Session 7 - Heat Transfer Measurements

THE SWOLLEN POLYMER TECHNIQUE FOR HEAT TRANSFER PROBLEMS - DIFFICULTIES AND ACHIEVEMENTS

N. Hay & D. Lampard

University of Nottingham, Great Britain

Abstract.

The swollen polymer technique is shown to have the potential of yielding full surface mapping of heat transfer coefficients in complex flows with speed and precision. Care is needed to achieve these ends. Problem areas are highlighted, and practical solutions discussed, and illustrated with results related to turbine heat transfer.

1. Introduction

The Swollen Polymer Technique is a mass transfer analogy method for the measurement of convective heat transfer coefficients. It is similar to the naphthalene sublimation method but the mass transfer is by evaporation of a small amount of an organic fluid with which a polymer coating applied to the surface has been saturated. The local thickness of the coating varies linearly with the mass loss. Since the optical properties of the coating are unaffected by the mass loss, the very small thickness changes may readily be measured using laser interferometry. This gives interference fringes which are contours of equal mass loss, or, if the concentration difference is fixed, contours of equal mass transfer coefficient

The technique thus has a number of advantages over the naphthalene method:

1. It gives a direct panoramic view of the variation of the heat transfer coefficient over the working surface without the need for point by point measurements.
2. The working surface goes through a reversible cycle. It can be used repeatedly simply by redipping in the swelling agent. No recasting of the surface is necessary.

Like the naphthalene method this technique has the limitation that it can only be used for isothermal experiments at room temperature. In the context of turbomachines it is suited to fundamental parametric investigations, not to the working model environment.

2. Experimental Method and Equipment

A detailed description of the sequence in a Swollen Polymer Technique experiment is given in Figure 1. Note the small order of magnitude of the changes in thickness involved.

