

# Advances in Optical Interferometry for Combined Heat and Mass Transfer and for Two-Phase Flow

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## ABSTRACT

Holography provides several new interferometric techniques which can be used for heat and mass transfer measurements. After a short discussion of the basic optical set-ups these new techniques are explained. Examples of measurements taken in two-phase flow with condensing bubbles and in simultaneous heat- und mass-transfer with sublimation and in a flame demonstrate the practical applications. In connection with the high-speed cinematography even ultra short phenomena can be experimentally studied and the change of the temperature- and concentration-field can be recorded. From the temperature-field the heat transfer coefficient and from the concentration-field the mass transfer coefficient are evaluated.

## 1. INTRODUCTION

Optical interferometric methods are of "non-invasive" nature which means that the sensor of the measuring technique has no interaction with the fluid to be investigated and that the phenomena of interest and the physical behaviour are not affected. Interferometric methods are used since many years as for example the method proposed by Mach-Zehnder. A difficulty with the classical interferometric methods - for example the Mach-Zehnder-method - is, that one always needs parallel to the real test section a so-called comparison chamber where everything going on in the real test section is reproduced, but not the heat transfer process one is interested in.

Gabor /1/ invented a new optical recording technique which he called "holography". In contrast to photography by which only the two-dimensional irradiance distribution of an object is recorded holography allows the recording and reconstruction not only of the amplitude but also of the phase-distribution of wave fronts. Making use of this unique property completely new interference methods could be developed. As holography demands a highly coherent light source it can be only performed by using a laser.

## 2. HOLOGRAPHIC INTERFEROMETRY

The general theory of holography and holographic interferometry is very comprehensive and cannot be described here in detail. Therefore, reference is made to the literature /2,3/. Here, only a few principles of the technique can be explained. In Fig.1 the holographic two-step image-forming process of recording and reconstructing an arbitrary wave front is illustrated. The object is illuminated by the laser as a monochromatic light source and the reflected, scattered light falls directly onto a photographic plate. This object wave usually has a very complicated wave front. According to the principle of Huygens we can, however, regard it to be the superposition of many elementary spherical waves. In order to simplify the matter only one wave is drawn in Fig.1. This wave is superimposed by a second one called "reference wave". If both waves are mutually coherent they will form a stable interference pattern when they meet on the holographic plate. This system of fringes can be recorded on a photographic emulsion. After its development the plate is called "hologram". The amplitude is recorded in the form of different contrasts of the fringes and the phase in the spatial variations of the pattern. If the plate is subsequently - after chemical processing and development - illuminated by a light beam similar to the original reference-wave the microscopic pattern acts like a diffraction grating with variable grating constant. The light transmitted consists of a zero order wave travelling in the direction of the reconstructing beam plus two first-order waves. One of these first-order waves travels in the same direction as the original object wave and has the same amplitude and phase distribution. Thus a virtual image is obtained. The other wave creates a real image of the object.

This holographic technique can be used instead of photography, for instance, for recording a swarm of very fast moving droplets produced in a high pressure injection nozzle as demonstrated in this symposium by Chavez in his paper on "Single- and double-pulsed holography for the characterization of sprays of the refrigerant R113 injected into its own saturated vapour".

Since in heat and mass transfer the temperature and concentration distribution in fluids is of special interest, a slightly different method is used instead of that described in Fig.1. Instead of watching the reflected object wave a wave - the object wave - having passed through the fluid in which the heat and mass transfer occurs is recorded. A commonly used arrangement of optical set-ups for holographic interferometry is shown in Fig.2. As in the on-light technique also with this through-light method the laser-beam is divided into an object- and a reference beam. Both beams are then expanded to parallel waves by a telescope which consists of a microscope objective and a collimating lense. The object wave passes through the test section in which the temperature is to be examined, whereas the reference-wave directly falls onto the photographic plate.

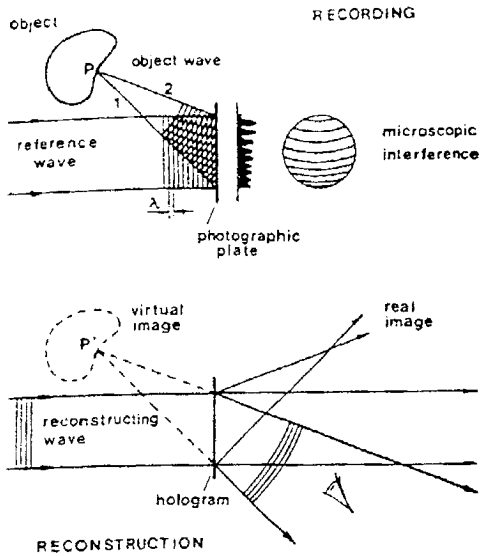


Fig.1 Principle of recording and reconstructing a wave front.

