玉 米 質 量 傳 遞 係 數

Mass Transfer Coefficients for Corn Kernels

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摘　要

本研究目的主要在以實驗方法測定玉米的質量傳遞係數，在一質量傳遞過程中，等率期爲最佳的時段，用以測定質傳係數，但由於玉米在乾燥或覆水過程中皆缺乏等率期，直接自玉米測定質傳係數變成非常困難，因此本實驗將採用苯揮發技術。

苯製球形顆粒在空氣管流中測試，結果與其它已發表的有關球形顆粒質傳係數相比較，用以驗證測試方法是適當，實驗結果較其它值略高，此可能是由於自然對流，但實驗數據相當穩定一經，顯示此方式仍可供採用。

用石膏做的模具與融蜜化的苯鑄造似玉米狀的苯顆粒，苯粒在測試管中以四種不同的懸掛方向進行測試，無向量數 (SHERWOOD 數，REYNOLDS 數，SCHMIDT 數) 被用以建立相關式，

$$Sh=Sh0+C1\ Re^{C2}\ Sc^{c3}$$

由相關式與實驗結果間的高相關係數與低標準誤差知二者相吻合。

F-統計方法被用來檢定苯粒在不同懸掛方向上的差異，統計結果明顯指出質傳係數與懸掛方向有關，以四種不同方向的混合結果推測出一通式，此通式將建議用於深層乾燥中，此種應用仍有待進一步實驗驗證。

Abstract

This research is devoted to quantifying the average mass transfer coefficients of corn kernels. The transfer coefficients are most easily determined during the constant rate period in a mass transfer process. Due to the lack of constant rate period for corn kernels in a drying or rewetting process, the naphthalene sublimation technique was adopted in this study.

Naphthalene spheres in a confined flow were tested. Outcomes were compared with the published equations. The experimental data of transfer coefficients were higher than the values of published expressions. The consistency of the measurements for spherical solids indicated the method to be repeatable.

Corn-like naphthalene solids cast from a dental plaster mold were tested in four different sample orientations corresponding to the air flow direction. The results were used to build the correlations in terms of dimensionless numbers (Sherwood number, Reynolds number, and Schmidt number). The correlation was

$$Sh = ShO + Cl\ Re^{C2}\ Sc^{1/3}$$

Sho was determined with experiment. All correlations fit experimental data sets well, based on the high multiple correlation coefficients and low standard deviations.

F-statistics were used to check the differences among the sample orientations. F-statistics showed significant difference existed among the four orientations. This could be partially explained by the natural convection. A general equation was derived based on the combined data set of all four orientations. The equation is recommended for deep-bed corn drying for the range of Re used in this experiment.

INTRODUCTION

The moisture tansfer in drying corn kernels can be segmented into two processes: moisture movement inside the kernel and moisture transfer between the kernel and drying medium. Moisture transfer between the kernel surface and drying medium can be represented by the moisture convection. A convective transfer coefficient is one of necessary parameters to estimate the moisture convection rate. The convective transfer coefficient can be determined experimentally.

The objectives of this study are:

1) To develop a methodology to measure the convective mass transfer coefficients of corn kernels.

2) To find relationships between the transfer coefficient and the orientation of a corn kernel inside a confined flow.

3) To develop a model to estimate the transfer coefficients in various sample orientations relative to fluid flow direction.

LITERATURE REVIEW

The equilibrium moisture content - EMC curve helps researchers to predict the potential final state of grain in a drying process corresponding to a well specified environment. But the EMC curve can not indicate how fast the state can be reached. To determine the rate, the actual heat and mass flux, must be described via heat and mass transfer theory. The fundamental concept of heat and mass transfer is heat or mass move only inside a physical potential field. It moves from a higher potential to a lower potential. For example, heat is only transferred from higher temperature to lower temperature without doing work according to the thermodynamic law. Mass flows also from a place of higher vapor concentration to a place of lower vapor concentration. Usually, the complicated and varied structures of various biological materials diversify the theories of mass transfer; therefore, there are several distinct theories about mass transfer related to biological substances. Four of the principal theories used to describe mass transfers inside bodies are 1) diffusion theory (Sherwood, 1929), 2) capillary theory (Buckingham, 1907), 3) evaporation and condensation theory (Henry, 1937), and 4) non-equilibrium thermodynamics theory (Luikov, 1964).

The above four major theories describing the interior mass transfer have all been used in drying area. However none of them have been found satisfactory for the whole drying process. Besides the interior transfer, a complete drying theory should include the external transfer- boundary condition, which describes the transport process between the sample surface and its surroundings.