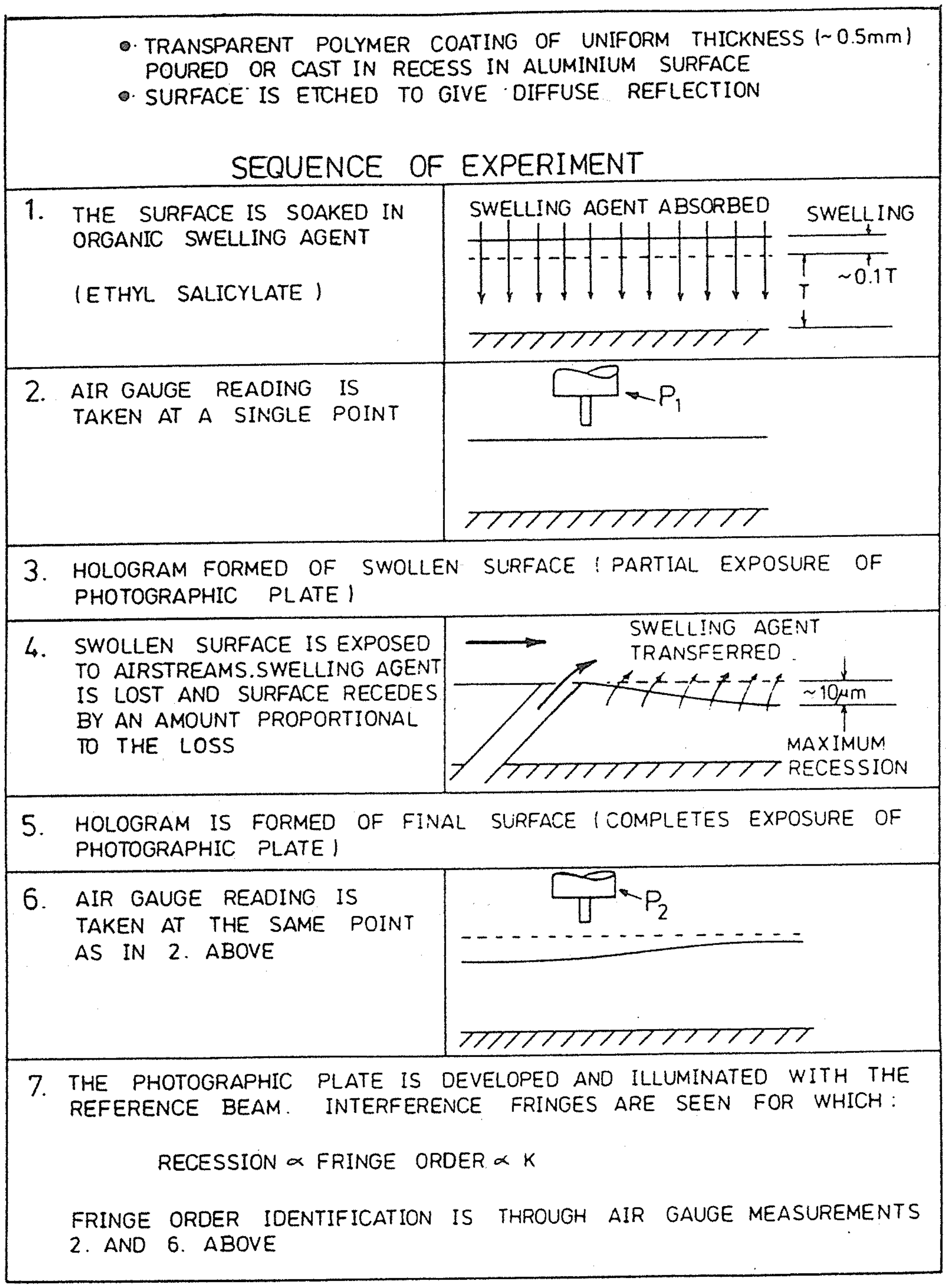

Figure 1: Description of the technique

The air gauge readings (stages 2 and 4, Figure 1) are needed to establish the order of the fringes obtained on the hologram. The hologram is formed by a double exposure before and after the working surface is subjected to the fluid flow (stages 3 and 5, Figure 1). Thus, it is the differences in the thickness of the polymer that are registered. This is convenient as it means that the accuracy of formation of the original surface is not critical.

The hardware needed in a Swollen Polymer Technique is as follows:

1. A wind tunnel for producing the desired conditions of the test.
2. An Optical System for forming holograms (Figure 2). This comprises the usual laser source, beam splitter mirror mounts, etc. The system is on a massive table mounted on air springs to isolate it from ground transmitted vibration.

   The system of Figure 2 is the front surface reflection double exposure method which gives frozen fringes. There are other methods which can be used (Ref 1) such as back reflection and live fringe methods. The one described here is the most suited to wind tunnel tests.

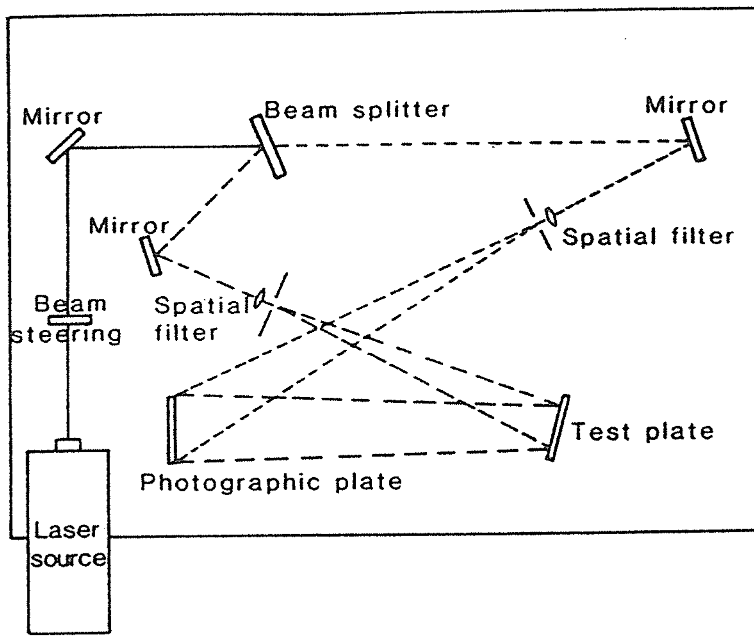

Figure 2: Optical system

3. A plate on which the polymer is cast and which constitutes the working surface
4. An air proximity gauge (Figure 3) for establishing the fringe order on the hologram.
5. Kinematic mounts (Figure 3) for the plate and the air gauge. The plate is photographed twice to form the double exposure hologram. In between, it is removed and taken to the wind tunnel. It must be replaced in its original position to within a fraction of the wavelength of the laser light used. Hence, the kinematic mount is needed to avoid the appearance of fringes due to replacement errors.

   Similarly, the air gauge is presented to the plate before and after the plate is moved to the wind tunnel and must be relocated precisely relative to the plate.

