disaccharides in a two-phase medium consisted of a milk product with a fruit layer in its bottom.

CHARACTERISTIC VALUES OF DIFFUSION COEFFICIENTS IN FOODS. APPLICABILITY OF THE DATA

As with other food/biological-material properties, mass diffusivities show variability due to seasonal, weather conditions, variety difference, degree of maturity and so on. From a survey of the data (Table 1), deviations of the values of the apparent diffusivities within the same kind of food, due to variability, are often found to be of the same order of magnitude as the deviation between values of different kinds of foods. On the other hand the statistical analysis of samples of diffusivity values of different kinds of foods, belonging though to same or relative food category, are found to belong to same

population. For example: meat, vegetables, fruits, food gels form such a population. A typical value of apparent diffusivity, for the above group of food categories, (magnitude kind of estimation), for a given temperature (25 °C), considered as (untreated) soft plant tissue is found to be: $D_{EFF} = 2 \cdot 10^{-10} \text{ m}^2/\text{s}$.

Hard structure foods such as nuts, the category of cereals, especially rice, show, under the conditions mentioned above (untreated, ambient temperature at °C), typically one order of magnitude less: $D_{EFF} = 10^{-11} \text{ m}^2/\text{s}$

Another important point is the effect of applying different measurement method. Due to the fractal character of Brownian motion of the molecular transport mechanism more and more details of the revealed the more microscopically powerful methods are used for the measurement of the property: examples of such methods are Laser Dynamic Light Scattering (for solutions), and also NMR methods (for both solutions and solids). For examples, results reported from NMR method give typically give one order of magnitude higher than other methods. This issue has also to be taken into consideration.

Moving to the consideration of the effect of pretreatment, it has already been established that several orders of magnitude could be the difference related to the diffusivity values of raw untreated food tissue. Classical is for example the case of different method of drying reported by Saravacos (1986). Different kind of treatment, it may change the porosity of structure to a varying degree. The effect of temperature, is also important and a misuse of Arrhenius type of temperature dependency is what happens, if cell membrane denaturation, or even other phase transition phenomena occur within the temperature range studied.

The data in the Database summarise and reflect the current State of the Art. For more accuracy own measurements should be made. Then the question remains, what is the use of the diffusion coefficient data that the Food Scientist/Engineer could make? A list of this kind and extension of applicability of this property is followed below:

- ▶ As an estimation of the order of magnitude for the diffusion coefficient
- ▶ As first input values to feed simulation programs, such as FINDIFF (Gekas et al., 1998), DIFFPACK (Numerical Objects AS- Oslo, Norway), PTC (Princeton Transport Code - Karatzas & Pinder, 1996).
- ▶ For a quick estimation of dimensionless numbers such as Biot (mass transfer across the boundary /mass transfer within a solid diffusion) and Fick number (dimensionless time in the transient period), defined as

$$B_i = \frac{kb}{D_{EFF}} \quad , \quad F_i = \frac{D_{EFF}t}{b^2}$$

where k is the mass transfer coefficient in the boundary layer,
 b is characteristic dimension of the food specimen
and t is the time

- ▶ Need for modeling with uncertainty, due to sometimes large variability observed

SOME TYPICAL PITFALLS WITH THE FICKIAN APPROACH IN FOODS

The food engineer should be aware of the following issues for the proper use of the apparent diffusion coefficient (D_{EFF}) and for the general application of the Fickian approach when considering mass transfer in foods:

- ▶ The dependence of D_{EFF} on concentration of the component being transferred. In this case the driving force for mass transfer is the differences in chemical potential and not the concentration difference (Gekas et.al .1998).
- ▶ The dependence of D_{EFF} on temperature. Application of an Arrhenious type relation is dubious, in cases of sudden changes in the tissue structure, as it is said in the forthcoming paragraphs.
- ▶ The dependence of D_{EFF} on volume changes taking place during dehydration (shrinkage) or re-hydration (swelling). Gekas (1992) compiles ways to quantify these effects. These include the use of
 - ▶ moving coordinates such as in Crank (1975)
 - ▶ convection terms in the transport equation (Bahia-Blanca approach)
 - ▶ specific flux terms, as in the regular-regime method

In the majority of cases the influence of changes in volume is ignored and then these effects are implicitly included in the value of D_{EFF} .

