

INFLUENCE OF VERTICAL DISTRIBUTION OF ABSORBATE IN A GASEOUS PHASE ON GAS ABSORPTION BY FALLING LIQUID DROPLET

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ABSTRACT

In this study we analyze mass transfer during gas absorption by a falling droplet with internal circulation which is caused by interfacial shear stresses. It is assumed that the gaseous phase consists of soluble and inert gases, and concentration of absorbate in the gaseous phase varies in a vertical direction. In the analysis we accounted for the accumulation of absorbate in the bulk of the droplet. The problem is solved in the approximation of a thin concentration boundary layer in the dispersed and continuous phases. The bulk of a droplet, beyond the diffusion boundary layer, is completely mixed, and concentration of absorbate is homogeneous and time-dependent in the bulk. By combining the generalized similarity transformation method with Duhamel's theorem, the system of transient conjugate equations of convective diffusion for absorbate transport in liquid and gaseous phases with time-dependent boundary conditions is reduced to a linear convolution Volterra integral equation of the second kind which is solved numerically. It is shown that non uniform vertical distribution of absorbate in a gaseous phase strongly affects mass transfer during gas absorption by a falling droplet.

INTRODUCTION

Gas absorption by falling liquid droplets is of relevance in chemical engineering, refrigeration, air pollution control and environmental engineering. The typical example are droplet sprays used for controlling air pollutants emission. Non uniform vertical distribution of absorbate in spray absorbers is formed due to different rates of gas absorption by droplets at the entrance of the absorber and at the exit of the absorber. Spray absorption and spray absorber design and analysis attracted considerable attention in recent years because of higher contact surfaces per unit volume and higher rates of mass transfer in spray absorbers in comparison with conventional falling film absorbers. The simplicity of the spray absorber design and the low price of the absorption chamber promise essential reduction of spray absorber price in comparison with a conventional falling film absorber.

Concentration measurements of CO_2 , SO_2 , NH_3 and other gases in the atmospheric boundary layer revealed vertical (altitudinal) dependence of the concentrations [1–5]. Concentration of gases, not associated with photosynthesis, e.g. SO_2 and NH_3 , has maximum at the Earth surface and decreases with height over the continents. The concentration of NH_3 over the continents decreases rapidly with altitude, reaching a constant background concentration in winter days about 1500 m above the ground, on warm days at about 3000 m above the ground [2, 4]. On warm days ground concentration of NH_3 is considerably higher than on cold days. Sulfur dioxide concentration in a ABL (atmospheric boundary layer) is higher during winter than during summer because of higher anthropogenic SO_2 production. In contrast

to concentrations of SO_2 and NH_3 over the continents, the profiles of concentration of these gases over an ocean have minimum at the ocean surface. This phenomenon is explained by a high solubility of SO_2 and NH_3 in a sea water whereby ocean acts as a sink of soluble gases [2, 4]. Diurnal and seasonal variations of CO_2 distribution with altitude occur due to competition between different phenomena, e.g. photosynthesis, respiration and thermally driven buoyant mixing [6–8]. During growing season over the continents concentration of CO_2 early in the morning at the ground is very high and sometimes reaches a value of 400 ppmv due to nocturnal CO_2 release by soil microbes and other biota. Concentration of CO_2 before the sunrise has a pronounced maximum at the surface, rapidly decreases with height, and the magnitude of the gradients of concentration is of the order of 10 ppmv/km. When the sun rises, the concentration of carbon dioxide at the surface decreases because the uptake of CO_2 due to photosynthesis exceeds the release of CO_2 due to respiration. Note that photosynthesis and thermally driven buoyant convection in the atmosphere are driven by solar radiation and have the same diurnal frequencies [7]. Photosynthesis and vertical mixing by convection act to decrease CO_2 in the lowermost part of the CO_2 profile. Joint influence of these two mechanisms results in the vertical distribution of CO_2 with minimum at the ground and increase of concentration with height. Minimum of CO_2 concentration at the ground is most pronounced in the afternoon [6]. Uptake of carbon dioxide due to photosynthesis decreases slowly in the evening and ceases approximately at the sunset. Correspondingly, from the afternoon to the sunset,

