Evaporation from a Water Drop in the Stream of Steam-air Mixtures

By

Ryozo Toei*, Morio Okazaki* and Katsuyuki Kubota*

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The evaporation from a single water drop in the stream of super-heated steam and various steam-air mixtures is investigated experimentally. The heat and mass transfer coefficients are calculated from the evaporation rates and the following experimental equations are obtained.

$$Nu=2.0+0.65\,Re_p^{1/2}\,Pr^{1/3}$$
$$9<Re_p<120 \qquad 0<(p_{Bm}/p_\pi)<0.98$$
$$Sh\,(p_{Bm}/p_\pi)^{-0.20}=2.0+0.65\,Re_p^{1/2}\,Sc^{1/3}$$
$$0<Re_p<120 \qquad 0.38<(p_{Bm}/p_\pi)<0.98$$

Introduction

On the liquid evaporation from a free surface of a liquid into the stream of gas, unidirectional diffusion and heat transfer occur through a stagnant gas film outside of the liquid surface. They are classified by the composition of the gas as follows;

i) p_A is far smaller than p_π

There are many studies in such a case. About a single drop evaporation, Frössling[1] and Ranz et al.[2] have presented the experimental formulas of h_c and k_G. These experimental formulas of k_G contain the term of p_{Bm}. But they did not change practically the gas phase compositions in their experiments. Therefore at least, from the view point of the effect of p_{Bm} on k_G, it may be said that these results are attributed to the formal application of the "Film Theory" for unidirectional diffusion, that is, k_G is proportional to $1/p_{Bm}$.

ii) p_A is equal to p_π

The evaporation of a liquid into the super-heated vapor of its own liquid

* Department of Chemical Engineering.

corresponds to this case. Since the evaporation temperature is very close to the boiling temperature under the surrounding total pressure,[3,4] k_G is too large to take its value by experiment, but h_c can be taken and there have been several reports on the evaporation and drying by super-heated steam from flat pans. Wenzel et al.[4] carried out the studies about super-heated steam drying and air drying using the same experimental apparatus, and got the results that the value of j_h in the former one was about 20% higher than the latter. Chu et al.[3,5] also gave the experimental equation of j_h for the evaporation and drying from the flat pan by the super-heated vapor and the value of j_h was higher than the Pohlhausen's theoretical equation[6].

iii) p_A is considerably large

This case lies between i) and ii). As the study being consciously changed on p_{Bm}, there has been the one of water evaporation into high humid air using a wetted wall column by Cairns et al.[7] The effect of p_{Bm} on h_c has been found as well as on k_G. After that, Westkaemper et al.[8] and Shulman et al.[9] have carried out similar works. The works cited above have shown the discrepancy between the "Film Theory" and the experimental results on k_G also.

On this paper, the effects of p_{Bm} on h_c and k_G are discussed, performing the experiments of evaporation from a single drop of water in the wide range of gas phase composition from air to super-heated steam.

1. Heat Transfer Coefficients

1.1 Experimental procedures

The experimental apparatus is shown in Fig. 1. The steam generator of the wetted wall column type with nitre bath jacket ④ was used and water was supplied by a constant rate pump, so the steam was generated at a constant rate. The steam generated was heated up to the appointed temperature in the super-heater ⑤, and led to the calming section ⑥ to make the eddies in the stream disappear and then to the convergent nozzle[10] ⑦ for uniforming the velocity distribution. The stream was flown uniformly through the test section ⑧ and condensed out in the condenser ⑨. In mixing air and steam, air was supplied through the orifice ⑫ from the top of ④ at constant rate.

The details of the test section are shown in Fig. 2. A droplet having about one to two millimeters diameter was suspended at the tail-end of a fine glass rod ⑧ by using a syringe, in a vertically upward-flowing stream of gas. Evaporation rates were determined by measuring the decrease of the diameter of the droplet on the photograph pictured by a camera at an interval 10 or 15 sec..

