Int. J. Heat Mass Transfer. Vol. 13, pp. 213–215. Pergamon Press 1970 Printed in Great Britain

SHORTER COMMUNICATIONS

ON THE LOCAL HEAT TRANSFER FROM ROUGH SPHERICAL PARTICLES

J. JOSS
Osservatorio Ticinese della Centrale Meteorologica Svizzera, Locarno-Monti

and

A. N. AUFDERMAUR
Eidgenössisches Institut für Schnee- und Lawinenforschung, Weissfluhjoch/Davos

(*Received* 30 *March* 1969)

1. INTRODUCTION

THE LOCAL heat transfer of ventilated rough spherical particles has recently attracted the interest of cloud physicists trying to understand the growth of rough and knobbly hailstones. Experimental studies were undertaken by Aufdermaur and Joss [1] and by Schuepp [2]. Both studies agreed in so far as a characteristic maximum of heat transfer appeared downstream from the forward stagnation point under the influence of roughness. However, according to Schuepp's experiments, the local differences smoothed out with increasing Reynolds number to an extent which was not expected from our experiments. Therefore, additional experiments were undertaken with similar particles and Reynolds numbers in order to find out, whether the heat transfer in air ($Pr = 0{\cdot}72$) would be similar to the mass transfer measured by Schuepp in a water tunnel by a chemiluminiscent method ($Sc \sim 1000$).

2. EXPERIMENTAL DEVICE

A brass sphere of 30 mm dia. and a local element of 87 mm^2 within the sphere (Fig. 1) were electrically heated and regulated individually to 0°C. The power consumed by the heater of the local element and the heater of the spherical body was measured in a cooled wind tunnel. In the working section of 500 cm^2 wind speed and temperature varied between 2·5 and 40 m/s and between -4 and -20°C respectively. For more information about the conditions, evaluation and errors of the experiment the reader is referred to an earlier description [1]. The turbulence in the present experiments was 0·4 per cent without grid and 5 per cent with grid G5 inserted. The spectral distribution was also described by Aufdermaur and Joss [2].

This new series of experiments was conducted with particles of the same roughness as in Schuepp's experiments. The roughness was achieved by sticking hemispherical metal caps of 3, respectively 5 mm dia. on to the sphere, corresponding to 5 and 8 per cent roughness (Fig. 1).

The thermal resistance at the interface sphere–metal cap was small enough to be negligible. This was checked by measuring the temperature difference between a metal cap and the brass sphere.

3. RESULTS

The results are given in terms of the dimensionless number $Nu.Re^{-\frac{1}{2}}.\ Pr^{-\frac{1}{3}}$. To calculate this number, the kinematic viscosity and thermal conductivity of air were taken for the temperature of the particle. The characteristic length was the diameter of a sphere of the same volume as the rough particle. For the area, the projection on the equivalent sphere was chosen.

Figure 2 shows the results plotted as a function of the polar angle φ from the forward stagnation point for three different Reynolds numbers. Roughness is given as a parameter for each curve. The results for a smooth sphere with roughness 0 per cent and the sphere covered by brass chips, roughness 1 per cent, are taken from our earlier experiments [1]. The heat transfer is gradually increased from the lowest to the highest Reynolds number. Under the influence of roughness, the local differences are not attenuated and the local maximum around $\varphi = 60°$ is typical. The additional influence of 5 per cent turbulence from grid G5 is moderate, and decreases for increasing roughness as can be seen from Table 1. This table gives the mean heat transfer number of the whole particle calculated by integrating the measured local values. The heating power consumed by the whole particle agreed with the values given in Table 1 within $\pm$ 7 per cent.

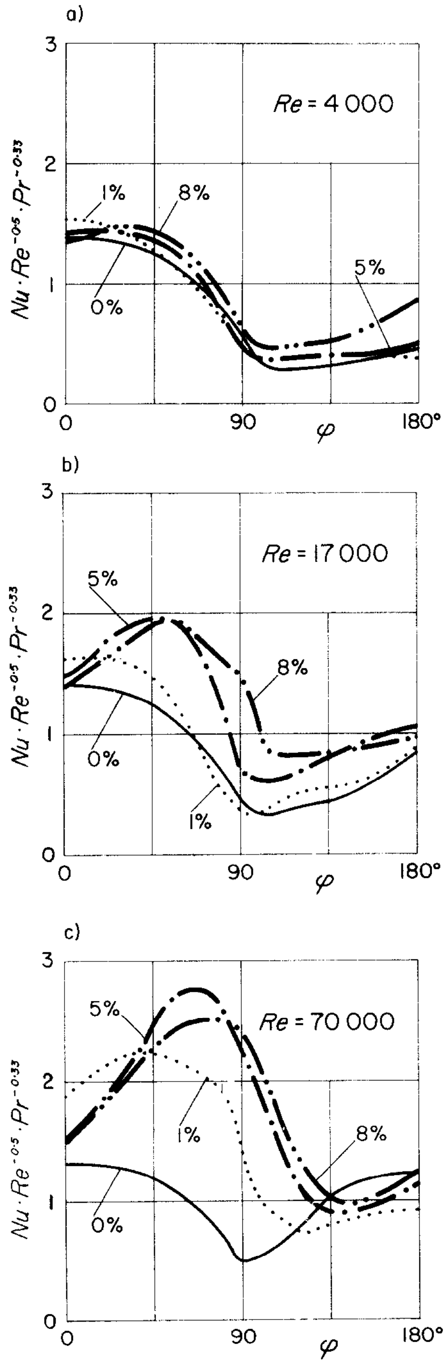

FIG. 2. $Nu.Re^{-\frac{1}{2}}.Pr^{-\frac{1}{3}}$ in function of the polar angle φ from the forward stagnation point. The roughness and the Reynolds numbers are given as parameters. Turbulence = 0·4 per cent.