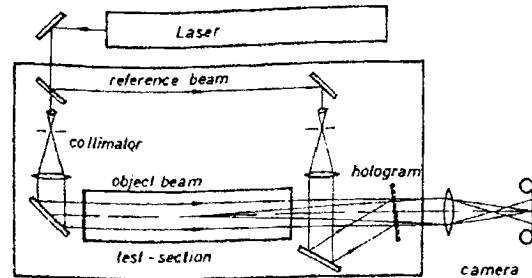


Fig.2 Holographic arrangement for transparent media examination.

In the literature one can find several proposals how to produce a holographic interferogram and how to arrange the optical set-ups /3,4/. Here only one possibility will be explained which can also be used for measuring transient heat transfer. It is called "real-time method", because it allows the observation of a process to be investigated continuously. This method is illustrated in Fig.3. After the first exposure by which the comparison wave is recorded and during which there is no heat transfer in the test section, the hologram is developed and fixed, remaining at its place or repositioned after developing accurately, the comparison wave is reconstructed continuously by illuminating the hologram with the reference wave. This reconstructed wave can now be superposed onto the momentary object wave. If the object wave is not changed and the hologram is precisely repositioned no interference fringes will be seen at first in this so-called "infinite-fringe-field adjustment".

Now the heat transfer process which is to be examined can be started. As a result a temperature field is formed in the fluid and the object wave receives an additional phase shift passing through this temperature field. Behind the hologram both waves interfere with each other and the changes of the interference pattern can be continuously observed or photographed even by the high speed cinematography.

A heat transfer process with very fast transient conditions is subcooled boiling at which the liquid boundary layer at the heated wall is superheated beyond the saturation temperature which would be in equilibrium to the existing pressure. As shown in Fig.4 this superheated boundary layer can be made visible very clearly. The interference fringes - black and white lines - are, in a first approximation, lines of constant temperature. The temperature difference between two interference fringes at any position in

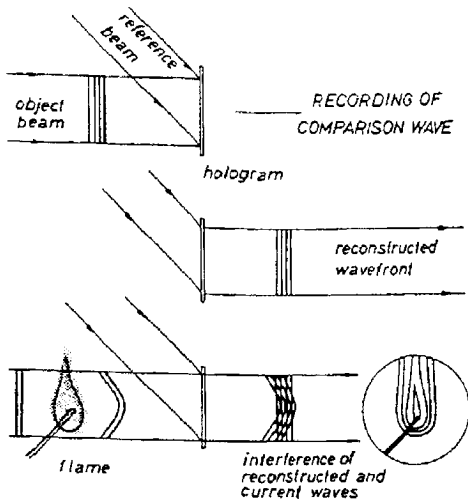


Fig.3 Principle of the real time method.

the boundary layer is constant. So the distance between the interference fringes is a measure of the temperature gradient, and from this we again can evaluate the heat flux and the heat transfer coefficient at the wall. As mentioned the water was slightly subcooled. The bubble shown in Fig.4 in a sequence of high-speed holograms is condensing again after detaching from the heated surface when leaving the superheated boundary layer. A common rotating-prism cine-camera was used for recording the holograms produced in the holographic plate by the method described in Fig.3. For improving the quality of the holograms the laser beam can be periodically interrupted by electro-optical means so that a laser "flash"-light is produced in an extremely short illumination time.

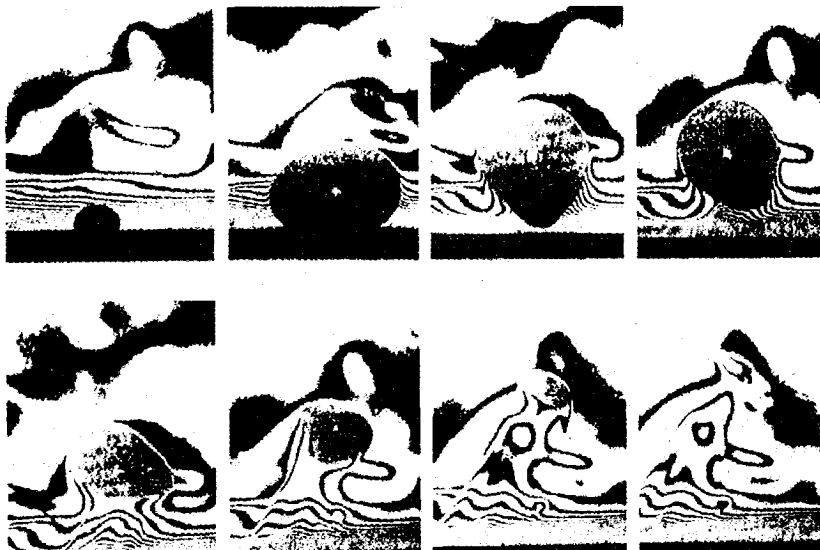


Fig.4 High-speed cinematography of interferograms of a growing and condensing steam bubble on a heated surface.  $p = 1$  bar, subcooling of water  $T = 8$  K, horizontal flow velocity  $w = 0.25$  m/s.