A typical hologram obtained in a test is shown in Figure 4. The test relates to film cooling studies. The fringes are loci of equal heat transfer coefficient downstream of a row of film cooling holes. An injection angle of 90°is featured at density ratios (injectant to

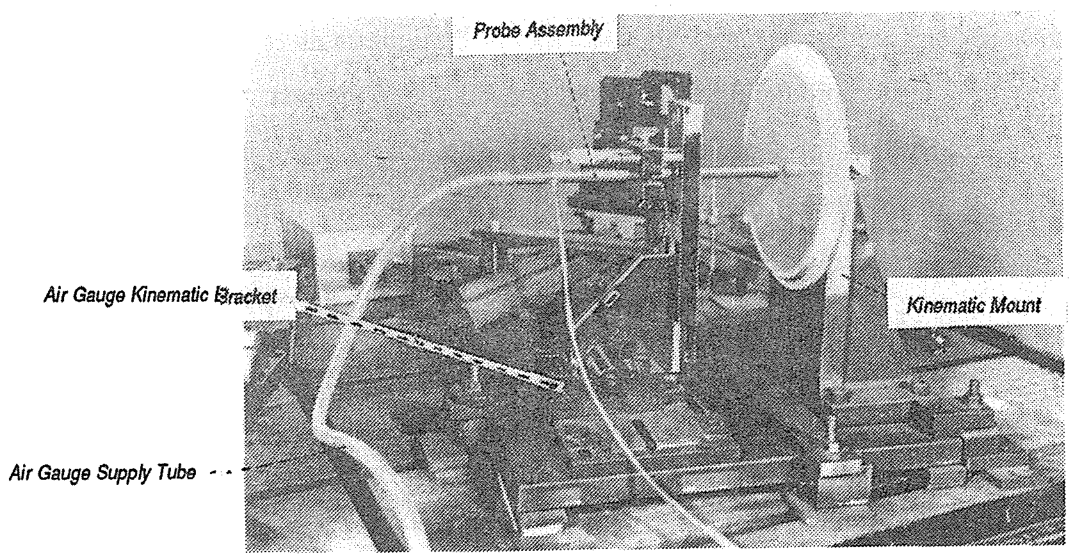

Figure 3: Air gauge in measuring position.

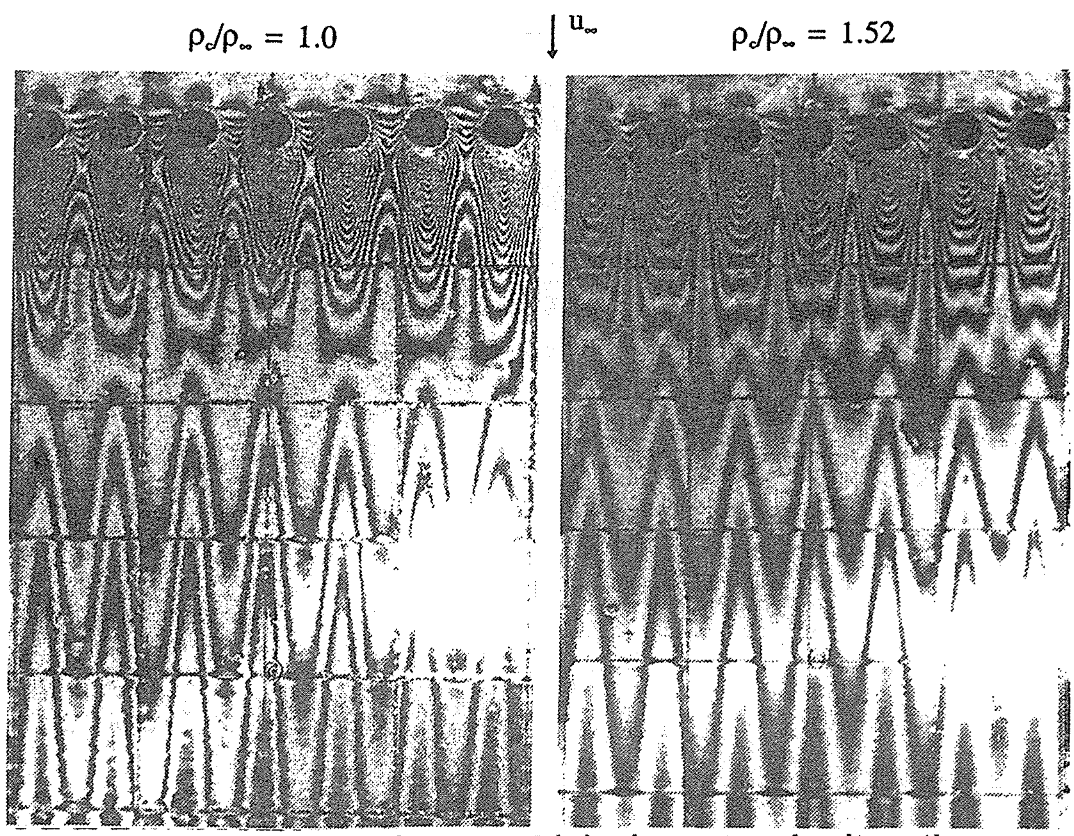

Figure 4: Fringe patterns for normal injection at two density ratios.

mainstream) of 1.0 and 1.52. The blowing rate M = 1 in both cases. Note the definition and detail obtained close to the holes.

