Pergamon

Int. J. Heat Mass Transfer. Vol. 37, No. 14, pp. 2139–2143, 1994
Copyright © 1994 Elsevier Science Ltd
Printed in Great Britain. All rights reserved
0017–9310/94 $7.00+0.00

0017–9310(94)E0065–3

Mass transfer from a drop—I. Experimental study and comparison with existing correlations

J. SCHWARZ and J. SMOLÍK
Institute of Chemical Process Fundamentals, Academy of Sciences of the Czech Republic,
Rozvojová 135, 165 02 Prague 6, Czech Republic

(*Received* 21 *December* 1993)

Abstract—An experimental study was conducted to measure the rates of mass transfer from a water drop, suspended from a quartz capillary in a stream of a hot air flowing upward in a vertical wind tunnel. Measurements were made for bulk temperature $T_\infty = 314$–449 K, drop temperature $T_0 = 287$–315 K, free stream velocity $U_\infty = 0.5$–1.7 m s^{-1}, drop diameter $d = 0.7$–2.3 mm, dimensionless driving force $B = 0.007$–0.068, $Re = 30$–180 and $Sc = 0.62$. The data were compared with results of previous works. It was found that existing correlations proposed for higher mass transfer conditions do not improve experimental data interpretation

INTRODUCTION

HEAT AND MASS transfer between drops and gas occur in many natural and technological processes. While in the atmosphere drops grow or evaporate at low ambient temperatures and hence at low mass transfer conditions, in industrial processes the evaporation of drops into a high-temperature environment is of importance. Consequently, mass transfer from a drop at such conditions has been the subject of both experimental and theoretical investigations.

On the basis of dimensionless analysis Frössling [1] showed that for mass transfer from a drop at forced convection Sh is directly proportional to $Re^{1/2}Sc^{1/3}$. To find the constant of proportionality he investigated the evaporation of water, nitrobenzene and aniline drops suspended in air. Experiments were carried out at room temperature for Reynolds number from about 2 to 600. Additional experiments were also made on evaporation of sphere of solid naphthalene for Re up to 1300. From the comparison with evaporation into still air the following correlation was found:

$$Sh = 2+0.552Re^{1/2}Sc^{1/3}. \tag{1}$$

Ranz and Marshall [2] studied the evaporation of aniline and benzene drops at room temperature and the evaporation of water drop up to 220°C, for Re from 2 to 200. The drops were suspended from a feed capillary in a laminar air jet. The experimental data were correlated with the equation:

$$Sh = 2+0.6Re^{1/2}Sc^{1/3}. \tag{2}$$

Hsu *et al.* [3] investigated the evaporation of *n*-heptane drops in an air jet at a free stream temperature of 38°C for Re from 65 to 320. In analysis of experimental data corrections for deviation from spherical drop form were considered. The effect of quantity $Re^{1/2}Sc^{1/3}$ on the rate of mass transfer was shown to be:

$$Sh = 2+0.544Re^{1/2}Sc^{1/3}. \tag{3}$$

The evaporation of mercy coated brass sphere in air was studied by Maxwell and Storrow [4]. The experiments were carried out at room temperature for Re ranging from 10 to 1500. The experimental data were found to be in agreement with the Frössling correlation.

Mass transfer from a naphthalene sphere suspended in a wind tunnel was investigated by Rowe *et al.* [5]. The experiments were conducted at room temperature for spheres 16 and 38 mm in dia. and for Re from about 100 to 1050. The spheres were weighted before and after the exposure to flow for a known period of time: the resulting mass transfer data were correlated by the equation:

$$Sh = 2+0.69Re^{1/2}Sc^{1/3}. \tag{4}$$

Downing [6] carried out mass transfer measurements on drops of water, benzene, *n*-hexane and acetone suspended from a thermocouple in air jet. Reynolds numbers ranged from 24 to 325 and temperatures ranged from 27 to 340°C. Mass transfer data were obtained from the rate of change of the drops diameter and the following correlation was suggested:

$$Sh = G(2+0.6Re^{1/2}Sc^{1/3}), \tag{5}$$

where:

NOMENCLATURE

B	dimensionless driving force defined by equation (12)
d	drop diameter [m]
D_{vg}	binary diffusion coefficient [m^2 s^{-1}]
G	correction for variable properties defined by equation (6)
P_v	partial vapour pressure [Pa]
Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number
Sh^0	Sherwood number for mass transfer without phase change
T	temperature [K]
U	velocity [m s^{-1}]
Z	correction for variable properties and high mass flux defined by equation (11).