### 3. SPECIAL TECHNIQUES IN TWO-PHASE FLOW FOR PHASE-INTERFACE HEAT TRANSFER

To evaluate the holograms shown in Fig.4 let us in a first step assume that there is only a two-dimensional temperature-field - not a three-dimensional one. The evaluation of a holographic interferogram is then very similar to that of the interference pattern recorded in a Mach-Zehnder-interferometer. Therefore, here only the basic equations will be given. In holography the object waves passing through the test section at different times are superposed and, therefore, reveal the changes in optical path lengths between the two exposures. Expressed in multiples  $S$  of a wave-length this change is calculated, too.

$$S(x,y) \lambda = l [ n(x,y)_2 - n(x,y)_1 ] \quad (1)$$

Where  $l$  is the length of the test section in which the refractive index  $n$  is varied, because of the temperature changes. The multiples of  $S$  is called interference order in the literature. The refractive index distribution  $n(x,y)$  during the recording of the two waves is - as mentioned above - assumed to be two-dimensional (no variation in light direction). Equ.(1) shows that initially only local variations can be determined. Only if the distribution of the refractive index  $n(x,y)_1$  during the recording of the comparison wave is known, absolute values can be obtained. Therefore, one usually establishes a constant refractive index field (constant temperature) while recording the comparison.

$$S(x,y) \lambda = l [ n(x,y)_2 - n_\infty ] \quad (2)$$

To obtain absolute values for the temperature field, the temperature at one point in the fluid has to be determined by thermocouple measurements. This is usually done in the undisturbed region, or at the wall of the test chamber. Equ.(2) is the equation of the ideal interferometry. It is assumed that the light-beam propagates in a straight line. Passing through a boundary layer the light-beams, however, are deflected, because of the refractive index gradients. The light deflection can be converted into an additional phase shift  $\Delta S$  if a linear distribution of the refractive index it is assumed to be within this small area.

$$\Delta S = \frac{n_0 \lambda l}{12 b^2} \quad (3)$$

In this equation  $b$  is the fringe width and  $n_0$  is the average refractive index.

In many applications an ideal two-dimensional field cannot be found. Often the boundary layer extends beyond the ends of the heated wall, or there are entrance effects or temperature variations along the path of the light-beam (axial flow in the test section). Therefore, only integrate

values are obtained. Having corrected the interferogram the obtained refractive index field can be converted into a density field. The relation is given by the Lorentz-Lorenz-formula where  $N$  is the molar refractivity and  $M$  is the molecular mass.

$$\frac{n^2 - 1}{n^2 + 2} \frac{1}{\rho} = \frac{N}{M} \quad (4)$$

If there is only one substance in the test section and the pressure is kept constant, the density variations can only be caused by temperature changes. If the fluid is a gas the situation is very simple, because its refractive index is very near to 1, which reduces Equ.(4) to the Gladstone-Dale-equation:

$$\frac{3}{2}(n - 1) \frac{1}{\rho} = \frac{N}{M} \quad (5)$$

With the simple Boyle-Mariotte-law and  $R$  as the gas-constant we then obtain the following formula which relates the fringeshift to the temperature:

$$T(x, y) = \left[ \frac{S(x, y) 2 \lambda R}{3 N p l} + \frac{1}{T_\infty} \right]^{-1} \quad (6)$$

For liquids the procedure is a little more complicated, because we have to take into account the real behaviour of the thermodynamic properties as a function of the temperature. Therefore, we have to use an equation of state for the refractive index  $n$  or we have to take the refractive index from tables interpolating the data with simple equations. Fortunately there are good data banks available in the literature for most of the fluids. However, it is also not difficult to measure the refractive index in a simple optical set-up.

With an equation for the refractive index as a function of the temperature we then can use Equ.(1) and we get the connection between the pattern of the interference fringes and the temperature field as shown in Equ.(7):

$$S(x, y) \lambda = l \frac{dn}{dT} [ T(x, y) - T_0 ] \quad (7)$$

Often local heat transfer coefficients are of special interest. In this case the temperature gradient at the wall or at a phase interface is determined by assuming a laminar boundary layer next to the wall or to the phase interface. The heat transfer coefficient is then obtained by:

$$\alpha = \frac{-k \left( \frac{dT}{dy} \right)_w}{T_w - T_\infty} \quad (8)$$

The assumption that the temperature field is two-dimensional and constant along the path of the beam travelling through the fluid is not valid in case of temperature fields around bubbles for example. The refractive index  $n$  is then a function of the radius  $r$  as demonstrated in Fig. 5, and we have to use Equ.(1) in its differential form

$$S \lambda = \int_0^l (n - n_0) dz \quad (9)$$

and we write it in spherical or cylindrical coordinates.

$$S(y) \lambda = \int_0^z [n(r) - n_0] dz \quad (10)$$

For spherical and cylindrical symmetry, Equ.(10) can be solved and integrated as described i.e. by Hauff and Grigull/5/ after transforming it in the form.