3. Difficulties with the Technique

3.1 The Mass Transfer Analogy

The most difficult task for workers using the mass transfer analogy approach is to convince the sceptics that the analogy does actually work.

The differential equations for heat transfer and for mass transfer in a boundary layer flow are:

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\frac{\partial^2 T}{\partial y^2} \qquad \text{(heat)} \tag{1}$$

$$u\frac{\partial C_A}{\partial x} + v\frac{\partial C_A}{\partial y} = D\frac{\partial^2 C_A}{\partial y^2} \qquad \text{(mass)} \tag{2}$$

When $\alpha = D$ the two equations are identical and so are their solutions. When $\alpha \neq D$ it is found experimentally that:

$$Nu = Sh\left(\frac{Pr}{Sc}\right)^n \quad \text{where } n \simeq 0.4 \tag{3}$$

This relationship is the source of contention in the use of the mass transfer analogy for heat transfer coefficient determination. More often it is the <u>change</u> in heat transfer coefficient due to a change in a geometrical or a flow parameter that is required. In this case, equation (3) shows that the ratios of Nusselt and Sherwood numbers are equal, independent of Prandtl and Schmidt numbers, or the value of n i.e.:

$$\frac{Nu_1}{Nu_2} = \frac{Sh_1}{Sh_2} \tag{4}$$

Numerous experimental results support this analytical deduction. Thus where ratios of heat transfer coefficients are required the main objection to the use of the mass transfer analogy is by-passed altogether.

3.2 The "Constant Rate Period"

The mass transfer coefficient, h_m is obtained in the experiment from:

$$h_m = \frac{\rho_{sc}\ \delta}{C_s\ t} \qquad (5)$$

where ρ_{sc} is the density of the swollen coating, δ the measured recession, C_s the concentration gradient and t the time of exposure in the wind tunnel. The driving potential for mass transfer C_s which is a function of the vapour pressure of the swelling agent just above the coating should ideally stay constant during the experiment. This may not be the case however as C_s depends on temperature, mass transfer, mass transfer rate and choice of polymer/swelling agent system. The period of an experiment when the reduction in C_s is below 5% is referred to as the "constant rate period".

Apart from the level at which the temperature is held constant, control of the constant rate period may be exercised through the choice of polymer/swelling agent system. Figure 5 shows the variation of the constant rate period with mass transfer coefficient for various systems. The choice will depend upon the level of mass transfer coefficient envisaged. The RTV 615 / n-tetradecane system gives a sufficiently long exposure time even for comparatively high levels of mass transfer coefficient and was the one chosen by the authors for film cooling studies. The drop in C_s is expected to be much lower than the arbitrary figure of 5% chosen for Figure 5 to illustrate the effect.

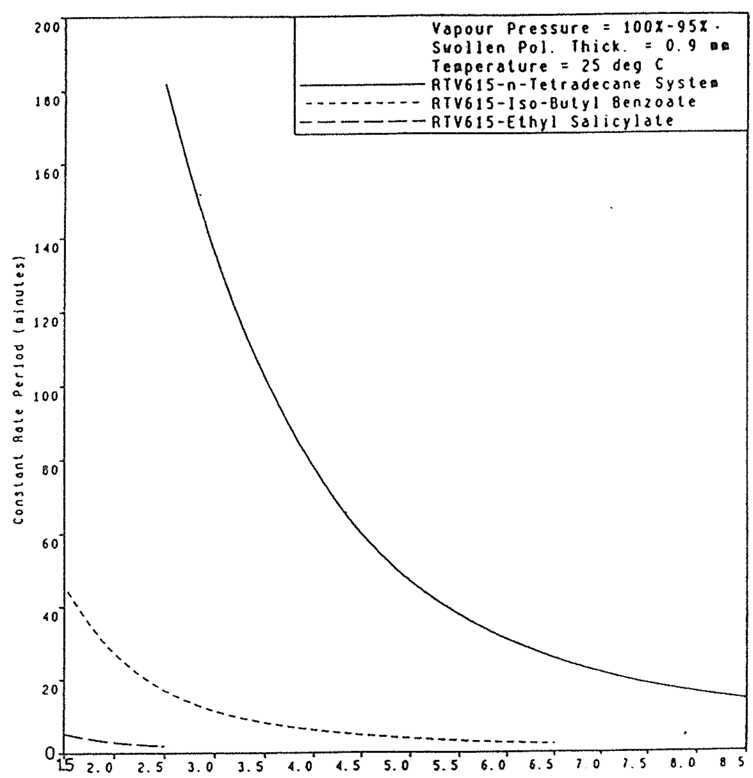

Figure 5: Comparison of predicted constant rate periods for three systems

3.3 Variation of the Change in Optical Path Length

The recession δ comes into the calculation of the mass transfer coefficient, h_m (see Equation 5). The recession is given by (Ref 2):