Greek symbols

μ	viscosity of gaseous mixture [Pa s]
ρ	density [kg m^{-3}]
ω	mass fraction of vapour.

Subscripts

g	air
v	water vapour
0	drop surface
∞	free stream.

$$G = 1-0.4(1-T_0/T_\infty). \tag{6}$$

To examine the rates of mass transfer from water drops Beard and Prupacher [7] developed a free fall experimental procedure. Two ranges of mass transfer were reported. For values of $Re^{1/2}\,Sc^{1/3}$ below 1.43:

$$Sh = 2+0.216(Re^{1/2}\,Sc^{1/3})^2 \tag{7}$$

and for $1.43 < Re^{1/2}\,Sc^{1/3} < 12.0$:

$$Sh = 1.56+0.616Re^{1/2}\,Sc^{1/3}. \tag{8}$$

The rate of evaporation of a tetrafluorodibromomethane drop suspended in air flow with temperatures from −40 to 750°C and Re ranging from 25 to 625 was measured by Blinov and Dobrovolskaya [8]. The data were correlated by the equation:

$$Sh = 2+0.56Re^{1/2}\,Sc^{1/3}. \tag{9}$$

Experimental study of mass transfer from a drop under high mass flux conditions was conducted by Chuchottaworn *et al.* [9]. The experiments were carried out for evaporation of water, methanol, *n*-hexane, *n*-pentane and carbon tetrachloride drops into a dry air. The drops were suspended from a capillary in a vertical wind tunnel and a liquid was supplied into them to keep constant size during the experiment. The experiments were carried out at temperatures from 296 to 364 K, for Re from 32 to 328 and Sc from 0.60 to 1.66. All the data were correlated by the following equation:

$$Sh = Z(2+0.37Re^{0.61}\,Sc^{0.51}), \tag{10}$$

where:

$$Z = \frac{(\rho_\infty/\rho_0)^{1/3}}{(1-\omega_0)[0.3+0.7(1+B)^{0.88}]} \tag{11}$$

and:

$$B = \left(\frac{\omega_0-\omega_\infty}{1-\omega_0}\right). \tag{12}$$

Mass transfer from water drops under stimulated free-fall conditions was reported by Wedding *et al.* [10]. Conditions for the study included temperatures of 5, 10, 15, and 20°C, relative humidity of 20 and 60% and initial drop diameters of 100, 250, and 400 μm. The mass transfer correlation was determined as:

$$Sh = 1.755+0.535Re^{1/2}\,Sc^{1/3}. \tag{13}$$

Yet another approach based on the numerical simulation of the drop evaporation has been used for mass transfer correlation. Renksizbulut *et al.* [11], considered the evaporation of an *n*-heptane drop injected into high temperature air with an initial Re of 100. The initial drop temperature was 298 K, the temperature of the air was 800 K. For Re ranging from 10 to 2000, the following mass transfer correlation has been developed:

$$Sh(1+B)^{0.7} = 2+0.87Re^{1/2}\,Sc^{1/3}. \tag{14}$$

Recently, Lage *et al.* [12] solved constant-property boundary-layer equations for momentum, mass and energy transport in the flow over the sphere. About 4000 data points obtained both for monocomponent and bicomponent drops were considered and the resulting correlation applicable for $0 < Re < 1000$ was found:

$$Sh = Sh^0(1+B)^{(-0.689)}\exp[(-0.0230)\ln^2(1+B)], \tag{15}$$

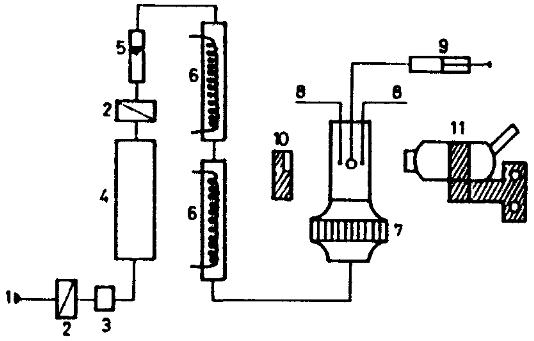
where the Sherwood number without phase change Sh^0 depends on surface tangential velocity.