$$S(y) \lambda = 2 \sum_{k=i}^{N-1} \Delta n_k [(r_{k+1}^2 - r_i^2)^{1/2} - (r_k^2 - r_i^2)^{1/2}] \quad (11)$$

In temperature-fields with very high gradients the deflection of the laser-beam, which is also demonstrated in Fig.5, cannot be neglected as it is done in the evaluating procedure described in /5/. High gradients of temperature are especially found in the liquid boundary layer around vapour bubbles in particular if condensation occurs. In such a case a complicated correction procedure for this deflection has to be used which is described by Nordmann/6/ and by Chen/7/. With the equations and corrections described there even temperature-fields around very tiny bubbles can be evaluated.

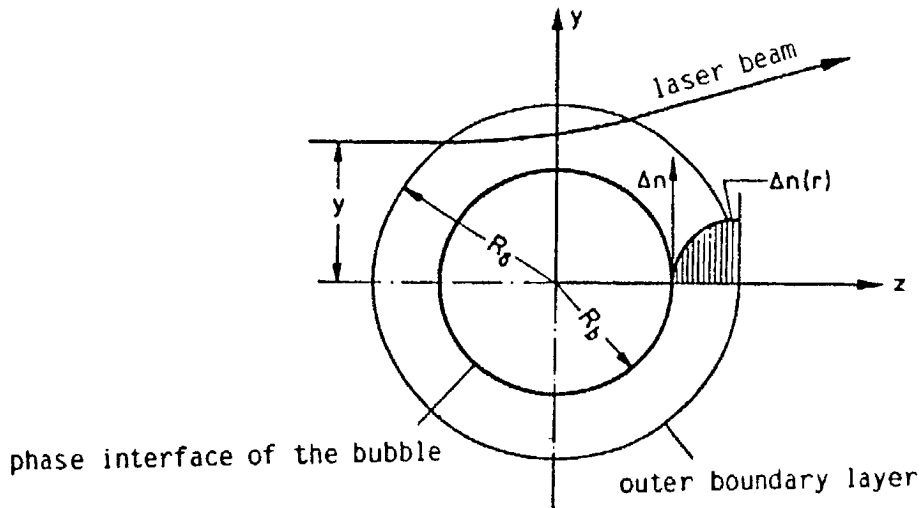


Fig.5 Beam deflection and optical conditions in a temperature field around a spherical bubble.

Boundary layers at the phase interface are usually very thin - in the order of a few hundredth of a millimeter - and it is difficult to investigate them with the interferometric procedure described up to now, because only a few interference fringes would be observed within this narrow area. Therefore, another interference method must be used. This is the so-called "finite fringe method". In this method after the reference hologram was produced a pattern of parallel interference fringes is created by tilting the mirror in the reference-beam of Fig.6 or by moving the hologram there within a few wave-lengths. The direction of that pattern can be selected as one likes and it is only depending on the direction of the movement of the mirror or the holographic plate. This pattern of parallel interference fringes is then distorted by the temperature field due to the heat transfer process. The distortion or deflection of the fringe from its original-parallel-direction is, in a first rough approximation, the temperature gradient and gives by using Equ.(8) the heat transfer coefficient. A short description how these interference patterns are evaluated is given in Fig.7. This figure demonstrates for the example of a temperature-field around a burning flame how these distorted interference fringes look like, depending on the original orientation of the parallel pattern.

Fig.8 and Fig.9 demonstrate the possibilities of using these techniques in flow with bubbles condensing in liquid. Fig.8 illustrates how the temperature-field can be evaluated and Fig.9 shows that this method can be used in high-speed cinematography and allows an inertialess and precise evaluation of the heat transfer coefficient at the phase interface of a condensing bubble.

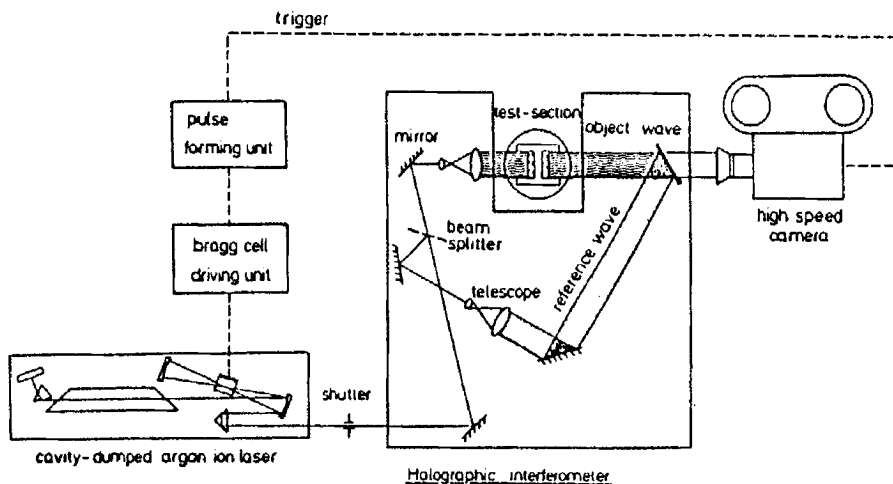


Fig.6 Arrangement for holographic interferometry with finite fringe method.



