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SHORTER COMMUNICATIONS

ROUGHNESS OF HEAT TRANSFER SURFACES

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IN CONVECTIVE heat-transfer experiments within small diameter commerical tubing, surface roughness can have a significant effect in turbulent flow, even when the surface is carefully prepared. The magnitude of this roughness effect depends on the ratio of roughness height to hydraulic diameter or to viscous sublayer thickness. In general, the roughness elements are not homogeneous in either size or distribution, and the roughness is usually categorized in terms of a relative roughness ratio, (ε/D_h), suggested by Nikuradse [1]. In this case ε must be defined as an "equivalent sand grain diameter' as given by Moody [2]; with a 0·1 in. (2·5 mm) channel, which is not unusual in compact heat exchangers, 100 μin. (2·5 μ) elements will raise the friction factor by 10 per cent or more for $Re \gtrsim 30000$. The value of ε will depend on the size, shape, flow orientation, and distribution of the actual elements. Typically, to avoid the problem of accurately describing the detailed texture of the surface, adiabatic friction factor measurements are conducted and the results are compared to the so-called Moody diagram in order to obtain equivalent sand grain roughness. If one has complete faith in his measurements and covers a wide range of Reynolds numbers, this approach is quite reasonable. However, in many cases the investigator is limited in flow range and would like to use the adiabatic results to verify his equipment performance. If the adiabatic results are used to determine effective roughness, other effects, due to measurement error, may thereby be hidden. Further, for the design engineer, results of previous experiments will not be useful unless he knows a priori that the surface roughness has an identical character to the previous studies. From either standpoint, it is preferable to have a good surface characterization which is established independently from the experiment.

In industrial applications, the surface roughness is often measured by means of a profilometer. In typical practice, its conical tracer has a radius of curvature of about 0·0005 in. (0·0013 cm). As shown schematically in Fig. 1, this instrument will have the same response for a large variety of roughness elements with identical pitch when the elements are considerably smaller than the radius of the tracer point. Further, the vertical displacement of the tracer point can be very much smaller than the depth of the roughness elements if this situation occurs.*

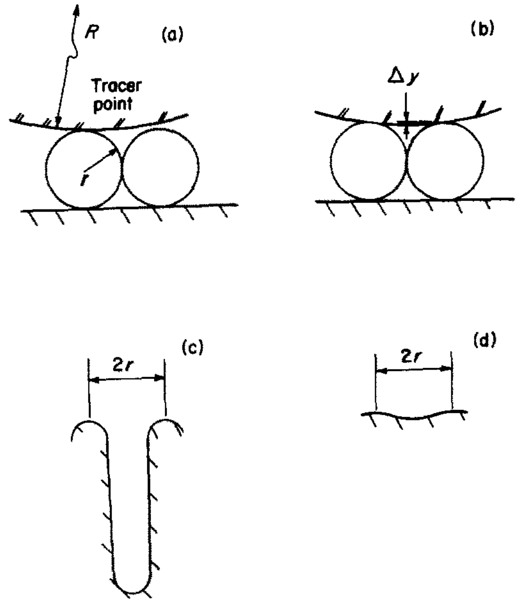

FIG. 1. Examples of surfaces causing identical profilometer point displacement, Δy, when $R \gg r$.

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* For an idealized two-dimensional case as shown in Figs. 1a and 1b, the maximum displacement of the tracer point is given by

$$\frac{\Delta y}{r} = 1 - \sqrt{\left[1 - \left(\frac{1}{1 - R/r}\right)\right]}.$$

The optical microscope can be used to obtain some information concerning surface roughness. However, in order to examine surfaces with roughness on the scale of 100 μin., it is necessary to use magnifications of about 1000 ×. At these magnifications the depth of focus is so short that the shape of the roughness element usually is not clear. It is possible to obtain order of magnitude estimates of the height of roughness elements by calibrating the microscope's mechanical focus mechanism and then measuring the travel required to focus on different regions of the surface. However, from an examination of a Moody diagram [2], it is evident that better resolution is necessary if one is to expect accurate results; in the "fully-rough" flow regime, doubling the roughness size leads to a ten to twenty-five per cent increase in friction factor but differences in depth of a factor of two may not be discerned with the optical method. Additionally, the shape in the vertical plane may be important [1] and it can not be readily determined optically.

MEASUREMENTS WITH THE SCANNING ELECTRON MICROSCOPE

The scanning electron microscope offers great potential as a tool for heat transfer surface characterization. Its extremely long depth of field overcomes many of the objections of the above methods. Shown in Fig. 2 are several photographs of surfaces from 0·1 in. square ducts being used for measurement of convective heat-transfer coefficients. The material is Inconel alloy 600 described by the manufacturer as having clean, bright, uniform outside and inside surfaces. It was temper-annealed before forming by extrusion. The inside surface is normally described by the manufacturer as having a 125 μin. RMS maximum surface roughness; measurements with a profilometer indicated a surface roughness of 20–30 μin. ($\simeq \frac{1}{2}\mu$). Photographs are obtained with a Polaroid camera mounted on the video display of a Cambridge "Stereoscan 600" scanning electron microscope.