The survey presented here shows that considerable differences appear between existing mass transfer correlations. They are caused by different experimental techniques and range of experimental conditions used, differences in thermophysical properties and reference conditions at which thermophysical properties were evaluated and in some cases even in the definition of the Sherwood number. Further, in some correlations various correction terms appear, which account for high mass flux conditions and effect of variable properties due to large differences in temperature and composition between free stream and drop surface. For this reason the direct intercomparison of existing formulas is, without knowledge of the original data, practically impossible. Therefore, we measured the mass transfer at the evaporation of a water drop and compared the experimental results with some mass transfer correlations. In these correlations the same definition of the Sherwood number and the same reference state for thermophysical properties were used as in the original studies.

EXPERIMENT

Experimental apparatus and procedures

The experimental apparatus is shown schematically in Fig. 1. The air was supplied from a compressor through a coalescing filter for removal of the rest of the oil aerosol from incoming air, a pressure regulator, a molecular sieve packed dryer, and a highly efficient filter that removed any fine particles. The desired flow was adjusted by a precise needle valve and measured by a rotameter. The humidity was monitored by means of a thin-film humidity sensor. The dry and clean air was heated to desirable temperature by passing it through two heaters and entered into a test section through a diverent–convergent nozzle with calming grids. The test section was a duralumin rectangular duct of 70 x 70 mm cross-section with large side-view double glass windows. In the middle of the duct, a 0.3 mm O.D. quartz capillary provided with water cooled housing was mounted by two-dimensional fine adjustment traversing supports. The cooling of the capillary kept the temperature of the added water close to the drop temperature. The pure water (distilled and purified by reverse osmosis) was supplied to an evaporating pendant drop by a microfeeder-operated 50 μl Hamilton syringe. The rate of feeding was calibrated by weighing of water dosed during a known period of time. Temperature of the drop was measured by a 25 μm dia. chromel–constantan thermocouple and temperature of gas by a 50 μm dia. one. Both of them were calibrated in the whole range of temperatures by comparison with HP 2108 quartz thermometer. The voltage produced by thermocouples was measured by precise digital voltmeter provided by compensating circuits. Each thermocouple was mounted on its own traversing support as a capillary, which allowed us to measure both temperatures inside the drop and profiles of temperature around the drop. Velocity profiles in the test section were measured by the P11 Dantec hot wire anemometer. A constant velocity region of 20 mm dia. was observed in the center of the test section, that was taken as a free stream velocity. It was measured as a preliminary function of gas temperature and flow rate determined by a rotameter. The obtained calibration curve was used for determining the experimental free stream velocity.



1. **compressed air**
2. **filter**
3. **pressure regulator**
4. **dehumidifier**
5. **flowmeter**
6. **heater**
7. **test section**
8. **thermocouple**
9. **microsyringe**
10. **flash**
11. **microscope with camera**

FIG. 1. Scheme of apparatus.

The drop was observed by stereo microscope and photographed by the attached camera. Temperature at several points inside the drop was measured preliminarily by traversing of the thermocouple. Since no appreciable temperature distribution was observed, the temperature measured inside the drop was taken for the temperature of the drop surface.

In a common experiment, the flow rate and the temperature of the air stream in the test section were first adjusted. Next, the water feeding system was turned on and the drop started to appear and grow at the end of the capillary. Typically the steady state was reached after 10–20 min when the drop size remained constant, and thus the rate of evaporation was equal to the rate of water adding. The thermocouples, flow rate, water feeding rate readings and ambient pressure were registered for the experimental data evaluation. To determine the mass flux density at the drop surface the size of the drop was measured on a slide screen projector. The surface of drop was calculated as a surface of an ellipsoid in which the shorter axis was the horizontal diameter of the drop and the longer one the distance between the bottom of the drop and the end of the capillary [9]. The distances were measured with an error of 15 μm.

RESULTS AND DISCUSSION

By using the technique described in the previous section we measured mass transfer from a water drop evaporated into a stream of hot air. Experiments were made in the range of conditions:

$T_0 = 287$–315 K, $T_\infty = 314$–449 K, $d = 0.7$–2.3 mm,

Table 1. Thermophysical properties

Equation	Unit	Range	Ref.
$\log (P_v) = 18.4979 - 2818.6/T - 1.6908 \log (T) - 5.7546 \times 10^{-3} T + 4.0073 \times 10^{-6} T^2$	P_v in Pa	273–323 K	[13]
$D_{vg} = 2.16 \times 10^{-5} (T/273.15)^{1.8}$	$m^2\ s^{-1}$	273–1493 K	[13]
$\mu_v = (-5.482 + 5.598 \times 10^{-2} T - 2.413 \times 10^{-5} T^2) \times 10^{-6}$	Pa s	270–470 K	[14]
$\mu_g = (0.1005 + 7.848 \times 10^{-2} T - 6.696 \times 10^{-5} T^2 + 3.376 \times 10^{-8} T^3) \times 10^{-6}$	Pa s	270–470 K	[14]

$$U_\infty = 0.5\text{–}1.7\ \mathrm{m\ s^{-1}}, \quad Re = 30\text{–}80, \quad Sc = 0.62,$$
$$P_{v,\infty} = 12.6\ \mathrm{Pa}, \quad B = 0.007\text{–}0.068.$$