- ▶ Evaluation of D_{EFF} entails that mass transfer is by a molecular diffusion mechanism, mainly (Case 1). Co –existence of several other mechanisms constitutes the Case 2 of transport (that is mechanical relaxation). The diagnosis of the exact mechanism is done experimentally with varying the thickness of a slice of food. If the measured variable (time taken for a predetermined change in concentration) is shown to be proportional to the square of the thickness then the predominant mechanism is diffusion, otherwise i.e. when the variable mentioned above is directly proportional to the thickness, Case 2 is the prevailing mechanism.
- ▶ An estimate of the BIOT number prior to the application of the Fickian model. Limitations of mass transfer in the boundary layer will result in changes in the boundary conditions. The evaluation of Biot number requires knowledge of the order of magnitude of the mass transfer coefficient in the boundary layer (Saravakos, 1986; Gekas, 1992). When the boundary layer contribution is negligible to the overall mass transfer detailed estimation of mass transfer is required.
- ▶ In initial and boundary conditions the distribution coefficient between the two phases should be taken into account. The latter coefficient is the quotient of the concentrations resulting from the equilibrium experiments and reflects the allegation that the driving force is not the concentration difference. In equilibrium conditions the distribution coefficient in terms of chemical potential should be equal to 1.

THE MODERN ON CELL-LEVEL APPROACH

Studies in mass transfer phenomena in foods have been increased in the last years and especially in the plant tissues, so the analysis can focus on cell level, taking into consideration changes that take place in the structure and composition of the processed plant tissues. When the Fickian analysis is applied in a complex system like the biological tissues, this may give misleading results. In the modern approach the driving force is the chemical potential. Alternative methods described by irreversible thermodynamics and the STEFAN – MAXWELL theory has come into force. It is worth noticing that physiologists are using the potential head of water (ψ) when studying mass transfer phenomena (normal conditions). The potential head in this case is related to the chemical potential with the following relation

$$\psi = \Delta\mu / V_m$$

where $\Delta\mu$ is the difference in chemical potential between a defined state and a reference state (often taken as the state of pure water where μ is 0). This entails that the value of ψ will be negative, V_m is the molar volume of water, approximately taken as $18 \text{ cm}^3/\text{mol}$. Physiologists have developed approaches for the determination of the potential head of water. Use of microthermothermometers methods is a current trend. In case of solutions the estimation of the potential head is related with the measurement of water activity and of osmotic pressure $\Delta\Pi$, parameters, which are related to the chemical potential according to the following relation

$$\Delta\mu = - V_m \Delta\Pi = RT \ln (a_w)$$

One of the most important outcomes of the modern approach is that a key role in modeling mass transfer phenomena is the comprehension of biological membranes. Let us consider the following two examples:

- ▶ Cell wall in foods like potatoes, apples and carrots can be considered as ultrafiltration membranes allowing only the flow of macromolecules. Cell wall also serves as mechanical barrier. Its strength determines product's texture. During blanching transfer of calcium ions is taking place from the protoplast through the intermediate lamella in the cell wall where they react with the activated pectin methylesterase (at $65-70^\circ \text{C}$). And resist temporally in the thermally induced collapse of the tissue texture. As already stated this process necessitates the use of blanching (as the first step before the main thermal process) for the inactivation of oxidative enzymes.
- ▶ The membrane, which surrounds the cell (plasma), as well as the vacuole (tonoplast), controls with active mechanisms the passage of the important ingredients in and out of the cell. As a result calcium concentration is maintained in a lower level inside the cell from the outside with the use of the membrane active system which transports calcium ions in the reverse direction of the chemical potential. This behavior can be explained by the use of the theory of Irreversible Thermodynamics, with the coupling of mass transfer with the chemical conversion of ATP to ADP which releases a amount of energy enabling the motion of the calcium ions to be reversed, Likewise, in case of potassium the transfer is again active, but the concentration is higher intracellularly. These

mechanisms can take place in a range where temperature is maintained lower than the critical temperature (T_d), when disorganization of the protein based carriers is taking place accompanied by abrupt changes in the mass transfer rates.

