

Study of Solid Dissolution Using the Rotating Disk Technique

Mass Transfer Coefficient

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The paper presents results from solids dissolution study using the rotating disk technique. The influence of three parameters (dissolution medium temperature, solute concentration in solution and the disk rotation speed) over the mass transfer was studied. From experimental results a correlation has been proposed between numbers Sherwood, Schmidt and Reynolds that is similar to that of Levich.

Keywords: solid dissolution, rotating disk technique, mass transfer coefficient

Dissolution of solid in liquid phase is an important step in chemical and electrochemical processes, mineral processing, agriculture, pharmaceuticals, environmental protection, and so on [1-11]. It is important to know the mechanism and kinetics of dissolution, the influence of several factors on the dissolution for both the smooth running of dissolution processes and for designing appropriate equipment [1, 3, 14, 15].

The solid dissolution in liquids is complex and takes place in several successive stages, two of which are most important: the passage of solute molecules from the solid in solution and the transfer of the separated molecules toward the bulk liquid phase [16-19]. In most cases, the second step determines the dissolution rate. The process is influenced by a number of factors that characterize properties of the solvent and solute and working conditions.

To study the dissolution of solids in liquids various techniques were used (the rotating/stationary disk, dissolution in agitated vessel, dissolution in fixed and fluidized beds with or without inert) and models of mass transfer were proposed [20-22].

The rotating disk technique is frequently used for the study of solids dissolution since it considers a single flow type, the hydrodynamic parameters can be easily controlled and the mass transfer surface does not vary [21-26].

For the mass transfer in the dissolution of the solid by rotating disk technique the mathematical model was derived by Levich [24]:

$$J = 0.62 \cdot D^{2/3} \cdot \nu^{-1/6} \cdot \omega^{1/2} \cdot (C_s - C_b) \quad (1)$$

where:

- J - is the flux of the solute, [kg m⁻² s⁻¹];
- D - diffusion coefficient of the solute, [m² s⁻¹];
- ν - kinematic viscosity of the dissolution medium, [m² s⁻¹];
- ω - angular speed of the disk, [s⁻¹];
- C_s - solute concentration at the solid surface (assumed to be equal to solid solubility in the dissolution medium), [kg m⁻³];
- C_b - solute concentration in the bulk solution, [kg m⁻³].

The Levich model is available for the dissolution of the solid controlled by the transport through the boundary layer from the solid surface, in the laminar flow regime, for the constant mass transfer surface area and the large volume of dissolution medium (sink condition).

In order to keep laminar flow conditions on the disk surface and sink conditions some restrictions must be satisfied:

$$Re = \frac{d^2 \cdot \omega}{\nu} < 2 \cdot 10^5 \quad \text{and} \quad C_b < 10\% C_s$$

where:

- d - disk diameter, [m];
- ω - angular speed of the disk, [s⁻¹];
- ν - kinematic viscosity of the dissolution medium, [m² s⁻¹];
- C_s - solute concentration at the solid surface (assumed to be equal to solid solubility in the dissolution medium), [kg m⁻³];
- C_b - solute concentration in the bulk solution, [kg m⁻³].

The value of the mass transfer coefficient from Levich's model is:

$$k = 0.62 \cdot D^{2/3} \cdot \nu^{-1/6} \cdot \omega^{1/2} \quad (2)$$

where:

- k - mass transfer coefficient, [m · s⁻¹];
 - D - diffusion coefficient of the solute, [m² · s⁻¹].
- For the solid dissolution using rotating disc technique, Levich established a relationship that correlate the Sherwood, Reynolds and Schmidt numbers:

$$Sh = 1.55 \cdot Re^{0.5} \cdot Sc^{0.33} \quad (3)$$

where:

- $Sh = \frac{k \cdot d}{D}$ - Sherwood number;
- $Re = \frac{n \cdot d^2}{\nu}$ - Reynolds number;
- $Sc = \frac{\nu}{D}$ - Schmidt number;
- n - rotating speed of the disc, [rot s⁻¹].

