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THE DETERMINATION OF LOCAL MASS-TRANSFER COEFFICIENTS BY HOLOGRAPHIC INTERFEROMETRY—I

GENERAL PRINCIPLES: THEIR APPLICATION AND VERIFICATION FOR MASS-TRANSFER MEASUREMENTS AT A FLAT PLATE EXPOSED TO A LAMINAR ROUND AIR-JET

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Abstract—Methods are described of applying the powerful techniques of holographic interferometry to the profilometric measurement of mass-transfer rates at solid–fluid interfaces, with great advantages of speed, precision and comprehensiveness of data acquisition and display.

Maintenance of virtually constant optical quality at the transferring surface, vital for the production of satisfactory interferograms, is effected by the use of a mass-transferring coating consisting of a smooth layer of elastomer initially charged with a volatile (or soluble) swelling agent. Shrinkage of this coating due to transfer of the swelling agent to the fluid stream can then be recorded as an array of interference fringes when reflection or transmission holograms of the initial and final states of the surface layer are superimposed. Such interferograms provide a synoptic record of the spatial variation of transfer coefficient over the entire surface viewed at the holographic plate.

The precision and completeness of the data provided by these methods is demonstrated here by their application to the mapping of the transfer coefficient variation over the surface of a flat plate exposed to normal or tangential laminar air jets of known velocity. For the former case the results agree closely with an available analytical solution.

NOMENCLATURE

d,	diameter of the nozzle [cm];
D,	diffusion coefficient for ethyl salicylate in silicone rubber coating [cm^2/s];
D',	diffusion coefficient of ethyl salicylate in air [cm^2/s];
h,	nozzle to plate distance [cm];
i_1,	angle between the illuminating beam and the normal to the surface;
i_2,	angle between the viewing beam and the normal to the surface;
k,	mass-transfer coefficient at solid–fluid interface [cm/s];
n,	positive integer describing the fringe order number;
p,	vapour pressure of ethyl salicylate over polymer coatings swollen to equilibrium with it [mm Hg];
T,	absolute temperature [°K];
u,	nozzle exit velocity [cm/s];
x,	radial distance from stagnation point [cm];
Re,	Reynolds number, $\frac{ud}{\nu}$;
Sc,	Schmidt number for ethyl salicylate/air system, $\frac{\nu}{D'}$;
Sh_x,	local Sherwood number at point x, $= \frac{kx}{D'}$.

Greek symbols

δ,	recession of the polymer coating;
δ_1,	initial thickness of polymer coating;
η,	refractive index of polymer coating;
Δ,	change of optical path length;
λ,	wavelength of laser light—633×10^{-7} cm;
ν,	kinematic viscosity of air;
ρ,	density of shrinking polymer coating;
ϕ,	volume fraction of swelling agent in swollen polymer coating;
χ_m,	constant for polymer/swelling agent system, characterizing the degree of interaction between the components. Derived from Flory–Huggins equation (degree of cross-linking not taken into account).

INTRODUCTION

THE POWERFUL technique of holographic interferometry has been widely used for the accurate measurement of surface displacement and deformation [1, 2]. It is a very sensitive non-contact method of measurement which allows the entire pattern of configurational change in the surface to be revealed panoramically, without the necessity of deducing it point by point.

The aim of this paper is to show how holographic interferometry may be applied to the profilometric determination of mass-transfer coefficients at solid–fluid interfaces and to demonstrate its substantial advantages over other available techniques of mass-transfer measurement. To this end, we here describe experiments in which a laminar round jet of air impinged normally on a flat plate from whose specially coated surface volatile material was transferred to the air stream. We show that examination of this system by holographic methods readily yields comprehensive information about the spatial variation of mass-transfer coefficient over the flat surface for a Schmidt number region not hitherto investigated experimentally; that these results are highly reproducible; and that those for the wall jet region, beyond a certain distance from the stagnation point, are in excellent agreement with the theoretical predictions of Scholtz and Trass [3].

GENERAL PRINCIPLES

In making a holographic interferogram, a photographic plate is first exposed in one of the standard optical systems for holography, such as that of Fig. 1, to obtain a hologram of the test object in its initial state. A second exposure is then made on the same plate after the object has suffered the surface displacement or deformation to be studied. At reconstruction of the double-exposed hologram by illumination with the coherent reference beam, a set of interference fringes is observed, the characteristics of which depend on the positional or configurational changes in the surface of the test object occurring between the making of the two holograms. The fringes are simply loci of equal displacement of the surface elements of the test object.

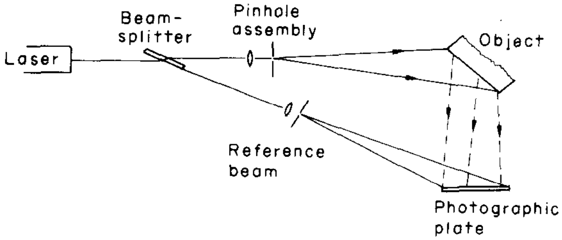

FIG. 1. Optical arrangement for recording a hologram.

The essential advantage of holographic, as opposed to classical, non-coherent, interferometry is that displacements of ordinary, optically imperfect, surfaces may be observed by the former technique, but not by the latter. All optical imperfections and details of the surface texture are subtracted out when holographic reconstructions of the initial and final configurations are compared.

This subtractive effect can only be complete, however, when the surface texture is unchanged in the displacement, as in a mechanical translation. If the displacement is due to the removal of the original surface layers of polycrystalline solid by sublimation or dissolution, as in a conventional profilometric mass-transfer experiment, the surface structure is altered and no distinct fringe system is produced when the initial and final states of the surface are compared holographically.

Accordingly, earlier attempts by one of us (N.M.) to apply holographic interferometry to measure small recessions of a solid naphthalene surface subliming into a stream of air proved unsuccessful, apparently because of changes in the optical quality of the surface during sublimation.

In the present work, this difficulty was overcome by replacing the subliming solid by a suitably chosen polymeric surface coating capable of being swollen in a reversible manner by a volatile or soluble swelling agent [4]. Transfer of this swelling agent to or from the polymer surface by the experimental fluid stream results in local changes in the coating thickness [5]. Unlike the surface of a subliming solid, the surface of the swollen polymer may remain essentially optically featureless during transfer. The change of coating thickness can thus be recorded interferometrically by superimposing holograms of the coated surface before and after the transfer.