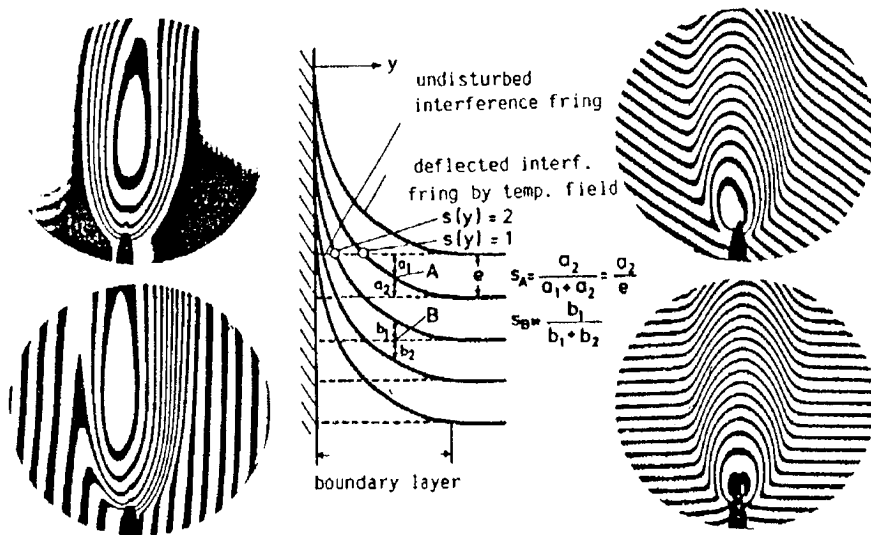


Fig.7 Finite fringe interferograms of the temperature field around a flame and their evaluation.

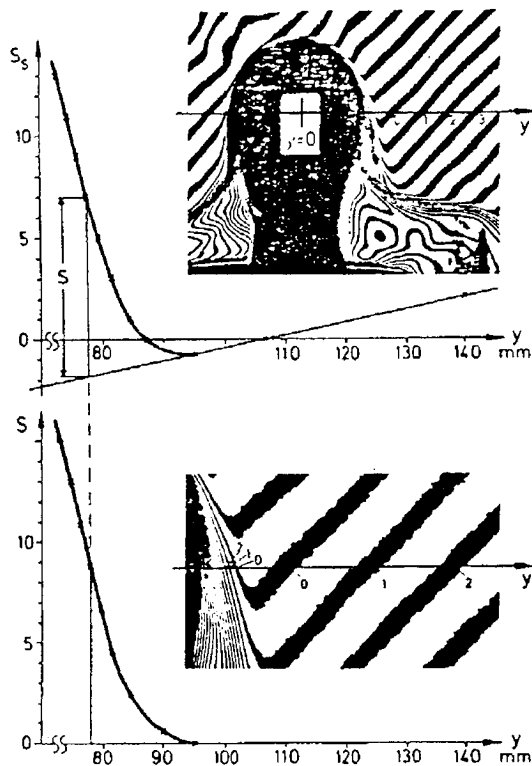


Fig.8 Interferograms around a condensing bubble and their evaluation.

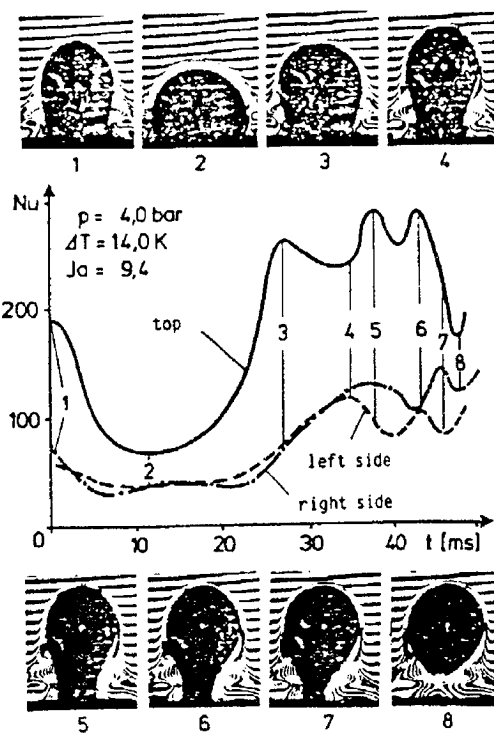


Fig.9 High-speed cinematography of interferograms around a condensing bubble and their evaluated heat transfer at the phase interface.