2.1 Boundary Conditions

For a drying problem, three types of boundary conditions are defined corresponding to the domain of interest (Lapidus and Pinder, 1981):

1) Dirchlet condition: A boundary condition that prescribes the values of the variables on the boundaries, such as given values of temperature and moisture concentration, is called the first type or Dirchlet boundary condition.

2) Neumann condition: A boundary condition that prescribes the values of the normal derivatives on the boundaries, such as an insulated or a symmetry point or line, is called the second type or Neumann boundary condition. This type of boundary condition is used only to describe a symmetrical or insulated boundary.

3) Cauchy condition: A boundary condition that prescribes the relationship between the values of the variable itself and its normal derivative on the boundaries, such as the boundary condition of mass (or heat) transfer specified via the diffusive and convective mass (or heat) fluxes, is called the third type of Cauchy boundary condition. Huang and Gunkel (1974) applied the third type boundary condition to their heat and mass transfer equations. Husain et al. (1972) also made the similar arrangement.

No matter what type of boundary condition is selected, its main objective is to supply values on the boundary for further calculation of the interior values. The third type of boundary condition is most often used to describe the outer boundarycondition so that the law of conservation of energy and mass is preserved. When applying the third type of boundary condition, it is necessary to have the diffusivity of the flow and mass transfer coefficient to compute the flux on the sample surface.

2.2 Convective Mass Transfer

Convective mass transfer defines the mass transferred as proportional to the logmean mass concentration and the interfacial area:

$$M' = h_m * A * C_{1m} \tag{1}$$

The mas transfer coefficient, hm, is related to the fluid diffusion coefficient and flow rate. However it is a formidable task to define the relationship among mass transfer coefficient, diffusion coefficient and the fluid flow. There are usually two kinds of tools used to describe the relationship, physical models and transport analogies among momentum, mass and heat transfer. The main physical model is the boundary layer theory. The most successful and useful analogy is the J-factor analogy (Chilton and Colburn, 1034). This analogy is based on experimental data for gases and liquids in both laminar and turbulent regions.

2.3 Measurement and Calculation of Transfer Coefficient

Based on the transfer coefficient definition, the coefficient can be computed via dividing the mass change rate by both the transfer area and the vapor concentration difference between bulk fluid and sample surface. However, only in the constant rate period is the vapor concentration difference between sample surface and surrounding air constant and determinable. Therefore, the measurement of mass transfer coefficient must be done during the constant rate period.

For most biological materials, a constant rate period does not exist. In order to overcome this obstacle, researchers have found substitute materials with the constant rate periods. For some organic chemicals, the saturated surface vapor concentration can be predicted using the thermodynamic equation of an equilibriium state. The other important criterion to select a substitute is the substitute material must have the capability to be cast or molded easily into the desired shapes. The measurements from such substitute samples have been collected and used to compute the mass transfer coefficients.

The naphthalene sublimation technique is selected in this work. The naphthalene sublimation technique has been applied to the research area of mass transfer by Christian and Kezios (1957), Skelland and Cornish (1963). This technique is especially good for measuring the local transfer coefficient with the aid of the profilometer. The average transfer coefficient can be calculated by either integrating the local transfer coefficient or weighing the total weight change divided by the total transfer area and the driving force (the concentration difference) in a unit of time.

2.4 Surface Transfer Area

There is no difficulty in calculating the areas of samples with the regular shapes. But most biological products do not have regular, identical or uniform shapes. The surface area of individual sample must be determined separately. Jindal et al. (1974) and Bakker-Arkema et al. (1971) developed procedures for area estimations for grains based on the unit of total transfer area for per cubic foot of samples. However, so far no model or equation has been developed to compute the surface area for an individual corn kernel.

EXPERIMENTAL PROCEDURES

3.1 Apparatus

The main apparatus in this study is a Thermo-Gravimetric Analysis System (CAHN TGA System 113) with a flow meter (Lab-Crest Scientific 10A1460-LK). The TGA is composed of three main parts: 1) the weighing system (CAHN 2000), 2) the temperature control system, and 3) the test chamber.

3.2 Sample Preparation

One of the important and critical points of the entire experiment is the preparation of naphthalene solids. Because naphthalene contracts as it solidifies, in many cases researchers have just coated naphthalene on the surface of prepared steel molds with simple geometric shapes. Since it is difficult to choose and prepare a typical steel mold for corn kernels to coat the naphthalene on the surface, pure naphthalene solids were made and used.