In extensive theoretical and experimental investigations of the behaviour of such swollen polymer coatings undergoing convective mass transfer of swelling agent to a stream in steady flow [5], it has been established in this laboratory that for a certain period t' after the commencement of transfer the shrinking rate remains sensibly constant. During this time, local rates of surface recession are everywhere effectively proportional to local fluid-side transfer coefficients; i.e. the diffusional resistance to transport from the interior of the coating is then negligible, while spatial variations of fluid-side transfer coefficient may be resolved over distances as small as the coating thickness, without significant errors due to lateral migration of swelling agent within the polymer.

The duration of the "constant rate" period, t', has been shown to depend upon the physico-chemical properties of the polymer/swelling agent system and upon the fluid-side mass-transfer coefficient, and charts are given in [5] from which t' can readily be determined when these factors are known. By proper choice of polymer and swelling agent, t' can be arranged to exceed the necessary duration of an experiment; under such conditions, measurements of the shrinking rate of the coating give reliable information about fluid-side mass-transfer coefficients.

Three methods have been used by us in the work described here to measure the recession of these plasticized polymer coatings interferometrically. These are:

(i) *Front-surface reflection method*

In this technique the surface of the test object is coated with a highly reflecting opaque layer of a polymer, swollen with a plasticizer of suitable volatility. The object is arranged on the optical table in such a way that specular reflections from it are received at the holographic plate. Superimposition of the holograms of the coated surface before and after exposure to the experimental fluid stream gives interference fringes, whose total number lying between any two points on the surface can be related to the difference between the recessions at those points when the geometry of the optical system and the wavelength of the light used are known [12].

(ii) *Transparent coating method*

This technique [4], suggested to us by Dr. K. Stetson, readily gives particularly well defined and well contrasted fringes, and was the first successfully used by us. In this method a diffusely reflecting substrate is coated with a transparent film of silicone rubber. Changes in the coating thickness cause changes in the optical path length of rays reflected from the substrate, owing to a difference in the refractive indices of polymer and air. Superimposition of the holograms of the coated surface before and after transfer therefore yield interference fringes from which the coating thickness changes can be deduced when the refractive index of the swollen coating, the angles of viewing and illumination and the wavelength of the light used are known.

This method has the considerable incidental advantage that a permanent reference grid can be ruled on the surface of the metal substrate to provide a co-ordinate system for locating the fringes.

(iii) *Transparent substrate method*

The test object itself is here transparent, and is surfaced with a transparent mass-transferring coating as before. The object beam is arranged to pass through the coated test body on its way to the photographic plate, where it forms a hologram by interference with the reference beam as usual. The superimposition of two such holograms formed before and after exposure of the coated surface to the experimental fluid again gives interference fringes which can be interpreted in terms of coating recession by the same methods as in the previous case, with the difference that the object beam traverses the mass-transferring coating once instead of twice.

The practical advantage of this method over the two previously described is that small deformations or displacements of the test object, at least those normal to its surface, do not generate fringes that distort, or may be confused with, those due to thickness changes in the coating caused by mass transfer. Thus, whereas methods (i) and (ii) necessitate the use of a test body having a very high degree of rigidity and dimensional stability, method (iii) does not.

GENERAL EXPERIMENTAL ARRANGEMENT

Optical system

The optical table used in the present work consisted of an 8 × 4 ft × 3·5-in thick steel-reinforced concrete slab with a smooth cemented surface, supported on two brickwork piers built up on pads of special antivibration rubber (McLennan Rubber Co. Ltd., Glasgow). The optical table was constructed *in-situ* and has been found to give adequate isolation against floor-borne vibrations, such as are apt to degrade the definition of the microscopic interference pattern forming the photographed hologram, reducing the brightness of the reconstructed image. The laser (Spectra-Physics 15 mW helium–neon) was mounted on an extension support, made of heavy steel angle, bolted to an end face of the concrete table. Although a laser of 1 mW power can be used successfully, problems of stability are much eased with the shorter times required with laser powers of 10 mW or more.

The arrangement of the optics for measuring coating thickness changes by holographic method (ii) is illustrated in Fig. 1. The laser beam is split by a 2-in dia optical glass plate, used here instead of the usual dielectric-coated beam splitter to give a satisfactory ratio of beam intensities for the case where the object is a diffuse reflector. The stronger, transmitted, beam from the beam splitter is passed through a microscope objective and a 20 μm pinhole. The latter acts as a spatial filter, removing from the beam fringe patterns created by dust particles on mirrors, in addition to minimizing multiple reflections between optical components prior to the pinhole. The emergent expanding beam of light scattered from the object surface is received at the holographic plate.

The part of the main beam that is reflected at the beam splitter is directed by two mirrors to a second microscope objective and pinhole assembly. The emerging expanding beam, thus refined, serves as the reference beam and illuminates the whole area of the holographic plate.

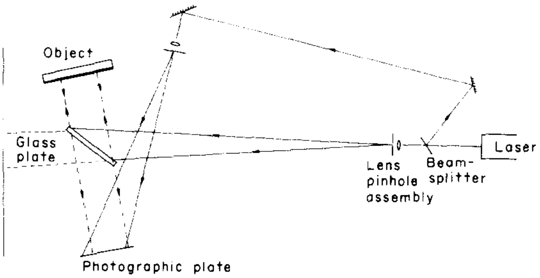

FIG. 2. Optical arrangement for front-surface reflection technique.

The optical arrangement for holographic method (i) is shown in Fig. 2. Using a glass plate (8 in square) one achieves normal illumination and normal viewing of the object. This arrangement has greater sensitivity than (ii) or (iii) and gives equally well defined and highly contrasted fringes.

The essential features of the optical arrangement for method (iii) are illustrated in Fig. 3.

The total path length of the object and reference beams, measured from the beam splitter to points where the rays meet again at the holographic plate, should be nearly equal for the central part of the object field. The difference of path length between rays reflected from the extremities of the object field and the corresponding rays of the reference beam is then minimized and the arrangement makes the best use of the coherence length available from the laser.

The angles between the illuminating and viewing directions and the normal to the object surface, whose values have to be known for the interpretation of the fringe patterns in terms of the magnitudes of the surface recessions, were measured by means of a toolmaker's vernier protractor to within 1° of arc.

