HOLOGRAPHY IN HEAT AND MASS TRANSFER

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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 in detail. Numerous examples demonstrate the practical applications. Compared with conventional Mach-Zehnder interferometry, holographic interferometry has many advantages. Any imperfections of windows, mirrors and lenses are eliminated. The experimental effort is reduced considerably and the costs of the equipment are low.

NOMENCLATURE

b : Fringe width
C : Concentration
k : Thermal conductivity
l : Model length
n : Refractive index
N : Molar refractivity
M : Molecular weight
p : Pressure
R : Gas constant
S : Interference order
T : Temperature
x,y,z : Cartesian coordinates
α : Heat transfer coefficient
δ' : Temperature boundary layer thickness
δ'' : Concentration boundary layer thickness
ϑ : Temperature
ρ : Density
λ : Wavelength

Subscripts
a : Air
b : Naphtalene vapor
j : Indentifies wavelength 6328Å
k : Indentifies wavelength 4579Å
m : Mixture
1 : Indentifies comparison wave
2 : Indentifies measuring wave

INTRODUCTION

Optical methods have been used for many years in heat and mass transfer because of their unique advantages. They do not influence the process examined. Because the measurement is inertialess therefore even ultra fast phenomena can be investigated, and instead of point by point measurements information about a whole field can be obtained by the evaluation of photographs.

Up to a few years ago the most common methods used were Mach-Zehnder and Michelson-interferometry as well as the various Schlieren and Shadowgraph methods, discribed comprehensively and in detail by Hauf and Grigull /1/. In 1949 Gabor /2/ 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 wavefronts. Making use of this unique property completely new interference methods could be developed. As holography demands a highly coherent light source, this could only be done after the invention of the laser about ten years ago; since then, however, the new holographic techniques have already found an enormously wide range of applications. The most important techniques, concerning the study of heat and mass transfer, will be discussed and illustrated by our experiments.

1. PRINCIPLES OF HOLOGRAPHY

The general theory of holography is so comprehensive that for a detailed discription one must refer to the literature /3, 4, 5, 6/. Here only the principles, necessary for understanding the holographic measurement techniques can be mentioned. In fig. (1) the holographic two-step image forming process of recording and reconstructing an arbitrary wavefront is illustrated. The object is illuminated by a monochromatic light source, and the reflected scattered light falls directly into a photographic plate. This object wave usually has a very complicated wavefront. 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. 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 photographic plate. This system of fringes can therefore be recorded on the photographic emulsion. After the development the plate is called "hologram". The microscopic pattern (in general it consists of about 1,000 lines per mm,depending on the angle between the beams and on the wavelength of the laser) contains all information about the wave. The amplitude is recorded in the form of different contrast of the fringes (in our example an intensity increase from ray 1 to ray 2 is assumed). The phase is recorded in the spatial variations of the pattern.

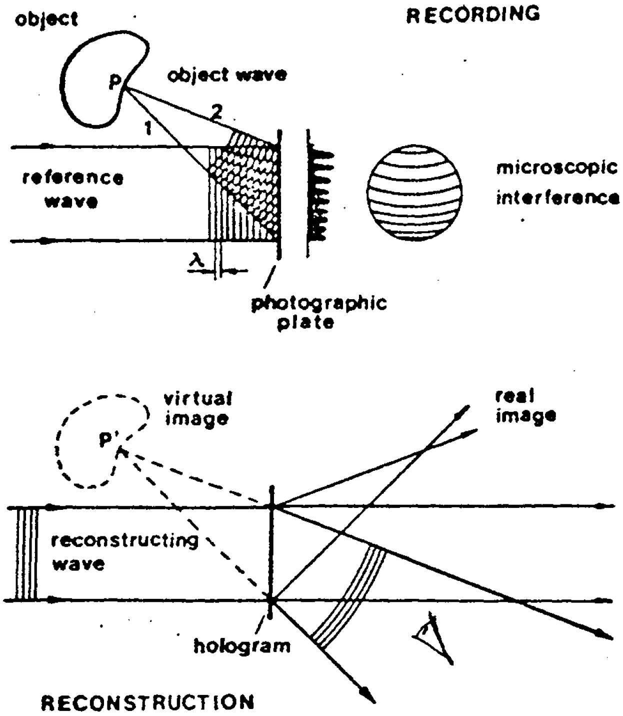


Fig. 1 Principle of recording and reconstructing a wavefront

If the plate is subsequently 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 reconstucting 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 usually appears unsharp and highly distorted. A special method for obtaining a distortion-free real image will be discussed later. Since the wave emerging from the object point P is recorded in each part of the hologram, this point can be seen even through only a small fraction of the plate. It can therefore be observed from various angles, limited only by the size of the hologram. This principle of recording is not restricted to a single spherical wave. The superposition of many waves will create a rather complicated interference pattern, but can still be recorded. In the reconstruction stage the whole image can be seen through each part of the hologram and thus a truly three-dimensional picture is obtained.

Making use of these recording properties even several different waves can be recorded one after the other on one single plate. Illuminating the plate with the original reference wave, the object waves will all be reconstructed simultainously and if they differ only slightly one from another they can interfere. This is the basic idea of holographic interferometry.

The new possibility of superposing diffusely reflected wavefronts has found many applications in a new kind of non destructive material testing and vibration analysis. 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 recording a reflected wave, the object wave having passed through the fluid in which the heat and mass transfer occurs is recorded.

2. BASIC HOLOGRAPHIC SET-UPS

Before discussing the various holographic interference methods it is necessary to explain the required optical set-ups. A most commonly used arrangement is shown in fig. (2). A laser serves as the light source.

