TABLE 4.3	BẢNG 4.3
Effect of Material Moisture Content and Temperature on Diffusivity	Ảnh hưởng của hàm lượng độ ẩm vật liệu và nhiệt độ đến độ khuếch tán
steady-state and transient-state methods. Transient methods are more popular because they can be run for as short as 10 s, during which time the moisture migration and other property changes are kept minimal.	các phương pháp trạng thái ổn định và trạng thái quá độ. Các phương pháp quá độ phổ biến hơn bởi vì chúng chạy trong khoảng thời gian ngắn khoảng 10 s, trong khoảng thời gian đó sự di chuyển độ ẩm và những thay đổi tính chất khác được giữ ở mức tối thiểu.
	transient-state: cũng có thể dịch là trạng thái chuyển tiếp.
4.3.2.1 Steady-State Methods	4.3.2.1 Các phương pháp trạng thái ổn định
In steady-state methods, the temperature distribution of the sample is measured at steady state, with the sample placed between a heat source and a heat sink.	Trong các phương pháp trạng thái ổn định, người ta đo sự phân bố nhiệt độ của mẫu ở trạng thái ổn định, trong đó mẫu được đặt giữa nguồn nhiệt và bộ tản nhiệt.
TABLE 4.4	BẢNG 4.4
Application Examples	Các ví dụ ứng dụng
Different geometries can be used, those for longitudinal heat flow and radial heat flow.	Người ta sử dụng các hình dạng khác nhau cho những dòng nhiệt dọc và những dòng nhiệt xuyên tâm.
4.3.2.2 Longitudinal Heat Flow (Guarded Hot Plate)	4.3.2.2 Dòng nhiệt dọc (đĩa hâm có bảo vệ)
The longitudinal heat flow (guarded hot plate) method is regarded as the most accurate and most widely used apparatus for the measurement of thermal conductivity of poor conductors of heat. This method is most suitable for dry homogeneous specimens in slab forms. The details of the technique are given by the American Society for Testing and Materials (ASTM) Standard C-177 [82].	Phương pháp dòng nhiệt dọc (đĩa hâm có bảo vệ) được xem là một công cụ chính xác nhất và phổ biến nhất để đo độ dẫn nhiệt của các vật dẫn nhiệt kém. Phương pháp này thích hợp nhất cho các mẫu khô đồng nhất ở dạng thanh. Để hiểu thêm về kỹ thuật này, bạn có thể tham khảo American Society for Testing and Materials (ASTM) Standard C-177 [82]. .
4.3.2.3 Radial Heat Flow	[redacted]
Whereas the longitudinal heat flow methods are most suitable for slab specimens, the radial heat flow	

techniques are used for loose, unconsolidated powder or granular materials. The methods can be classified as follows:

Cylinder with or without end guards
Sphere with central heating source
Concentric cylinder comparative method

[redacted]

4.3.2.4 Unsteady State Methods

Transient-state or unsteady-state methods make use of either a line source of heat or plane sources of heat.

TABLE 4.5
Methods for the Experimental Measurement of Thermal Conductivity

Method	Ref.
Steady-state method	
Longitudinal heat flow (guarded hot plate)	82
Radial heat flow	83
Unsteady-state method	
Fitch	84, 85
Plane heat source	86
Probe method	87, 88

In both cases, the usual procedure is to apply a steady heat flux to the specimen, which must be initially in thermal equilibrium, and to measure the temperature rise at some point in the specimen, resulting from this applied flux [83]. The Fitch method is one of the most common transient methods for measuring the thermal conductivity of poor conductors. This method was developed in 1935 and was described in the National Bureau of Standards Research Report No. 561. Experimental apparatus is commercially available.

4.3.2.5 Probe Method

[redacted]

The probe method is one of the most common transient methods using a line heat source. This method is simple and quick. The probe is a needle of good thermal conductivity that is provided with a heater wire over its length and some means of measuring the temperature at the center of its length. Having the probe embedded in the sample, the temperature response of the probe is measured in a step change of heat source and the thermal conductivity is estimated using the transient solution of Fourier’s law. Detailed descriptions as well as the necessary modifications for the application of the above-mentioned methods in food systems are given in Refs. [83,89,90].