Figures 2a and 2b are at successively higher magnifications with a sample of the test section material still in the "as received" condition. The direction of the drawing and, hence, the flow direction in the tube are approximately in the vertical direction on the picture. While the contrast is not optimized, a number of ridges are visible in the flow direction. In the right-hand photograph, the region around one of the ridges has been magnified by another order of 10. The contrast is better here; one large ridge along the right-hand side is quite evident and a smaller, more jagged one appears down the center of the figure. By tilting the sample holder through five degrees, another photograph of the same view was obtained. Thus, it is possible to obtain three dimensional effects. By examining the two pictures in a stereoscopic viewer it is possible to assess the size, shape, orientation and distribution of the roughness elements. It should be noted that the angle between views must be small for the purpose of visualization, but in order to make three-dimensional measurements the angle between views should be larger. For the surfaces shown, the roughness elements are essentially oriented vertically with respect to the surface. Thus, only one picture is necessary to obtain the required measurements as long as the viewing angle is substantially off the perpendicular. In this particular case, with the surface oriented at an angle of 46° for Figs. 2a and 2b, trigonometric calculations indicate:

1. Scattered and irregularly shaped roughness elements as high as 3 μ (about six times larger than indicated by the profilometer).
2. Randomly spaced ridges about 2–3 μ in height, 4–5 μ in width, 5–10 μ in length and typically spaced about 5 μ apart.

Thus, the surface is comparable to longitudinally-finned tubing in some respects. Since the ridges are oriented parallel to the flow direction very little effect on friction is expected. The main contribution is likely to be from the isolated roughness elements. Though as large as 3 μ, their irregular size and spacing make it difficult to interpret them in terms of an equivalent sand grain distribution. At best, it can probably be claimed that the equivalent sand grain diameter would be less than 3 μ and, consequently, the relative roughness would be less than 0·0013 for a 0·1 in. duct.

If the same material is heated in air, more illuminating pictures are obtained. Figures 2c and 2d show views of the inner surface of the test section used by Battista and H. C. Perkins [3]. While it might have been desirable to compare the same spot on the same specimen before and after use, such an approach was not possible partly due to limited availability of the scanning electron microscope. However, the two specimens were from the same production run by the manufacturer. The specimens were mounted adjacent to one another on the same sample holder at the same time prior to preparation for viewing. Thus, the two specimens underwent identical preparation procedures and any differences in their appearances are believed to be primarily a consequence of cyclic heating in air.

While the detailed temperature–time history was not recorded for the heated specimen, it has been estimated from memory that it was cycled from room temperature to approximately 1700° R a number of times. The total heating time was probably of the order of several weeks. Heating experiments were conducted with pressurized air flowing through the tube. Despite the difference in contrast, it seems reasonably clear that the two photographs at magnifications of 450 × show markedly different surface textures. One could quite readily characterize the heated surface as being represented by a "sand grain" type of roughness. Due to press of time, no stereoscopic photographs were taken of this sample, but it appears reasonable to claim that the depth dimension and the horizontal dimensions of these surface elements are approximately the same. Typical dimensions then would be about 7 μ (300 μin.). Since the hydraulic diameter of this test section was approximately 0·1 in. (0·25 cm) the relative roughness would be 0·003. From another assessment of the photographs, the typical spacing is found to be about 25 μ (1000 μin.). Comparing these values to Schlichting's measurements [1], at this spacing we would expect the "equivalent sand grain roughness" to be about the same as our measurements of the roughness. However, Schlichting's results show significant variation with spacing in this range.

In comparison with the measurements on the fresh tubing, it appears that the relative roughness doubled or tripled as a consequence of the cyclic heating. The resulting increase