Table 1. Mean value of $Nu.Re^{-\frac{1}{2}}.\ Pr^{-\frac{1}{3}}$ for the whole particle

	Particle roughness (height/dia)				
Re	0%	1%	5%	8%	Turbulence
4000	0·70	0·72	0·75	0·87	
17 000	0·73	0·81	1·18	1·33	0·4%
70 000	0·91	1·46	1·89	1·89	
4000	0·91	0·89	0·84	1·01	
17 000	1·02	1·23	1·44	1·59	5%
70 000	1·25	1·81	2·06	2·02	

4. CONCLUSIONS

Our experiments show a marked disagreement with Schuepp's results in so far as for our particles of e.g. 8 per cent roughness the ratio of the local maximum to the minimum transfer amounts to about 2·5 for both Re = 17 000 and Re = 70 000, whereas in Schuepp's experiments this ratio gets smaller with increasing Reynolds number (1·6 at Re = 40 000, same roughness). Furthermore, roughness is effective in the liquid system at a considerably smaller Reynolds number than in air. On the other hand, agreement with Schuepp and List [4] was found in so far as the total transfer increases under the influence of roughness up to a factor of two.

A possible explanation for the different transfer characteristics could be the difference of three orders of magnitude between the Prandtl and the Schmidt number of the two systems. As a consequence we expect the transfer boundary layer in air to be ten times bigger than in water for the same Reynolds number. Therefore, the liquid system is more sensitive to roughness, e.g. at Re = 4000 we measure an increase due to roughness of the total heat transfer of up to 20 per cent (Table 1) where Schuepp [2] finds up to 100 per cent. At Re = 4000 the boundary layer in air is of the order of 0·5 mm, the same range as the roughness elements used in the experiments, whereas in water the boundary layer was always considerably smaller than the roughness elements used. Hence we should not expect similarity at this Reynolds number. At $Re \sim$ 70 000 the roughness is large with respect to a hypothetical laminar transfer boundary layer in both systems. Under these conditions the roughness elements cause turbulence, which again makes the similarity theory questionable. Therefore it is understandable that the experiments in the two systems show different results.

REFERENCES

1. A. N. AUFDERMAUR and J. JOSS, A wind tunnel investigation on the local heat transfer from a sphere, including the influence of turbulence and roughness, *Z. Angew. Math. Phys.* **18**, 852–866 (1967).