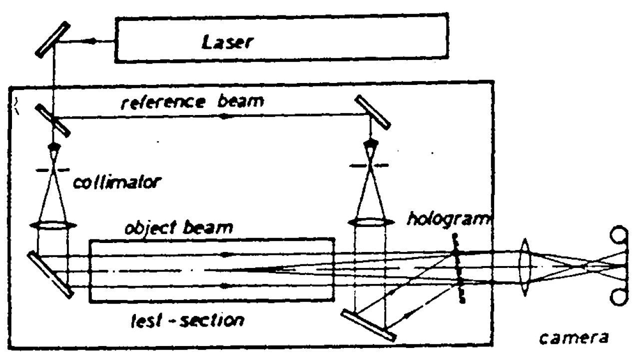


Fig. 2 Holographic arrangement for the examination of transparent media

By means of a beam splitter the laser beam is divided into an object and reference beam. Variable beam splitters are especially useful for allowing easy adjustment of the intensities of the beams. Both beams are then expanded to parallel waves by a telescope which consists of a microscope objective and a collimating lens. The object wave passes through the test section, in which the temperature or concentration field is to be examined, whereas the reference wave directly falls onto the photographic plate.

As already mentioned, holography demands a highly coherent light source. Therefore today lasers are used exclusively. Continuous measurements can only be made with continuous wave lasers, as there are He-Ne-lasers, Argon- and Krypton-lasers. For ultra fast processes pulsed ruby lasers can be more advantageous.

To obtain bright reconstructions from a hologram, the interference pattern between object and reference wave must be stable during the exposure of the plate. Therefore the optical components are mounted on a vibration free table. To avoid even those vibrations which can be caused by a watercooled laser, it is sometimes necessary to place the laser away from the optical set-up. All the optical components need not be of high optical quality as in conventional interferometry, since only relative changes of the object wave are measured. This will be demonstrated and discribed in detail in the following chapters. Since by interferometric techniques only two dimensional refractive index distributions can be measured with great accuracy, in most cases parallel object waves are used.

For some applications, however, a diffuse illumination of the test section may be more advantageous or even necessary.

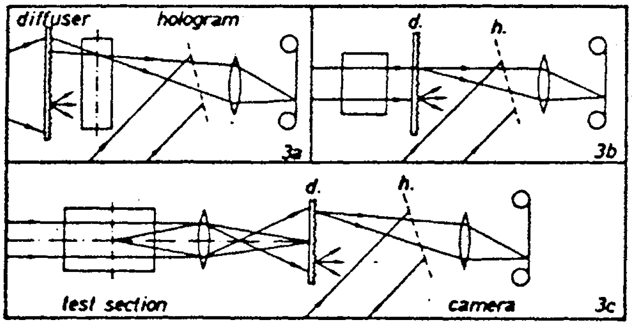


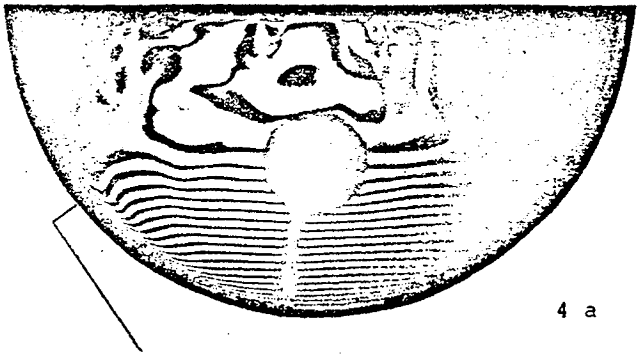
Fig. 3 Holographic set-ups with diffuse illumination of the hologram

As shown in fig. (3), this can easily be done by inserting a diffuser into the object beam. The test section can now be examined from different angles, and thus additional information about the phase object is obtained. This is necessary for the measurement of completely irregular fields, as will be discribed later.

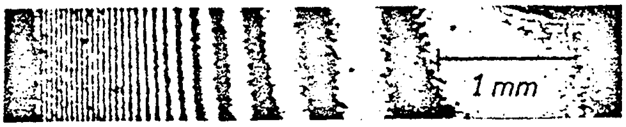
A diffuse illumination can also be chosen if the diameter of the object is bigger than the available photographic plates or the lenses necessary for a parallel beam. There is, however, one disadvantage. Taking photographs of the object wave, the different beams which form an image point pass through the test section at various angles. It is therefore not easy to get proper interferograms, and also the evaluation is much more complicated. Especially near the walls no interference lines will be obtained, if the format of the hologram is smaller than the object.

The advantage of parallel illumination of the test section and diffuse illumination of the hologram can be combined if a set up like that in (3 b) or (3 c) is chosen. In fig. (3 b) the parallel object wave passes through the test section and is then projected onto a diffuser. Using a mask, in front of the holographic plate, many object waves can be recorded on one single hologram by subsequent exposure of different parts of it. This set-up can, however, only be used in the case of low interference lines densities. High fringe densities can be recorded, if an additional lens is placed between the test section and the diffuser. As shown in fig. (3 c), the wave is correctly focused onto the screen and thus high quality interferograms can be made.

Although the method of making an interferogram has not been discribed yet, examples will be given for demonstrating the parallel and diffuse illumination technique. Fig. (4, 5, 6) show the temperature field at free convection of a fluid with internal heat sources /7/. The walls of the semicircular cavity were uniformly cooled. The diameter of the model (200 mm) was relatively large, therefore diffuse illumination was used to get a view of the whole field.