[redacted]

4.3.3 DATA COMPILATION

Despite the limited data of effective moisture diffu- sivity, a lot of data are reported in the literature for thermal conductivity. Data for mainly homogeneous materials are available in handbooks such as the Handbook of Chemistry and Physics [91], the Chemical Engineers’ Handbook [92], ASHRAE Handbook of Fundamentals [93], Rohsenow and Choi [94], and many others. For foods and agricultural products, data are available in Refs. [83,88,95-97]. For selected pharmaceutical materials, data are presented by Pakowski and Mujumdar [98].

[redacted]

Some data for thermal conductivity are presented in Table 4.6. These values are distributed as shown in Figure 4.6. The distribution is different from that of moisture diffusivity (Figure 4.2), which is normal. For thermal

[redacted]

conductivity, the values are uniformly distributed in the range 0.25 to 2.25 W/(m K), whereas a lot of data are accumulated below 0.25 W/(m K).

4.3.4 FACTORS AFFECTING THERMAL CONDUCTIVITY

The thermal conductivity of homogeneous materials depends on temperature and composition, and empirical equations are used for its estimation. For each material, polynomial functions of first or higher order

TABLE 4.6

Effective Thermal Conductivity in Some Materials

Material	Temperature (°C)	Thermal Conductivity (W/(m K))	Ref.
Aerogel, silica	38	0.022	94
Asbestos	427	0.225	94
Bakelite	20	0.232	94
Beef, 69.5% water	-18	0.622	99
Beef fat, 9% water	-10	0.311	100
Brick, common	20	0.173-0.346	94
Brick, fire clay	800	1.37	94
Carrots	-15 to -19	0.622	101
Concrete	20	0.813-1.40	94
Corkboard	38	0.043	94
Diatomaceous earth	38	0.052	94
Fiber-insulating board	38	0.042	94
Fish	-20	1.50	100
Fish, cod, and haddock	-20	1.83	102
Fish muscle	-23	1.82	103
Glass, window	20	0.882	94
Glass wool, fine	38	0.054	94
Glass wool, packed	38	0.038	94
Ice	0	2.21	94

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

Magnesia	38	0.067	94
Marble	20	2.77	94
Paper		0.130	94
Peach	18-27	1.12	104
Peas	18-27	1.05	104
Peas	-12 to -20	0.501	101
Plums	-13 to -17	0.294	101
Potato	-10 to -15	1.09	101
Potato flesh	18-27	1.05	104
Rock wool	38	0.040	94
Rubber, hard	0	0.150	94
Strawberries	18-27	1.35	104
Turkey breast	-25	0.167	100
Turkey leg	-25	1.51	100
Wood, oak	21	0.207	94

are used to express the temperature effect. A large number of empirical equations for the calculation of thermal conductivity as a function of temperature and humidity are available in the literature [83,92].

For heterogeneous materials, the effect of geometry must be considered using structural models. Utilizing Maxwell's and Eucken's work in the field of electricity, Luikov et al. [105] initially used the idea of an elementary cell, as representative of the model structure of materials, to calculate the effective thermal conductivity of powdered systems and solid porous materials. In the same paper, a method is proposed for the estimation of the effective thermal conductivity of mixtures of powdered and solid porous materials.

Since then, a number of structural models have been proposed, some of which are given in Table 4.7. The perpendicular model assumes that heat conduction is perpendicular to alternate layers of the two phases, whereas the parallel model assumes that the two phases are parallel to heat

[redacted]