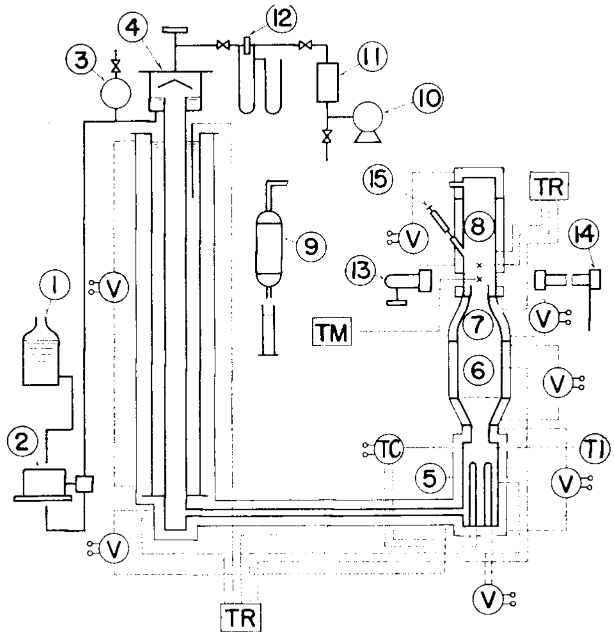


Fig. 1. Experimental apparatus.

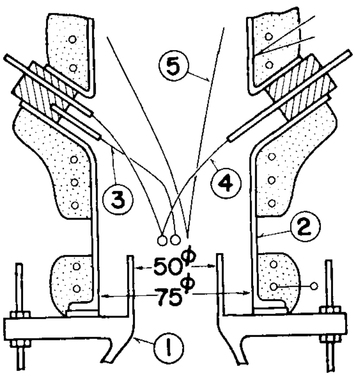


Fig. 2. Test section.

The temperature of the drop was measured by the fine thermocouple ④ with which the drop was suspended. (It was estimated that the errors in measuring the temperature of the drop were less than 0.05°C.)

1.2 Transport properties used

Transport properties used for the calculations were cited from the following literatures.

Viscosity	air: D'Ans and Lax[11] steam: Licht and Stechert[12]
	mixed gas: Wilke's formula[13]
Thermal conductivity	
	air: Keyes[14] steam: Kagakukogaku-benran[15]
	mixed gas: Lindsay-Bromley's formula[13]
Heat capacity	air: Keyes[14] steam: Landolt-Börnstein[16]
	mixed gas: the weighed mean value on molar fractions

1.3 Calculation of heat transfer coefficients

(1) Calculation procedure of heat transfer coefficients

As neglecting the temperature distribution in the drop, the heat balance is taken as follows:

$$-(\rho_l \lambda / A)(dV/d\theta) = q_T = q_c + q_k + q_r \tag{1}$$

$$q_c = q_T - q_r - q_k = h_c'(t_v - t_l) \tag{2}$$

$$(1/A)(dV/d\theta) = (1/2)(dD_p/d\theta) \tag{3}$$

Eqs. (1) and (3) give the next equation;

$$h_c' = \frac{(\rho_l \lambda/2)(dD_p/d\theta) + q_r + q_k}{(t_v - t_l)} \tag{4}$$

Considering the sensible heat increase of the evaporatee water vapor across the gas film;[17]

$$h_c = N h_c' \tag{5}$$

where

$$N = \frac{C_{pA}(t_v - t_l)/\lambda}{ln\{C_{pA}(t_v - t_l)/\lambda + 1\}} \tag{6}$$

(2) Radiative heat transfer rate, q_r In this experiment, the wall temperature of the test section, t_s, was adjusted equal to the gas temperature, t_v. Hence q_r was calculated by the following equation;

$$q_r = 1.356 \times 10^{-4} \left\{ \left(\frac{t_s + 273}{100} \right)^4 - \left(\frac{t_l - 273}{100} \right)^4 \right\} F_A F_E \tag{7}$$

F_A was equal to one, because the drop was entirely enclosed with the wall. As the surface area of the drop was far smaller than that of the wall, F_E was estimated to be equal to the emissivity of water, 0.95. At most, q_r was less than 15% of q_T.

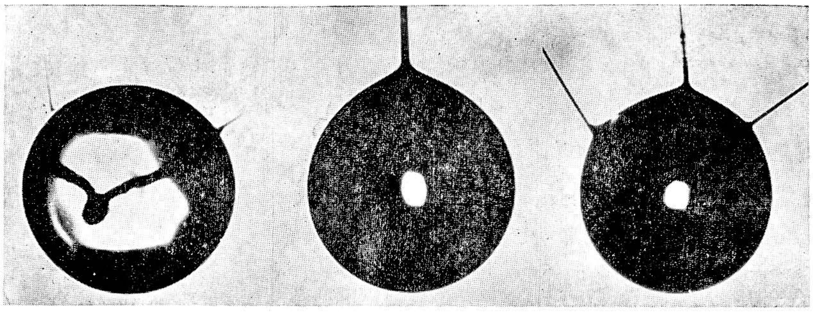
(**3**) Conductive heat transfer rate, q_k The rates of conductive heat transfer to the drop from the fine glass rod and the thermocouple were estimated as follows respectively:

$$q_k = k_k\left(\frac{A_k}{A}\right)\frac{dt_k}{dx}\bigg|_{x=0} = \frac{\pi r_k^2 k_k\sqrt{\alpha}\,(t_v-t_l)}{A} \qquad (8)^*$$

$$\alpha = 2h_k/k_k r_k$$

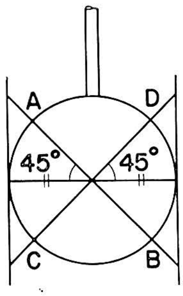
The value of h_k was estimated by the literature 18). At most, q_k was less than about 5% of q_T.

(**4**) The mean diameter of the drop, D_p The typical photographs are shown in Fig. 3. The arithmetic mean value of the two diameters measured on the directions of the diagonal lines, as shown in Fig. 4, was used as D_p.



(a) (b) (c)

Fig. 3. Photographs of water drops.



$$\frac{\overline{AB}+\overline{CD}}{2} = D_p$$

Fig. 4. Diameter of drop.

1.4 Experimental results for heat transfer

Experimental conditions were as follows:

$G = 2.52\times10^{-2}\sim12.0\times10^{-2}$ g/cm² sec $\qquad t_v = 42\sim155$°C

$\Delta t = t_v - t_l = 24\sim55$°C $\qquad (p_{B\infty}/p_\pi) = 0\sim0.98$

$Re_p = 9\sim120$**

* Refer to Appendix.

** When there is no notice, mean values in transfer path were used as transport properties in non-dimensional numbers.

During the evaporation of the drop, t_l was maintained at the constant temperature which might be considered as a sort of the wet bulb temperature decided by the gas phase condition. Of course as the decrease of p_{Bm}, t_l approaches the boiling temperature under the total pressure of the circumference.

In the case of super-heated steam, t_l was equal to the boiling temperature as same as the previous works[3,4]. The boiling of the drop has not been observed. The photographs of the drops suspended with the $40\mu\phi$ thermo-couple and the fine glass rod are shown in Fig. 3 (a) and (b). The typical experimental results for heat transfer are shown in Table 1.

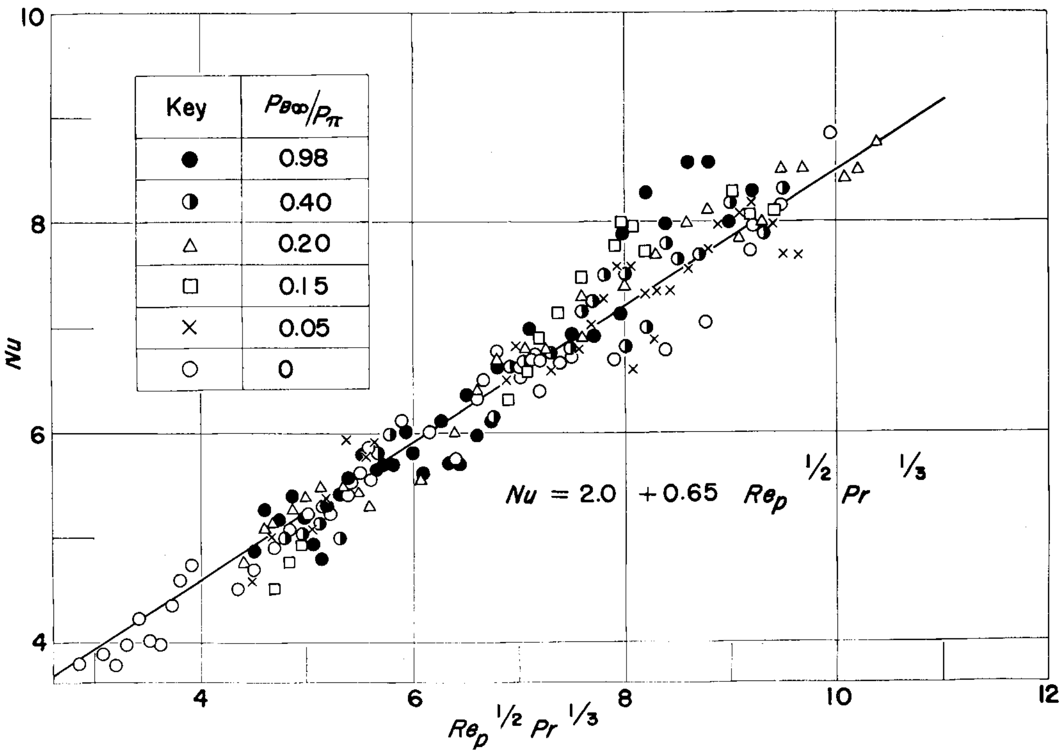


Fig. 5. Correlation of Nu vs. $Re_p^{1/2} Pr^{1/3}$.