As follows from the dimensionless driving force B the experimental data were obtained at low mass transfer conditions but the influence of the mass flux from the drop could be also expected. Therefore, we compared the data with predictions by both low and high mass transfer correlations. In these comparisons the same definitions of the Sherwood number and the same reference states for evaluation of the thermophysical properties were used as in original papers. The thermophysical properties we used in these comparisons are listed in Table 1. The temperature-dependent expressions were obtained by fitting of the tabulated data [13, 14] for the range of temperatures of interest by the method of non-linear least squares.

The results of comparison with predictions by mass transfer correlation of Ranz and Marshall [2] are given in Fig. 2. From this figure it can be seen that the experimental data lay about 10% below the prediction and that the deviation increases at higher Reynolds numbers. It indicates that at these conditions mass flux from the drop increases the characteristic length for heat and mass transfer and thus reduces their rates [11, 12]. In Fig. 3 the experimental data are compared with predictions by Downing [6]. This correlation also does not account for higher mass flux but it includes an empirical correction for the variation of thermophysical properties with temperature. As shown in Fig. 3 the agreement of experimental data with Downing's correlation is quite good but the scatter of the data has increased. Figure 4 shows the comparison between the experiment and correlation suggested by Chuchottaworn *et al.* [9]. This correlation includes corrections for both high mass flux conditions and the effect of variable thermophysical properties, and therefore a good agreement with experimental data could be expected. However, mass transfer predicted by this correlation is about 10% lower than obtained from experiments and the data exhibit higher scatter. Another correlation, developed by Renksizbulut *et al.* [11], for evaporation of a drop

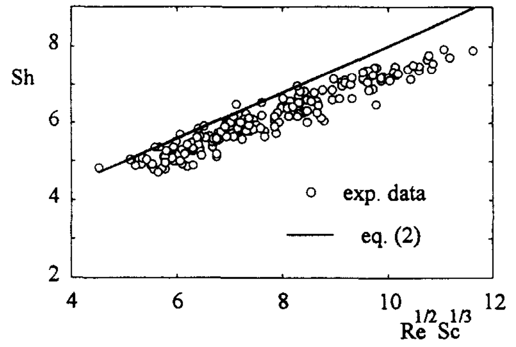


FIG. 2. Comparison of experimental data with the correlation of Ranz and Marshall.

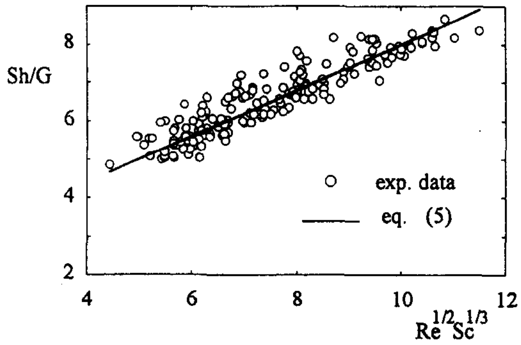


FIG. 3. Comparison of experimental data with the correlation of Downing.

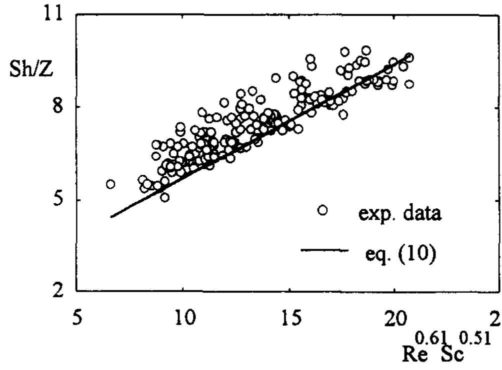


FIG. 4. Comparison of experimental data with the correlation of Chuchottaworn *et al.*