[redacted]

conduction. In the mixed model, heat conduction is assumed to take place by a combination of parallel and perpendicular heat flow. In the random model, the two phases are assumed to be mixed randomly. The Maxwell model assumes that one phase is continuous, whereas the other phase is dispersed as uniform spheres. Several other models have been reviewed in Refs. [107,110,111], among others. The use of some of these structural models to calculate the thermal conductivity of a hypothetical porous material is presented in Figure 4.7. The parallel model gives the larger value for the effective thermal conductivity, whereas the perpendicular model gives the lower value. All other models predict values in between. The use of structural models has been successfully extended to foods [108,112], which exhibit a more complex structure than that of other materials, whereas this structure often changes during the heat conduction. A systematic general procedure for selecting suitable structural models, even in multiphase systems, has been proposed in Ref. [113]. This method is based on a model discrimination procedure. If a component has unknown thermal conductivity, the method estimates the dependence of the temperature on the unknown thermal conductivity, and the suitable structural models simultaneously. An excellent example of applicability of the above is in the case of starch, a useful material in extrusion. The granular starch consists of two phases, the wet granules and the air-vapor mixture in the intergranular space.	[redacted] [redacted] [redacted]

The starch granule also consists of two phases, the dry starch and the water. Consequently, the thermal conductivity of the granular starch depends on the thermal conductivities of pure materials (i.e., dry pure starch, water, air, and vapor, all functions of temperature) and the structures of granular starch and the starch granule. It has been shown that the parallel model is the best model for both the granular starch and the starch granule [113]. These results led to simultaneous experimental determination of the thermal conductivity of dry pure starch versus temperature. Dry pure starch is a material that cannot be isolated for direct measurement.

[redacted]

4.3.5 THEORETICAL ESTIMATION

As in the case of the diffusion coefficient, the thermal conductivity in fluids can be predicted with satisfactory accuracy using theoretical expressions, such as the formulas of Chapman and Enskog for monoatomic gases, of Eucken for polyatomic ones, or of Bridgman for pure liquids. The thermal conductivity of solids, however, has not yet been predicted using basic ther-mophysical or molecular properties, just like the analogous diffusion coefficient. Usually, the thermal conductivities of solids must be established experimentally since they depend upon a large number of factors that cannot be easily measured or predicted.

[redacted]

A large number of correlations are listed in the literature for the estimation of thermal conductivity as a

[redacted]

function of characteristic properties of the material. Such relations, however, have limited practical utility since the values of the necessary properties are not readily available. A method has been developed for the prediction of thermal conductivity as a function of temperature, porosity, material skeleton thermal conductivity, thermal conductivity of the gas in the porous, mechanical load on the porous material, radiation, and optical and surface properties of the material’s particles [105]. The method produced satisfactory results for a wide range of materials (quartz sand, powdered Plexiglas, perlite, silica gel, etc.). It has been proposed that the thermal conductivity of wet beads of granular material be estimated as a function of material content and the thermal conductivity of each of the three phases [114]. The results of the method were validated in a small number of materials such as crushed marble, slate, glass, and quartz sand. Empirical equations for estimating the thermal conductivity of foods as a function of their composition have been proposed in the literature. In particular, it has been suggested that the thermal conductivity of foods is a first-degree function of the concentrations of the constituents (water, protein, fat, carbohydrate, etc.) [97].	[redacted] [redacted] [redacted]

4.4 INTERPHASE HEAT AND MASS checked 16/5 2 h 23 TRANSFER COEFFICIENTS 4.4.1 DEFINITION The interphase heat transfer coefficient is related to heat transfer through a relative stagnant layer of the flowing air, which is assumed to adhere to the surface of the solid during drying (generally heating or cooling). It may be defined as the proportionality factor in the equation (Newton's law) Q = hHA(TA — T) (4.5) where hH (kW/(m2 K)) is the surface heat transfer coefficient at the material-air interface, Q (kW) is the rate of heat transfer, A (m2) is the effective surface area, T (K) is the solid temperature at the interface, and Ta (K) is the bulk air temperature. By analogy, a surface mass transfer coefficient can be defined using the following equation: J = hMA(XA — Xas) (4.6) where hM (kg/(m2 s)) is the surface mass transfer coefficient at the material-air interface, J (kg/s) is the rate of mass transfer, A (m2) is the effective surface area, XAS (kg/kg) and XA (kg/kg) are the air humidities at the solid interface and the bulk air. Equation 4.5 and Equation 4.6 are used in cases in which the drying is externally controlled. This occurs when the Biot number (BiH, BiM) for heat and mass transfer is less than 0.1 [5]. Volumetric heat and mass transfer coefficients are often used instead of surface heat and mass transfer coefficients. They can be defined	4.4 HỆ SỐ TRUYỀN NHIỆT LƯỢNG VÀ KHỐI LƯỢNG LIÊN PHA 4.4.1 ĐỊNH NGHĨA Hệ số truyền nhiệt liên pha có mối liên hệ với quá trình truyền nhiệt qua một lớp khí lưu thông tương đối chậm, chúng ta giả sử lớp khí này gắn với bề mặt vật rắn trong quá trình sấy khô (nói chung là cấp nhiệt hoặc làm lạnh). Chúng ta định nghĩa nó là hệ số tỉ lệ trong phương trình (định luật Newton) [redacted]