The fringes formed in holographic interferometry can in general be located at any distance from the object plane. In the particular case when the direction of viewing coincides with that of the surface displacement vector, the fringes can be located in the plane of the object surface by suitable arrangement of the optics.

In the present work, the relative positions of the object, photographic plate and object-beam expander were arranged using a "Holo-diagram" [6, 7] traced on the optical table, so as to locate the fringes on the surface of the object, which was a flat plate in all these experiments. The essential principle of this arrangement is that the object plane is set as nearly as possible to lie in the surface of an ellipsoid whose focii are at the beam splitter and the photographic plate.

Experiments in which this optical set up was used gave fringes that maintained the same aspect whatever part of the developed hologram was viewed by the illumination of the reference beam. The fringes could thus be photographed without distortion or uncertainty of interpretation.

In the technique of double-exposure holographic interferometry used exclusively here, it was found experimentally that the ratio of the intensity of the reference beam to that of the object beam, measured at the photographic plate holder, could be as high as 16:1 to 25:1 with satisfactory results.

Photographic technique

The optimum exposure was determined by trial and was found to be related to the particular processing procedure employed. It was found experimentally that Agfa–Gevaert 8E70 and 8E75 plates exhibit a wider exposure tolerance than available alternatives. The former were accordingly used in almost all the holographic interferometry experiments. Fig. 4 gives a plot, determined by the authors, of the Gossen Luna Six exposure meter reading vs exposure time in seconds for the 8E70 plates.

The technique used to process the holograms was as follows. The development time was about 2–3 min in the recommended developer, Agfa–Gevaert G280C, at 20°C. After developing, the plate, which was mounted in a specially designed stand in which it remained fixed throughout the entire experiment, was immersed in water and rinsed by raising and lowering a special constructed fluid container, such as was used for all the processing liquids. Next, the plates were fixed for 3–4 min in Agfa–Gevaert G334 fixer and then rinsed in water. The plates were finally soaked in *iso*-propyl alcohol and allowed to dry in air.

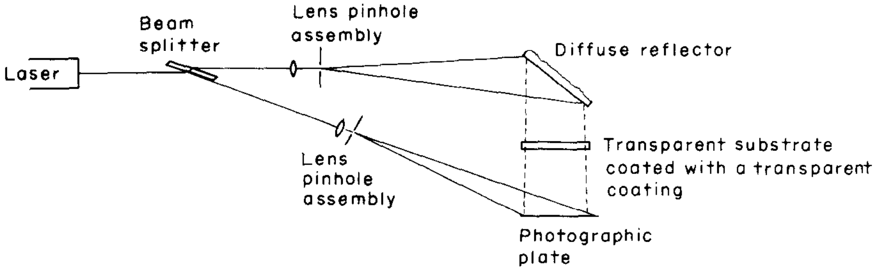

FIG. 3. Optical arrangement for transparent substrate method.

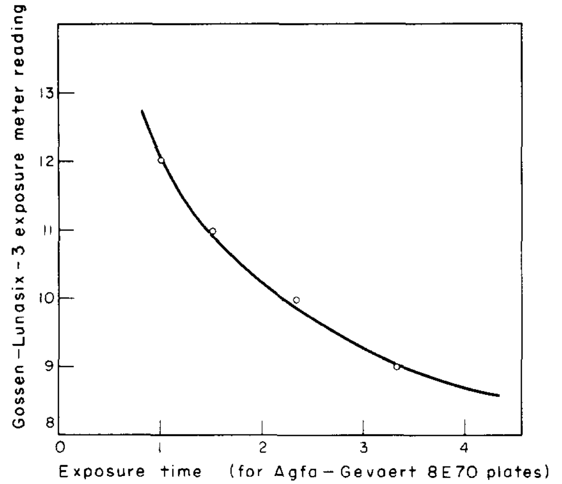

FIG. 4. Exposure times for holographic plates as a function of light intensity.

Apparatus for wall jet experiments

The flat substrate plates were 7 × 7in square. In the experiments employing methods (i) or (ii) they were of $\frac{1}{2}$in thick aluminium alloy; for method (iii) the plate was of perspex. These plates were coated with a cast layer of silicone rubber initially about 0·050in thick, which was then swollen to equilibrium, by immersion in a bath of ethyl salicylate. An opaque, specularly reflecting, silicone rubber coating was used for method (i); a transparent coating for methods (ii) and (iii).

For most of the experiments described here the coated plate was bolted to the face of a heavy steel angle block or, in the case of method (iii) supported at the edges by a stiff open frame, placed on the optical table, upon which it remained fixed throughout the duration of the entire experiment. In a few experiments the plate was demountably supported by a specially designed stand [8] which allowed it to be removed and relocated with great precision.

The jets used were 12in long straight tubes of 0·158 and 0·25in i.d., supported in a stand having a magnetic base by which it could be precisely located on a mild steel plate fixed to the holographic bench so that the issuing jet of air impinged normally (or in a few experiments, tangentially) on the coated plate. The jet tube was removed before each exposure of the photographic plate recording the holograms.

A flow of dry air, metered by means of a rotameter, was supplied to the jet by means of flexible tubing.

Coating materials and swelling agent

In the front-surface reflection technique, white, highly reflecting silicone rubber (CCS9161) was used; in the transparent coating methods, the diffusely reflecting or transparent substrate was coated with a cast layer of EP411 silicone rubber (I.C.I., Stevenston, Ayrshire). The polymer films were swollen to equilibrium with ethyl salicylate by immersion in the ester at the commencement of each experiment. Both types of rubber increase in thickness by about 15 per cent on saturation with the ester.

The refractive index of the unswollen film of transparent rubber, cast on the prism of an Abbe refractometer, was obtained by the usual procedure and read from the direct reading scale in the instrument. The measured value was found to be in excellent agreement with the value given by the manufacturer.

In order to study the refractive index variation with concentration of the swelling agent in the rubber coating, a thin film of dry rubber, of known weight, was pressed hard against the refractometer prism to expel air from between the two. The refractive index as read from the scale agreed with the result obtained by casting a film of rubber on the prism. This procedure was repeated with the film swollen with ethyl salicylate to varying degrees known from the change in weight. These results are plotted in Fig. 5.