$$\delta = \frac{\frac{n\lambda}{2}}{\left[\frac{\eta - \cos(i_1-\alpha)}{\cos\alpha} + \frac{\eta - \cos(i_2-\beta)}{\cos\beta}\right]} \qquad (6)$$

where n is the fringe order, λ the wavelength of the laser light and η is the refractive index of the polymer. The various angles are defined in Figure 6. The value of the bracket in the denominator depends on i_1 and i_2 the illuminating and viewing angles. Now i_1 and i_2 cannot be arranged to be equal over the whole surface. However, the error resulting in the case of a flat surface is very small (< 1%).

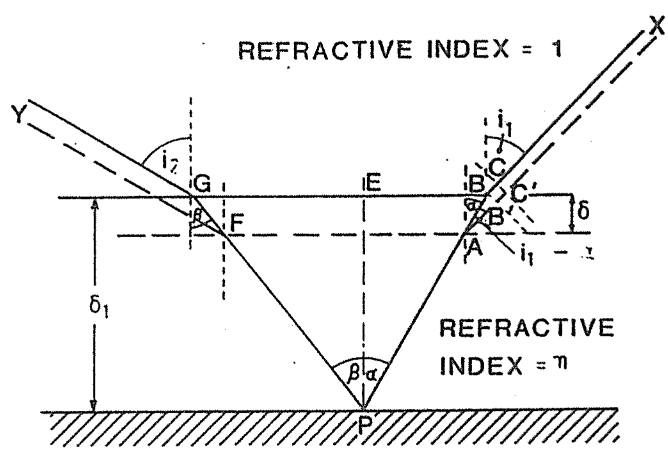

Figure 6: Definition of angles in equation 6

For curved surfaces the change in path length becomes a function of position on the surface. Hence δ is no longer proportional to the fringe order n and becomes a function of position. Thus image processing would be needed if loci of constant h_m are required.

3.4 Physical Property Values

Obviously as the physical property values enter into the calculation of h_m (e.g. C_s, η etc), these need to be known accurately. It is best to choose a polymer/swelling agent system for which accurate data are available such as the RTV 615 / n-tetradecane system.

3.5 Spurious Fringes

As we are measuring minute changes in dimensions care must be taken that only changes due to the evaporation of the swelling agent are present. Problems with the appearance of spurious fringes have been encountered and solved. In a careful investigation involving some 200 tests, potential sources due to the following possible causes were examined:

1. Stresses in the plate due to mounting.
2. Deflection of the plate due to pressure.
3. Deflection due to temperature variation.

The investigation revealed that spurious fringes were caused by small changes in temperature of the plate. Thus very careful temperature control is needed on and off the holographic table and within the working section of the tunnel. Environmental enclosures were built around the wind tunnel working section and around the optical table. Both were kept within 0.5°C of the wind tunnel air temperature. This, in turn, was maintained constant within 0.5°C. The swelling agent bath and plate were kept within the environmental enclosure.

These precautions eliminated the spurious fringes.

3.6 Fringe Order Determination

An air gauge is used to determine the fringe order on the hologram by measuring the actual recession at one point on the plate. Hence, the order of the fringe appearing on the hologram at that point can be deduced. This provides a datum for determining the fringe orders for the rest of the hologram.

The air gauge uses a small low speed jet of air which impinges upon the surface of the plate. Evaporation will take place at the point of measurement due to jet impingement and inaccuracy of the reading will result. This unwanted further evaporation can be eliminated if the air used in the air gauge probe is saturated with swelling agent. To achieve this, the air is bubbled through swelling agent reservoirs, dried and then channelled to the air gauge.

4. Achievements

4.1 Consistency and Accuracy

With the above careful precautions, a high degree of consistency and accuracy is achieved.

Figure 7 shows the repeatability of the results from two separate but identical tests. The holograms obtained are practically identical.