the distribution of CO_2 concentration undergoes a change from increasing with height to decreasing with height [3]. After the sunset the surface uptake of CO_2 by vegetation ceases, and soil/plant respirations once again enriches the surface layer with CO_2 . The CO_2 concentration near the ground steadily increases from the sunset till the next sunrise. The fluxes of CO_2 due to photosynthesis and respiration are by one order of magnitude larger than the fluxes resulting from the anthropogenic emissions. During dormant season the release of CO_2 due to respiration exceeds the uptake of CO_2 due to photosynthesis and vertical mixing by convection weakens. These processes produce profile with higher CO_2 concentration at the surface and lower concentration aloft over the land. Distribution of concentration with minimum of CO_2 at the ground is impossible during dormant season.

Information about the evolution of vertical CO_2 profile with time allows calculating CO_2 fluxes in a ABL. Vertical transport of CO_2 in ABL is an integral part of atmospheric CO_2 transport and is important in understanding the global CO_2 distribution pattern. An improved understanding of the CO_2 cycle is essential for the analysis of global climate change. Clouds and rains play essential role in vertical redistribution of CO_2 and other solvable gases in the atmosphere. Scavenging of solvable gases, e.g. SO_2 , NH_3 and CO_2 , by rains and clouds contribute to the evolution of vertical distribution of these gases. At the same time the existence of vertical gradients of solvable gases in the atmosphere affects the rate of gas absorption by rain droplets. Note that the existing models of global transport in the atmosphere (see, e.g. [6, 8]) do not take into account influence of rains on biogeochemical cycles of different gases.

Due to differences in solubility of gases in liquids, mass transfer during absorption of soluble gas by droplets in the presence of inert admixture can be continuous-phase controlled, liquid phase controlled or conjugate. Continuous-phase controlled mass transfer by falling droplets was discussed in [9–12]. Liquid-phase controlled mass transfer was studied, e.g., in [13–14]. Mass transfer controlled by both phases was analyzed in [15–19].

Accumulation of the dissolved atmospheric gases in a falling water droplet during absorption taking into account vertical distribution of the absorbate concentration in a gaseous phase and circulation of liquid inside a droplet caused by shear stresses at the interface, can be determined by solving a conjugate problem of unsteady convective diffusion with time-dependent boundary conditions. Analytical solution of this problem requires application of more sophisticated methods in the theory of heat and mass transfer (see, e.g. [20–21]). In all previous studies mass transfer during gas absorption by falling liquid droplets was investigated for homogeneous distribution of absorbate in a gaseous phase. In this study we investigate the influence of the absorbate inhomogeneity in a vertical direction in a gaseous phase on the rate of gas absorption by falling droplets. The suggested approach involves application of the generalized similarity transformation to a system of nonstationary equations of convective diffusion and a Duhamel's theorem. The problem

is reduced to a numerical solution of a linear convolution Volterra integral equation of the second kind.

DESCRIPTION OF THE MODEL

Consider absorption of a soluble gas from a mixture containing an inert gas by a moving droplet. At time $t = 0$ the droplet begins to absorb gas from a host medium occupying a large volume as compared with the droplet's volume. Distribution of the concentration of absorbate in the gaseous phase in the vertical direction is assumed to be known (see Fig. 1).