A one piece dental plaster open mold was used for samples with corn shapes (Sheng, 1985).

3.3 Testing Procedures

Before placing the samples inside the testing tube, the tube had been preheated to and maintained at 40°C. In the most stable stage the temperature cycling of 1°C was still expressed. The minimum point of the temperature cycle was found to be the best time in setting the samples. The sample was hung at the tube center. The readings from weight measurement unit were recorded at five minutes interval. Some deviation of mass loss rates was caused from the cyclic temperature change, and unstable air flow rate. Therefore, the value of mass change rate per minute was recorded as the average value for 30 minutes period.

3.3.1 Spherical Solids

The initial weights of spherical samples were within the range of 1.20 to 1.34 gm. The operating range of air flow rates was from 6.29 to 54.54 cm^3/s (0.8 to 6.93 ft^3/hr). The rates of weight change were about 0.239 to 0.581 mg/min for spherical solids.

3.3.2 Solids with corn shapes

The operating range of air flow rates in corn-like shapes tests was from 9.74 to 61.57 cm^3/s (1.18 to 7.43 ft^3/hr. A low air velocity for actual corn drying is 12.6 cm/s. Tests using very low air flow rate of 1 cm^3/s (0.12 ft^3/hr) were also conducted to measure the transfer coefficients with the stagnant air. In this study, four different orientations of samples according to the direction of air flow were tested: upstream, downstream, side and normal. They are shown in Figure 1. In each orientation, 22 runs were conducted.

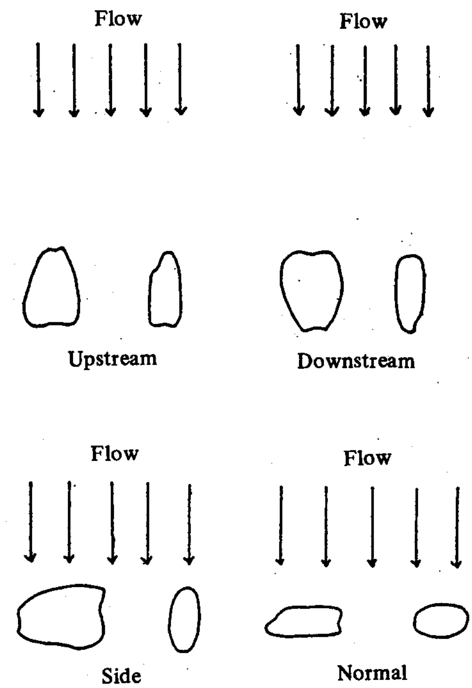

Figure 1: Sample orientations

Because the corn-like solids were not completely identical, different samples might have different transfer areas. Data on size changes for a sample were used to approximately compute the transfer area. The tests were extended for 1 to 2 hours longer than the time period required to collect transfer coefficient data. This allowed changes of sample sizes (length width, and thickness) to be measurable. The samples were measured in three directions. The measurements were done using a micrometer with 0.001 cm accuracy. The actual changes in thickness, width, and length were from 0.012 to 0.028 cm.

MODEL DEVELOPMENT

4.1 Types of Convective Mass Transfer Models

The following general type of correlation has been used to describe convective mass transfer processes for spheres inside a uniform flow.

$$Sh = Sh0 + C1\ Re^{C2}\ Sc^{C3} \qquad (2)$$

Eqn. (2) makes the predicted results consistent with experimental or theoretical value at near zero Reynolds number. Sh0 can be determined experimentally. After finding Sh0, Eqn. (2) can also be rearranged into a linear form, with the aid of a logarithmic transformation.

4.2 Exponent of Schmidt Number

There is not a constant or universally accepted value for the exponent of Schmidt number, Sc. Grafton (1963) and Garner and Suckling (1958) assumed a power of one third by correlating the forced convective mass transfer data from naphthalene spheroids. Steinberger and Treybal (1960) also built a correlation for spheres with the exponent value of one third. The value of the exponent of Schmidt number can be determined experimentally, if the data covers a wide range of Sc. Without conducting experiments with a range of Schmide number, most researchers have assigned a number of one third. The value of C3 was assumed to be one third in this study.