4 a



4 b

Fig. 4 Temperature field in a semicircular cavity. Diffuse and parallel object beams

According to fig. (3 a) no interference lines can be distinguished very close to the wall, therefore the evaluation of heat transfer coefficients is not possible in this case. In another experiment with the same model, a plane wave was used as in fig. (2). Now fringe densities up to 25 1/mm could be resolved as shown in fig. (4 b). A parallel object beam was also used for the investigation of heat transfer at free convection in rectangular cavities. Fig. (5) shows the temperature field which is obtained when the fluid (water) is heated from below and cooled from above. A very regular, rollerlike convection can be observed. For comparison reasons in fig. (6) the temperature field is shown, which is obtained, when the fluid is heated by internal heat sources.

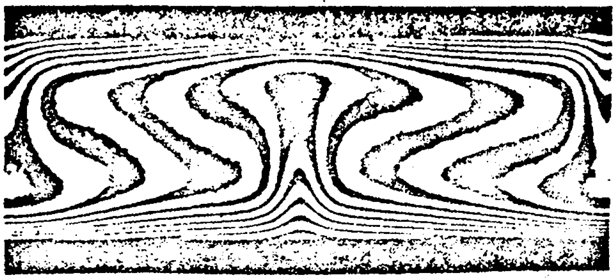


Fig. 5 Temperature field in a liquid layer heated from below. Parallel object beam used for recording the interferogram

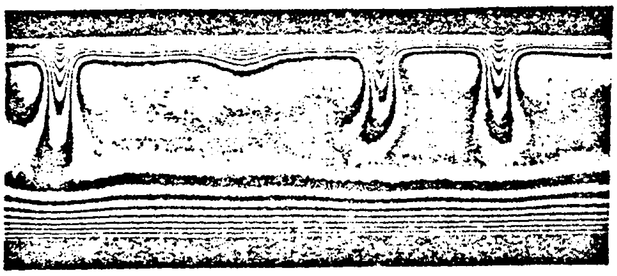


Fig. 6 Temperature field in a liquid layer heated by internal heat sources

The convection rather disintegrates into a series of non-uniform eddies, changing with time in size, position and number.

3. HOLOGRAPHIC INTERFEROMETRY

In order to point out the fundamental differences between holographic interferometry and conventional interference methods it is necessary to remember how, for example, the most commonly used two beam interferometer of the Mach-Zehnder type works as shown in fig. (7).

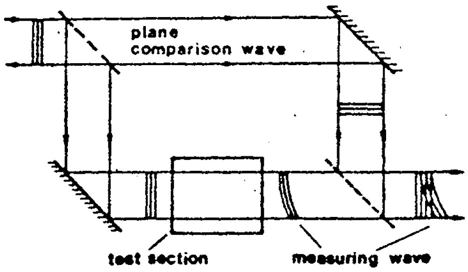


Fig. 7 Mach-Zehnder-Interferometer

A plane wave is divided into two separate beams by means of a semitransparent mirror. The measuring beam passes through the test section where the initially plane wave gets an additional phase shift because of local temperature or concentration variations. This distorted wavefront is superimposed onto the undistorted comparison beam, which did not pass through the measuring section. The resulting interferogram reveals the differences in optical path length between the two beams. From these differences the temperature or concentration fields in the section are calculated subsequently.

In holograhic interferometry two waves are superposed, which passed through the test section at different moments. Therefore changes, which occur between the two recordings, are measured.

The superposition of two object waves can be accomplished by various techniques, which will be described in detail.

First, however, we must recall that this macroscopic interference between the two object waves must be clearly distinguished from the microscopic interference, which already occurs by the superimposing of reference and object waves in the recording stage of a hologram. Therefore, we shall call the object waves comparison and measuring wave.

3.1 DOUBLE EXPOSURE TECHNIQUE

As already mentioned, several object waves can be recorded one after the other on one hologram. By illumination with the reference wave they are all simultaneously reconstructed. If they differ only slightly from one another they will interfere macroscopically. In the interference pattern the differences between the object waves is discernible. This principle is used for the double exposure technique illustrated in fig. (8).

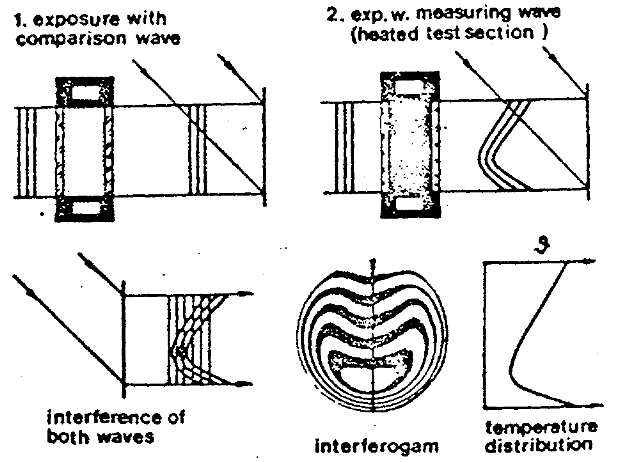


Fig. 8 Principle of the double exposure technique

As an example the temperature distribution in a heated tube is chosen. In a first exposure the wave passing through the test section with constant temperature distribution is recorded. This wave may, however, already be distorted because of imperfections in the windows of the test-chamber or by distortions caused by pressure. After recording of the comparison beam the phenomena to be investigated is started. In this case the temperature field is established by heating the walls of the tube. Now the incoming wave receives a continious additional phase shift due to the temperature changes. This resulting wave front called the measuring beam is recorded on the same plate. After processing, the hologram is repositioned and illuminated by the reference beam. Now both object waves are reconstructed simultaneously and will interfere. The interference picture can be observed or photographed.