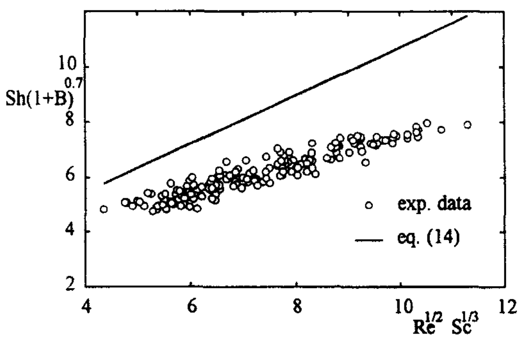


FIG. 5. Comparison of experimental data with the correlation of Renksizbulut *et al.*

in high temperature flow, is based on simulated data of transient vaporization of n-heptane drop. The mass transfer rates predicted by this correlation are compared with experimental data in Fig. 5. As can be seen this correlation systematically overpredicts the rate of mass transfer for the given range of experimental conditions. The discrepancy might be caused by the fact that this correlation was obtained for substantially higher mass flux conditions than investigated in this study.

The differences between existing mass transfer correlations and differences between them and experimental data presented here indicate that further theoretical and experimental studies are needed. Therefore, we plan to investigate the evaporation of drops of more volatile liquid to extend the experimental data to a higher mass transfer rate region.

CONCLUSIONS

We investigated mass transfer at evaporation of a water drop into a hot air stream. The experimental data were compared with mass transfer correlations developed for both low and high mass flux conditions. Good agreement was found with mass transfer correlation proposed by Downing [6] which includes empirical correction for variable thermophysical properties. Additional investigations of mass transfer at evaporation of drops at high mass flux conditions are needed in view of large differences in the form of existing correlations and a lack of experimental data.

REFERENCES

1. N. Frössling, Über die Verdunstung fallender Tropfen, *Gerlands Beitr. Geophys.* **52**, 170–216 (1938).
2. W. E. Ranz and W. R. Marshall, Evaporation from drops, *Chem. Engng Prog.* **48**, 141–146 (1952).
3. N. T. Hsu, K. Sato and B. H. Sage, Material transfer in turbulent gas streams: influence of shape on evaporation of drops of n-heptane, *Industr. Engng Chem.* **46**, 870–876 (1954).
4. R. W. Maxwell and J. A. Storrow, Mercury vapour transfer studies, *Chem. Engng Sci.* **6**, 204–214 (1957).
5. P. N. Rowe, K. T. Claxton and J. B. Lewis, Heat and mass transfer from a single sphere in an extensive flowing fluid, *Trans. Instn Chem. Engrs* **43**, T14–T31 (1965).
6. C. G. Downing, The evaporation of drops of pure liquids at elevated temperatures: rates of evaporation and wet-bulb temperatures, *A.I.Ch.E. Jl* **12**, 760–766 (1966).
7. K. V. Beard and H. R. Pruppacher, A wind tunnel investigation of the rate of evaporation of small water drops falling at terminal velocity in air, *J. Atmos. Sci.* **28**, 1455–1464 (1971).
8. V. I. Blinov and L. P. Dobrovolskaya, O vlianii temperatury na isparenie kapel zhidkosti v vozdushnom potoke, *Inzh. Fiz. Zh.* **23**, 686–691 (1972).
9. P. Chuchottaworn, A. Fujinami and K. Asano, Experimental study of evaporation of a volatile pendant drop under high mass flux conditions, *J. Chem. Engng Japan* **17**, 7–13 (1984).
10. J. B. Wedding, J. Y. Kim and R. S. Dennison, Mass transfer from water droplets under simulated free fall conditions, *Atmos. Envir.* **20**, 1039–1045 (1986).
11. M. Renksizbulut, R. Nafziger and X. Li, A mass transfer correlation for droplet evaporation in high-temperature flows, *Chem. Engng Sci.* **46**, 2351–2358 (1991).
12. P. L. C. Lage and R. H. Rangel, Multicomponent heat and mass transfer for flow over a droplet, *Int. J. Heat Mass Transfer* **36**, 3573–3581 (1993).
13. N. B. Vargaftik, *Tables on the Thermophysical Properties of Liquids and Gases* (2nd Edn), pp. 43–44, 634. Hemisphere, Washington, DC (1975).
14. Y. S. Touloukian, S. C. Saxena and P. Hestermans, *Thermophysical Properties of Matter* (*The TRPC Data Series*), Vol. 11, *Viscosity*, pp. 96, 611. IFI/Plenum, New York (1975).