4.3 Exponent of Reynolds Number

The constant, C2, has been given various values ranging from about 0.4 to 0.6 in equations presented for forced convective mass transfer from rigid solids (Lochiel and Galderbank, 1964; and Evnochides and Thodos, 1961). When a laminar boundary layer exists for a sphere inside a uniform flow, a theoretical value of 0.5 would be expected. The empirical equations presented for overall mass transfer have been expressed in terms of the square root of Re (Garner and Suckling, 1958); and Ranz and Marshall, 1952). There were also other values of the exponent for Re that were reported (Steinberger and Treybal, 1960; Yuge, 1960: and Pasternak and Garvin, 1960; Beg, 1975). Rowe et al. (1965) proposed that the exponent of Re for both heat and mass transfer tended to increase with the increase of Re. In this study, the actual experimental range of Re was form 12.4 to 108.9 for spheres, and 14.8 to 90.0 for corn-like samples. The flow is a laminar flow in this work, because of the low Re. The low Re in tests might actually bring the value of the exponent of Re lower than the proposed range of 0.4 to 0.6, because of the effect for natural convection.

4.4 Parameters of Calculating Dimensionless Numbers

All the parameters related to the calculations of dimensionaless numbers are discussed in the following sections.

Based on the data given in International Critical Tables (1932) and Saboya and Sparrow (1968), the following linear model for solid naphthalene density was developed for use in this work.

$$Den = 1.1655 - 0.0007677\ T_c \qquad (3)$$

Christian and Kezios (1957) utilized the published data of kinematic viscosity for an air and naphthalene vapor mixture from 21 to 35°C. Their equation was

$$V_k = 0.1320 + 0.000942\ T_c \qquad (4)$$

Eqn. (4) is assumed to be good for the calculation of kinematic viscosity at

40°C. The extrapolated result is V_k = 0.1697 cm^2/s.

Christian and Kezios (1957) employed the semi-empirical correlation of diffusivity for a binary gases system from Gilland (1934) to the air and naphthalene vapor system. Their semi-empirical equation is

$$D = 1.2621 * 10^{-5} T_a \quad (5)$$

using this expression, for 40°C and 1 atm pressure, the value of diffusivity is 0.06994 cm^2/s.

A spherical solid has an obvious diameter which can be used to compute Sh and Re. Corn-like solids do not have any typical measurable length which can be used to compute Sh and Re directly. It becomes necessary to make an artificial diameter for calculations of Sh and Re. For this study, the diameter is defined as

$$d = (6V/pi)^{1/3} \quad (6)$$

For a uniform flow, it is easy to pick up the velocity to calculate Re. But if a confined flow is inside a relative small pipe, the flow will have a parabolic velocity is usually chosen to represent the velocity for calculation of Re. For this study, the velocity is total air flow rate divided by whole tube cross sectional area.

$$V_e = M_r/A_{tu} \quad (7)$$

The mass transfer coefficient is computed by dividing the mass change rate by the product of total transfer area and the logmean vapor concentration difference. The mass loss rate was recorded directly during the testing. The total transfer area and naphthalene vapor concentration were computed using the following procedure.

Because total transfer area could not be measured or computed directly for a corn-like solid, an indirect method is developed to quantify the tranfer area. It is similar to Henderson and Pabis (1961) assumption that the shape of a corn-like solid is assumed as a rectangular body. The toal volume change of a solid after a test is the sum of volume changes of six faces. The volume change of each face is the product of the shrinkage in normal direction and the area of the face. The total volume change is also expressed as the total transfer area times average normal change over the whole area.

$$d_l = \frac{W\,T\,d_L + W\,L\,d_T + L\,T\,d_W}{2\,(W\,T + W\,L + T\,L)} \quad (8)$$

Then the total transfer area is

$$A = d_v/d_l \quad (9)$$

This method only roughly estimates the total transfer area. However, an easy and practical way to accurately estimate the total area of an irregular body was not available.

The vapor concentration next to a naphthalene solid is considered to be in an equilibrium state with the air and solid. This equilibrium vapor concentration is considered to be the saturated vapor concentration. Gil'denblat et al. (1968) measured the saturated vapor pressure of solid naphthalene between 25 and 50°C, and presented an equation with a standard deviation of 0.033 mm-Hg as:

$$\log_{10} P_v = 11.424 - 3722.6/(T_c + 273.16) \quad (10)$$

Eqn. (10) was used in this study. The vapor pressure can be converted into vapor concentration by assuming the naphthalene vapor obeys the perfect gas law. This is generally good for low pressure gases.

$$C_s = W_e/V = P_v\, M/(R_u\, T_a) \qquad (11)$$

RESULTS AND DISCUSSION

The test results of spherical naphthalene solids were used to validate the methodology. The results of the tests were used to derive mass transfer coefficients equations in the form of Eqn. (2).