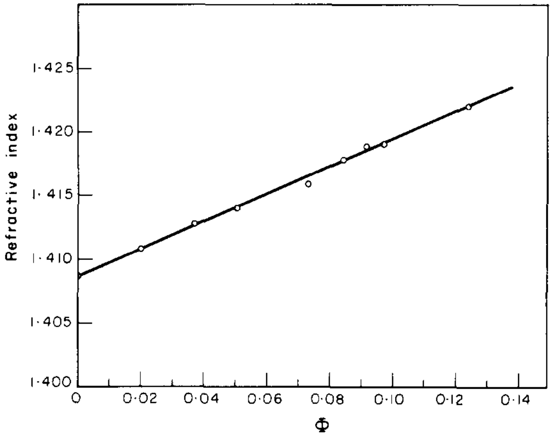

FIG. 5. Refractive index of EP411 silicone rubber swollen to various degrees in ethyl salicylate, as a function of volume fraction of ethyl salicylate in the swollen rubber.

It is evident that the variation of refractive index with composition is very small over the composition range of practical importance here (90–100 per cent equilibrium). This fact greatly simplifies the estimation of coating thickness changes from the optical measurements.

A sorption kinetic technique was employed to measure the degree of equilibrium swelling, the swelling interaction parameter χ_m and the concentration averaged diffusion coefficient for the EP411 silicone rubber/ethyl salicylate system. Using these experimentally determined values of $\chi_m = 1{\cdot}54$ and $D = 1{\cdot}8 \times 10^{-6}$

cm^2/s, the calculated value of t', the mass-transfer "constant-rate period", determined from the general theory for plasticized polymer coatings [5] for the highest mass transfer flux encountered here was found to be much higher than the duration of the experiments in the present work. No significant non-uniformity or fall of transfer rate due to the depletion of the ester content of the coating would therefore be expected during the course of these experiments. In the case of EP411 silicone rubber coatings swollen with ethyl salicylate, the density of the shrinking material, which has to be known in calculating the extent of mass transferred from optical measurements of recession, was estimated by assuming that no overall volume change occurs on mixing. This assumption has been experimentally verified by us for similar systems, such as thiokol/ethyl salicylate and silicone rubber (CCS9161) ethyl salicylate systems.

Measurements of the vapour pressure of ethyl salicylate over polymer coatings swollen to equilibrium at various temperatures, required for the calculation of absolute values of mass-transfer coefficient from the observed transfer rates, were obtained by a transpiration method, described in detail in [5]. The vapour pressure values are plotted as a function of temperature in Fig. 6. The results are in good agreement with the extrapolated data of Ramsay and Young [9] for the pure ester.

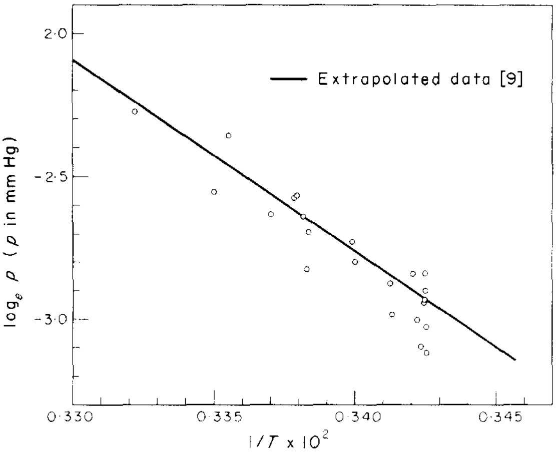

FIG. 6. Vapour pressure of ethyl salicylate over polymer coating swollen to equilibrium, as a function of temperature.

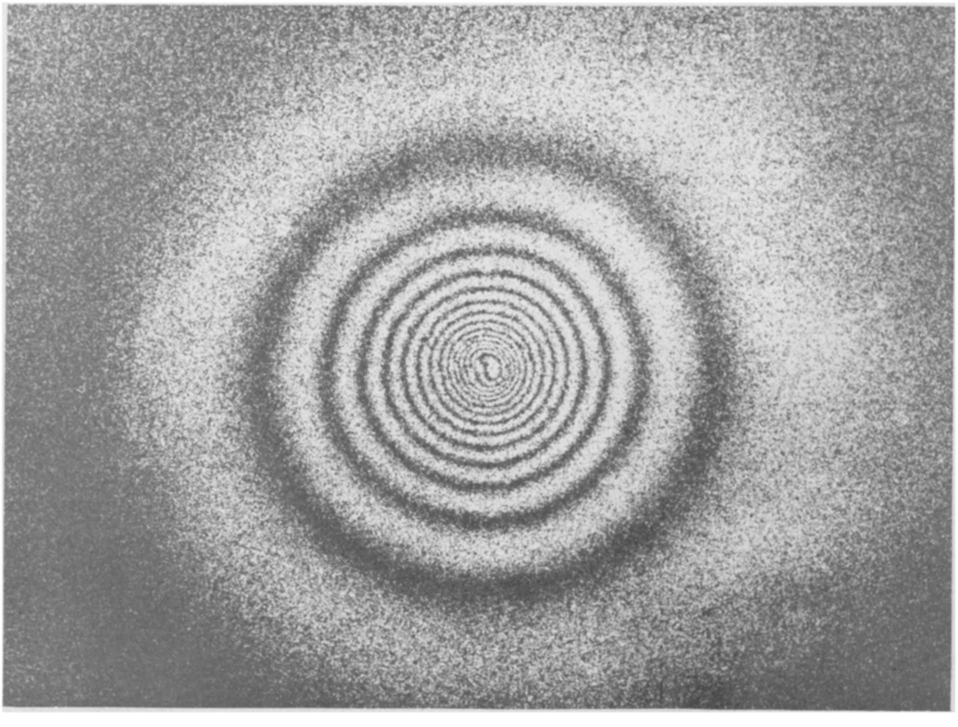

FIG. 7. Fringes obtained by holographic interferometry, recording mass transfer of ethyl salicylate from a transparent silicone rubber coating on a flat transparent plate, exposed to a normal air jet.