The correlation of Nu vs. $Re_p^{1/2}\ Pr^{1/3}$ obtained in the present work is shown in Fig. 5. As shown in Fig. 5, the results have no significant differences with the gas composition, therefore the equation for the correlation in Fig. 5 was obtained in the full range of gas phase composition ($p_{Bm}/p_\pi = 1 \sim 0$) within 15% error as follows:

$$(h_c D_p/k) = 2.0 + 0.65\ (D_p G/\mu)^{1/3} (C_p \mu/k)^{1/3} \tag{9}$$

Table 1. Experimental conditions and data for heat transfer.

$p_{B\infty}/p_\pi$	$G\times10^2$	t_v	t_l	D_p	$-dD_p/d\theta\times10^4$	$q_T\times10^3$	$q_c\times10^3$	$h_c\times10^3$	Nu	Re_p	Pr
[—]	[g/cm² sec]	[°C]	[°C]	[cm]	[cm/sec]	[cal/cm² sec]	[cal/cm² sec]	[cal/cm² sec °C]	[—]	[—]	[—]
0	2.52	147.1	100.0	0.1684	4.33	112	93.0	2.02	5.56	31.0	1.02
				0.1549	4.53	117	98	2.12	5.37	28.5	"
				0.1411	4.87	126	106	2.29	5.28	26.0	"
				0.1260	5.23	135	114	2.46	5.06	23.2	"
				0.1099	5.57	144	121	2.61	4.69	20.2	"
0.05	7.68	133.9	99.7	0.1618	4.30	112	98	2.89	7.69	90.5	0.998
				0.1527	4.80	124	110	3.26	8.19	85.4	"
				0.1429	5.00	130	115	3.40	7.99	79.9	"
				0.1328	5.10	132	117	3.46	7.56	74.3	"
				0.1225	5.05	131	115	3.40	6.89	68.9	"
0.20	10.39	132.7	95.0	0.1671	5.30	138	124	3.34	8.73	116	0.926
				0.1509	5.80	152	136	3.67	8.66	104	"
				0.1322	6.10	159	143	3.85	7.96	91.8	"
				0.1127	7.15	187	169	4.54	8.00	78.0	"
				0.0901	8.20	215	192	5.17	7.29	62.3	"
0.40	6.94	118.3	85.4	0.1577	4.20	111	99	3.06	7.26	66.2	0.849
				0.1492	4.15	110	98	3.01	6.76	62.6	"
				0.1408	4.35	115	103	3.16	6.70	59.1	"
				0.1318	4.60	122	109	3.35	6.65	55.3	"
				0.1223	4.60	122	108	3.33	6.13	51.2	"
0.98	3.96	42.1	18.1	0.1592	1.83	53.5	48.5	2.04	5.18	34.3	0.699
				0.1513	1.83	53.5	48.1	2.03	4.90	32.6	"
				0.1425	2.07	60.5	54.7	2.30	5.23	30.7	"
				0.1328	2.20	64.3	57.9	2.44	5.17	28.6	"
				0.1223	2.33	68.1	60.8	2.56	5.00	26.3	"

2. Mass Transfer Coefficients

2.1 Experimental procedures

The precision of the measuring data was demanded more severely in the determination of mass transfer coefficient than in the one of heat transfer coefficient. For this sake, the junction of the fine thermo-couple was fixed about one millimeter below the tail-end of the fine glass rod. The drop was suspended with both, as the junction of the thermo-couple should be surely placed in the drop.*

The compositions of gases were obtained by analysis of the sample gas directly sucked from the test section. The water vapor was caught out in the P_2O_5-tube and the volume of the air dried up was measured by the method of replacement with salt-saturated water. (It was estimated that the errors in the analysis of the compositions of the gases were less than 0.2%.)

2.2 Transport properties used

The diffusivity of water vapor in air that was calculated by Ranz et al.[2] based on the literature 19) was used.