5.1 Spherical Naphthalene Solids

The results of spherical solids were compared with three selected published equations: Brian and Hales' (1969), Ranz and Marshall's (1952), and Steinberger and Treybal's (1960) models (Figure 2). The transfer coefficients, as represented by Sh, were shown to be higher than the predicted values from three proposed equations. Even though the consistency in measurements of Sh does not indicate the methodology is an accurate measurement of the transfer coefficient of a solid inside a pipe flow, the developed methodology is repeatable. Figure 2 also shows that the correlation form represents the experimental data well.

5.2 Corn-like Naphthalene Solids

The corn-like solids were not identical in their shapes and sizes. The samples weights varied within the range of 0.422 to 0.643 gm. The mass change rates, from 0.156 to 0.250 gm/min, depended on the sample size and applied air flow rate. For corn-like solids, Sh0 was determined by separate experiment and used to develop the model.

5.2.1 Sherwood Number in An Infinitely Stagnant Air (Sh0)

Two runs for each sample orientation were conducted with TGA to estimate the constant Sho. In the tests, the actual applied Re was about 0.1. If no air had been forced to pass through the testing chamber, the air inside the tube would have reached the saturated state and the process of mass transfer would have stopped. The results of Sh0 showed that the differences among various orientations were insignificant. The average value was 2.866.

The data from TGA were compared with the results from the tests inside a

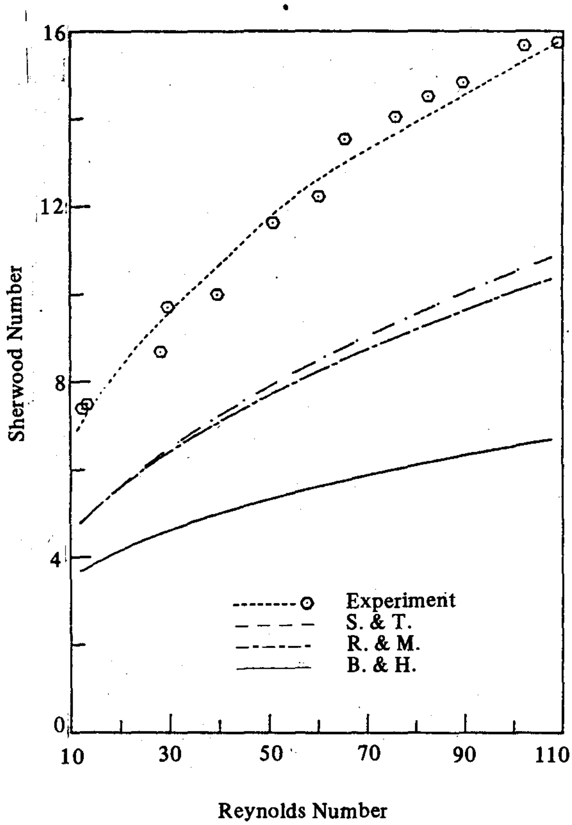

Figure 2: Experimental data of spherical solids are compared with published equations.

well sealed chamber. The data of the sealed chamber were slightly higher than the values of TGA. One possible explanation of low Sh0 for the tests with TGA is a flow with very low velocity inside the testing tube may actually restrict the occurrence of natural convection and reduce the transfer rate. The air moved downward through the tube and would partially offset the pure natural convection.

5.2.2 Four Kernel Sample Orientations

The constants of correlations in four orientations are presented in Table 1. Figures 3 to 6 show the correlations in four orientations. The values of exponents of Reynolds number (C2) are lower than the proposed range, 0.4 to 0.6. In upstream orientation, the exponent of 0.36 was slightly below the anticipated region. In the other three sample directions, the exponents of Re within the range from 0.24 to 0.3 were further below the anticipated range.

Table 1 shows that the sums of square errors and standard deviations in four orientations are not constant. However, all the standard deviations are less than 0.25. The small standard deviations imply that the correlations can predict the transfer coefficients well in all four orientations.

5.2.3 A General Equation for Four Orientations

The correlations in four orientations within the experimental Re range are shown in Figure 7. The differences among four correlations are significant especially at both ends of the experimental Re range. The upstream orientation had lower predictions at low Re and higher predicted values at high Re than the other three orientations. The predicted results in downstream direction are located between the upstream and side directions.

Table 2 lists the significant levels of F-statistics for all possible combined data sets. F-statistics for some combinations are significant at both 1 and 5 percent levels; therefore, the transfer coefficients in these orientations can be shown to be different from each other.