The main difference from classical interferometry is, that the object beam is compared to itself. This allows a range of new applications, improvements and simplifications of optical interferometry compared to conventional techniques. Since both waves pass through the same test section any imperfections on the windows, mirrors and lenses are eliminated. Examinations even at very high pressure can be made, because the deformation of the windows can be compensated.

An example, investigated with the double exposure technique is given in fig. (9).

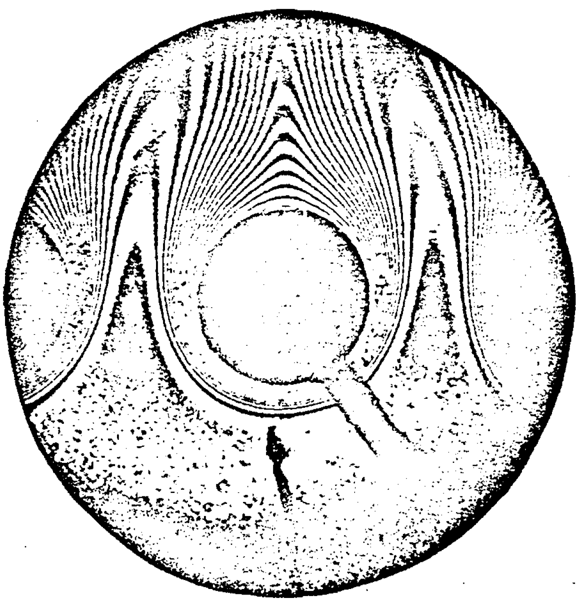


Fig. 9 Temperature field around a tube bundle at free convection

The interference pattern shows the field of isotherms around heated horizontal tubes at free convection. The temperature difference between two isotherms is about 2.3 K. In the region of high heat transfer, at the stagnation point, the closely spaced isotherms indicate a large temperature gradient, whereas at the rear only a moderate one exists. The special advantages of the double exposure technique are: The method is very simple and reliable. Only little experimental effort is needed. The interference pattern is recorded and can be looked at or photographed at any time.

There are, however, also some drawbacks. The most favourable moment for recording the measuring wave cannot be determined in advance, because the interferogram can only be seen after processing the plate. Instationary processes cannot be continuously observed. The recorded measuring wave cannot be reconstructed separately from the comparison wave. Therefore it cannot additionally be examined by the usual Schlieren- or Shadowgraph methods. For each interferogram the reference condition must be created thus much time is needed for the experiments.

3.2 SUPERPOSITIONS-TECHNIQUE

In the double exposure technique, the measuring and comparison beams are recorded on the same photographic plate. For some applications it may be advantageous to record the two object beams not on one single hologram but on two separate ones. This can be done by simply exchanging the photographic plates between the two exposures.

However, to superimpose the two waves a special optical set-up, like that in fig. (10) is necessary.

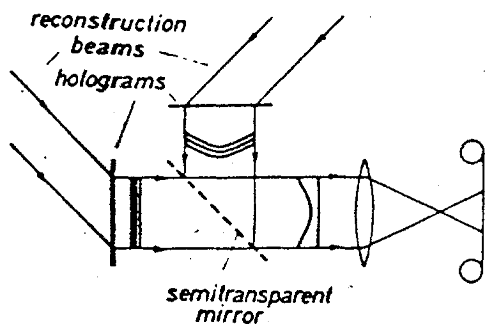


Fig. 10 Arrangement for superposing two holograms

The reconstructed wave fronts are superimposed by a semitransparent mirror and can thus interfere with one another. This technique has the following advantages. The interference pattern can be studied by using the infinite fringe field and finite fringe field adjustment alternately. This is accomplished by a slight adjustment of the beam-splitter.

In fig. (11) three various adjustments of one single interferogram are shown. In the infinite-fringe field position (fig. 11 a) the interference lines can be interpreted as isotherms. Using a superposed horizontal fringe field (fig. 11 b) the order of the interference lines can be controlled by counting the intersections along a straight line. The vertical adjustment (fig. 11 c) allows the determination of maximum fringe density.

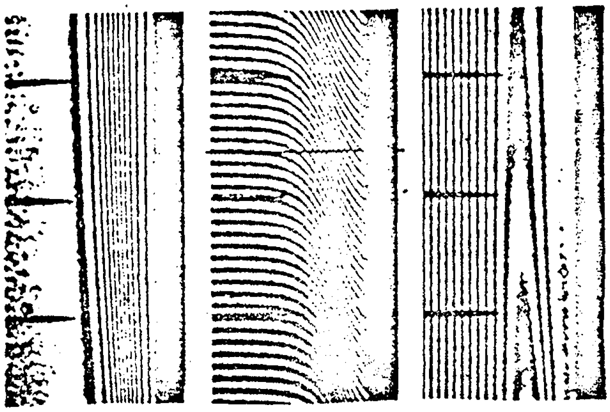


Fig. 11 Finite and infinite fringe field adjustments

This interferogram shows the superposed temperature- and concentration boundary layer at a vertical wall. Although combined heat and mass transfer will be discussed later, it should already be mentioned that in this case the maximum fringe density is not immediately at the wall. The superposition technique has some further advantages. Since the comparison wave is recorded only once on its own hologram, a great number of measuring waves can be recorded in sequence without establishing the state of comparison between the exposures. It is also possible to compare the measuring waves with each other in order to get interferograms, which directly show the changes between the different exposures.