RESULTS

Jet normal to plate

Double-exposure or frozen fringe interferograms for this case, obtained by recording on the same photographic plate holograms of the initial and exposed states of the transferring coating, had the general aspect of Fig. 7 for all three methods of holographic measurement described above. This photograph of the reconstruction of a double-exposed hologram shows the system of interference fringes obtained by method (iii); the fringes here correspond to the changes of optical path length for rays traversing a transparent plate coated with a shrinking layer of transparent mass-transferring polymer. As in the other two methods of holographic measurement of coating recession described above, the fringes are loci or contours of equal coating shrinkage, at nearly equal increments of recession, and are thus in principle circles concentric with the point of impingement of the jet, if that is uniformly round and set accurately normal to the plate. Slight misalignment or irregularity of the jet orifice, or the presence of dust particles or other disturbances to flow on the plate surface, readily produce discernible distortions in the fringe pattern like those visible in the figure.

The fringe system was apparently unaffected by jet-plate spacing within wide limits.

Our experiments fulfilled all the conditions which are shown in [5] to ensure that rates of recession are everywhere proportional to local values of the air side mass-transfer coefficient. For the quantitative comparison of the radial profile developed by the mass-transferring surface in a known time with that deducible from the known radial variation of mass-transfer coefficient over a surface exposed to a normal laminar jet, experiments at seven different air jet Reynolds numbers (255, 533, 1033, 1203, 1560, 1836 and 1870) were performed under particularly carefully controlled conditions such that the jet was accurately normal to the plate and the fringes were truly circular, orthogonal fringe diameters agreeing to within a few percent in all cases. Method (ii) was used to obtain the interferograms for these experiments. The metal substrate plate was ruled with reference lines of known grid spacing, so that the scale of the enlarged (× 1·75) photographs from which the fringe diameters were measured could be accurately found. In most of these experiments the period of exposure to the jet was 8–20 min, sufficient for the formation of about thirty measurable fringes in an enlarged photograph. In studying the variation of mass-transfer coefficient near the stagnation point, shorter periods of exposure were used. The results obtained are discussed in the next section.

In a few experiments the mass-transferring plate was removed from its mount on the optical table after the initial hologram was made, exposed to the air-jet elsewhere, and replaced in the specially designed support [8] for the making of the final hologram. The interference fringe pattern proved identical with that obtained in experiments in which the plate remained fixed on the holographic table throughout. This result testifies to the extreme precision with which the test object can be relocated in a suitably designed support, and is of importance in demonstrating the applicability of holographic methods of mass-transfer measurement to situations where the test surface cannot be examined *in-situ*.

Jet tangential to plate

Some exploratory experiments were made with a 0·158 in (i.d.) circular tube discharging a metered flow of air parallel to a flat diffusely reflecting plate coated with an EP411 transparent film initially swollen to equilibrium in ethyl salicylate. The jet axis was in the plane of the surface of the coated section (6-in square), which was preceded by a coplanar uncoated starting section (length 2·75 in), with no step or discontinuity at the junction.

Figures 8 and 9 are photographs of double-exposed holograms obtained by method (ii) in experiments performed at nearly the same Reynolds numbers but of different duration. Though previous results have been reported for heat transfer from two-dimensional (rectangular) tangential wall jets, no comparable studies appear to have been made with round jets.

DISCUSSION OF RESULTS FOR EXPERIMENTS WITH LAMINAR JET NORMAL TO PLATE

To determine the recession at a given point on the surface from an interferogram, one must know the ordinal number of the fringe passing through that point with respect to the zeroth fringe corresponding to the position of the unchanged surface. In these experiments, portions of the surface sufficiently far from the jet suffered no sensible shrinkage in the experimental period; the zeroth order fringe was therefore in principle the outermost, and the ordinal number of any other fringe on the interferogram was its number counted inwards from this datum.

In most of the experiments with a normally directed jet, however, it was desired to expose the mass-transferring surface to the flow for a sufficient time to generate a substantial number of fringes on the hologram. The zeroth order fringe then lay outside the field of observation and could not be used as a reference. The fringe order number was determined in these circumstances by assigning a number by trial to the outermost visible fringe such that the fringe diameter/ordinal number relation for the whole set of

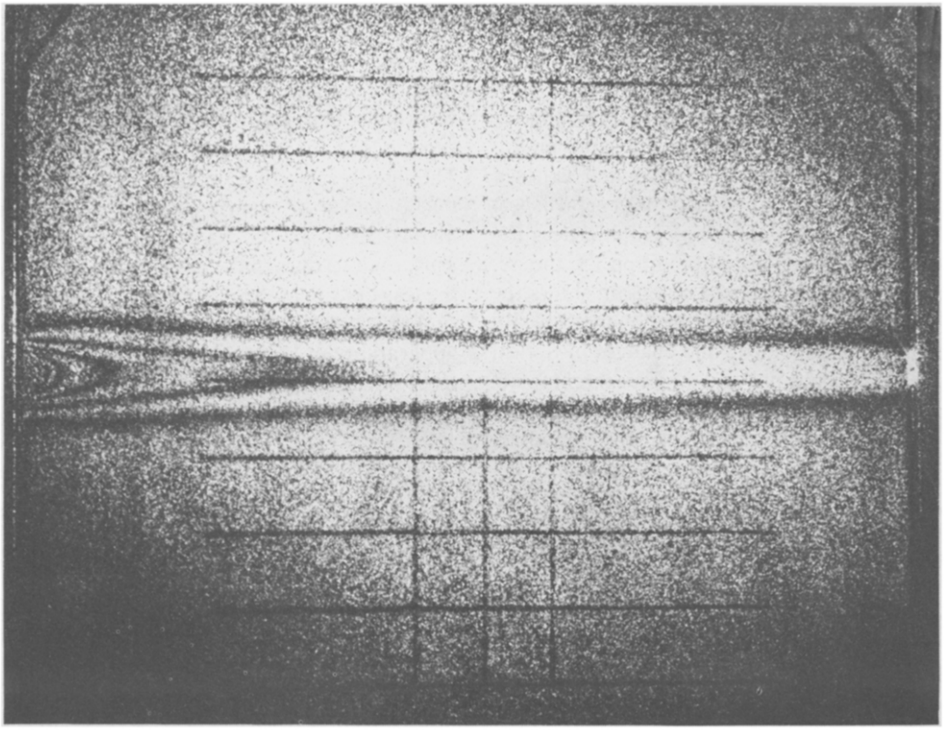

FIG. 8. Fringes obtained by holographic interferometry, recording mass transfer of ethyl salicylate from a transparent silicone rubber coating on a flat, diffusely reflecting substrate, exposed to a tangential laminar round air jet for 6 min. ($Re = 1010$; Grid spacing = $\frac{1}{2}$ in.)