using the equations

$hvH = ahH$ (4 . 7)

$hvM = ahM$ (4 . 8)

where a is the specific surface defined as follows:

$a = A/V$ (4 . 9)

where A (m2) is the effective surface area and V (m3) is the total volume of the material.

Different coefficients can be defined using different driving forces.

4.4.2 METHODS OF EXPERIMENTAL MEASUREMENT

The methods of experimental measurement of heat and mass transfer coefficients are summarized in Table 4.8, and resulted mainly from heat and mass transfer investigations in packed beds. Heat transfer techniques are either steady or unsteady state. In steady-state methods, the heat flow is measured to-gether with the temperatures, and the heat transfer coefficient is obtained using Newton's law. Three different methods for heating are presented in Table 4.8.In unsteady-state techniques, the temperature of the outlet air is measured as a response to variations of the inlet air temperature. A transient model incorporating the heat transfer coefficient is used for analysis. Step, pulse, or cyclic temperature variations of the input air temperature have been used. Drying experiments during the constant drying rate period have also been used for estimating heat and mass transfer coefficients. A generalization of this method for simultaneous estimation of transport

[redacted]

[redacted]

properties using drying experiments is presented in Section 4.7.

4.4.3 DATA COMPILATION

All the data available in the literature are in the form of empirical equations, and they are examined in the next section.

4.4.4 FACTORS AFFECTING THE HEAT AND MASS TRANSFER COEFFICIENTS

Both heat and mass transfer coefficients are influenced by thermal and flow properties of the air and, of course, by the geometry of the system. Empirical equations for various geometries have been proposed in the literature. Table 4.9 summarizes the most popular

TABLE 4.8

Methods for the Experimental Measurement of Heat and Mass Transfer Coefficients

Method	Ref.
Steady-state heating methods	
Material heating	115
Wall Heating	116
Microwave heating	117
Unsteady-state heating methods	
Step change of input air temperature	118,119
Pulse change of input air temperature	120,121
Cyclic temperature variation of input air	122,123
Constant rate drying experiments	124,125
Simultaneous estimation of transport properties using drying experiments	

[redacted]

[redacted] sấy

khô [redacted]

equations used for drying. The empirical equations incorporate dimensionless groups, which are defined in Table 4.10. Some nomenclature needed for understanding Table 4.9 is also included in Table 4.10.	sấy khô [redacted]
Equation T9.1 through Equation T9.5 in Table 4.9 are the most widely used equations in estimating heat and mass transfer coefficients for simple geometries (packed beds, flat plates).	[redacted]
For packed beds, the literature contains many references. In 1965, Barker reviewed 244 relevant papers [183]. The equation suggested by Whitaker [130] is selected and presented in Table 4.9 as Equation T9.7. It has been obtained by fitting to data of several investigators (see Refs. [126,127]). Equation T9.6 for flat plates comes from the same investigation [130], and it is also included in Table 4.9. In drying of granular materials, the equations reviewed in Ref. [136] should be examined.	[redacted]
Rotary dryers are usually controlled by heat transfer. Thus, Equation T9.8 through Equation T9.10 in Table 4.9 are proposed in Ref. [131] for the estimation of the corresponding heat transfer coefficients.	[redacted]
Heat and mass transfer in fluidized beds have been discussed in Refs. [6,137-140]. The latter reviewed the most important correlations and proposed Equation	[redacted]