This is especially useful for experiments which are carried out over a long period of time. It can also be used when the fringe density caused by temperature gradients is too high to be recorded on one interferogram.

As each measuring beam can be reconstructed separately one can easily use other optical methods (Schlieren- and Shadowgraph methods) for the study of the phase object in the test section. Therefore the most suitable method can be chosen after the experiment has been done.

There are, however, considerable disadvantages which make this technique difficult to use. The semitransparent mirror must be of high optical quality and ground flat to about 1/10 of the wavelength of light used. This mirror and the plate holders must be positioned extremely accurately and the reconstruction waves must be identical to the original reference waves. Because of this relatively complicated experimental set-up the method has not often been used so far. In the following chapters two techniques are discribed by which most of the possibilities discussed can be achieved with less experimental effort.

3.3 MULTIPLE EXPOSURE TECHNIQUE USING DIFFERENT REFERENCE BEAMS

One disadvantage of the ordinary double exposure technique is that the two objectwaves cannot be reconstructed separately This is due to the fact that only one reference wave serves for the recording of the two wavefronts. If, however, each object beam is recorded by a reference beam of its own, then it can also be reconstructed independantly from the others. To achieve this, the reference wave must be coded in a suitable manner, in order to avoid cross modulation of the different waves. This can be done easily by using different angles between the object and reference beams. One possible optical setup is shown in fig. (12).

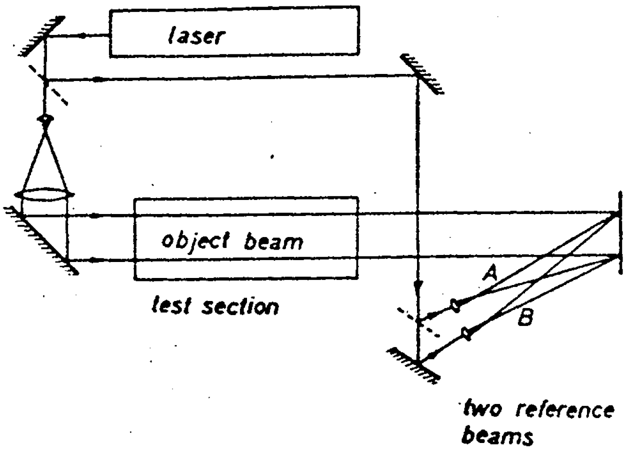


Fig. 12 Optical set-up with two reference beams

If the mean angles between the beams are sufficiently large, only the corresponding object waves will be reconstructed with significant efficiency. This arrangement offers some interesting possibilities. The comparison and measuring waves are recorded by using the two reference beams alternately. In the reconstruction step the interferogram can again be evaluated using the fringe or infinite fringe field adjustment. This is accomplished by varying one of the reference beams.

It is also possible to record the comparison beam with both reference waves and then two successive measuring waves using only one reference beam for each. The two resulting interferograms can be reconstructed seperately or superimposed, which results in a kind of moiré pattern.

The necessary optical arrangement is rather simple and the variation of this technique most suitable to the problem can easily be chosen.

Although the following interferograms in fig. (13), showing the temperature field around a bundle of heated tubes, were taken in a conventional set-up with only one reference beam, they may serve for demonstrating an application example of the discussed technique.

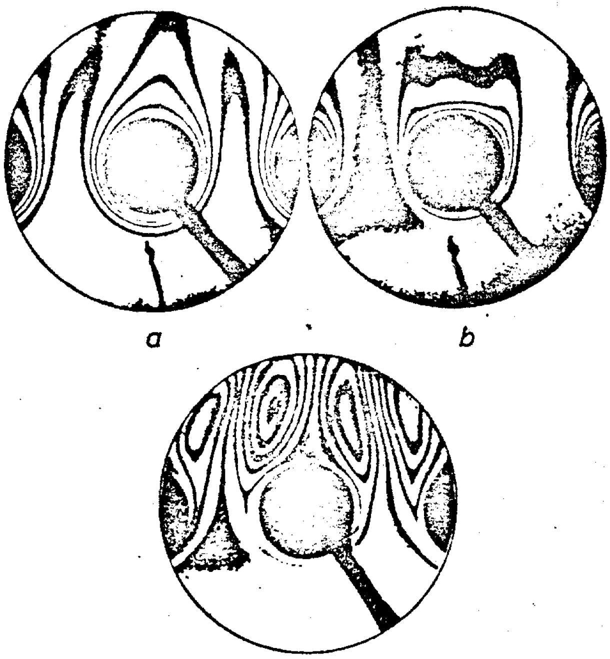


Fig. 13 Temperature field around a bundle of heated tubes at forced and free convection

Let us assume that the undisturbed comparison wave is holographically recorded by using only the reference beam A. Then the tubes are heated up in order to get a temperature field at free convection. The resulting objectwave is recorded by both reference beams. Now an additional flow is introduced to obtain forced convection. The second measuring wave is recorded, using reference beam B only. Thus two interferograms are recorded on the plate. The hologram in fig. (13 a) shows the temperature field at free convection, whereas the second one (fig. 13c) directly reveals changes of the temperature distribution caused by the additional flow. For comparison an ordinary interferogram of the temperature field at forced convection is given in fig. (13b).

For practical reasons the number of seperate reference waves and exposures is limited. Only a few measuring waves can be recorded subsequently. This is not the case if the following method is used.

3.4 MULTIPLE EXPOSURE TECHNIQUE USING TWO OBJECT BEAMS

If the temporal changes of the interference pattern are of special interest, the following method can be applied fig. (14).