The objectives of the current work are to study the dissolution of urea in distilled water and in aqueous solution of the solute, to investigate the influences of various parameters (temperature, rotating speed of the disk, nature of the dissolution medium) on the mass transfer coefficients and to compare the experimental results with calculated values based on existing models in the literature.

Experimental part

Studies of solid dissolution using the rotating disk technique were carried out in an experimental installation (fig. 1) consisting of: jacketed vessel of 1500 mL volume,

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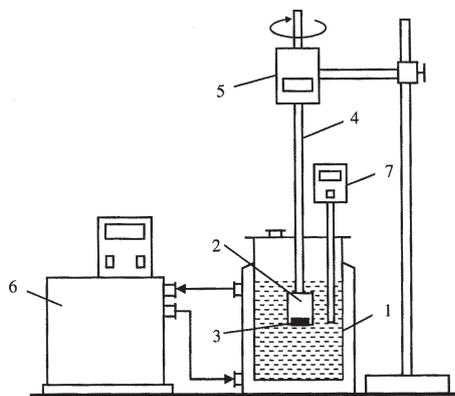


Fig. 1. Schematic of experimental setup for dissolution studies: 1-jacketed vessel; 2-rotary device; 3-solid sample; 4-rotating shaft; 5-electrical motor; 6-thermostat; 7 - digital thermometer

rotary device with the study sample, stirring mechanism with a shaft which fixates the cylindrical device, electrical motor with variable speed, thermostat, digital thermometer.

Experimental determinations have been made using urea as solute. A test disk with a diameter of 20 mm was used in the measurements. The disk-shaped samples were made by pressing the powdered urea in the die of the cylindrical device at 250 MPa using a laboratory press type PIKE CrushIR. The cylindrical device was attached to the shaft of a stirring mechanism VELP SCIENTIFICA type DLS VELP and immersed in solvent; only the bottom face of the disc was exposed to the dissolution medium.

In the solid dissolution, the effects of three parameters were investigated: rotating speed of the disc, temperature and the dissolution medium. The parameters used in the present study are given in table 1.

During each experiment, the temperature has been kept constant with hot water circulating in the vessel jacket. The sample temperature was measured with a digital thermometer placed in the vessel. The duration of the experiments was measured with a digital chronometer.

The amount of dissolved substance was determined by sample weighted before and after each experiment with an analytical balance (0.1 mg accuracy). The surface of solute disc in contact with the dissolution medium, A , was considered constant.

Results and discussions

The experimental values of the mass transfer coefficients were determined from the mass transfer equation:

$$\Delta m = k \cdot A \cdot (C^* - C) \cdot \Delta t \quad (4)$$

where:

Δm -amount of dissolved substance, [kg];

k - mass transfer coefficient, [m s^{-1}]; A - contact surface, [m^2];

$\Delta C = C^* - C$ - concentration gradient across the diffusion layer, [kg m^{-3}];

Δt - dissolution time, [s].

The effect of rotating speed of the disk on the mass transfer coefficient for urea dissolution in distilled water and in solutions with 40 g urea at 100 g water at different temperatures of the dissolution medium is given in figures 2 and 3. Similar variations were obtained for urea dissolution in solutions with 30 g urea at 100 g water.

It can be seen in these figures that the mass transfer coefficient increases with increasing of the rotating speed of the disk both in urea- water system and in urea-solution system. This result was expected because increasing the rotating speed of the disk reduces the thickness of the

Table 1
PARAMETERS OF INTEREST FOR THE SOLID DISSOLUTION BY ROTATING DISC METHOD

Solute	Rotating speed of the disc, [rot min^{-1}]	Temperature, [$^{\circ}\text{C}$]	Dissolution medium
Urea	100; 200; 300; 400	25; 30; 35; 40	distilled water aqueous solution of urea: - 30 g urea/100 g water - 40 g urea/100 g water

