Conjugate mass transfer during gas absorption by falling liquid droplet with internal circulation

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Abstract

We considered conjugate mass transfer during absorption of a gas by a falling droplet with internal circulation. Gaseous phase is assumed to contain inert admixtures, and resistance to mass transfer in both phases is taken into account. Mass flux is directed from a gaseous phase to a droplet, and the interfacial shear stress causes a fluid flow inside the droplet. Droplet deformation under the influence of the interface shear stress is neglected. Absorbate accumulation in the bulk of dispersed phase is taken into account. The problem is solved in the approximations 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. The thermodynamic parameters of a system are assumed constant. 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 Volterra integral equation of the second kind which is solved numerically. Theoretical results are compared with the available experimental data.
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1. Introduction

Removal of gases from polluted air and gaseous streams by water drops is an important mass transfer operation in air pollution control and engineering. Mass transfer to droplets is of fundamental importance in many naturally occurring phenomena and industrial processes involving sprays, e.g. atmospheric physics, wet

deposition. Gas scavenging by atmospheric water droplets include absorption of SO_2, CO_2, HCl, NH_3, NO_x (nitric oxide and nitrogen dioxide), CFCs, methane and some other gases. Sources of these gases in the atmosphere are briefly reviewed in the following.

Sulfur dioxide (SO_2) is emitted from a smokestack as a result of various fossil fuels combustion, e.g. crude oil and coal. Gaseous SO_2 usually contains small amounts of SO_3, and then it is converted to sulfuric acid in the presence of water, forming acid fogs and acid rains. Fundamental mechanism of the acid rain formation partially results from sulfur oxidation and absorption by water droplets in the atmosphere. Comprehensive

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Nomenclature

D_i molecular diffusion coefficient, $\mathrm{m^2\,s^{-1}}$

D square root of the diffusivities ratio, $\sqrt{D_1/D_2}$

k coefficient in Eq. (1)

$N_i = -D_i\rho_i(\partial x_i/\partial y)$ mass flux density, $\mathrm{kg\,m^{-2}\,s^{-1}}$

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

$Sc = v_i/D_i$ Schmidt number

t time, s

$T = tUk/R$ dimensionless time

U translational velocity of a droplet, $\mathrm{m\,s^{-1}}$

v_r, v_θ velocity components, $\mathrm{m\,s^{-1}}$

V droplet volume, $\mathrm{m^3}$

x mass fraction of an absorbate

x_{10} initial value of mass fraction of absorbate in a droplet

$X_1 = (x_1 - mx_2(\infty))/(x_{10} - mx_2(\infty))$ dimensionless mass fraction of an absorbate in the liquid phase

$X_2 = (x_2 - x_2(\infty))/(x_{10} - mx_2(\infty))$ dimensionless mass fraction of an absorbate in the gaseous phase

$X_b(\tau_1) = (x_b(t) - mx_2(\infty))/(x_{10} - mx_2(\infty))$ dimensionless mass fraction of an absorbate in the bulk of a droplet

y distance from the surface of a droplet, m

$Y = y/R$ dimensionless distance from the surface of a droplet

Greek symbols

$\gamma = \rho_1/\rho_2$ 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, $\mathrm{kg\,m^{-1}\,s^{-1}}$

v_i kinematic viscosity of a fluid, $\mathrm{m^2\,s^{-1}}$

ρ_i density at the bulk of fluid, $\mathrm{kg\,m^{-3}}$

$\tau_i = tD_i/R^2$ dimensionless time

Subscripts

0   value at the inlet

1   liquid phase

2   gaseous phase

∞ value at infinity

b   value in the bulk of a droplet

r   radial direction

s   value at the interface

θ tangential direction

description of this particular mass transfer process is conducive to understanding the wet acid deposition in the environment.

Oxides of nitrogen (NO_x) such as nitric oxide and nitrogen dioxide, and carbon dioxide (CO_2) may be generated by different types of combustors, e.g., boilers and furnaces. The major source of CO_2 on geologic time scales is volcanic activity.

The main source of atmospheric ammonia is agriculture (see, e.g. Van Der Hoek, 1998), and the remaining minor sources are industries, humans, pets, wild animals, landfills and households products (see Sutton et al., 2000). Agricultural emissions of ammonia are associated mainly with animals waste (mainly cattle, poultry, pigs and sheep) and with fertilizers, mainly ammonium sulfate, ammonium nitrate, ammonia, urea and ammonium phosphate, (see, e.g. Buijsman and Erisman, 1988). The contribution of vehicles to non-agricultural NH_3 emissions has been considered to be negligible until 1995 (Sutton et al., 1995). In the last few years, however, an increase of NH_3 emission due to the

introduction of petrol-engine vehicles equipped with catalytic converters has been reported in the literature (see Moeckli and Sigrist, 1996; Fraser and Cass, 1998).

Hydrogen chloride (HCl) is generated during combustion of municipal solid waste (MSW) containing certain types of plastics (Rhyner et al., 1995, pp. 262–267). When the hydrogen chloride is transferred to particles containing moisture, strong acids are formed. These acidic aerosols may cause serious corrosion and erosion of the equipment. In order to remove this hazardous air pollutant (HAP), water is often blended with basic chemicals such as NaOH and KOH to wash the flue gas. As a result, HCl is captured from the flue gas into the absorbing material.

Major sources of methane are such as rice agriculture, cattle and biomass burning.

Chlorofluorocarbons (CFCs) have been used for many applications, but mostly for refrigeration and air conditioning. In earlier years, they were used as aerosol propellants, and in more recent years they have been used for blowing polyurethane foams. A large amount