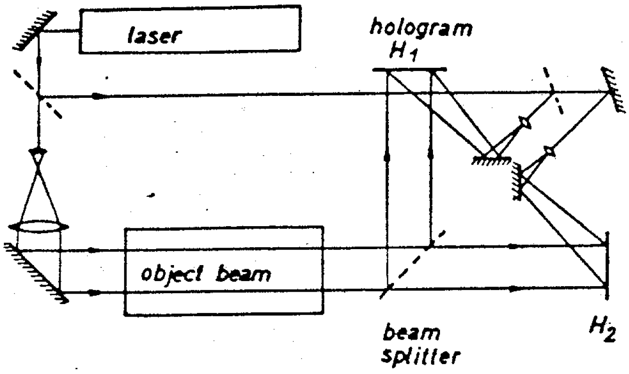


Fig. 14 Optical arrangement using two object beams

After having passed the test section, the object beam is divided into two parts by means of a beam splitter (which does not have to be of high optical quality) and can now be recorded alternately on two holographic plates. For example the comparison wave is recorded only on hologram H_1. Then both holograms H_1 and H_2 are exposed by a measuring wave simultaneously. After replacing H_1 one by another plate H_3 the third exposure of the measuring beam can be taken, and so on and so forth.

By this technique the interference pattern directly reveals the temporal changes of the measuring beam, and there is no delay as in the usual one-hologram-set up, when the plates are replaced. This can be applied in various ways. High fringe densities resulting from big temperature gradients can be resolved by exposing several holograms during the increase of the temperature gradient. In some cases this technique can be also applied to the examination of simoultaneous heat and mass transfer, if the temperature and concentration field can be established one after the other. Then the difference between comparison field and pure temperature field is recorded on hologram H_1 whereas the difference between the temperature and the combined temperature and concentration field can be evaluated from hologram H_2.

3.5 REAL-IMAGE INTERFEROMETRY

Discussing the principles of holography it has already been mentioned that by reconstructing a hologram not only a virtual but also a real image can be obtained.

In holographic double exposure interferometry this real image is very useful because it has distinct properties. In order to demonstrate this the ordinary method of taking photos of an interference pattern is shown in fig. (15).

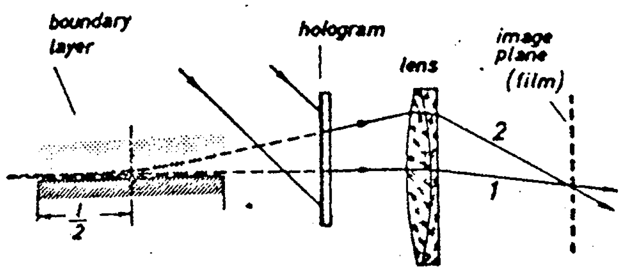


Fig. 15 Arrangement for taking pictures of the virtual image

The two beams, recorded at different times, are superimposed in the reconstruction stage. Sharp and undistorted interference patterns can only be obtained if by a lens the beams are correctly focused onto the film. This is demonstrated by observing the beam which is nearest to a heated plate. If constant temperature is provided while recording the comparison wave, this beam travels through the test section in a straight line. The measuring beam, however, is deflected in the boundary layer because of the temperature gradient. It therefore gives the impression of originating from near the middle of the test section. In order to get clear interference patterns of high contrast these two beams must be superimposed. This is done by a lens, focused on the middle of the test section. This process can be simplified by using the real image. A real undistorted image is obtained when a parallel reference beam is used, and the hologram is reconstructed with the conjugate reference wave. This can be done by inverting the direction of the reference wave or by simply turning the hologram itself around, as shown in fig. (16).

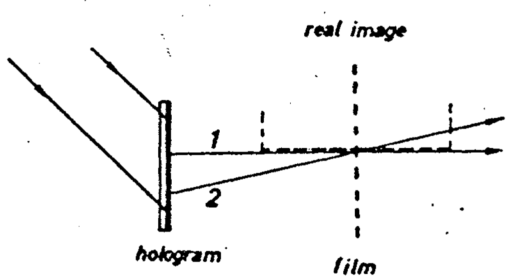


Fig. 16 Arrangement for establishing a real image

The corresponding beams of the two waves recorded then form a real image of the interference pattern, and intersect in the focusing plane. In this position the recording medium (e.g. a sheet of film) is placed. No additional lenses, which might distort the image, are necessary. The real image can also be easily examined by a microscope, and thus very narrowly spaced fringes can be studied more easily than by conventional methods.

Two photos will illustrate this. The interference picture in fig. (17) shows a bubble condensing in water. The hologram was made by using an argon laser with an output of 1 W for $\lambda = 5145$ Å, and resulting exposure times of 1/2000 sec. The closely spaced fringe field on top of the bubble indicates a considerable temperature gradient. However, the fringes cannot directly be converted into isotherms, because the temperature field is axial symetric rather than two dimensional.