The constants of equations for all orientations combinations are listed in Table 2. The orientations of corn kernels corresponding to the air flow are not fixed in a deep bed corn drying process. It is improper to used the correlation of a particular sample orientation to represent the average transfer coefficient. In this study, only four sample orientations were tested. Although the differences among four orientations are significant, at this stage, the general equation derived from

Table 1.
Correleations for corn-like solids

direction	Sh0	C1	C2	C3	R	s.d.
upstream	2.866	.758	.384	.333	.927	.213
downstream	2.866	1.241	.253	.333	.893	.206
side	2.866	1.265	.236	.333	.799	.263
normal	2.866	1.118	.272	.333	.820	.278

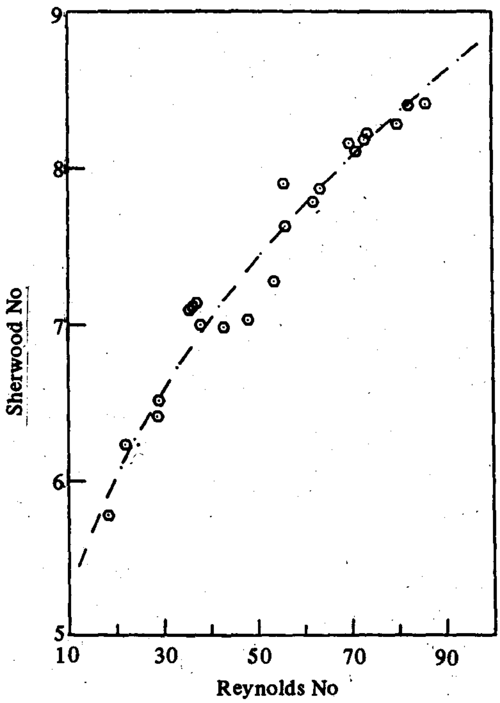

Figure 3: Correlation and experimental data of corn-like solids in upstream orientation.

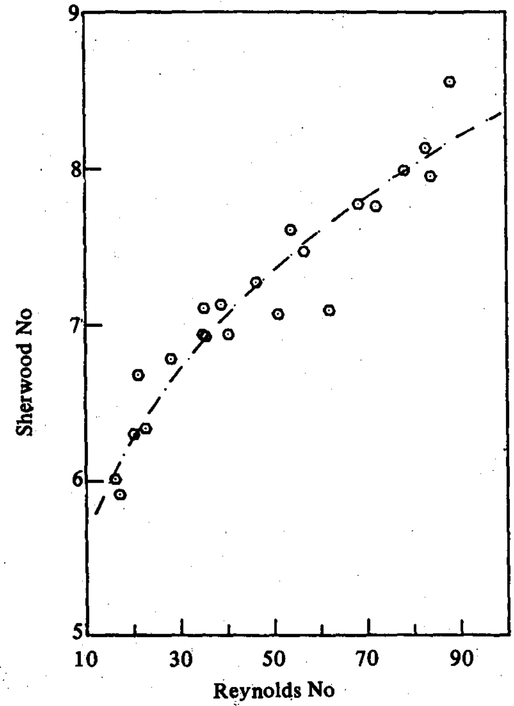

Figure 4: Correlation and experimental data of corn-like solids in downstream orientation.

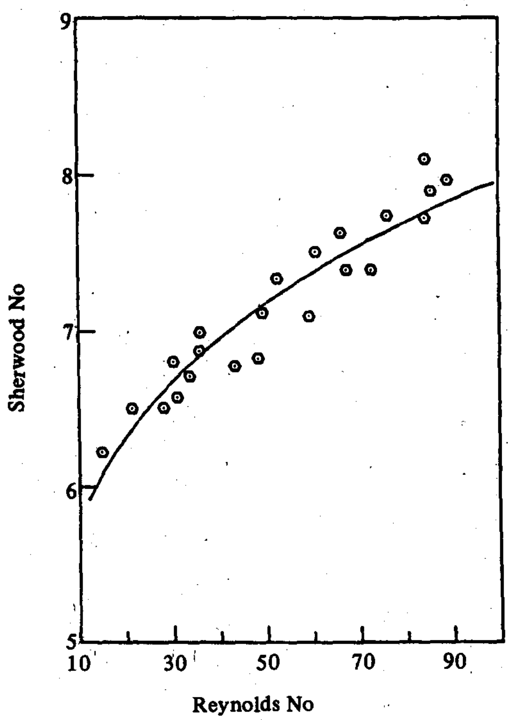

Figure 5: Correlation and experimental data of corn-like solids in side orientation.