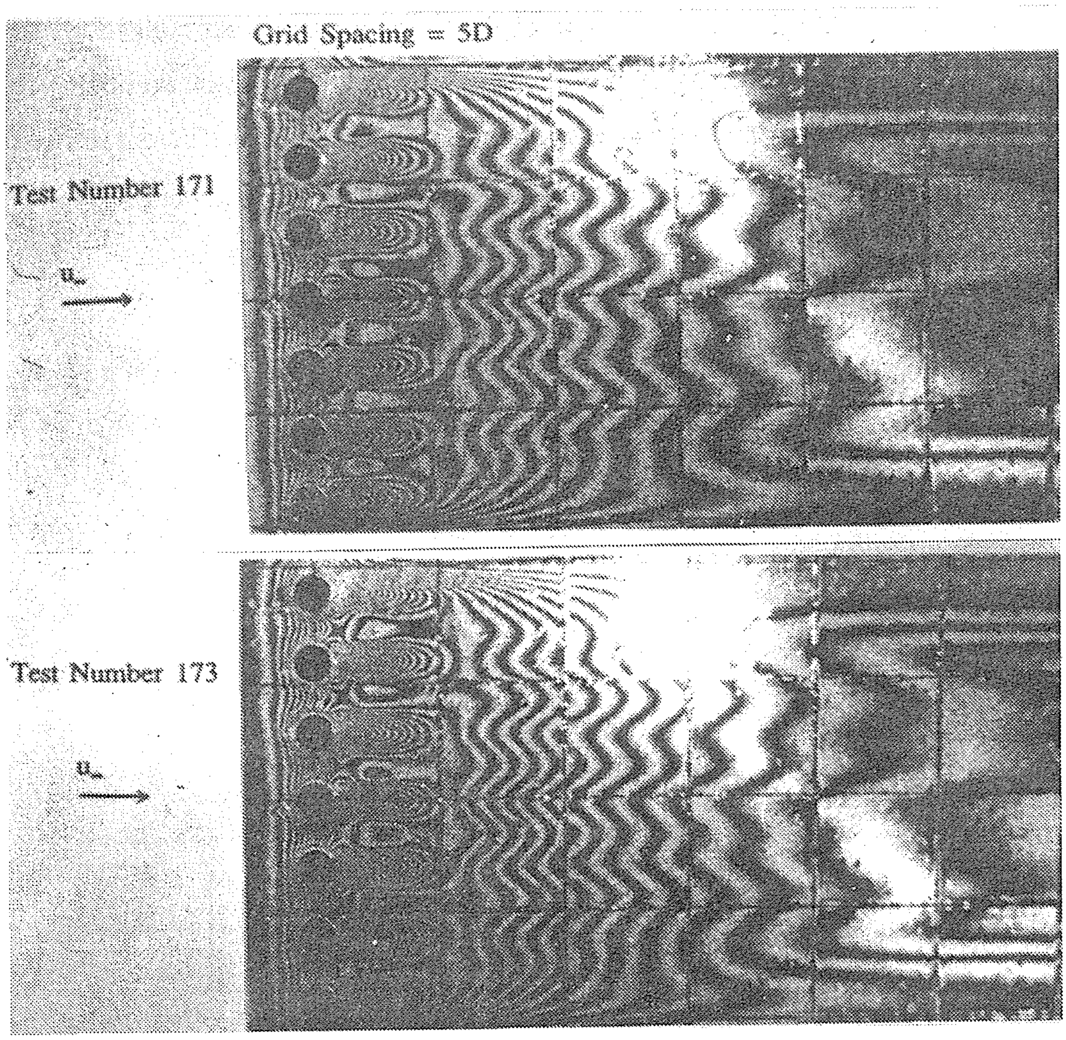

Figure 7: Comparison of holograms for two identical tests at M = 2 with normal injection

The corresponding h/h_o contours are shown in Figure 8. The error in the h/h_o from one test to the next is of the order of 3%.

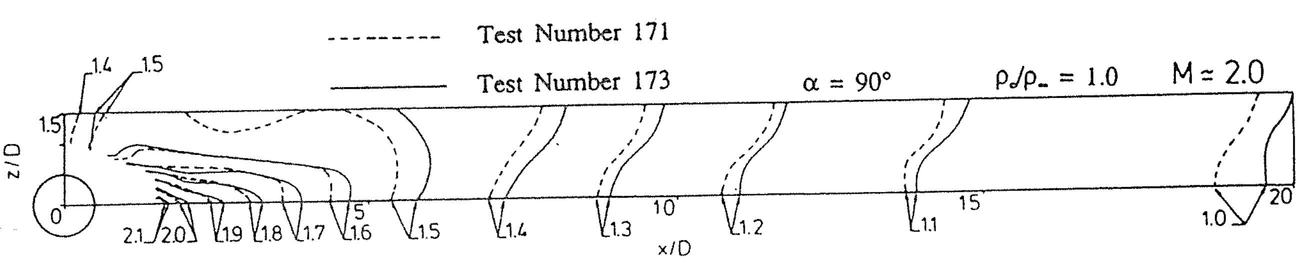

Figure 8: Repeatability check on h/h_o from Fig.7 holograms.