2.3 Calculation of mass transfer coefficients

The mass balance is taken as follows:

$$-(\rho_l/M_A A)\ (dV/d\theta) = k_G(p_{A0}-p_{A\infty}) \tag{10}$$

From Eqs. (3) and (10), k_G was calculated by Eq. (11).

$$k_G = -\frac{\rho_l}{2M_A(p_{A0}-p_{A\infty})}\left(\frac{dD_p}{d\theta}\right) \tag{11}$$

The effect of mass transfer rate on k_G[20] was 0.9% at most on this case, therefore no correction was done.

2.4 Experimental results for mass transfer

Experimental conditions were as follows:

$G = 3.96\times10^{-2}\sim12.0\times10^{-2}$ g/cm² sec $\qquad t_v = 42\sim142°C$

$\Delta p = p_{A0}-p_{A\infty} = 12.0\sim24.9$ mmHg

$(p_{Bm}/p_\pi) = 0.38\sim0.98 \qquad Re_p = 9\sim120$

The typical experimental results for mass transfer are shown in Table 2. The

* Some error was produced by heat conduction through thermo-couple in temperature measurement, but was negligible when the junction of the thermo-couple was submerged about 1 mm into the drop. (Fig. 3 (c))

Table 2. Experimental conditions and data for mass transfer.

p_{Bm}/p_π	$G\times 10^2$	t_v	t_l	Δp	D_p	$-dD_p/d\theta\times 10^4$	$k_G\times 10^7$	Sh	$Sh\left(\frac{p_{Bm}}{p_\pi}\right)^{-0.20}$	Re_p	Sc
[—]	[g/cm² sec]	[°C]	[°C]	[mmHg]	[cm]	[cm/sec]	[mol/cm² sec mmHg]	[—]	[—]	[—]	[—]
0.384	6.96	141.6	87.56	15.3	0.2124	6.80	12.0	6.15	7.45	87.9	0.630
					0.2052	6.90	12.1	6.02	7.29	84.8	»
					0.1986	6.85	12.1	5.79	7.01	82.1	»
					0.1915	7.08	12.5	5.76	6.98	79.2	»
					0.1485	6.95	12.2	5.44	6.59	76.3	»
0.546	7.55	141.6	80.33	22.4	0.1806	7.90	9.52	5.95	6.72	75.7	0.630
					0.1726	8.15	9.81	5.87	6.63	72.3	»
					0.1643	8.55	10.3	5.86	6.61	68.9	»
					0.1555	8.65	10.4	5.61	6.33	65.3	»
					0.1470	8.75	10.6	5.36	6.05	61.6	»
0.746	7.82	120.2	66.84	24.9	0.1981	6.05	6.60	5.58	6.97	81.5	0.636
					0.1920	6.15	6.71	6.47	6.86	78.9	»
					0.1858	6.30	6.88	6.41	6.79	76.4	»
					0.1794	6.60	7.20	6.47	6.86	73.8	»
					0.1726	6.90	7.53	6.52	6.91	70.9	»
0.982	8.17	62.0	30.2	15.9	0.1682	3.13	5.44	6.72	6.74	71.0	0.665
					0.1553	3.73	5.79	6.61	6.63	65.5	»
					0.1416	3.57	6.21	6.45	6.47	59.7	»
					0.1267	3.88	6.75	6.28	6.30	53.4	»
					0.1106	4.15	7.21	5.87	5.89	46.5	»

correlation of Sh vs. $Re_p^{1/2}\ Sc^{1/3}$ obtained in the present work is shown in Fig. 6. It is shown that as the decrease of p_{Bm}/p_π, the values of Sh corresponding to the same value of $Re_p^{1/2}\ Sc^{1/3}$ decrease. The values of Sh at $Re_p^{1/2}\ Sc^{1/3}=7.5$ are plotted in Fig. 7, and it may be said that Sh is proportiona.l to $(p_{Bm}/p_\pi)^{0.20}$. The correlation of $Sh(p_{Bm}/p_\pi)^{-0.20}$ vs. $Re_p\ Sc^{2/3}$ is shown in Fig. 8. Then the following equation was obtained within $\pm 15\%$ error.

$$\left(\frac{k_G M_m D_p p_{Bm}}{\rho \mathscr{D}_v}\right)\left(\frac{p_{Bm}}{p_\pi}\right)^{-0.20} = 2.0+0.65\left(\frac{D_p G}{\mu}\right)^{1/2}\left(\frac{\mu}{\rho \mathscr{D}_v}\right)^{1/3} \tag{12}$$