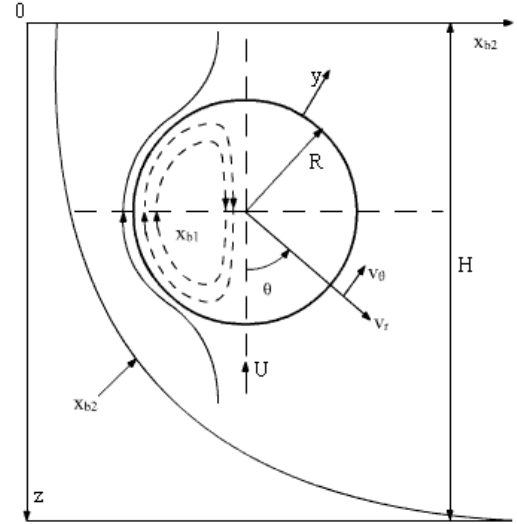


Fig. 1 Schematic view of a falling droplet

In the analysis we account for the resistance to mass transfer in both phases and employ the approximation of the infinite dilution of the absorbate in the absorbent. The thermodynamic parameters of the system are assumed constant. Convective diffusion is determined by fluid velocity at the droplet's surface. The thicknesses of the diffusion boundary layers in both phases are assumed small compared with the droplet's size, and tangential molecular mass transfer rate along the surface of a spherical droplet is assumed small compared with a molecular mass transfer rates in the normal direction. The bulk of a droplet, beyond the diffusion boundary layer, is completely mixed and concentration of absorbate is homogeneous in the bulk. The assumptions about the circulation inside a droplet and that the droplet has a spherical shape are valid in the following ranges of the falling in air water droplet radii, Reynolds numbers and velocities: $0.1 \text{ mm} \leq R \leq 0.5 \text{ mm}$, $10 \leq \text{Re} \leq 300$ and $0.7 \leq U \leq 4.5$

$(\text{m} \cdot \text{s}^{-1})$. Effects of turbulent diffusion and turbulent flow in the air must be taken into account for droplets with $R > 0.8 \text{ mm}$ [13], and they are neglected in the present study. Analysis of fluid flow around a moving droplet showed that at different Reynolds numbers the tangential and radial fluid velocity components in the vicinity of a gas-liquid interface can be approximated by the following equations (see, e.g. [22], p. 392):

$$v_\theta = -kU \sin \theta, \quad v_r = \frac{2kU}{R} y \cos \theta, \quad (1)$$

where coefficient k is equal to 0.04 in the range of the external flow Reynolds numbers ($Re = 2UR\rho_2 / \mu_2$) from 10 to 300 (see, e.g., [22], p. 386). Equations (1) are valid for $y \ll R$. The dependence of the terminal fall velocity of liquid droplets on their diameter is presented in [22]. Following the approach suggested in [21] we arrive at the transient equations of convective diffusion for the liquid and gaseous phases which account for convection in radial and tangential directions:

$$\frac{\partial X_i}{\partial \tau_i} + Pe_i \left\{ -\sin \theta \frac{\partial X_i}{\partial \theta} + 2Y \cos \theta \frac{\partial X_i}{\partial Y} \right\} = \frac{\partial^2 X_i}{\partial Y^2}, \quad (2)$$

where $i=1,2$. Equations (2) are written in a frame attached to the falling droplet. Since the velocity of the droplet fall is known and $z = U \cdot t$, the vertical coordinate-dependent boundary conditions can be transformed to time-dependent boundary conditions. The vertical coordinate z is aligned with the direction of the droplet fall. The initial and boundary conditions to Eqs. (2) read:

$$X_2 = X_{b2}(\tau_2) \quad \text{as } Y \rightarrow \infty, \quad (3)$$

$$X_1 = X_{b1}(\tau_1) \quad \text{as } Y \rightarrow -\infty, \quad (4)$$

$$X_1 = mX_2 \quad \text{at } Y = 0, \quad (5)$$

$$N_1 = N_2 \quad \text{at } Y = 0, \quad (6)$$

$$\text{where } N_i = -D_i C_i \frac{\partial x_i}{\partial y}, \quad X_{b1}(\tau_1) = \frac{x_{b1}(t) - mx_{b20}}{x_{b10} - mx_{b20}},$$

$$X_{b2}(\tau_2) = \frac{x_{b2}(t) - x_{b20}}{x_{b10} - mx_{b20}}, \quad y = r - R, \quad y \ll R$$

$$X_1 = \frac{x_1 - mx_{b20}}{x_{b10} - mx_{b20}}, \quad X_2 = \frac{x_2 - x_{b20}}{x_{b10} - mx_{b20}},$$

$$Pe_i = \frac{RkU}{D_i}, \quad Y=y/R, \quad \tau_i = \frac{tD_i}{R^2} \quad \text{and coefficient } m \text{ is a}$$

dimensionless Henry constant that characterizes the solubility of gases in liquids. The equations of convective diffusion (2) describe the change in concentration near the gas-droplet interface inside and outside the droplet. The solution can be obtained using of a similarity transformation [21].