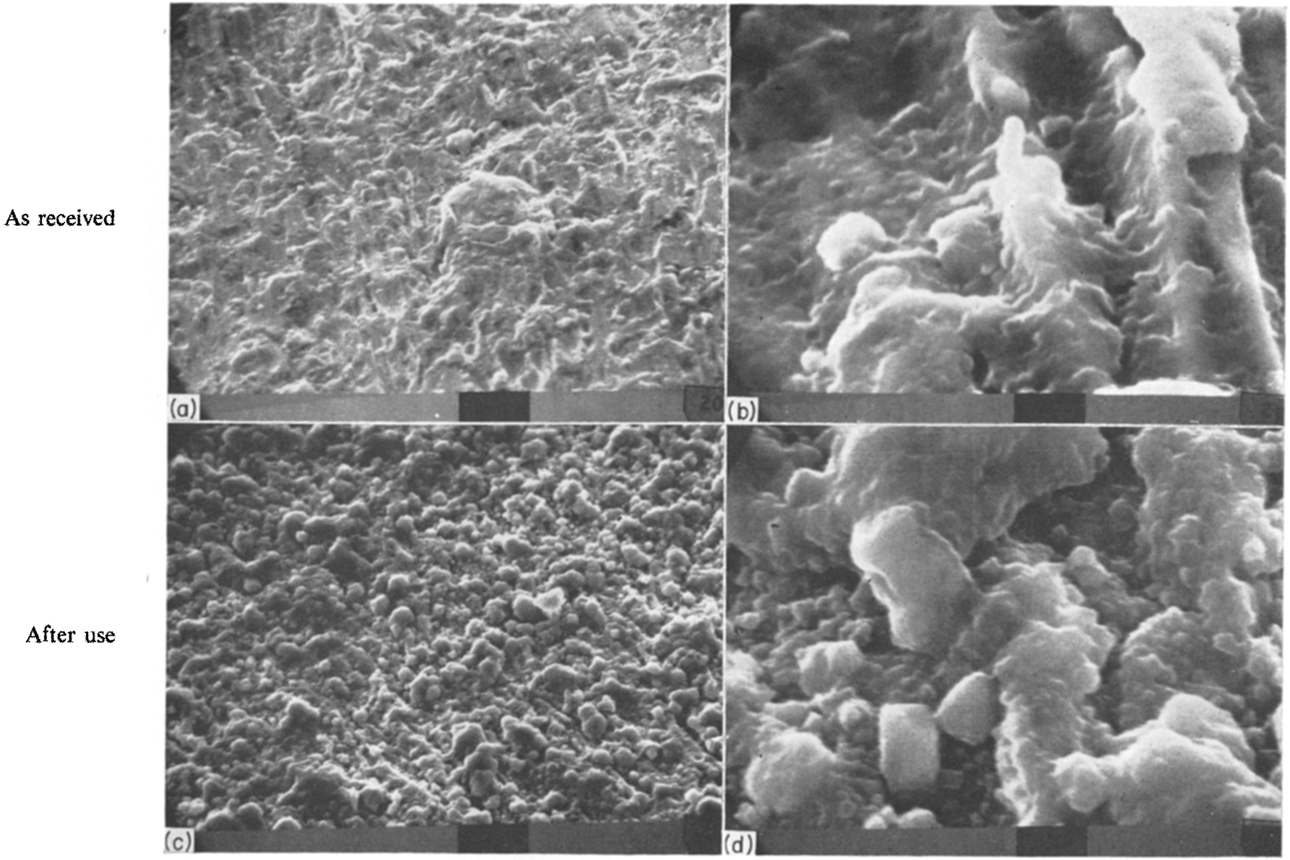

FIG. 2. Scanning electron microscope comparison of a fresh surface (upper) with surface after use in moderate temperature convective heat transfer experiment (lower). In left-hand photographs small black rectangle is 20 μ across, while in right-hand two it represents 2μ.

Magnifications: (a) and (c) 450×.
(b) and (d) 4500×.

in friction factor would be ten to twenty per cent for $Re \gtrsim 30000$.

The metallurgical explanation for the apparent increase in roughness may come from either of two main sources. It is evident that there has been some surface oxidation, but whether the increase in roughness is due to repeated cracking of the protective oxide film (as may occur with nickel–chromium alloys such as Inconel [4]) or whether it may be due to depletion of specific components from preferential attack has not been determined in the present study.

SUMMARY

A scanning electron microscope was used mainly for order-of-magnitude measurements in the present study. Further, only a few measurements were possible due to the short time the equipment was available. However, these limited measurements showed a significant change in roughness dimensions and shape due to heating of Inconel and, perhaps more importantly, demonstrated a new means to measure natural roughness elements smaller than the radius-of-curvature of the typical industrial profilometer. It seems clear that the scanning electron microscope offers considerable potential for more complete characterization of the texture of the surfaces employed in convective and radiative heat transfer applications. By using electronic signal processing, it is likely that useful measurements of the size spectra could be readily recorded and reduced. The improved characterization of the shape is also valuable.

ACKNOWLEDGEMENTS

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REFERENCES

1. H. Schlichting, *Boundary Layer Theory*, 4th ed. McGraw-Hill, New York (1960).
2. L. F. Moody, Friction factors for pipe flow, *Trans. Am. Soc. Mech. Engrs* **66**, 671 (1944).
3. E. Battista and H. C. Perkins, Turbulent heat and momentum transfer in a square duct with moderate property variations, *Int. J. Heat Mass Transfer* **13**, 1063–1065 (1970).
4. J. Moreau and J. Bénard, Étude comparés du mecanisme de l'oxydation des alliages binaires fer–chrome, nickel–chrome et nickel–aluminum, *C.R. Acad. Sci. Paris* **237**, 1417 (1953).

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CORRECTION ON THE LENGTH OF ICE-FREE ZONE IN A CONVECTIVELY-COOLED PIPE

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NOMENCLATURE

Bi,	Biot number, hR/k;
h,	heat transfer coefficient;
k,	thermal conductivity;
Pe,	Péclét number $\bar{U}R/\kappa$;
R,	pipe radius;
T,	temperature;
U,	axial velocity;
x,	dimensionless axial distance, $X/(Pe\,R)$;
λ,	eigenvalue;
Γ,	Gamma function;
ϵ,	superheat ratio, $(T_{in} - T_f)/(T_f - T_c)$;
κ,	thermal diffusivity.

Subscripts

c,	external coolant;
e,	ice-free length;
f,	interface;
in,	inlet;
w,	water.