Opinion against models based on the chemical potential came often from the side of the experimentalists and its sharpened edge was the alleged difficulty (or rather impossibility) to measure the chemical potential of components. This situation has radically been changed the last one or two decades, since a considerable progress has been made in the development of several methods just for the measurement of the chemical potential of components in solutions and also in cellular structures. Measuring methods include (Rahman 1995):

- ▶ use of standardized solutions
- ▶ partial vapour pressure measurement
- ▶ hygrometric instruments (especially the electrical hygrometer)
- ▶ isopiestic transfer measurement
- ▶ suction potential
- ▶ microcalorimetric methods, gaining importance during the last few years

CONCLUSION – MODERN TRENDS

Apparent or effective diffusivity data, obtained through various measurement methods, are abundant in the literature. Their use should be made cautiously by the Food Scientist/Engineer, taking into account the special issues associated with the concept of this food property. The applicability of the data should be limited into preliminary uses such as first input values into software packages, estimation of dimensionless numbers to be used as criteria, first order analysis and order of magnitude analysis.

The construction DOPPOF (Database of Physical Properties of Foods) is intended to include selected and evaluated data that reflect the present State of the Art. For more accurate data, own measurements to a particular system should be used or what is better recommended try to follow the modern at cell level approach using the chemical potential as the driving force. The latter approach gains a growing importance the last five years or so and it is expected that it will become an established State of the Art.

Appendix

LIST OF SYMBOLS

Latin Symbols

a_w	Activity
b	characteristic dimension of the food specimen (m)
B_i	Biot number
C	concentration of solute in the semi infinite medium (kmol/m ³)
C_0	concentration of the surrounding medium (kmol/m ³)
C_∞	initial concentration in the semi infinite medium (kmol/m ³)
D	diffusion coefficient (m ² /s)
D_{EFF}	effective diffusion coefficient (m ² /s)
F	flux parameter (kg ² m ⁴ /s)
F_i	Fick number
k	mass transfer coefficient (m/s)
PDE	partial differential equation
R	gas constant (J/kmol K)
t	time (s)
T	temperature (°C or K)
T_d	critical temperature (°C or K)
V_m	molar volume of water (cm ³ /mol)
X	water content (kg/kg)
Greek Symbols	
$\Delta\Pi$	osmotic pressure (Pa)
ζ	Boltzman parameter
μ	chemical potential (kJ/kmol)
π	the number 3.14...
ψ	potential head of water (Pa)