METHOD OF SOLUTION

Since the boundary conditions (3)–(4) to Eq. (2) are functions of time, the solution can be found by combining the similarity transformation method with Duhamel's theorem. Equations (2) are solved by assuming first that the concentration of the absorbate in the bulk of the liquid phase in Eqs. (3)–(4) is constant. Let us introduce the following self-similar variables [21]:

$$\eta_i = \frac{y}{\delta_i(t, \theta)} = \frac{Y}{\Delta_i}. \quad (7)$$

Variables η_i allow us to transform a system of partial differential equations (2) into a system of ordinary differential equations:

$$\frac{d^2 X_i}{d\eta_i^2} + 2\eta_i \frac{dX_i}{d\eta_i} = 0, \quad (8)$$

where

$$\Delta_i^2 = \frac{4}{Pe_i \sin^4(\theta)} \times$$

$$\left\{ \cos(\theta) - \frac{1}{3} \cos^3(\theta) - \left[\frac{1-f(\theta, T)}{1+f(\theta, T)} - \frac{1}{3} \left(\frac{1-f(\theta, T)}{1+f(\theta, T)} \right)^3 \right] \right\}, \quad (9)$$

$f(\theta, T) = \text{tg}^2\left(\frac{\theta}{2}\right) \exp(2T)$ and $T = Pe_i \tau_i = tUk/R$ is a dimensionless time. Boundary conditions for Eqs. (8) read:

$$X_2 = X_{b2}(T) \quad \text{as } \eta_2 \rightarrow \infty, \quad (10)$$

$$X_1 = X_{b1}(T) \quad \text{as } \eta_1 \rightarrow -\infty, \quad (11)$$

$$X_1 = mX_2 \quad \text{at } \eta_1 = \eta_2 = 0, \quad (12)$$

$$N_1 = N_2 \quad \text{at } \eta_1 = \eta_2 = 0, \quad (13)$$

where $N_i = -D_i C_i \frac{\partial x_i}{\partial y}$. Solutions of Eqs. (8), \bar{x}_i , with a constant boundary conditions at $y \rightarrow \pm\infty$ read:

$$\bar{x}_1 = A_1 \text{erf}|\eta_1| + A_2 \quad (14)$$

$$\bar{x}_2 = A_3 \text{erf}(\eta_2) + A_4, \quad (15)$$

where $A_1, A_2, A_3,$ and A_4 are constants of integration. Substituting Eqs. (14)–(15) into boundary conditions (10)–(13) and assuming that x_{b1} and x_{b2} are independent of time, allows us to determine the constants of integration:

$$A_1 = \frac{x_{b1} - mx_{b2}}{1 + \gamma m D}, \quad A_2 = \frac{mx_{b2} + x_{b1} \gamma m D}{1 + \gamma m D},$$

$$A_3 = \frac{\gamma D [mx_{b2} - x_{b1}]}{1 + \gamma m D}, \quad A_4 = \frac{x_{b2} + x_{b1} \gamma D}{1 + \gamma m D}.$$

Applying Duhamel's theorem to Eqs. (14) and (15) yields a solution of Eqs. (2) with time-dependent boundary conditions at the infinity:

$$x_1(Y, \theta, T) = \frac{\partial}{\partial T} \int_0^T \left[x_{b1}(\lambda) - \frac{x_{b1}(\lambda) - mx_{b2}(\lambda)}{1 + m\gamma D} \text{erfc}\left(\frac{Y}{\Delta_1(\theta, T - \lambda)}\right) \right] d\lambda \quad (16)$$

$$x_2(Y, \theta, T) = \frac{\partial}{\partial T} \int_0^T \left[x_{b2}(\lambda) - \frac{(x_{b1}(\lambda) - mx_{b2}(\lambda))}{(1+m\gamma D)(\gamma D)^{-1}} \operatorname{erfc} \left(\frac{Y}{\Delta_1(\theta, T-\lambda)} \right) \right] d\lambda \quad (17)$$