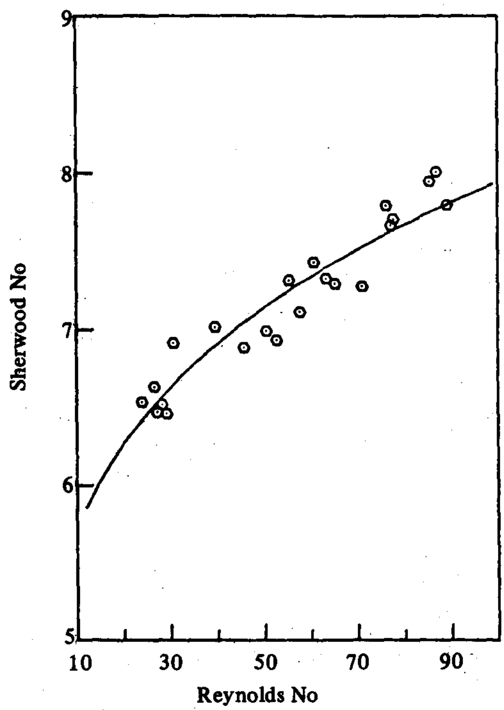

Figure 6: Correlation and experimental data of corn-like solids in normal orientation.

Table 2.
Correlations for orientations combinations

dir	Sh0	C1	C2	C3	R	s.d.	F.V.	d.f.
U+D	2.866	1.020	.307	.333	.881	.241	5.449	3, 38
U+S	2.866	1.006	.303	.333	.795	.313	10.842	3, 38
U+N	2.866	.936	.323	.333	.826	.287	6.350	3, 38
D+S	2.866	1.284	.239	.333	.813	.254	3.136	3, 38
D+N	2.866	1.228	.252	.333	.839	.241	1.662	3, 38
S+N	2.866	1.191	.254	.333	.807	.254	.482	3, 38
U+D+S	2.866	.817	.281	.333	.813	.276	6.753	6, 57
U+D+N	2.866	1.070	.291	.333	.836	.269	4.846	6, 57
U+S+N	2.866	1.044	.292	.333	.794	.298	5.651	6, 57
D+S+N	2.866	1.242	.247	.333	.814	.254	1.667	6, 57
U+D+S+N	2.866	1.119	.276	.333	.807	.271	4.670	9, 76

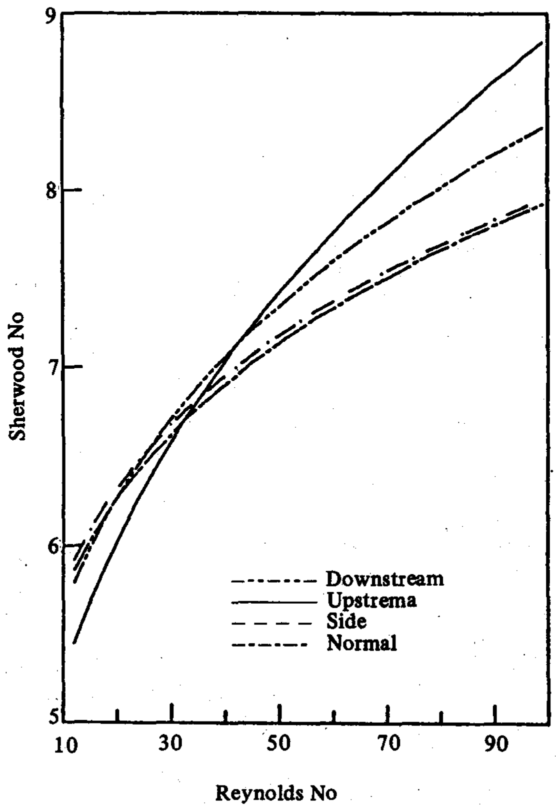

Figure 7: Correlations of corn-like solids in four orientations.

the combined data set of all four orientations is still proposed for use in deep bed drying models.

5.3 Transfer Coefficients for Corn Kernels

The primary object of this study is to derive the equations which can be used to estimate the transfer coefficients of corn kernels in a drying process. Although the equations were derived based on the experimental data of corn-like naphthalene solids, they can be applied to corn kernels. The procedures are:

1) find the kinematic viscosity and diffusivity of an air and water vapor mixture.