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Table 1

Characteristic Values of Diffusion Coefficients of Foods

<i>Category</i>	<i>Subcategory</i>	<i>Kind of Property</i>	<i>Range of conditions</i>	<i>Range of property values (m²/s)</i>
Beverages	Coffee extract	Moisture diffusivity	T = 30 - 70 °C X _w (db) = 0.2 - 1.0	0.16 - 2.3 × 10 ⁻¹⁰
Cereal	Biscuit	Moisture diffusivity	T = 77 - 91 °C	0.41 - 0.62 × 10 ⁻¹⁰
	Pasta	Moisture diffusivity	T = 40 - 74 °C X _w = 0.05 - 0.27	0.8 - 9.3 × 10 ⁻¹¹
	Rice, whole	Moisture diffusivity	T = 30 - 50 °C	0.4 - 9 × 10 ⁻¹¹
	Sorghum, whole	Moisture diffusivity	T = 20 - 50 °C	0.9 - 3 × 10 ⁻¹¹
	Wheat, raw	Moisture diffusivity	T = 70 °C X _w (wb) = 10-30%	1.0 - 3 × 10 ⁻¹¹
	White beans	Moisture diffusivity	T = 50 - 82 °C	0.9 - 12.1 × 10 ⁻¹⁰
Dairy	Cheese	Salt diffusivity	T = 4 - 60 °C X _{salt} = 0 - 20%	1.0 - 5.5 × 10 ⁻¹⁰
	Milk skimmed	Moisture diffusivity	T = 30 - 50 °C X _w (db) = 0.3-0.8	0.24 - 2.1 × 10 ⁻¹⁰
	Yogurt concentrated	Moisture diffusivity	T = 30 - 50 °C X _w = 0.1 - 2.5	0.5 - 30 × 10 ⁻¹⁰
Fish	Bombay duck frozen	Moisture diffusivity	T = 40-70 °C R. Hum. = 30-60 %	1 - 3.5 × 10 ⁻¹⁰
	Cod frozen	Moisture diffusivity	T = -5 till -30 °C	0.25- 7 × 10 ⁻¹¹
	Cod brined	Moisture diffusivity	T = 20 °C	0.3- 2.3 × 10 ⁻¹⁰
	Dab	Moisture diffusivity	T = 30 °C X _{fat} = 0.5%	2.7 × 10 ⁻¹⁰
	Dogfish	Moisture diffusivity	T = 30 °C X _{fat} = 4-16.3 %	0.2 - 2.4 × 10 ⁻¹⁰
	Herring	Moisture diffusivity	T = 30 °C X _{fat} = 1.5-16.2 %	0.1 - 1.9 × 10 ⁻¹⁰
	Mackerel	Moisture diffusivity	T = 30 °C X _{fat} = 0.7 - 6.3%	1.1 - 2.2 × 10 ⁻¹⁰
	Megrin	Moisture diffusivity	T = 30 °C X _{fat} = 0.5%	2.6 - 3.1 × 10 ⁻¹⁰
	Plaice	Moisture diffusivity	T = 30 °C X _{fat} = 0.3%	2.9 × 10 ⁻¹⁰
	Witch	Moisture diffusivity	T = 30 °C X _{fat} = 0.2%	2.5 × 10 ⁻¹⁰
Flavor	d-Limonene pol.sealant film	Flavor diffusivity	T = 25 - 45 °C	0.04- 0.19 × 10 ⁻¹²
Fruits	Apple	Moisture diffusivity	T = 30- 70 °C X _w (db) = 0.2-1.0	0.9-28 × 10 ⁻¹⁰
		Oxygen diffusivity	T = 20 °C	2.7 × 10 ⁻¹⁰
		CO ₂ diffusivity	T = 20 °C	3.2 × 10 ⁻¹⁰
	Apple dried	Pectin diffusivity	T = 90 °C r _p = 0.25-0.81 mm	0.7-0.8 × 10 ⁻¹⁰
	Apple freeze- dried	Toluene diffusivity	T = 30 °C	1.5 × 10 ⁻⁶
	Apple osm. process	Moisture diffusivity Soluble solids	T = 20 - 50 °C X _{sr} % = 45 - 65	1.4- 5.5 × 10 ⁻¹⁰