The variable x_{b1} is an unknown function of time which can be determined by means of an integral material balance over the droplet [23]:

$$-VC_1 \frac{dx_{b1}}{dt} = 2\pi R^2 \int_0^\pi N_1|_{Y=0} \sin \theta d\theta. \quad (18)$$

Substituting expression for the absorbate concentration in the droplet (Eq. 16) into Eq. (18) yields:

$$X_{b1}(T) = 1 + K \int_0^T [X_{b1}(\lambda) - mX_{b2}(\lambda)] \int_0^\pi \frac{\sin \theta}{\Delta_1(\theta, T-\lambda)} d\lambda, \quad (19)$$

$$\text{where } K = \frac{3}{Pe_1 \sqrt{\pi(1+m\gamma D)}}, \quad Pe_1 = \frac{UkR}{D_1}.$$

Eq. (19) is a linear convolution Volterra integral equation of the second kind. For the linear vertical distribution of absorbate in the atmosphere or in absorber:

$$x_{b2} = x_{b20} + \operatorname{grad} x_{b2} \cdot z, \quad (20)$$

where x_{b200} - concentration of an absorbate at the ground or at an outlet, x_{b20} - concentration of an absorbate at the height H from the ground, or at an inlet, z is directed from the cloud to the ground or from the inlet to the outlet, $\operatorname{grad} x_{b2} = (x_{b200} - x_{b20})/H$ and $z = U \cdot t$. Since the droplet falls with a constant velocity U , Eqs. (19) and (20) yield the following integral equation:

$$X_{b1}(T) = 1 + K \int_0^T [X_{b1}(\lambda) - B \cdot \lambda] \int_0^\pi \frac{\sin \theta \cdot d\theta}{\Delta_1(\theta, T-\lambda)} d\lambda, \quad (21)$$

where $B = \frac{m(x_{200} - x_{20})R}{(x_{10} - mx_{b20})k \cdot H}$. Eq. (19) can be written

in the following form:

$$f(T) = \int_0^T f(\lambda)K(T, \lambda) d\lambda + g(T). \quad (22)$$

After discretization on a uniform mesh with an increment h and using trapezoidal integration rule Eq. (22) can be reduced to a system of linear algebraic equations with a triangular matrix:

$$f(0) = g(0),$$

$$(1 - 0.5h \cdot K_{i,i}) \cdot f_i = h(0.5K_{i,0} + \sum_{j=1}^{i-1} K_{ij} \cdot f_j) + g_i, \quad (23)$$

where $i=1, \dots, N$, $f_i = f(i \cdot h)$, $g_i = g(i \cdot h)$, $K_{ij} = K(i \cdot h, j \cdot h)$.

In order to solve the system of equations (23) it is required to calculate $N^2/2$ values of the kernel K_{ij} . Since $K(T, \lambda) = K(T-\lambda)$, $K_{ij} = K((i-j) \cdot h)$ and, consequently, $K_{i+1,j} = K((i+1-j) \cdot h) = K((i-(j-1)) \cdot h) = K_{i,j-1}$.

Therefore at each time step, i , it is necessary to calculate only one value of the kernel K_{i0} because all the other values were already determined: $K_{i,1} = K_{i-1,0}$, $K_{i,2} = K_{i-1,1}$.

RESULTS AND DISCUSSION

Results of numerical solution of Eq. (21) with linear altitude distribution of concentration of carbon dioxide in a gaseous phase are presented in Fig. 2 and Fig. 3. Calculations are performed for negligibly small initial concentration of the dissolved gas in a droplet. We compared the results obtained using the model of gas absorption in the case of uniform distribution of soluble gases in a gaseous phase with those obtained when concentration of soluble gases varies with altitude.