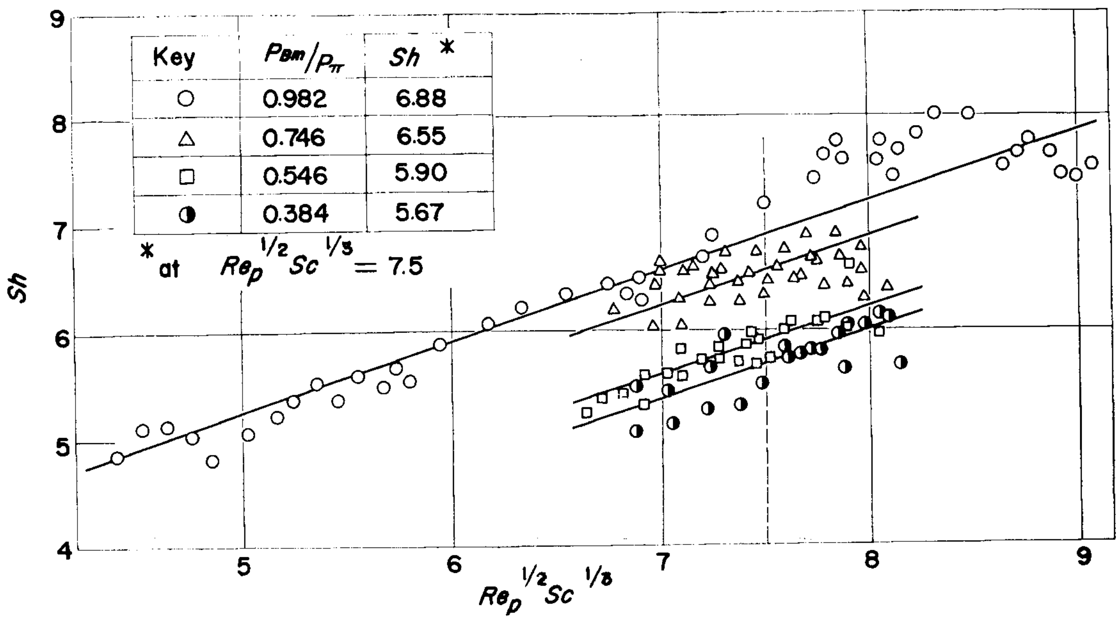


Fig. 6. Correlation of Sh vs. $Re_p^{1/2}\ Sc^{1/3}$.

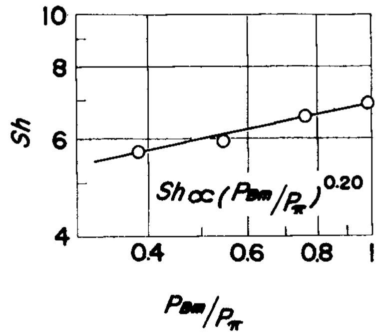


Fig. 7. Correlation of Sh vs. p_{Bm}/p_π.

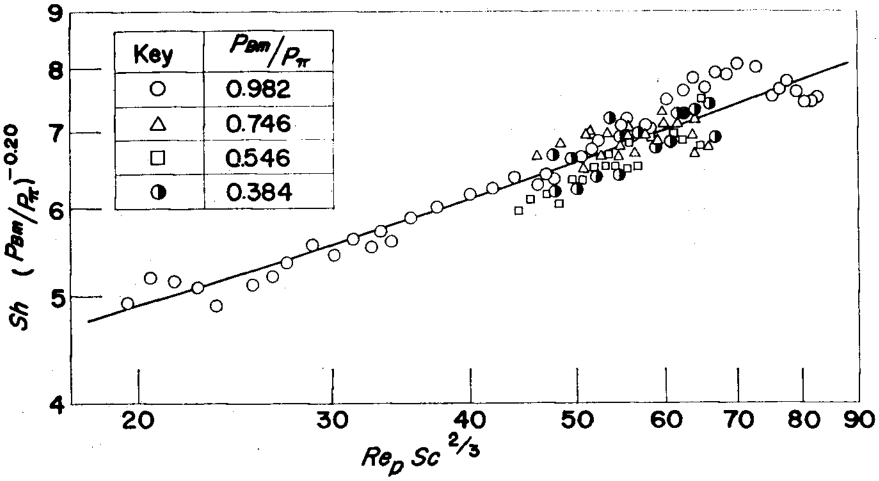


Fig. 8. Correlation of $Sh\ (p_{Bm}/p_\pi)^{-0.20}$ vs. $Re_p Sc^{2/3}$.