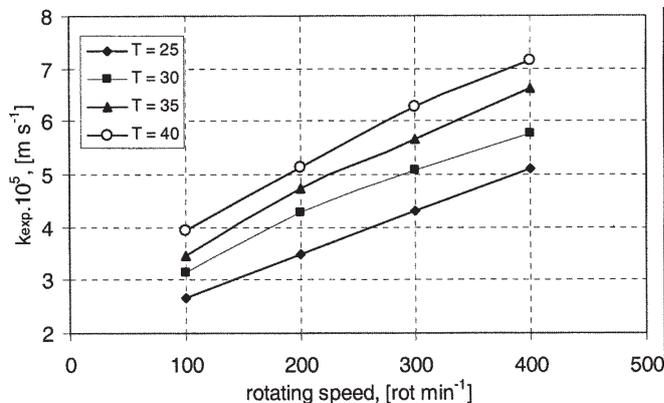


Fig.2. The influence of rotating speed of the disk on mass transfer coefficient at urea dissolution in distilled water

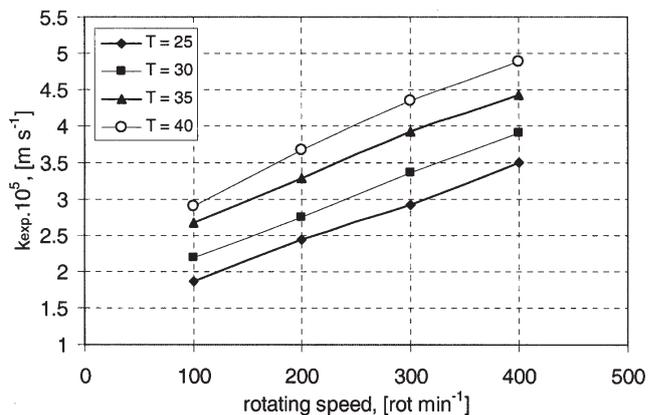


Fig. 3. Influence of rotating speed of the disk on mass transfer coefficient at urea dissolution in solution with 40g urea at 100 g water

boundary layer and enhances the transfer of the solute in bulk solution in accordance with literature [24].

Also, in figures 2 and 3, is observed that the mass transfer coefficient increases with increasing temperature. The temperature increasing causes an increase of the urea solubility and of the diffusion coefficient of the solute and a decrease of the viscosity of the dissolution medium.

Figure 4 represents the mass transfer coefficient for urea dissolution in distilled water and in aqueous solutions of urea at 25 $^{\circ}\text{C}$ and we can see that the dissolution proceeds more rapidly in water than in solution.

The existence of solute in solution reduces the dissolution rate due to the decrease of the concentration gradient and mass transfer coefficient is lower [27, 28]. When dissolving urea in water and sink conditions are met, the concentration gradient is equal to the solubility while dissolving urea in solution concentration gradient is even lower as the concentration of the solution is higher.

Similar variations were obtained for urea dissolution at other temperatures.

According to equation 2, plotting mass transfer coefficient versus square root of angular speed yields information about the governing mechanism for solute

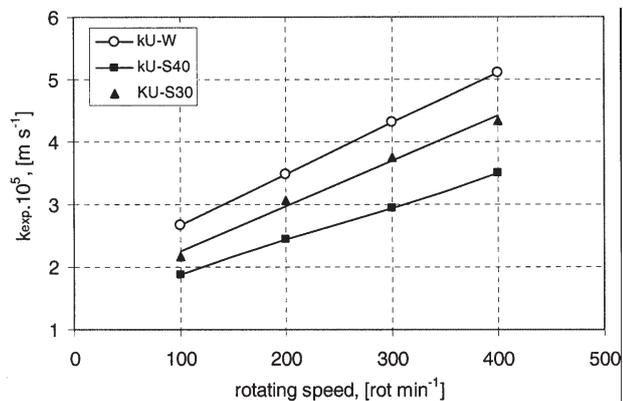


Fig. 4. The influence of the dissolution medium on mass transfer coefficient at urea dissolution in distilled water (U-W) and in solution with 30 g urea at 100 g water (U-S30) and 40 g urea at 100 g water (U-S40).