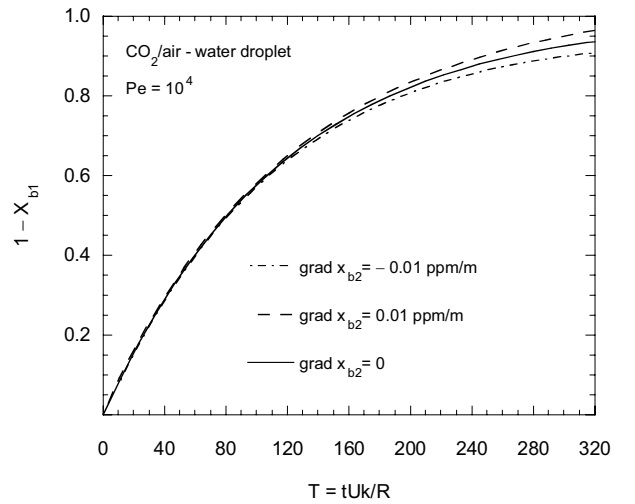


Fig. 2. Dependence of the concentration of the dissolved gas in the bulk of a water droplet vs. time for absorption of CO_2 by water in spray absorber (average concentration of CO_2 in a gaseous phase is 600 ppm).

The comparison showed that vertical distribution of absorbate concentration in a spray tower (Fig. 2) and in the atmospheric boundary layer (Fig. 3) strongly affects mass transfer during gas absorption by falling liquid droplets. When concentration of the absorbate is constant, the absorbate concentration in the droplet attains saturation after a certain time interval, and at the final stage of their fall droplets do not absorb soluble trace gases (see Fig. 2 and Fig. 3). In the calculations it is assumed that concentration of the absorbate in a gaseous phase in the case with constant concentration of absorbate is equal to the height-averaged value of the concentration.

When concentration of absorbate in the gaseous phase decreases with altitude, droplets absorb soluble gas during all the fall. Consequently, in this case concentration of soluble gas inside droplets at the bottom of a spray tower or at the ground increases.

When concentration of soluble gas increases with altitude, after some time droplets begin to release the dissolved gas. Consequently, beginning at some altitude gas absorption is

replaced by gas desorption. Gas exchange between falling droplet and gaseous phase leads to the redistribution of free soluble gases in the spray tower or in an atmosphere. Therefore concentration of soluble gas inside droplets at the bottom of a spray tower or at the ground decreases (see Fig. 2 and Fig. 3).

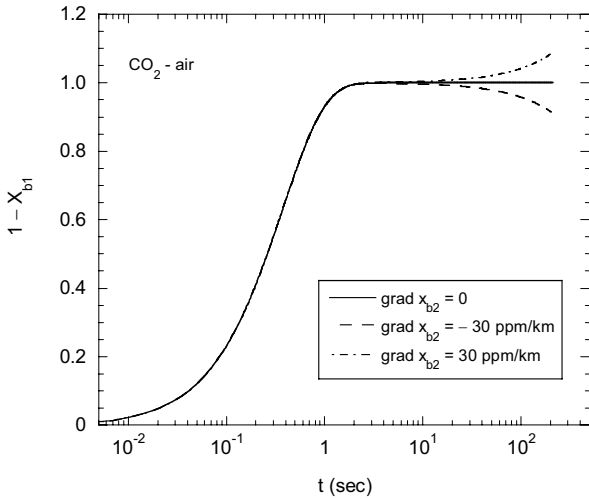


Fig. 3. Dependence of the concentration of the dissolved gas in the bulk of a water droplet vs. time for absorption of CO_2 by water in the atmosphere (average concentration of CO_2 in the atmosphere is 300 ppm), $x_{b10} = 0$.

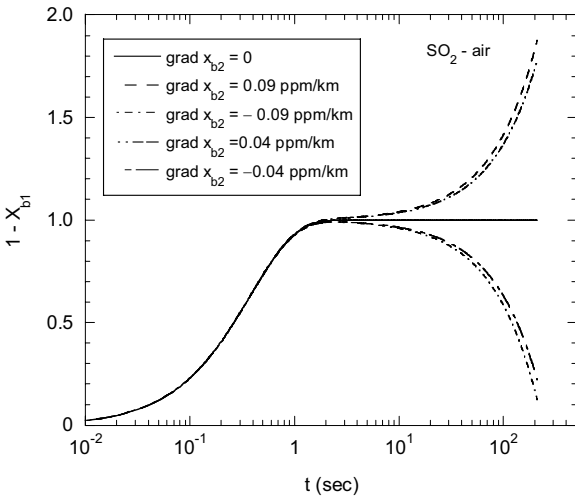


Fig. 4. Dependence of the concentration of the dissolved gas in the bulk of a water droplet vs. time for absorption of SO_2 by water in the atmosphere (average concentration of SO_2 in the atmosphere is 0.01 ppm), $x_{b10} = 0$.