		diffusivity	DE = 18 - 50	
	Apple peeled+SO ₂	Moisture diffusivity	T = 70 °C R.humidity = 10 %	0.4 - 2.4 × 10 ⁻¹⁰ 36.2 × 10 ⁻¹⁰
	Avogado	Moisture diffusivity	T = 60 °C X _{oil} (db) = 4.7- 16	3.1 - 11 × 10 ⁻¹⁰
	Bananas raw	Moisture diffusivity	microwave air (warm)	3-16 × 10 ⁻⁹ 0.3 - 2.7 × 10 ⁻⁹
	Bananas osm. dried	Moisture diffusivity Sucrose diffusivity	T = 30- 50 °C X _{sr} % = 47 - 72	1.6- 4.8 × 10 ⁻¹⁰
	Coconut Albumen	Moisture diffusivity	T = 45- 110 °C X _w (db) = 0.2- 0.6	1.3- 4.3 × 10 ⁻¹⁰ 1.0-12.8 × 10 ⁻¹⁰
	Date	Moisture diffusivity	T = ambient R. humidity % = 45-70	0.114 × 10 ⁻¹⁰
	Grapes pretreated	Moisture diffusivity	T = 30- 90 °C X _w (db) = 0.2 - 4	0.05-17.5 × 10 ⁻¹⁰
	Mango osm. dried	Moisture diffusivity	T = 50- 70 °C a _w = 0.95- 0.99	6.0 -10.2 × 10 ⁻¹⁰
	Peach freeze-dried	Toluene diffusivity	T = 27 °C	1.9 × 10 ⁻⁶
	Pineapple osm. dried	Moisture diffusivity	T = 20 °C X _w (db) = 0.2 - 2 solid gain: 0-19.5%	2.5 - 1 × 10 ⁻¹⁰
	Strawberries raw blanched	Moisture diffusivity	T = 55° C X _{glucose} = 0- 51 %	3.2 - 5.4 × 10 ⁻¹⁰ 5.4-12.5 × 10 ⁻¹⁰
Meat	Beef osm. dried	NaCl diffusivity	T = 30 - 85 °C OD time =10-370 (min)	5 - 39 × 10 ⁻¹⁰
	Chicken Frankfurter	DOA diffusivity Na ⁺ diffusivity	Irradiation dose (kGy) 0-9 T = 58 - 81 ° C X _w (db)=0.06	1.0-5.2 × 10 ⁻¹⁷ 14 - 22 × 10 ⁻¹⁰
	Pork sausage	Cl ⁻ diffusivity Moisture diffusivity	T = 20 °C X _{fat} = 13.3 - 25%	19 - 86 × 10 ⁻¹⁰ 4.7-5.7 × 10 ⁻¹¹
Model Foods	Agar gel	Dye (amaranth) diffusivity Chromate diffusivity Sorbic acid diffusivity		0.6- 4.9 × 10 ⁻¹⁰ 9 - 11.2 × 10 ⁻¹⁰
	Agarose gel	Thiamine diffusivity Glucose diffusivity Acetic acid diffusivity Chromate diffusivity	T = 20 - 80 °C C _{agar} . (%) =2-6 T = 20 - 70 °C	6.7- 7.3 × 10 ⁻¹⁰ 4.3- 16.7 × 10 ⁻¹⁰ 4.5- 13.2 × 10 ⁻¹⁰ 7.5 -22.0 × 10 ⁻¹⁰
	Alginate gum Carrageenan gel	Moisture diffusivity Dye (amaranth) diffusivity	T = 30 °C T = room	3 × 10 ⁻¹⁰ 0.5 - 1.3 × 10 ⁻¹⁰
	Cellulose system	Moisture diffusivity Tripalmitin diffusivity	T = 53 - 80 °C T = 50 °C X _w =0.03-0.19	3.1 - 5.3 × 10 ⁻¹⁰ 0.4 - 8.3 × 10 ⁻¹²
	Cereals (ready-to-eat) Dough-raisin	Moisture diffusivity Moisture diffusivity	T = 20 °C T = 15 - 70 °C X _w (db) = 0.2-0.6	0.03- 8.6 × 10 ⁻¹⁰ 0.9 - 4.9 × 10 ⁻¹⁰
	Gelatin	Dye (amaranth) diffusivity	T = ambient	2.0 - 7.6 × 10 ⁻¹²
	Glucose	Moisture diffusivity	T = 30 - 70 °C	0.1 - 4.6 × 10 ⁻¹⁰