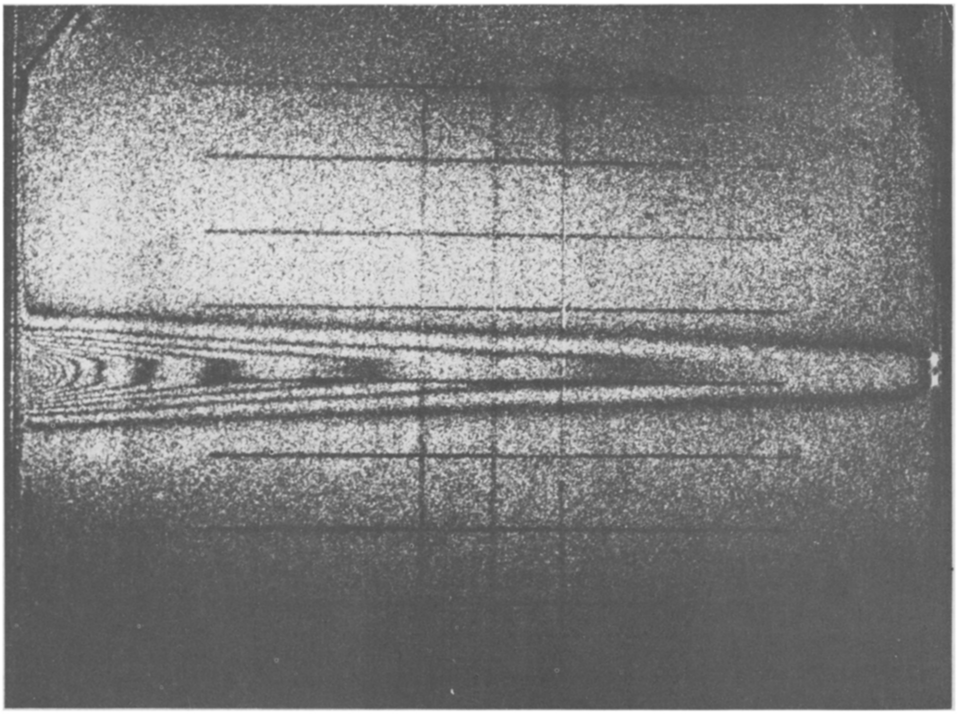

FIG. 9. Fringes obtained by holographic interferometry, recording mass transfer of ethyl salicylate from a transparent silicone rubber coating on a flat, diffusely reflecting substrate, exposed to a tangential laminar round air jet for 15 min. ($Re = 1010$; Grid spacing = $\frac{1}{2}$ in.)

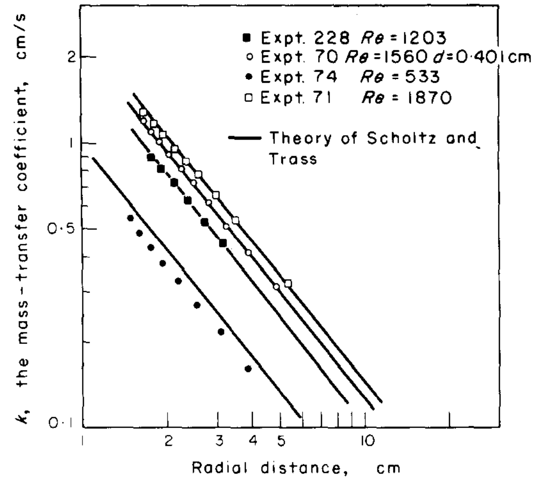

FIG. 10. Comparison of experimental and theoretical mass-transfer coefficients at a flat plate exposed to a normal laminar jet of air.

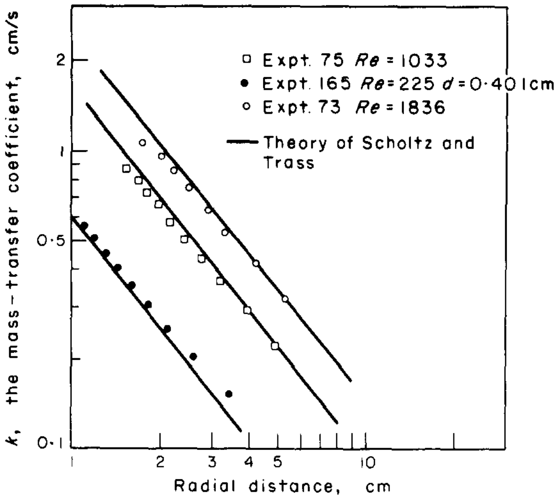

FIG. 11. Comparison of experimental and theoretical mass-transfer coefficients at a flat plate exposed to a normal laminar jet of air.

fringes was of the form predicted from the radial variation of transfer rate given by the theory of Scholtz and Trass [3]. Typically, in our experiments yielding a conveniently large number of distinguishable fringes over the surface of our standard 7-in square mass-transferring specimens, the outermost dark fringe was found to be the third of the complete set on the above basis. Any other assignment of ordinal number gave a variation of recession with fringe diameter very dissimilar to that predicted from Scholtz and Trass's theory.

The ordinal numbers of the fringes being thus established, the recession of the coating from its initial position could be determined at each fringe from the known wavelength of the laser light used and the geometry of the optical system. The corresponding values of the mass-transfer coefficient could then be calculated from a value of the coating density, estimated as explained above, and from measurements of the coating vapour pressure and refractive index made by methods previously discussed.

These calculated local mass-transfer coefficient values, plotted as a function of radial distance from the point of jet impingement in Figs. 10 and 11, agree closely for $x/d > 2{\cdot}5$ for all but the two lowest Reynolds numbers with the mass-transfer coefficients at corresponding points calculated from the theory of Scholtz and Trass, using an estimate of the diffusivity of ethyl salicylate in air obtained from the Lennard–Jones expression [10], based on kinetic theory. Figure 12 combines all the data for $x/d > 2{\cdot}5$ in a single plot of $Sh_x(x/d)^{0{\cdot}25}$ against Reynolds number, revealing the close overall agreement with the theoretical relation of Scholtz and Trass.