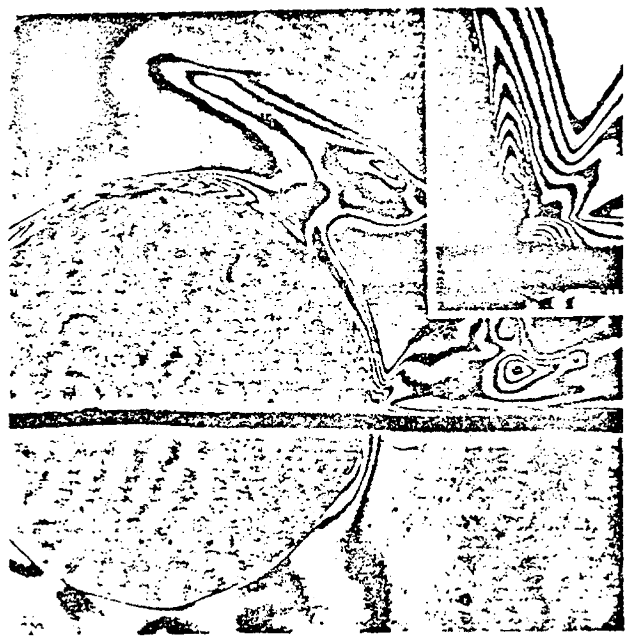


Fig. 17 Temperature field around a bubble during condensation

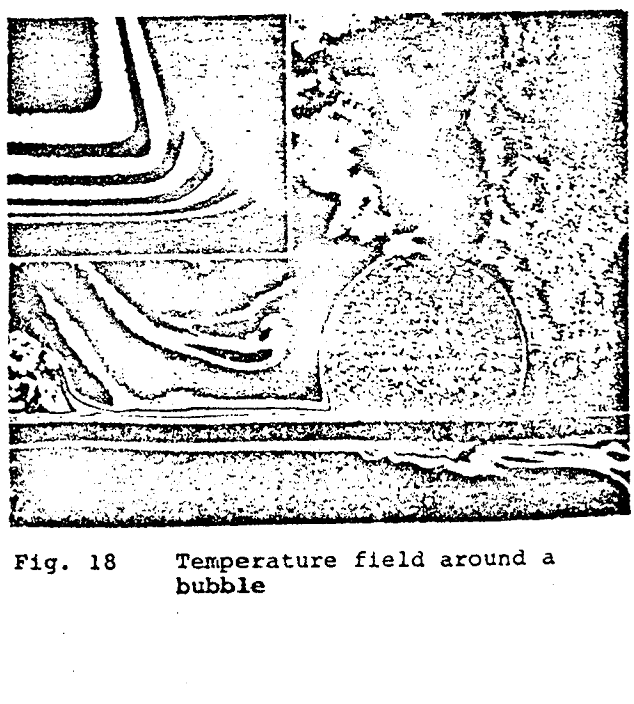


Fig. 18 Temperature field around a bubble

Fig. (18) shows a bubble shortly before leaving the heating surface, which consisted of an electrically heated wire. The very narrow interference lines in the boundary layer around the wire and near the bubble could only be photographed by focusing onto the real-image.

Using holographic interferometry we hope to get new information about the heat transfer mechanism near the phase boundary of the bubbles during condensation in subcooled liquids. Further results can be found in /8/.

3.6 REAL-TIME-METHOD

With all techniques discribed so far, the investigated process cannot be continously observed. This is a very essential disadvantage of all the holographic multiple-exposure techniques, in comparison to classical interferometry (for example Mach-Zehnaer-Interferometry). However, this disadvantage can be overcome, if the real-time-method (single-exposure-method) is used, as illustrated in fig. (19).

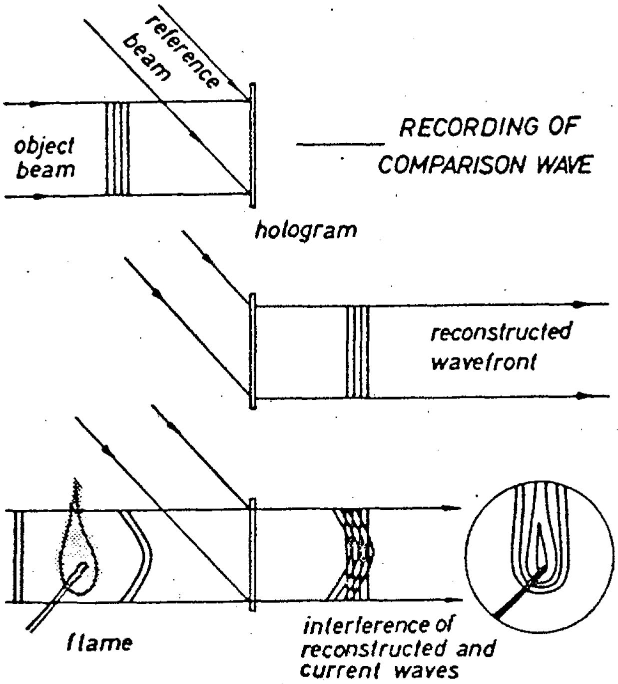


Fig. 19 Principle of the real-time-method

After the first exposure by which the comparison wave is recorded, the hologram is developed and fixed. Remaining at its place or repositioned 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 precisely repositioned, no interference fringes will be seen at first (infinite-fringe-field adjustment). Now the heat or mass transfer process, which is to be examined, can be started. In our example the wave receives an additional phase shift passing through the temperature field of a burning match. Behind the hologram both waves interfere with each other, and the changes of the interference pattern can be continously observed or photographed on still or movie film.

The real-time-method demands an accurate reconstruction of the comparison wave, therefore the hologram must be repositioned precisely at its original place. This can be done by using a precision plate holder. The difficulties involved in repositioning the plate are entirely abolished, if the hologram is not removed, but processed at its place. This is done by using a "liquid plate holder", consisting of a cuvette, in which the photographic plate is inserted. In order to avoid the long drying process and to compensate a shrinkage of the photographic emulsion, the plate is soaked in water and also exposed in the tank, filled with water. Subsequentely it is developed and fixed. For the reconstruction the cuvette is filled with water again. The whole process does not take more than about 10 minutes. This rather convenient technique has however two disadvantages which should be mentioned.