Oilseeds	Meat emulsion	Moisture diffusivity	$X_w(db) = 0.2-1$ $T = 42-58\text{ }^\circ\text{C}$ $X_w = 0.6-0.9$ $F/P = 1.2 - 3$	$0.6 - 30.6 \times 10^{-10}$
	Protein-water	Lysosyme diffusivity		1.7×10^{-10}
	Starch gel	Moisture diffusivity	$T = 80 - 100\text{ }^\circ\text{C}$	4.4×10^{-12}
			$X_w (db) = 0.02-0.90$ $T = 30-50\text{ }^\circ\text{C}$	$1.4 - 6.6 \times 10^{-10}$ $1.9 - 5.2 \times 10^{-10}$
	Wheat gluten	Sorbic acid diffusivity	$T = 4 - 20\text{ }^\circ\text{C}$	$0.3 \times 10^{-15} -$ 7.5×10^{-12}
	Wheat-Raisin	Moisture diffusivity\	$T = 25\text{ }^\circ\text{C}$	$0.8 - 8.8 \times 10^{-13}$
	Coconut kernel osm.dried	Moisture diffusivity	$T = 25 - 45\text{ }^\circ\text{C}$ $X_{sr} = 40 - 70\text{ }^\circ\text{Brix}$	$18 - 40 \times 10^{-10}$
	Corn kernel	Moisture diffusivity	$T = 50 - 60\text{ }^\circ\text{C}$	$0.8 - 1 \times 10^{-10}$
	Lupin kernel	Moisture diffusivity	$T = 25\text{ }^\circ\text{C}$	$0.4-4.5 \times 10^{-12}$
	Peanut kernel	Vapor diffusivity	$T = 32.2 - 43.2\text{ }^\circ\text{C}$	$5.6-31.5 \times 10^{-7}$
Vegetables	Sunflower kernel	Liquid diffusivity		$5.2-23.6 \times 10^{-11}$
		Moisture diffusivity	$T = 40 - 50\text{ }^\circ\text{C}$	$0.7 - 1.7 \times 10^{-10}$
	Carrots blanched diced or prefrozen and/ or submerged in brines	Moisture diffusivity	$T = 60- 80\text{ }^\circ\text{C}$	$3.0 - 7.6 \times 10^{-10}$
		Moisture diffusivity	$T = 15- 100\text{ }^\circ\text{C}$	$5 - 24.1 \times 10^{-10}$
		Lactic acid diffusivity	$X_{(lactic\ acid)} = 0.5-2\%$	$1.9 - 6.8 \times 10^{-10}$
		Reducing Sugar diffusivity	$X_{(NaCl)} = 0-20\%$	$2.3-25.1 \times 10^{-10}$
	Carrots blanched	Reducing Sugar diffusivity	$T = 65-100\text{ }^\circ\text{C}$	$0.16-5.1 \times 10^{-10}$ $10 - 34 \times 10^{-10}$
		Sucrose diffusivity		$6 - 30 \times 10^{-10}$
		Total Solid diffusivity		$2.5- 14 \times 10^{-10}$ $14-25.3 \times 10^{-10}$
	cooked	Moisture diffusivity		$14-25.3 \times 10^{-10}$
	Garlic	Moisture diffusivity	$T = 35-75\text{ }^\circ\text{C}$ $X_w(db) = 0.06 - 1.36$	$0.34-3.45 \times 10^{-10}$
	Onion	Moisture diffusivity	$T = 25- 65\text{ }^\circ\text{C}$	$0.2 - 2.3 \times 10^{-10}$
	Onion	$D_{water+flavor}$	$T = 25$	$0.02-10.2 \times 10^{-11}$
	Peas	Moisture diffusivity	$T = 30-65\text{ }^\circ\text{C}$	$3.1 - 6.6 \times 10^{-10}$
	Potatoes, raw	Moisture diffusivity	$T = 25-90\text{ }^\circ\text{C}$ $X_w (db) = 0.3 - 4$	$2.0 - 38 \times 10^{-10}$
Moisture diffusivity		$T = 30-70\text{ }^\circ\text{C}$ $X_w (db) = 0.2- 1.5$	$0.2 - 3.1 \times 10^{-10}$	
NaOH diffusivity		$T = 25-70\text{ }^\circ\text{C}$ $X_{NaOH} (\%) = 4.3-20$	$0.02 - 2 \times 10^{-10}$ (skin) $8.2- 23.3 \times 10^{-10}$ (flesh)	
NaCl diffusivity		$T = 80-85\text{ }^\circ\text{C}$ $X_{(NaCl)} (\%) = 3-5$ $T = 20\text{ }^\circ\text{C}$	$21.1-24.9 \times 10^{-10}$ $\times 10^{-10}$	
		$X_{(NaCl)} (\%) = 1-3$ $T = 5-120\text{ }^\circ\text{C}$	$2.5 - 44.5 \times 10^{-10}$	
		$X_{(NaCl)m} (\%) = 1-5$ $T = 54-81\text{ }^\circ\text{C}$	$2.6 - 6.4 \times 10^{-10}$	
blanched		Moisture diffusivity		