Results of numerical calculations of gas absorption of SO_2 by rain droplet falling in the atmosphere with a linear altitude distribution of concentration of SO_2 in a gaseous phase are presented in Fig. 4. Calculations are performed for negligibly small initial concentration of the dissolved gas in the droplet and for different values of the concentration gradient. As well as in the case of CO_2 absorption when concentration of SO_2 in the gaseous phase decreases with altitude, droplets absorb sulfur dioxide during all fall period. When concentration of sulfur dioxide increases with altitude, after some time droplets begin to release the dissolved gas. As can be seen from Fig. 4 the increase of the concentration

gradient enhances the rate of gas exchange between the rain droplets and the atmosphere.

Results of numerical calculations of gas exchange between the initially saturated to the concentration mx_{b20} falling droplet and a gaseous phase are shown in Fig. 5.

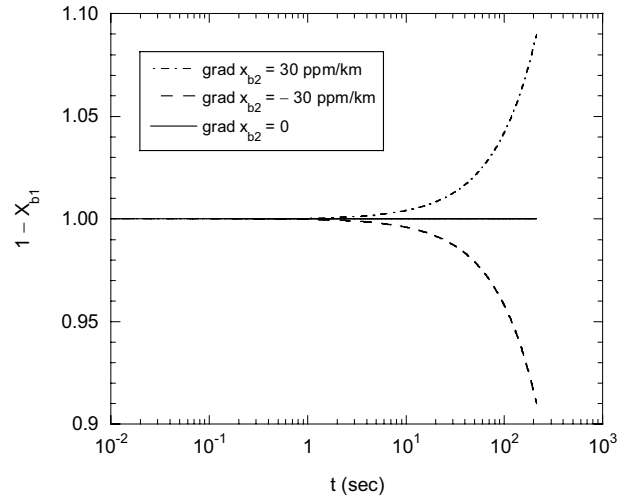


Fig. 5. Dependence of the concentration of the dissolved gas in the bulk of a water droplet vs. time for absorption of CO_2 by water in the atmosphere (average concentration of CO_2 in the atmosphere is 300 ppm), $x_{b10} = mx_{b20}$.

If concentration of the absorbate in a gaseous phase is homogeneous and equal to x_{b20} , gas exchange between droplet and gaseous phase during all droplet fall period is negligibly small. When concentration of soluble gas in the gaseous phase decreases with altitude, droplet absorbs soluble gas during all fall period. If concentration of soluble trace gases in the gaseous phase increases with altitude, droplet desorbs soluble gas during all the period of its fall.

SUMMARY AND CONCLUSIONS

In this study we considered conjugate mass transfer during soluble gas absorption by a falling droplet with the internal circulation from a mixture containing an inert gas using approximation of a thin concentration boundary layer in the liquid and gaseous phases and accounting for the absorbate accumulation in the bulk of the liquid. The bulk of a droplet, beyond the diffusion boundary layer is completely mixed and concentration of absorbate is homogeneous and time-dependent in the bulk. The system of transient partial parabolic differential equations of convective diffusion in liquid and gaseous phases with time-dependent boundary conditions was solved by combining the similarity transformation method with Duhamel's theorem. The simple form of the obtained solutions allows using them in the analysis of the dependence of the rate of mass transfer on different parameters, e.g., upon the radius of the droplet, diffusion coefficient, gradient of absorbate concentration in a gaseous phase etc. The obtained solution can be used for validating modeling procedures for solving more involved problems of gas absorption by falling liquid droplets.