T9.1 Packed beds (heat transfer)	[redacted]
T9.2 Packed beds (mass transfer)	[redacted]
T9.3 Flat plate (heat transfer, parallel flow)	[redacted]
T9.4 Flat plate (heat transfer, parallel flow)	[redacted]
T9.5 Flat plate (heat transfer, perpendicular flow)	[redacted]
T9.6 Flat plate (heat transfer, parallel flow)	[redacted]
T9.7 Packed beds (heat transfer)	[redacted]
T9.8 Rotary dryer (heat transfer)	[redacted]
T9.9 Rotary dryer (heat transfer)	[redacted]
T9.10 Rotary dryer (heat transfer)	[redacted]
T9.11a Fluidized beds (heat transfer)	[redacted]
T9.11b Fluidized beds (heat transfer)	[redacted]
T9.12a Fluidized beds (mass transfer)	[redacted]
T9.12b Fluidized beds (mass transfer)	[redacted]
T9.13 Droplets in spray dryer (heat transfer)	[redacted]
T9.14 Droplets in spray dryer (mass transfer)	[redacted]
T9.15 Spouted beds (heat transfer)	[redacted]
T9.16 Spouted beds (mass transfer)	[redacted]
T9.17 Pneumatic dryers (heat transfer)	[redacted]
T9.18 Pneumatic dryers (mass transfer)	[redacted]
T9.19 Impingement drying	[redacted]
Several equations for various configurations 133-135 For nomenclature, see Table 4.10. character of the flow path of the particles in a bed with zones under different aerodynamic conditions [6].	[redacted]

However, Equation T9.15 and Equation T9.16 of Table 4.9 can be used.

Heat transfer coefficients for pneumatic dryers have been reviewed in Ref. [6]. The majority of authors examined and use an equation similar to Equation T9.13 and Equation T9.14 of Table 4.9 for spray dryers. For immobile particles, the exponent of the Re number is close to 0.5 and for free-falling particles, it is 0.8. Equation T9.17 of Table 4.9 is proposed. The mass transfer coefficient could be estimated by the analogy Sh = Nu [6]. In extensive reviews [133-135], correlations for estimating heat and mass transfer coefficients in impingement drying under various configurations are discussed.

The calculated heat and mass transfer coefficients using some of the equations presented in Table 4.9 are plotted versus air velocity with some simplifications in Figure 4.8 and Figure 4.9. These figures can be used to estimate approximately the heat and mass transfer coefficients for various dryers. The simplifications made for the construction of these figures concern the drying air and material conditions. For instance, the air temperature is taken as 80oC, the air humidity as 0.010 kg/kg db, and the particle size as 10 mm (typical drying conditions). For other conditions, the equations of Table 4.9 should be used.

T9.11 and Equation T9.12 of Table 4.9 for the calculation of heat and mass transfer coefficients,

[redacted]

respectively. Further information for fluidized bed drying can be found in Ref. [141].

Vibration can intensify heat and mass transfer between the particles and gas. The following correction has been suggested for the heat and mass transfer coefficients when vibration occurs [6]

hH= hH(A'/'/uA)065 (4.10)

Hm> = hM(Af /ua)0 65 (4.11)

where u (m/s) is the air velocity, A (m) the vibration amplitude, and f (s—1) the frequency of vibration. Further information on vibrated bed dryers can be found in Ref. [142].

For spray dryers, the popular equation of Ranz and Marshall [132] is presented in Table 4.9 (Equation T9.13 and Equation T9.14). They correlated data obtained for suspended drops evaporating in air.

Heat and mass transfer in a spouted bed has not been fully investigated yet because of the complex

4.4.5 THEORETICAL ESTIMATION

No theory is available for estimating the heat and mass transfer coefficients using basic thermophysical properties. The analogy of heat and mass transfer can be used to obtain mass transfer data from heat transfer data and vice versa. For this purpose, the Chilton-Colburn analogies can be used [129]

JM = JH = f/2 (4.12)

where f is the well-known Fanning friction factor for the fluid, and jH and jM are the heat and mass transfer factors defined in Table 4.10.