blanched	Reducing Sugar diffusivity	T = 70-100 °C	0.1- 0.17 × 10 ⁻¹⁰
osm.dried	Moisture diffusivity	T = 50 °C	2.2 × 10 ⁻¹⁰
	Soluble solids diffusivity	DE=38	0.7 × 10 ⁻¹⁰
	Moisture diffusivity	T = 52-68 °C, X _{Sr} = 45-60 %	2.3-4.5 × 10 ⁻¹⁰
prepeeled	Ascorbic Acid diffusivity	T = 25 °C	5.5 × 10 ⁻¹⁰
	Citric Acid diffusivity		4.3 × 10 ⁻¹⁰
pretreated (surfactants)	Moisture diffusivity	T = 40 °C	8.75-11.72 × 10 ⁻¹⁰
Pimiento Peppers	NaOH diffusivity	T = 72 °C X _(NaOH) (%) =8	5.5 × 10 ⁻¹²
Soybeans	Moisture diffusivity	T = 50- 78 °C X _w (db) = 0.4- 1	0.5 - 3 × 10 ⁻¹⁰
Sugar beet diced	Moisture diffusivity	T = 40- 84 °C	0.4-1.3 × 10 ⁻¹⁰
Tomato diced	Moisture diffusivity	T = 60- 80 °C u = 0.4-1.8 m/s	6.6-23.6 × 10 ⁻¹⁰
	NaOH diffusivity	T = 72 °C X _(NaOH) (%) = 8	2.0 × 10 ⁻¹²
	CO ₂ diffusivity	T = 10 °C	× 10 ⁻⁸
Tomato concentrates (15 %solids)	Moisture diffusivity	T = 60-100 °C	1.7-64.6 × 10 ⁻¹⁰

Symbols used with Table 1:

B	thickness (m)
db	dry basis
DE	dextrose equivalent
DOA	irradiation
osm.	osmotically
pol.	polymeric
pretr.	pretreated
r_p	particle radius (mm)
T	temperature (degrees Celsius)
u	air velocity (m/s)
w	water
wb	wet basis
X	content (w/w) or %
X_{fat}	fat content (w/w) or %
X_{salt}	salt content (w/w) or %
X_w	moisture content kg/kg or %
X_{Sr}	sucrose content (w/w) or %

Figure Captions

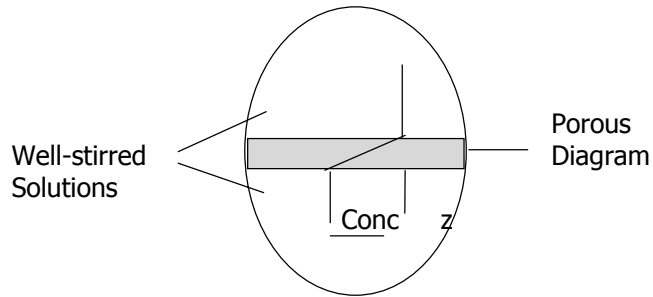


Figure 1. A diaphragm cell for measuring diffusion coefficients. The concentration profile within the diaphragm has essentially the linear, steady-state value.

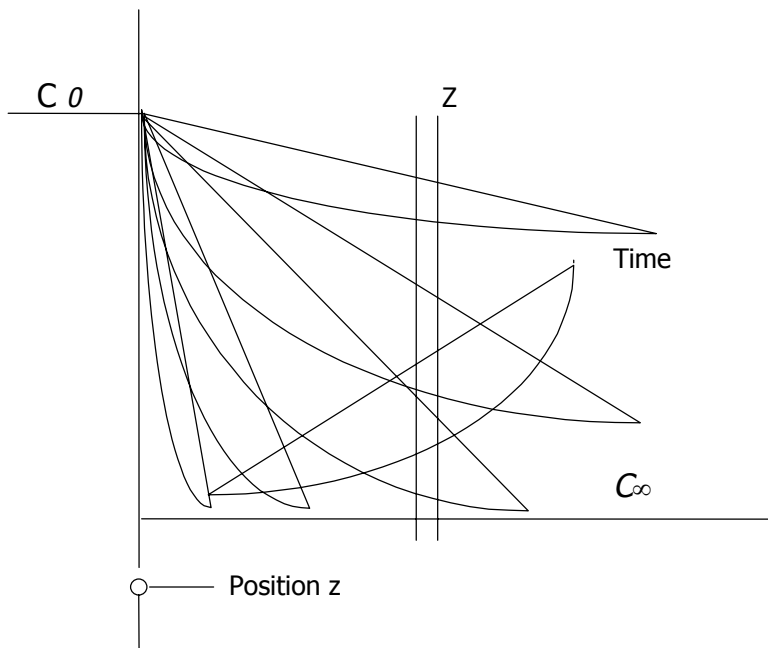


Figure 2. Diffusion in a semi infinite slab. Free diffusion. Diffusion occurs in the region to the right.