3. Comparison with Previous Works

About the heat transfer coefficient h_c, there has been no influence of composition of gas on Nu and the equation for Nu obtained in the present work agreed practically with the one of Ranz et al.[2] Hence these results do not agree with the one of Cairns et al.[7] who have observed the effect of (p_{Bm}/p_π) on Nu. The present result differs from the one of Wenzel et al.[4] also, by which there was difference between super-heated steam and air.

About the mass transfer coefficient k_G, the value of k_G was in proportion to $(p_{Bm}/p_\pi)^{-0.8}$ in the present work. The previous works are summarized in Table 3

Table 3. Effects of partial pressure of non-diffusional component on mass transfer coefficient.

Author	System	p_{Bm}/p_π	n*
Film theory			1
Hanks & McAdams[21]	Ammonia-air (Absorption)	0.35–0.94	1
Hinchley & Himus[22]	Water-air (Evaporation)	0.55–0.99	1
			0
Wade[23]	Water, acetone, benzene-air (Evaporation)	0.68–0.99	1
			0
Boelter, et al.[24]	Water-air (Evaporation)	0.5 –0.99	0.75
Gilliland & Sherwood[25]	Water, solvent-air (Evaporation)	0.7 –0.99	1
Cairns & Roper[7]	Water-air (Evaporation)	0.15–0.97	0.83
Westkaemper[8]	Tetrachloromethane-air (Evaporation)	0.30–1.0	(0.83)
Shulman & Delany[9]	Tetrachloromethane-air (Evaporation)	0.10–0.50	2/3
This work	Water-air (Evaporation)	0.38–0.98	0.80

* n : $k_G \propto p_{Bm}^{-n}$

from the view point of the effect of p_{Bm} on k_G. The experiments by Hanks et al.[21], Hinchley et al.[22], Wade[23], Boelter et al.[24] were not carried out for the purpose of investigating the effect of p_{Bm}, and these results have been rearranged by Cairns et al.[7], hence may not have a high reliability. The work of Gilliland et al.[25] had no wide variation of p_{Bm} and the effect of p_{Bm} on k_G may not be so correct also. Cairns et al.[7] have obtained experimentally the results that $h_c \propto (p_{Bm}/p_\pi)^{-0.27}$ and $n=0.83$ for k_G, in Table 3. Shulman et al.[9] have obtained that $n=2/3$ for k_G using the packed column. The present result shows fairly good agreement with their results.

From Eqs. (9) and (12), the analogy between heat and mass transfer can be obtained. These two equations are shown on Fig. 9 and the results by previous workers for a single sphere are plotted on the same figure. The equations obtained in the present work show good agreement with those data for the wide range of $Re_p Pr^{2/3}$ or $Re_p Sc^{2/3}$.

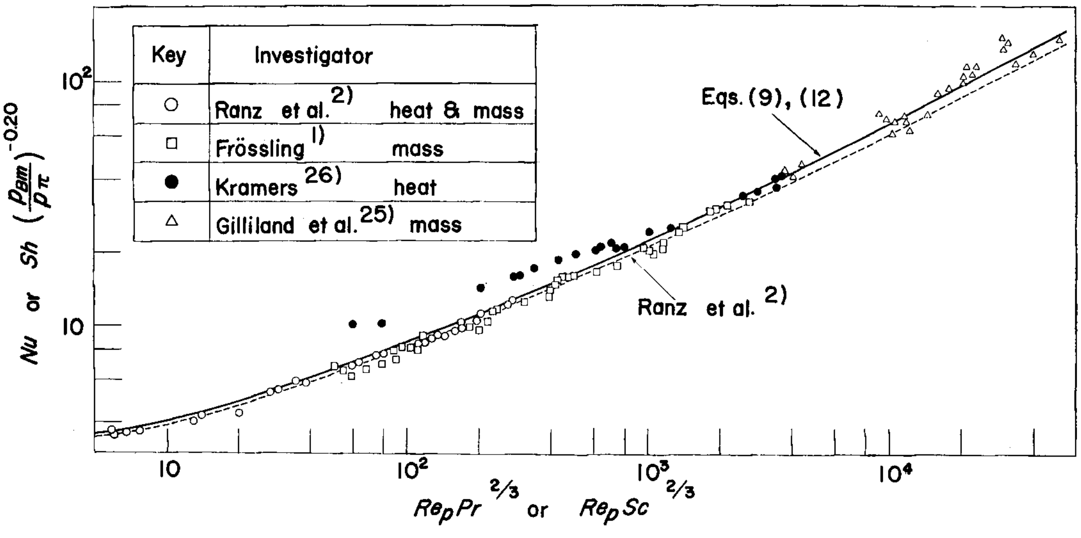


Fig. 9. Comparison of Eqs. (9) and (12) with other works.