#### 4. TWO-WAVELENGTHS INTERFEROMETRY FOR SIMULTANEOUS HEAT AND MASS TRANSFER

Interferometric methods allow only the measurement of variations in the refractive index within the test section. When they are caused by a temperature-, concentration- or pressure-change alone, these fields can be determined from the evaluation of the interference pattern. If, however, the refractive index is changed simultaneously by more than one parameter the interferograms cannot be evaluated directly. Therefore, coupled heat and mass transfer processes can be examined by interferometric methods only, if one of the two fields is obtained by an additional measuring method. Only by assuming identical profiles of temperature and concentration the interferograms can be evaluated without additional measurements, as El-Wakil /8/ did. There is, however, one method to determine the temperature and the concentration field by optical means only and this is the so-called two-wavelengths interferometry. This is done by applying the dependence of the refractive index on the wavelength of the light to determine the temperature- and concentration fields by means of separate interferograms taken at different wavelengths. Ross and El-Wakil /9/ used this two-wavelengths interferometry in a modified Mach-Zehnder-interferometer for the study of the evaporation and combustion of fuels. Panknin /4/ used this basic idea and developed a sophisticated method for holographic interferometry.

The problem with two-wavelengths interferometry is that the two interferograms have to be superimposed very accurately. Here, the peculiarity of the holography allowing the recording of different interference pattern on one and the same plate is a great help to overcome these difficulties. A simple set-up for the holographic two-wavelengths interferometry is shown in Fig.10. It resembles very much the arrangement of Fig.2, and, actually, the only difference is that two lasers are used as light sources. The beams of the He-Ne-laser ( $\lambda_j = 6.328 \text{ \AA}$ ) and of the argon laser ( $\lambda_k = 4.579 \text{ \AA}$ ) intersect and, therefore, only one shutter is needed and equal exposure times at both wavelengths are guaranteed. The beams are then superimposed by means of a beam splitter. Thus, one gets two objects- and two reference-waves at the different wavelengths.

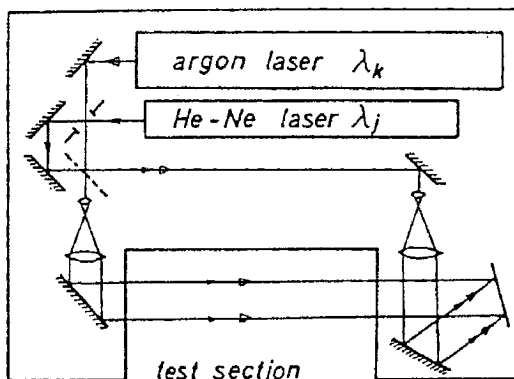


Fig.10 Optical set-up for holographic two-wavelength interferometry.

It has to be mentioned that only the object-wave  $\lambda_j$  is reconstructed by the reference-wave  $\lambda_j$ , but also a false object-wave  $\lambda_k$  is obtained and vice versa. These unwanted waves, however, emerge at different angle from the hologram and can, therefore, easily be separated from the original waves. For the evaluation of the interferograms here only some simple equations shall be presented. For a more detailed study reference is made to the work by Panknin /4/. In gas we can use the Gladstone-Dale-equation, Equ.(5), and the ideal gas law which relates the fringe shift to the temperature- and concentration-distribution in a heat and mass transfer boundary layer.

$$S(x, y) \lambda = \frac{3 p l}{2 R} N_m \left[ \frac{1}{T(x, y)} - \frac{1}{T_\infty} \right] \quad (12)$$

The molar refractivity  $N_m$  for a mixture of two gaseous components is given by

$$N_m = N_a C_a + N_b C_b; \quad \text{with } C_a + C_b = 1 \quad (13)$$

where  $N_a$  and  $N_b$  are the molar refractivities of the components in their pure form and  $C$  is the concentration of the component in the mixture. During the recording of the comparison wave the temperature distribution  $T$  in the test section is constant and there are only two components of the mixture.

Combining Equ.(12) and (13) we obtain for each wavelength

$$S(x, y) \lambda = \frac{3 p l}{2 R} \left[ \frac{1}{T(x, y)} (N_a + C_b(x, y)) (N_b - N_a) - \frac{N_a}{T_\infty} \right] \quad (14)$$

eliminating  $C_b(x, y)$ . The temperature  $T(x, y)$  can be calculated:

$$S_j(x, y) \frac{\lambda_j}{N_{b_j} - N_{a_j}} - S_k(x, y) \frac{\lambda_k}{N_{b_k} - N_{a_k}} = \frac{3 p l}{2 R} \left[ \frac{1}{T(x, y)} - \frac{1}{T_\infty} \right] \left[ \frac{N_{a_j}}{N_{b_j} - N_{a_j}} - \frac{N_{a_k}}{N_{b_k} - N_{a_k}} \right] \quad (15)$$

After determining the temperature distribution only one interferogram is used to calculate the concentration profile.