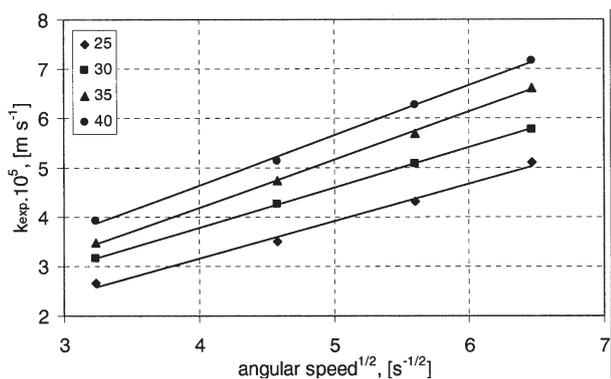


Fig. 5. The mass transfer coefficient vs. square root of angular speed for urea- distilled water system

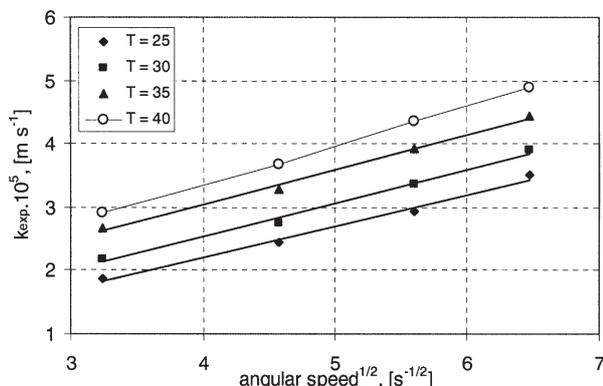


Fig. 6. Mass transfer coefficient vs. square root of angular speed for urea- solution system (40 g urea/100 g water)

dissolution. In figures 5 and 6 the dependencies for urea-water and urea-solution systems are presented as a function of square root of angular speed. The linear dependence demonstrates mass transfer control in all cases, in accordance with Levich equation.

The concordance between experimental values of the mass transfer coefficients and theoretical values from Levich model (eq. 3) is presented in figure 7. The solid diagonal line represents a perfect correlation between calculated and experimental mass transfer coefficients.

For urea - distilled water systems, at temperatures higher than 25°C, the experimental values of mass transfer coefficients exceed the theoretical ones. The reason for this behaviour may be the erosion roughness that occurs on the surface of disc which makes the effective area to be greater than the geometric area. This behaviour has been observed in other studies of dissolution [2, 25, 29, 30].

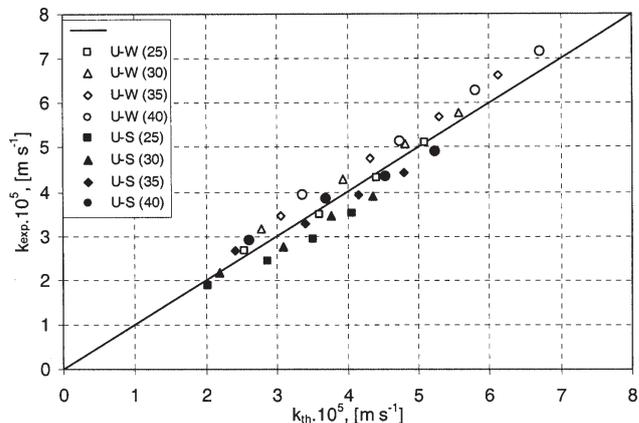


Fig. 7. Experimental versus theoretical mass transfer coefficient for urea-distilled water and urea- solution systems (40 g urea/100 g water).