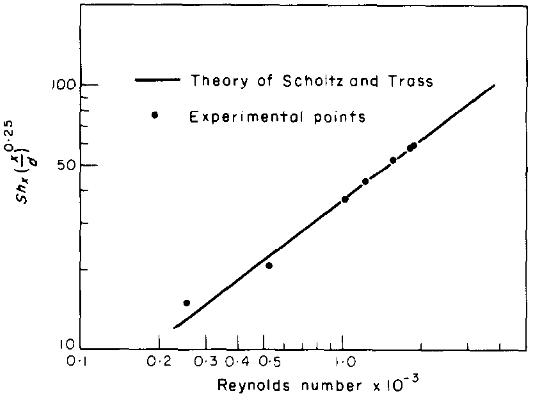

FIG. 12. Variation of Sherwood number with Reynolds number. Comparison with theory of Scholtz and Trass ($Sc = 2{\cdot}86$).

For the lowest Re number (255), the mass-transfer coefficients measured here are 5–15 per cent higher than those predicted by the theory. At $Re = 533$, the measured mass-transfer coefficients for $x/d > 2{\cdot}5$ fall about 5–12 per cent below the line representing the theory of Scholtz and Trass. These authors likewise report large deviations from their theory in this Re range, which they associate with the formation of a toroidal vortex around the jet in these circumstances. However, even at these low Re values, it appears from Figs. 10 and 11 that the radial variation of the measured mass-transfer coefficients is still of the form predicted by the theory—contrary to the experimental findings of Scholtz and Trass. It is noteworthy, however, that the latter results were obtained with a liquid jet at a very much higher Schmidt number, viz. 1000–4000 compared with 2·86 in these experiments.

The wall jet theory of Scholtz and Trass is not valid in the region of the stagnation point and in general for $x/d < 2 \cdot 5$. To investigate this region, diameters of sets of fringes of small x/d obtained in experiments of short duration at nearly the same Reynolds numbers but at different nozzle to plate distances, were measured from enlarged (× 1·55) photographs. Fringes right up to the impingement point could be counted in each such photograph.

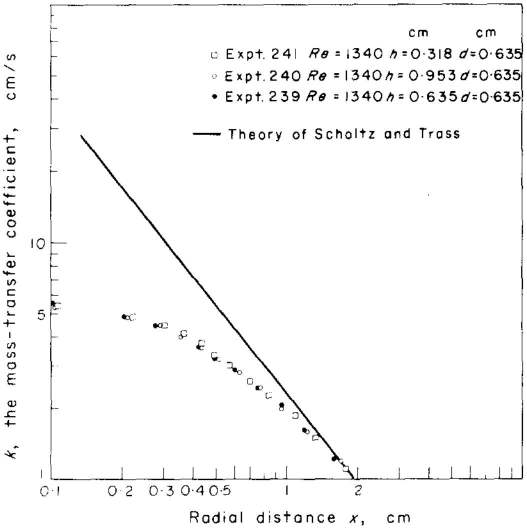

FIG. 13. Mass-transfer coefficients near the impingement point, at different nozzle to plate distances.

Mass-transfer coefficients, plotted in Fig. 13 for $Re = 1340$ and nozzle to plate distances of 0·5, 1 and 1·5d, are found to be independent of nozzle–plate spacing, both at the stagnation point and in the region close to it, as are those in the wall jet region more remote from that point. These results are in agreement with those of Gardon and Akfirat [11] who found that for Re less than 2000 and nozzle to plate distances of 0·5–5·0d the stagnation point Nusselt numbers depend on jet Reynolds number only.

CONCLUSIONS

The holographic technique of local mass-transfer measurement described here has yielded detailed and precise experimental data for the spatial variation of mass-transfer coefficient for laminar wall–jet systems of low Schmidt number. In the case of a normal jet, the new data confirm the analytical theory of Scholtz and Trass for a region more than 2·5 in jet diameters from the axis.

In the circumstances of these experiments the new holographic method proves to have the following striking advantages over other profilometric techniques hitherto used in this laboratory or known to us:

(a) Even using crude direct methods of fringe measurement, the consistency and reproducibility of the holographic technique is in the region of 1 per cent—almost an order of magnitude better than that obtainable with the most refined conventional profilometric methods.

(b) The speed with which mass-transfer data for a given test object can be recorded is immeasurably greater than in the point by point surveys of classical profilometry. Apart from the gain of convenience, this feature of the holographic method avoids uncertainties and inaccuracies due to still-air losses during measurement.

(c) The whole character of the spatial variation of mass transfer over the test-object surface is revealed in its entirety and in every detail in a single photograph. The wealth of information provided by the interferogram, the fineness of spatial resolution obtainable and the immediately intelligible nature of the data display, are distinctive features of the holographic method apparently unparalleled by other techniques.

These substantial, and in many respects unique, advantages recommend the methods of holographic interferometry for solid surface mass transfer investigations of every kind. Fundamental experimental studies of transfer processes at solid surfaces, as well as technological or engineering development investigations of skin friction and heat-transfer phenomena using mass-transfer analogues, should prove rewarding fields for the application of holographic techniques similar to those described here.

The most serious limitation of the relatively undeveloped method described above, at present restricting the generality of its application, is the difficulty experienced in the general case of assigning the proper ordinal numbers to the fringes. In our present application, this difficulty may be overcome by arranging that the zeroth order fringe lies in the field of view as a reference; or, more conveniently, by making use of the fact that, for the case of a normal laminar jet, the form of the spatial variation of surface transfer rate is known for a substantial part of the field. In very many situations neither of these expedients is available. We are accordingly developing more general methods of identifying the fringe order in mass-transfer interferograms.