Equ.(15) shows that there is a difference between the phase shifts for the two wavelengths which is used for the measurement of the temperature. This difference is usually very small. Therefore the two wavelengths used should be as

far apart as possible. The dependence of  $N(\lambda)$  is also very small and gets larger proportions only in the vicinity of an absorption line which, however, is usually not in the visible range. This limits the choice of substances to those molar refractivities which vary considerably over the wavelengths used. Some test fluids suitable for this technique are Naphtalene, Carbondisulphide, Bencene, and Hexane. The position of the fringes has to be determined very accurately at the same place in the two interferograms. To achieve this, the interference contrast distribution has to be recorded photometrically, thus allowing a very high reading accuracy by use of a precision screw with digital output.

A simple application example of the two-wavelengths technique is given in Fig.11. In order to demonstrate the differences in the phase shift only the upper and lower halves of the interferograms are shown and the evaluation is made at the intersection of the pictures. The interferograms show the heat and mass transfer boundary layer at a vertical wall with free convection. The mass transferred was Naphtale-  
ne into air.

Fig.12 gives a comparison of heat and mass transfer data on a vertical plate measured by the two-wavelengths holographic interferometry with predicted values by Wilcox /10/ which are based on measurements with conventional technique. This comparison demonstrates that the holographic method is quite reliable and guarantees a good accuracy.

Heat and mass transfer experiments were also performed in a burning flame with Hexane flowing out of a horizontal porous cylinder and oxidizing after evaporation. Fig.13 shows the two interferograms obtained with the two wavelengths  $\lambda_j$  and  $\lambda_k$  i.e. with the He-Ne-laser and the argon-laser. In this interferogram the finite fringe method was

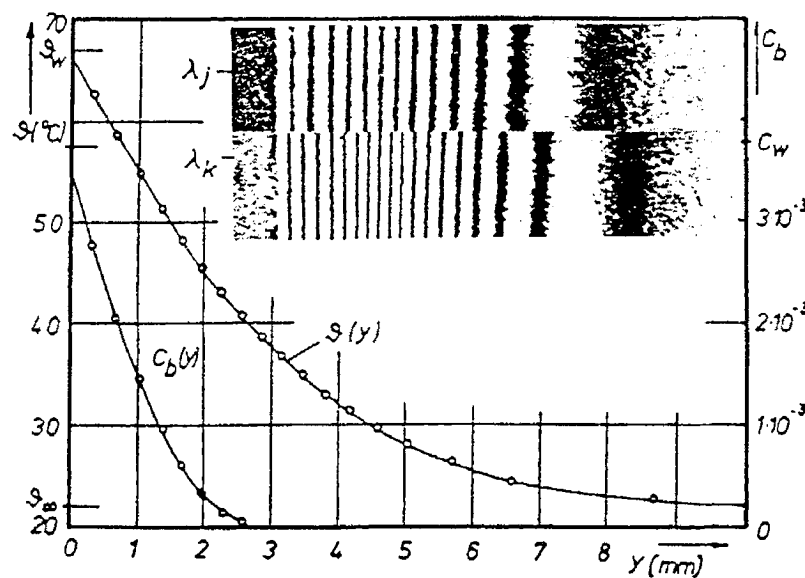


Fig.11 Temperature and concentration profiles in a laminar boundary layer.

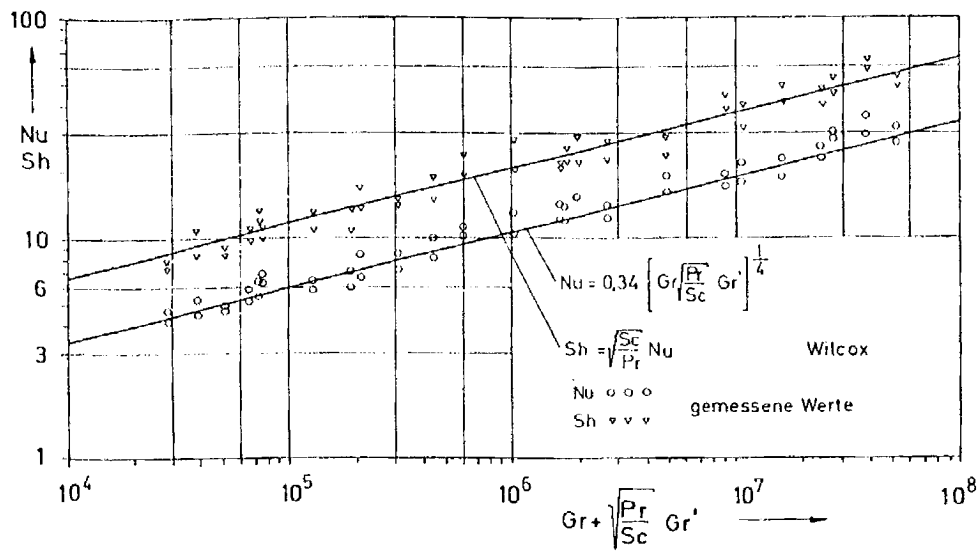


Fig.12 Comparison between experimental measurements and the theoretical relations from Wilcox /10/.