The accuracy on the absolute value of the mass transfer coefficient is within ±4.5% as can be seen in Figure 9 (Ref 3), where a comparison with the Stanton number values given by Kays and Crawford is shown. When ratios of heat transfer coefficient are required as against absolute values, still better accuracy may be expected.

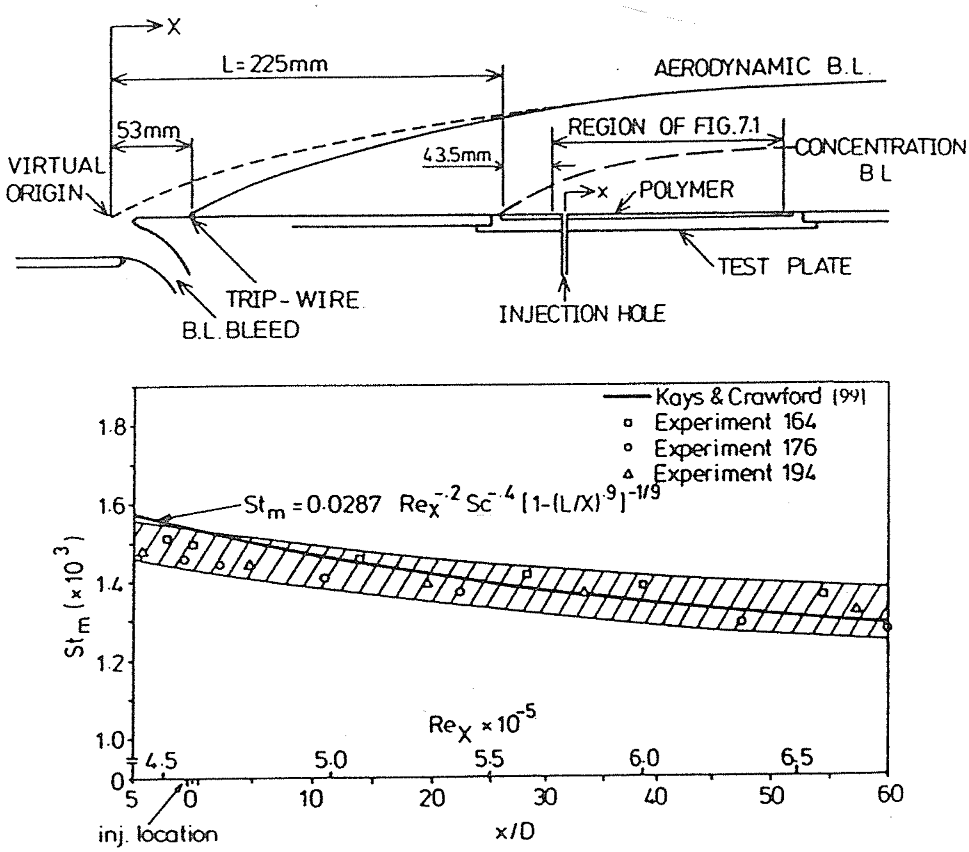

Figure 9: Streamwise variation of Stanton number with no injection.

4.2 Validations

In the field of turbomachinery, the technique has been validated for the following situations:

(a) Film cooling studies with unity and non-unity density ratio (Ref 4).

(b) The simultaneous measurement of effectiveness and heat transfer on a film cooled surface (Ref 5).

(c) The effect of density ratio and acceleration on the heat transfer coefficient on a film cooled surface.

An example of results obtained using the technique is shown in Figure 10 (Ref 6).