[redacted]

[redacted]

Discrepancies of the above classical analogy have been discussed in Ref. [143].

In air conditioning processes, the heat and mass transfer analogy is usually expressed using the Lewis relationship

^H/^M = Cp(4.13)

where cp (kJ/(kg K)) is the specific heat of air.

4.5 DRYING CONSTANT

4.5.1 DEFINITION

The transport properties discussed above (moisture diffusivity, thermal conductivity, interface heat, and mass transfer coefficients) describe completely the drying kinetics. However, in the literature sometimes (mainly in foods, especially in cereals) instead of the above transport properties, the drying constant K is used. The drying constant is a combination of these transport properties.

The drying constant can be defined using the so- called thin-layer equation. Lewis suggested that during the drying of porous hygroscopic materials, in the falling rate period, the rate of change in material moisture content is proportional to the instantaneous difference between material moisture content and the expected material moisture content when it comes into equilibrium with the drying air [144]. It is assumed that the material layer is thin enough or the air velocity is high so that the conditions of the drying air (humidity, temperature) are kept constant throughout the material. The thin-layer equation has

[redacted]

the following form: $-dX/dt = K(X - Xe)$ (4.14) where X (kg/kg db) is the material moisture content, Xe (kg/kg db) is the material moisture content in equilibrium with the drying air, and t (s) is the time. A review of several other thin-layer equations can be found in Refs. [76,145]. Equation 4.14 constitutes an effort toward a unified description of the drying phenomena regardless of the controlling mechanism. The use of similar equations in the drying literature is ever increasing. It is claimed, for example, that they can be used to estimate the drying time as well as for the generalization of the drying curves [6]. The drying constant K is the most suitable quantity for purposes of design, optimization, and any situation in which a large number of iterative model calculations are needed. This stems from the fact that the drying constant embodies all the transport properties into a simple exponential function, which is the solution of Equation 4.14 under constant air conditions. On the other hand, the classical partial differential equations, which analytically describe the four prevailing transport phenomena during drying (internal-external, heat-mass transfer), require a lot of time for their numerical solution and thus are not attractive for iterative calculations. 4.5.2 METHODS OF EXPERIMENTAL MEASUREMENT The measurement of the drying	[redacted] [redacted] [redacted]

constant is obtained from drying experiments. In a drying apparatus, the air temperature, humidity, and velocity are controlled and kept constant, whereas the material moisture content is monitored versus time. The drying constant is estimated by fitting the thin-layer equation to experimental data.	[redacted]
4.5.3 FACTORS AFFECTING THE DRYING CONSTANT The drying constant depends on both material and air properties as it is a phenomenological property representative of several transport phenomena. So, it is a function of material moisture content, temperature, and thickness, as well as air humidity, temperature, and velocity.	[redacted]
Some relationships describing the effect of the above factors on the drying constant are presented in Table 4.11. Equation T11.1 and Equation T11.2 are Arrhenius-type equations, which take into account the temperature effect only. The effect of water activity can be considered by modifying the activation energy (Equation T11.1) on the preexponential factor (Equation T11.2). Equation T11.1 and Equation T11.2 consider the same factors in a different form. Equation T11.4 takes into account only the air velocity effect, whereas Equation T11.5 considers all the factors affecting the drying constant. Table 4.12 lists parameter values for typical equations of Table 4.11. Equation T11.2 and Equation T11.5 were applied to shelled corn [150] and to green pepper [35],	[redacted]

respectively, and the results are presented in Figure 4.10. The effects of air temperature and velocity, as well as particle dimensions, are shown for green pepper drying, whereas the air temperature and the small air-water activity effects are shown for the low air temperature drying of wheat.

4.5.4 THEORETICAL ESTIMATION

It is impossible to estimate an empirical constant using theoretical arguments. The estimation of an

TABLE 4.11

Effect of Various Factors on the Drying Constant

[redacted]