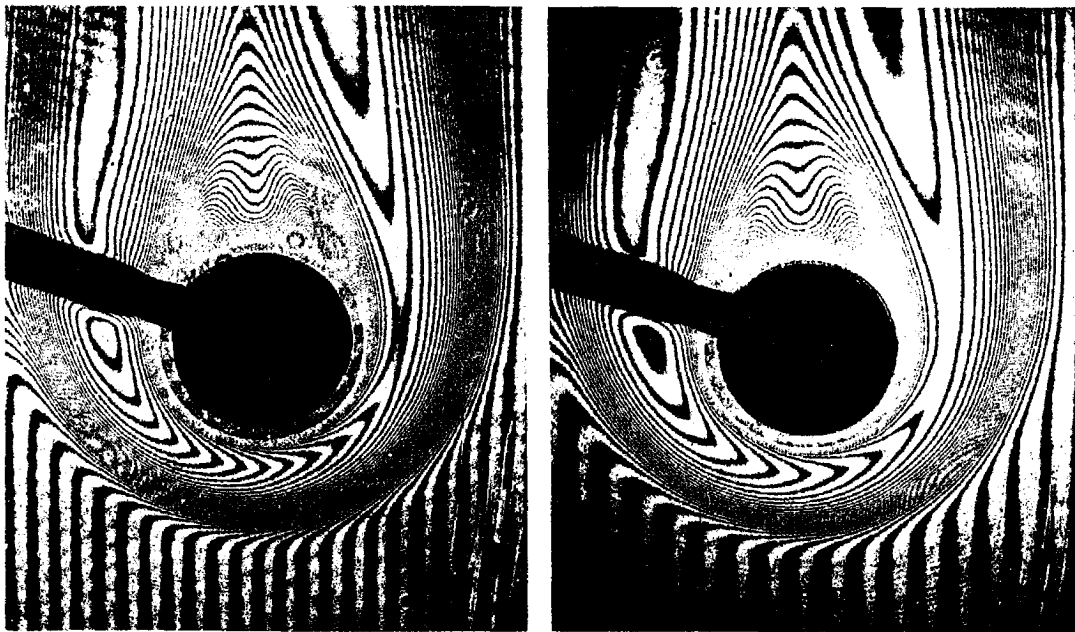


Fig.13 Finite fringe interferogram of a flame taken with two different laser beams of wavelength  $\lambda_j$  (right) and  $\lambda_k$  simultaneously.

used as described in section 3. The temperature field in this flame evaluated from the interferograms in Fig.13 is given in Fig.14 which clearly demonstrates the benefit of this optical method by instantaneously presenting a complete information about the temperature distribution in the flame.

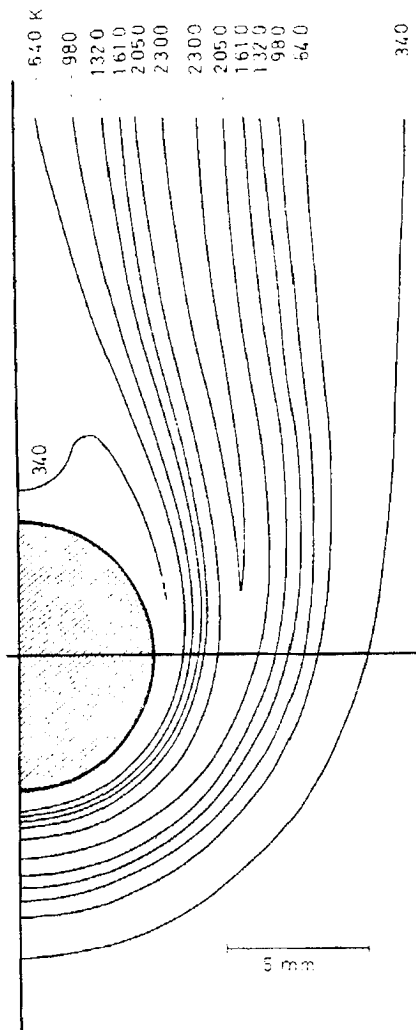


Fig.14 Evaluation of the temperature field in the flame from the interferogram of Fig.18.

## 5. FINAL REMARKS

In contrast to conventional interferometric methods, e.g. Mach-Zehnder and Michelson interferometry, holographic interferometry offers the considerable advantage of greater experimental and technical simplicity together with equal accuracy of measurement. It means, that the necessary optical arrangements are much cheaper, the time needed for adjustment of the equipment and taking measurements is also greatly reduced. High quality glass, lenses and mirrors are not necessary. Since the test chamber is illuminated twice within a short period of time only the temporal changes caused by the phenomena are measured. Therefore measurements can be made even in high pressure autoclaves where the windows are warped because of the pressure.

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