The results obtained in this study can be summarized as follows:

1. The suggested model of gas absorption by falling liquid droplet in the presence of inert admixtures takes into account a number of effects that were neglected in the previous studies, such as the effect of dissolved gas accumulation inside a droplet and effect of absorbate inhomogeneity in a gaseous phase on a rate of mass transfer.
2. It is showed that the dependence of the radius-averaged concentration vs. time in a falling droplet is determined by a linear convolution Volterra integral equation of the second kind which is easier to solve than the original system of partial differential equations.
3. Vertical inhomogeneity of solute concentration in the gaseous phase strongly affects mass transfer during gas absorption by a falling liquid droplet. When concentration of soluble trace gases in the atmosphere decreases with altitude, droplets absorb trace gases during all the fall. When concentration of soluble trace gases increases with altitude, beginning from some altitude gas absorption is replaced by gas desorption.
4. Concentration of the dissolved gas in a droplet at the ground is independent on the initial concentration of the dissolved gas in a droplet
5. It is demonstrated that the increase of the concentration gradient of absorbate in a gas enhances the rate of gas exchange between the droplet and the gaseous phase.

The developed model can be used for the analysis of scavenging of hazardous gases in atmosphere by rain droplets or gas absorption in spray absorbers and can be incorporated into the computer codes.

NOMENCLATURE

C_i	molar density at the bulk of fluid, $\text{mol} \cdot \text{m}^{-3}$
D_i	molecular diffusion coefficient, ($\text{m}^2 \cdot \text{s}^{-1}$)
D	square root of the diffusivities ratio, $\sqrt{D_1/D_2}$
k	coefficient in Eq. (1)
$N_i = -D_i C_i \frac{\partial x_i}{\partial y}$	molar flux density, $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$
m	distribution coefficient
$Pe_i = kRU/D_i$	Peclet number for a moving droplet
r	radial coordinate, m
R	droplet radius, m
$Re = 2UR\rho_2/\mu_2$	external flow Reynolds number for a moving droplet
$Sc = \nu_i/D_i$	Schmidt number
t	time, s
$T = tUk/R$	dimensionless time

U	translational velocity of a droplet, $\text{m} \cdot \text{s}^{-1}$
v_r, v_θ	velocity components, $\text{m} \cdot \text{s}^{-1}$
V	droplet volume, m^3
x	molar fraction of an absorbate
x_{b10}	initial value of molar fraction of absorbate in a droplet
x_{b20}	value of molar fraction of an absorbate in a gas phase at height h
x_{b200}	value of molar fraction of absorbate in a gas phase at a bottom of a spray tower or on the ground
$x_{b1}(t)$	molar fraction of absorbate in a bulk of a droplet
$x_{b2}(t)$	molar fraction of an absorbate in a bulk of a gas phase
$X_1 = \frac{x_1 - mx_{b20}}{x_{b10} - mx_{b20}}$	dimensionless molar fraction of absorbate in the liquid phase
$X_2 = \frac{x_2 - x_{b20}}{x_{b10} - mx_{b20}}$	dimensionless molar fraction of an absorbate in the gaseous phase
$X_{b1}(t) = \frac{x_{b1}(t) - mx_{b20}}{x_{b10} - mx_{b20}}$	dimensionless molar fraction of an absorbate in the bulk of a droplet
$X_{b2}(t) = \frac{x_{b2}(t) - x_{b20}}{x_{b10} - mx_{b20}}$	dimensionless molar fraction of an absorbate in the bulk of a gas phase
y	distance from the surface of a droplet, m
$Y = y/R$	dimensionless distance from the surface of a droplet
z	coordinate in a vertical direction, m
Greek symbols	
$\gamma = C_1/C_2$	molar densities ratio
δ_i	thickness of a diffusion boundary layer, m
$\Delta_i = \delta_i/R$	dimensionless thickness of a diffusion boundary layer
λ	variable, Eqs. (16) – (17)
η_i	similarity variable, Eq. (7)
θ	angle, rad

μ_i	dynamic viscosity of a fluid, $\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$
ν_i	kinematic viscosity of a fluid, $\text{m}^2 \text{s}^{-1}$
ρ_i	density at the bulk of fluid, $\text{kg} \cdot \text{m}^{-3}$
$\tau_i = tD_i / R^2$	dimensionless time

Subscripts

0	value at the inlet (in absorber) or on the height H (in the atmosphere)
1	liquid phase
2	gaseous phase
b	value in the bulk
r	radial direction
θ	tangential direction

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