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REFERENCES

1. K. A. Haines and B. P. Hildebrand, Interferometric measurements using the wavefront reconstruction technique, *Appl. Optics* **5**, 1972 (1966).
2. E. Archbold, J. M. Burch and A. E. Ennos, The application of holography to the comparison of cylinder bores, *J. Phys. E.* **44**, 489 (1967).
3. M. T. Scholtz and O. Trass, Mass transfer in the laminar radial wall jet, *A.I.Ch.E. Jl* **9**, 548 (1963).
4. D. N. Kapur and N. Macleod, Determination of local mass transfer coefficients by holography, *Nature, Phys. Sci., Lond.* **237**, 57 (1972).
5. N. Macleod and R. B. Todd, The experimental determination of wall–fluid mass-transfer coefficients using plasticized polymer surface coatings, *Int. J. Heat Mass Transfer* **16**, 485 (1973).
6. N. Abramson, The holo-diagram: a practical device for making and evaluating holograms, *Appl. Optics* **8**, 1235 (1969).
7. N. Abramson, The holo-diagram—III. A practical device for predicting fringe patterns in hologram interferomtery, *Appl. Optics* **9**, 2311 (1970).
8. N. Macleod and D. N. Kapur, A kinematically designed mount for the precise location of specimens for holographic interferometry, *J. Phys. E.* **6**, 423 (1973).
9. *Handbook of Chemistry and Physics*, 49th Edn, p. D-128. Chemical Rubber, Ohio (1968).
10. R. D. Reid and T. K. Sherwood, *The Properties of Gases and Liquids*, 2nd Edn. McGraw-Hill, New York (1966).
11. R. Gardon and J. C. Akfirat, Heat-transfer characteristics of impinging two-dimensional air jets, *J. Heat Transfer* **88C**, 101 (1966).
12. D. N. Kapur, The profilometric determination of mass transfer coefficients by holographic interferometry, Ph.D. Thesis, University of Edinburgh (1973).

DETERMINATION DES COEFFICIENTS DE TRANSFERT MASSIQUE LOCAUX PAR HOLOGRAPHIE INTERFEROMETRIQUE

Résumé—On décrit des méthodes d'application des techniques puissantes de l'holographie interférométrique à la mesure des profils des flux massiques aux interfaces solide–fluide, avec les avantages de la rapidité, de la précision et de la clarté des informations contenues dans les résultats.

On maintient une qualité optique constante à la surface de transfert, nécessaire à la production d'interférogrammes satisfaisants, en utilisant un revêtement transférant de la matière qui consiste en une couche lisse d'élastomère initialement chargée d'un agent volatile (ou soluble). Le rétrécissement de ce revêtement, dû au transfert massique peut être enregistré comme un arrangement des franges d'interférence lorsque les hologrammes de réflexion ou de transmission des états initial et final de la surface sont superposés. De tels interférogrammes donnent une vue synoptique de la variation spatiale du coefficient de transfert sur toute la surface vue sur la plaque holographique.

La précision et la qualité des résultats fournis par cette méthode sont démontrées par l'étude de la variation du coefficient de transfert sur la surface d'une plaque plane exposée à des jets d'air laminaires tangentiels ou normaux, de vitesse connue. Les résultats, dans le premier cas, s'accordent bien avec la solution analytique connue.

DIE BESTIMMUNG VON ÖRTLICHEN STOFFÜBERGANGSKOEFFIZIENTEN MIT HILFE DER HOLOGRAPHISCHEN INTERFEROMETRIE ALLGEMEINE GRUNDLAGEN: IHRE ANWENDUNG UND ÜBERPRÜFUNG FÜR STOFFÜBERGANGSMESSUNGEN AN EINER EBENEN PLATTE IN EINEM LAMINAREN RUNDEN LUFTSTRAHL

Zusammenfassung—Es werden Methoden zur Anwendung der leistungsfähigen Technik der holographischen Interferometrie auf die profilometrische Messung von Stoffströmen an der Grenzfläche fest-flüssig beschrieben. Das Verfahren bietet große Vorteile bezüglich der Schnelligkeit, Genauigkeit und Dichte von Datenaufnahme und Darstellung.

Die Konstanz der optischen Verhältnisse an der Übergangsfläche, die wesentlich für die Aufnahme von befriedigenden Interferogrammen ist, wird beeinflußt durch die Verwendung einer Stoffübergangsschicht, die aus einer glatten Schicht aus Elastomeren besteht, welche anfangs mit einem flüchtigen (oder löslichen) Treibmittel angereichert wird. Das Zusammenschrumpfen dieser Schicht als Folge des Überganges des Treibmittels an den Fluidstrom kann als eine Folge von Interferenzbildern wiedergegeben werden, wenn Reflexions- oder Transmissionshologramme des Anfangs- und Endzustandes der Oberflächenschicht überlagert werden. Solche Interferogramme liefern eine übersichtliche Darstellung der örtlichen Verteilung der Übergangskoeffizienten über die gesamte Oberfläche, die auf der holographischen Platte gezeigt wird.

Die Genauigkeit und Vollständigkeit der Daten, die durch diese Methode geliefert werden, wird hier gezeigt bei der Darstellung der Variation der Übergangskoeffizienten auf der Oberfläche einer ebenen Platte in senkrechten oder tangentialen laminaren Luftstrahlen bekannter Geschwindigkeit. Im ersten Fall stimmen die Ergebnisse mit einer analytischen Lösung überein.

ОПРЕДЕЛЕНИЕ ЛОКАЛЬНЫХ КОЭФФИЦИЕНТОВ МАССОПЕРЕНОСА С ПОМОЩЬЮ ГОЛОГРАФИЧЕСКОЙ ИНТЕРФЕРОМЕТРИИ — I. ОБЩИЕ ПРИНЦИПЫ: ИХ ПРИМЕНЕНИЕ И НАДЕЖНОСТЬ ПРИ ИЗМЕРЕНИИ МАССОПЕРЕНОСА НА ПЛОСКОЙ ПЛАСТИНЕ, ОБТЕКАЕМОЙ ЛАМИНАРНЫМ ПОТОКОМ ВОЗДУХА

Аннотация — Описывается применение результативного метода голографической интерферометрии для профилеметрических измерений скоростей массопереноса на поверхностях раздела твердое тело-жидкость, дающего большие преимущества в быстроте, точности и доступности получения данных и их воспроизведении.

На поверхности переноса поддерживается необходимая для получения удовлетворительных интерферограмм постоянная оптическая чистота, которая достигается с помощью массопереносного покрытия, состоящего из гладкого растворяющегося эластомера. Уменьшение толщины этого покрытия, благодаря переносу растворяющегося вещества в поток жидкости, регистрируется в виде интерференционных полос, которые образуются при наложении первоначального и конечного состояний поверхностного слоя. Такие интерферограммы обеспечивают синоптическую запись пространственного изменения коэффициента переноса по всей поверхности, обозреваемой на голографической пластине.

Точность и надежность данных, которые обеспечиваются этими методами, демонстрируются на примере их применения для определения коэффициента переноса, изменяющегося на поверхности плоской пластины, обтекаемой нормальной или тангенциальной ламинарной воздушной струями с известной скоростью. В первом случае результаты хорошо согласуются с известным аналитическим решением.