Conclusion

For the purpose of determining the effects of the partial pressure of non-diffusional component on heat and mass transfer coefficients, the evaporations from a single water drop in the stream of super-heated steam and various steam-air mixtures were investigated experimentally. The heat and mass transfer coefficients were calculated from the evaporation rates, and Eqs. (9) and (12) were obtained.

Appendix

The schematic look of a fine glass rod submerged into a water drop is shown in Fig. A. The following assumptions may be permitted for this case.

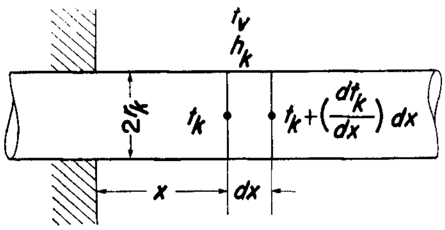


Fig. A. Schematic diagram of fine glass rod.

(i) The length of the rod is infinite. (ii) The temperature distribution of the rod on radial direction is negligible. (iii) The heat transfer coefficient between the rod and gas is constant and far smaller than the one between the rod and water. (iv) The temperature of the gas is constant along the rod.

From these assumptions, the diffential equation of stationary heat conduction is obtained as follows:

$$\left.\begin{aligned} &\frac{d^2t_k}{dx^2}-\frac{2r_kh_k}{k_kA_k}(t_k-t_v)=0 \\ &\text{B.C. } x=0; \quad t_k=t_l \\ &\qquad x=\infty; \quad t_k=t_v \end{aligned}\right\} \tag{a}$$

Solving Eq. (a),

$$t_k=t_v-(t_v-t_l)\,e^{-\sqrt{\alpha}\,x} \tag{b}$$

$$\alpha=2h_k/k_kr_k \tag{c}$$

Differentiating Eq. (b) with x gives Eq. (d).

$$\left.\frac{dt_k}{dx}\right|_{x=0}=(t_v-t_l) \tag{d}$$

Eq. (8) is derived from Eq. (d).

Nomenclature

A	:	surface area of drop	[cm^2]
C_p	:	specific heat of gas at constant pressure	[cal/g°C]
D_p	:	diameter of drop	[cm]
$\mathcal{D}_v$	:	diffusivity of water vapor in air	[cm^2/sec]
F_A	:	angle factor for radiation	[—]
F_E	:	emissivity factor for radiation	[—]
G	:	mass flow rate of gas	[g/cm^2 sec]
h_c	:	heat transfer coefficient	[cal/cm^2 sec °C]
h_c'	:	apparent value of heat transfer coefficient	[cal/cm^2 sec °C]
h_k	:	heat transfer coefficient between the glass rod and the main gas stream	[cal/cm^2 sec °C]
j_h	:	j-factor for heat transfer	[—]
k	:	thermal conductivity of gas	[cal/cm sec °C]
k_G	:	mass transfer coefficient	[mol/cm^2 sec mmHg]
k_k	:	thermal conductivity of the glass rod	[cal/cm sec °C]
M	:	molecular weight	[g/mol]
N	:	correction factor of Ackermann's effect	[—]
Nu	:	h_cD_p/k, Nusselt number	[—]
p	:	partial pressure	[mmHg]
P	:	$C_p\mu/k$, Prandtl number	[—]
q	:	rate of heat transfer to drop	[cal/cm^2 sec]
q_c	:	rate of heat transfer to drop by condutcion and convection of gas	[cal/cm^2 sec]
r	:	radius	[cm]
Re_p	:	D_pG/μ, Reynolds number	[—]
Sc	:	$\mu/\rho\mathcal{D}_v$, Schmidt number	[—]
Sh	:	$k_GM_mD_p\,p_{Bm}/\rho_m\mathcal{D}_v$, Sherwood number	[—]
t	:	temperature	[°C]
V	:	volume of drop	[cm^3]
x	:	distance	[cm]

Greek letters

Δ	:	difference in value of variable across the transfer path	[g/cm sec]
μ	:	viscosity of gas	[g/cm sec]
θ	:	time	[sec]
λ	:	latent heat of vaporization	[cal/g]
ρ	:	density	[g/cm^3]

Subscripts

A : for diffusing component
B : for non-diffusing component
k : for glass rod
l : for liquid
m : average value in the transfer path for gas mixture
r : for radiation
s : for wall of test section
T : total value
v : for gas mixture
π : total value
o : at the interface
∞ : in the main stream

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