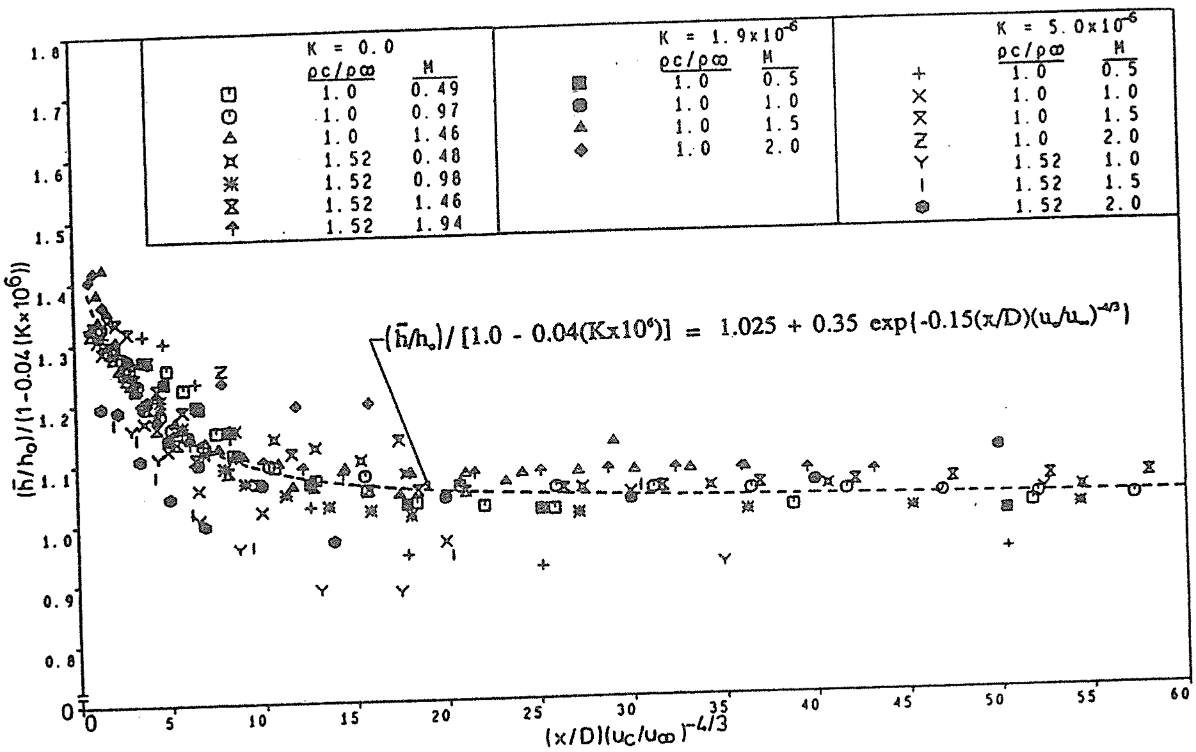

Figure 10: Correlation of h/h_o data for $0 \leq K \leq 5 \times 10^{-4}$ and $0.5 \leq u_c/u_\infty \leq 1.5$ for a single row of holes injecting at $\alpha = 35°$.

5. Future Developments

The slowest of the processes involved in this technique of measuring heat transfer coefficients is the photographic process when the holographic plate is developed and fixed.

Work is in progress on electronic methods of recording frozen fringes so as to eliminate the photographic process. Dr N McLeod, the originator of the Swollen Polymer Technique first attempted to use Electronic Speckle-Pattern Interferometry (ESPI). The method suffers from too much loss of definition. More recently he has introduced a new method using a thermoplastic plate. Excellent results have been obtained with no loss of definition; the problem in this case lies with the very high cost of the equipment. Electronic recording of the image has the added advantage of allowing image processing to be readily applied to the holograms. This would facilitate the interpretation of frozen fringe holograms from curved surfaces.

References.

1. Kapur D N and Macleod N, "The determination of local mass-transfer coefficients by holographic interferometry", Int. J. Heat Mass Transfer, Vol. 17, pp 1151 - 1162, 1974.

2. Hay N, "Heat transfer measurements in steady state facilities", two invited lectures, von Karman Institute for Fluid Dynamics Lecture Series on "Measurement techniques in turbomachines", 25 February - 1 March 1985. Published by the von Karman Institute, Rhode St Genese, Belgium.

3. Ammari H D, Hay N and Lampard D, "Simulation of cooling film density ratios in a mass transfer technique", 34th ASME Int. Gas Turbine and Aeroengine Congress, Toronto, 1989. ASME Paper No. 89-GT-200.

4. Ammari H D, Hay N and Lampard D, "The effect of density ratio on the heat transfer coefficient from a film cooled flat plate". Transactions of the ASME, Journal of Turbomachinery, Vol. 112, pp 444 - 450, July 1990.

5. Hay N, Lampard D, Maali R and Burns I, "Simultaneous determination of heat transfer coefficient and adiabatic wall effectiveness on a film cooled surface using the Swollen Polymer Technique", 8th Int. Heat Transfer Conference, San Francisco, August 1986.

6. Ammari H D, Hay N and Lampard D, "Effect of acceleration on the heat transfer coefficient on a film cooled surface", 35th ASME Int. Gas Turbine and Aeroengine Congress, Brussels, 1990. ASME Paper 90-GT-8.