2) measure or assume a sample geometry and size, and the air flow rate.

3) calculate the dimensionless numbers, Re and Sc.

4) compute Sh by placing the calculated Re and Sc into the derived equations.

Fortes and Okos (1981) adopted the Ranz and Marshall's (1952) equation in their drying model for corn kernels. Because the equation was originally derived for single spheres, the effects or orientations of corn kernels were ignored by them. The general predictions equations of four orientations, as well as the Ranz and Marshall equation are presented in Figure 8. Figure 8 shows that the derived equations have higher predictions of Sh at low Re and lower Sh at high Re. The natural mass convection is the likely reason for high Sh at the low Re range. This study has been conducted only within the Re range of 15 to 90. The effect of natural convection within this relatively low and narrow range of Re yields the prediction equations having lower exponent values of Re (C2) than the proposed range of 0.4 to 0.6, therefore the derived correlations are not recommended to be used by extrapolation.

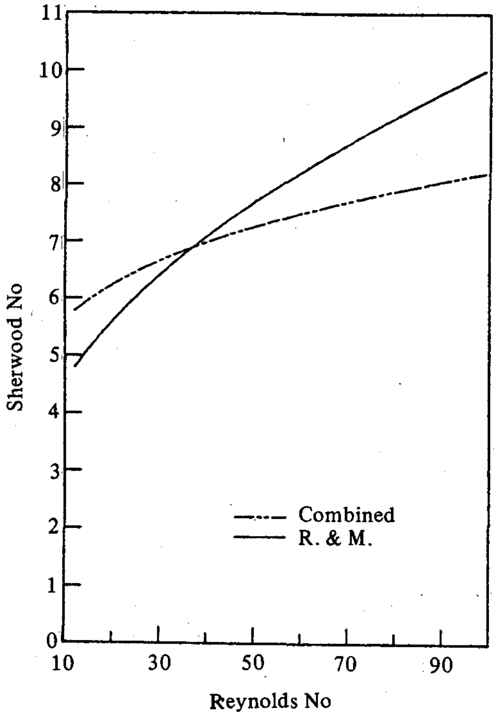

Figure 8: The general correlation of corn-like solids is compared with Ranz and Marshall's equation for spheres.

CONCLUSIONS AND RECOMMENDATIONS

A primary goal of this study was to develop a methodology to measure convective mass transfer coefficients of corn kernels in a drying process. The consistency of measurements of mass transfer coefficients for spherical samples indicated that the technique of naphthalene sublimation was a repeatable method to determine the transfer coefficient. Although the data of corn-like samples showed less consistency than the data of spherical samples, low standard deviations and high multiple correlation coefficients still strongly pointed out that this method was also good for samples with irregular shapes such as corn kernels.

This study has been devoted to measuring the convective mass transfer coefficients for corn kernels, it is evident that further studied should be conducted to emphasize the following points:

1) A methodology should be developed to determine the local transfer coefficients for solids with irregular shapes. Measurements of local transfer coefficients can be integration over the whole transfer area, and should then be compared with the experimental average value.

2) The experimental mass transfer coefficients should be further validated by heat transfer experiment using the transport analogy between heat and mass transfer. A heat transfer coefficient can be converted into a mass transfer coefficient. The transport analogy of J-factor is most commonly used.

3) The experimental devices should be further modified in order to conduct the experiments with the Re range higher than 90.

NOMENCLATURES

- A : sample total transfer area, cm^2
- A_{tu} : tube cross sectional area, cm^2
- C_{lm} : logmean vapor concentration, gm/cm^3
- C_s : surface vapor concentration, gm/cm^3
- D : diffusivity, cm^2/s
- d : diameter, cm
- Den : density, gm/cm^3
- d_L : length difference in a test, cm
- d_l : average normal shrinkage on sample surface, cm
- d_T : thickness difference in a test, cm
- d_v : volume change, cm^3
- d_w : width difference in a test, cm
- h_m : transfer coefficient, cm/s
- L : length, cm
- M : molecular weight, kg/kg mole
- M′ : total mass transfer rate, gm/s
- M_r : volumetric flow rate, cm^3/s
- P_v : pressure, atm (or mm-Hg)
- R_u : universal gas constant, 8314.34 : m^3 pa/kgmole K
- T : thickness, cm
- T_a : absolute temperature, K
- T_c : temperature, C
- V : volume, cm^3
- V_e : fluid velocity, cm/s
- V_k : kinematic viscosity, cm^2/s
- W : width, cm
- W_e : weight, gm

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