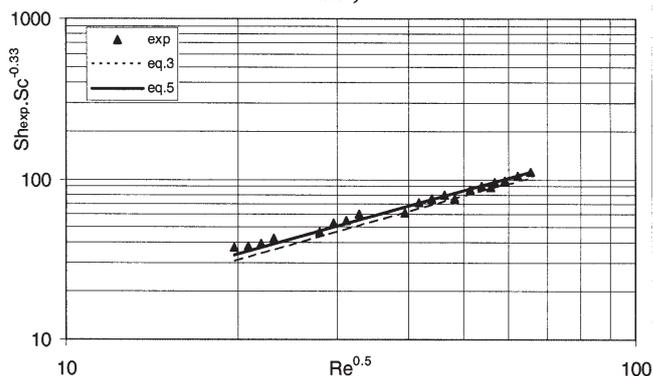


Fig. 8. Effect of the Reynolds number on the Sherwood number for urea dissolution in distilled water

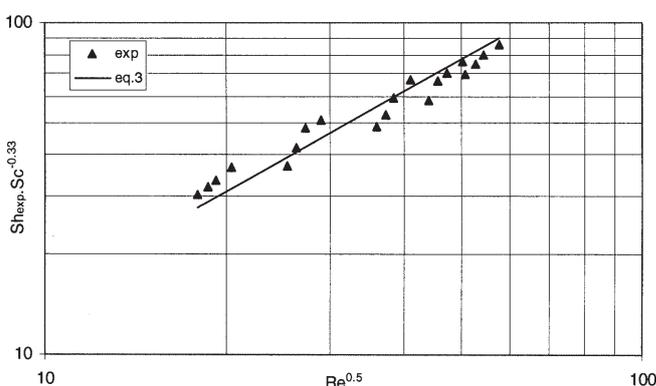


Fig. 9. Effect of the Reynolds number on the Sherwood number for urea dissolution in aqueous solution of urea (40 g urea to 100 g water)

In the case of urea dissolution in aqueous solution of urea, the experimental values of the mass transfer coefficient are lower than the theoretical values which can be explained by the high values of solute concentration in the dissolution medium ($C_b > 10\% C_s$). Moreover, Skinner shows that if the solute concentration in the dissolution medium exceeds sink conditions such differences may occur [30].

In order to establish the effect of the Reynolds number on mass transfer coefficients, the experimental data are presented in figures 8 and 9 using dimensionless numbers.

The Reynolds, Schmidt and Sherwood numbers were calculated for urea dissolution in distilled water and urea solutions (the diameter of the discs 20 mm) for the parameters from table 1. The urea solubility and physical constants of the dissolution medium were taken from literature [31, 32].

Figures 8 and 9 demonstrate that, the Reynolds number increase determines an increase in the Sherwood number.

From the Levich model (eq. 3) and with experimental results, was derived a relationship for the urea dissolution in distilled water (eq. 5):

$$Sh = 1.7 \cdot Re^{0.5} \cdot Sc^{0.33} \quad (5)$$

Relationship (5) differs from the Levich equation (3) only by the value of the numeric coefficient.

The concordance between the experimental values and the calculated values from equations 3 and 5 are presented in figure 8.

The difference between the experimental and calculated values of the Sherwood number with equation 5 is less than 10% for approximately 95% of data while the concordance with the Levich model is poor.

In case of the dissolution of urea in concentrated solutions of urea the difference between experimental values of the Sherwood number and those calculated from the Levich model is significant because one condition of the model is not respected (sink conditions).

Conclusions

The rotating disc technique was used to investigate the dissolution of urea in distilled water and in aqueous solutions of urea as a function of the rotating speed of the disc, temperature and dissolution medium.

The dissolution was found to be controlled by diffusion through boundary layer in all cases.

The mass transfer coefficient has been positively influenced by the increase of the rotating speed of the disc and of the temperature.

The urea dissolution proceeds more rapidly in water than in solution because, in the first case, the gradient of the concentration is high.

From the experimentally values of the mass transfer coefficient for urea dissolution in distilled water was proposed a relationship using dimensionless numbers. The agreement between the experimental values and those calculated from the relationship proposed is very good while the concordance with calculated values from Levich equation is only satisfactory.

The experimentally values of the mass transfer coefficient for urea dissolution in concentrated solutions are not in agreement with the calculated values from Levich model.

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