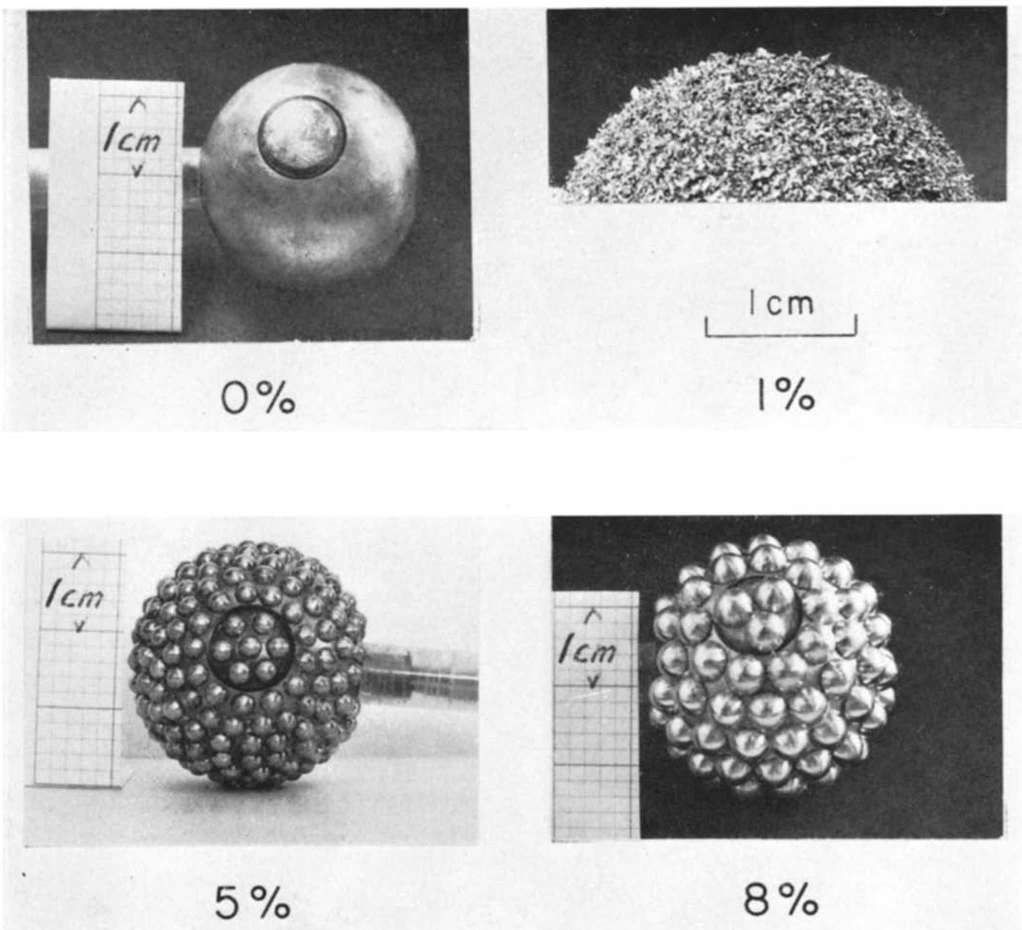

FIG. 1. Roughness of the four test particles.

2. P. H. SCHUEPP, Studies of the local heat and mass transfer of spherical hailstone models, *Proc. Int. Conf. Cloud Phys.*, Toronto, 416–421 (1968).
3. A. N. AUFDERMAUR and J. JOSS, Errata—a wind tunnel investigation on the local heat transfer from a sphere, including the influence of turbulence and roughness, *Z. Angew. Math. Phys.* **19**, 377 (1968).
4. P. H. SCHUEPP and R. LIST, The effect of surface roughness and turbulence on the heat and mass transfer of hailstones, *5th Conf. Severe Local Storms*, St. Louis, 287–292 (1967).

Int. J. Heat Mass Transfer. Vol. 13, pp. 215–218. Pergamon Press 1970. Printed in Great Britain

TWO-DIMENSIONAL SOLIDIFICATION IN A CORNER

L. M. JIJI*, K. A. RATHJEN† and T. DRZEWIECKI‡

(*Received* 19 *March* 1969)

NOMENCLATURE

C_p, specific heat at constant pressure $\left[\frac{\text{Btu}}{\text{lbm°F}}\right]$;
K, thermal conductivity $\left[\frac{\text{Btu}}{\text{min ft°F}}\right]$;
L, latent heat of fusion $\left[\frac{\text{Btu}}{\text{lbm}}\right]$;
T, temperature [°F];
T_i^*, dimensionless initial temperature $\equiv \frac{K_L}{K_s}\frac{T_i - T_F}{T_F - T_W}$;
T_L^*, dimensionless liquid temperature $\equiv \frac{K_L}{K_s}\frac{T_L - T_F}{T_F - T_W}$;
T_s^*, dimensionless solid temperature $\equiv \frac{T_s - T_F}{T_F - T_W}$;
t, time [min];
x, distance [ft];
x^*, dimensionless distance $\equiv \frac{x}{2\sqrt{(\alpha_s t)}}$;
y, distance [ft];
y^*, dimensionless distance $= \frac{y}{2\sqrt{(\alpha_s t)}}$.

Greek symbols
α, thermal diffusivity $= \frac{k}{\rho C_p}\left[\frac{\text{ft}^2}{\text{min}}\right]$;
β, ratio of latent to sensible heat $= \frac{L}{C_{p_s}(T_F - T_W)}$;
ρ, density $\left[\frac{\text{lbm}}{\text{ft}^3}\right]$.

Subscripts
F, freezing condition;
i, initial condition;
L, liquid region;
o, refers to condition on the interface $x = y$;
s, solid region;
W, wall condition.

* The City College of The City University of New York, N.Y.
† Grumman Aircraft Engineering Corporation, Bethpage, N.Y.
‡ Harry Diamond Laboratories, Washington, D.C.

INTRODUCTION

HEAT conduction in systems undergoing phase transformation is encountered in numerous engineering systems. Examples are freezing, melting, ablation, welding and casting. Much of the research in this field has been theoretical in nature, based on one-dimensional models. Limited theoretical, as well as experimental, work has been done on two-dimensional systems [1–4].

This note presents experimental findings of two-dimensional solidification of liquid in a corner. Comparisons are made with an analytical solution to this problem which was obtained in [1]. The problem considered in [1] is that of freezing or melting of a liquid, initially at a uniform temperature and filling the quarter-space $x, y > 0$, subject to a constant wall temperature.

EXPERIMENTAL APPARATUS

The apparatus consisted of a 12 in. square container, 2 in. deep with a 2 in. brass channel fitted along two sides. Polyurethane foam was used to insulate the four sides of the square. Air gaps 1 in. deep were provided to insulate the two other sides of the container. The system is illustrated in Fig. 1.

Temperature measurements were made with a grid of 37 chromel–alumel thermocouples. Thermocouple locations were arranged to check symmetry and interface location. A Sanborn recorder was used to monitor thermocouple readings. The accuracy of temperature readings is $\pm 0{\cdot}1$°F.