Long-time examinations over a couple of days cannot be made, because the photographic emulsion soaked with water, finally peels from the glass plate. If the tank is not manufactured precisely, using high quality glass plates for the windows, it will act like a bad lense, when filled with water, and high precision measurements are not possible. Even smallest temperature changes of the water must be avoided, otherwise additional unwanted interference fringes will be obtained.

Because of this an ordinary precision plate holder is often more favourable. Using this type in a long-duration test, we succeeded in maintaining an infinite-fringe field adjustment for six months, until the hologram was accidentaly distroyed. The most important advantage of the real-time method is - as mentioned - the possibility of continuously observing and recording the interference pattern. But there are some further advantages. The comparison state has to be established only once for the recording of the comparison wave. Thus much time is gained for the experiments. Only one of the rather expensive photographic plates is needed for the experiment and a large number of interferograms can be taken on ordinary film.

There are however also some disadvantages. A relatively expensive developing cuvette or a similar expensive precision plate holder is needed. Instationary interference patterns can be investigated only by using either the infinite or the finite fringe field adjustment. The object beam should not change within the time, necessary for processing the photographic plate, since otherwise it cannot be controlled whether the plate was correctly repositioned or not.

The possibilities of using the real-time-method are demonstrated by two examples. For a long time the local heat transfer coefficients and boundary layer properties in axial flown tube bundles have been of interest. In fig. (20) the triangular flow section formed by three rods of such a bundle is shown. From the interference fringe pattern along the circumference of the three heated rod segments the local heat transfer coefficients can be calculated. (Since the object beam gets its fringe shift on its way through the test section, the heat transfer coefficients are integrate values).

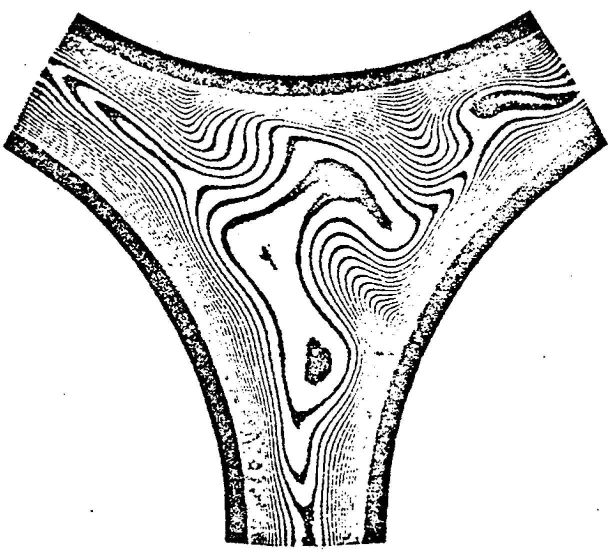


Fig. 20 Temperature field in a triangular flow section Re = 2200

This picture was made in the transition from laminar to turbulent flow, where the flow pattern varied strongly with time. The different thickness of the boundary layer can be clearly distinguished. A much more uniform flow was obtained at lower Reynold numbers and in more closely spaced tube bundles, as shown in fig. (21).

The investigation /9/ was carried out for analysing the heat transfer during emergency cooling of liquid-metal fuel elements.

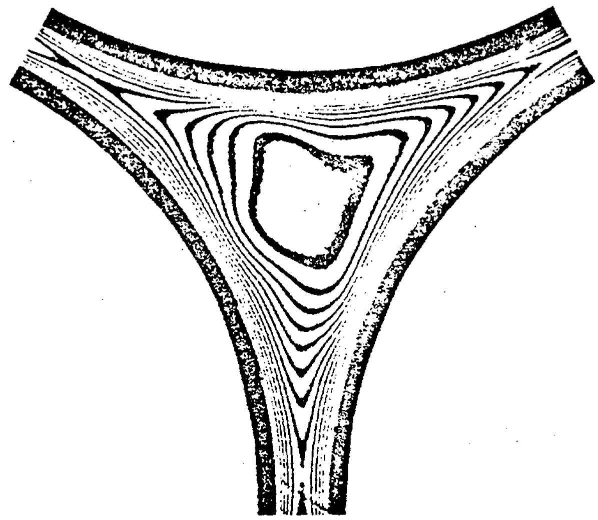


Fig. 21 Temperature field in a triangular flow section Re = 1050

Using a high speed camera even films with many thousand frames per second can be taken. This of course requires a sufficiently powerful laser. In our experiments the 5145 A emission (power 1 W) of an argon laser was used, allowing film speeds of up to 10.000 frames/sec. Several pictures enlarged from such a film are shown in fig. (22). The film was made with 2500 frames/sec.

For the investigation of temperature and heat transfer conditions around steam bubbles at subcooled boiling /8/, many of such films were made. In this case the test fluid was water at a pressure of 0.3 bar.

The bubbles rose from an electrically heated wire of 0.4 mm dia. Note that the time, in which the bubble grows to its maximum size is about ten times shorter than the condensation period. During the recording of the comparison wave, the fluid was already at its temperature, but the wire was not heated yet. Therefore deformations of the windows and temperature fields outside of the testchamber could be eliminated, and only two interference lines can be seen in the undisturbed area. In spite of this the interference lines in the boundary layer cannot directly be interpreted as isotherms, since the field is not two dimensional. Assuming spherical bubbles and rotational symmetry of the temperature field around the wire and the bubble, the interferograms can be evaluated using the Abel integration.

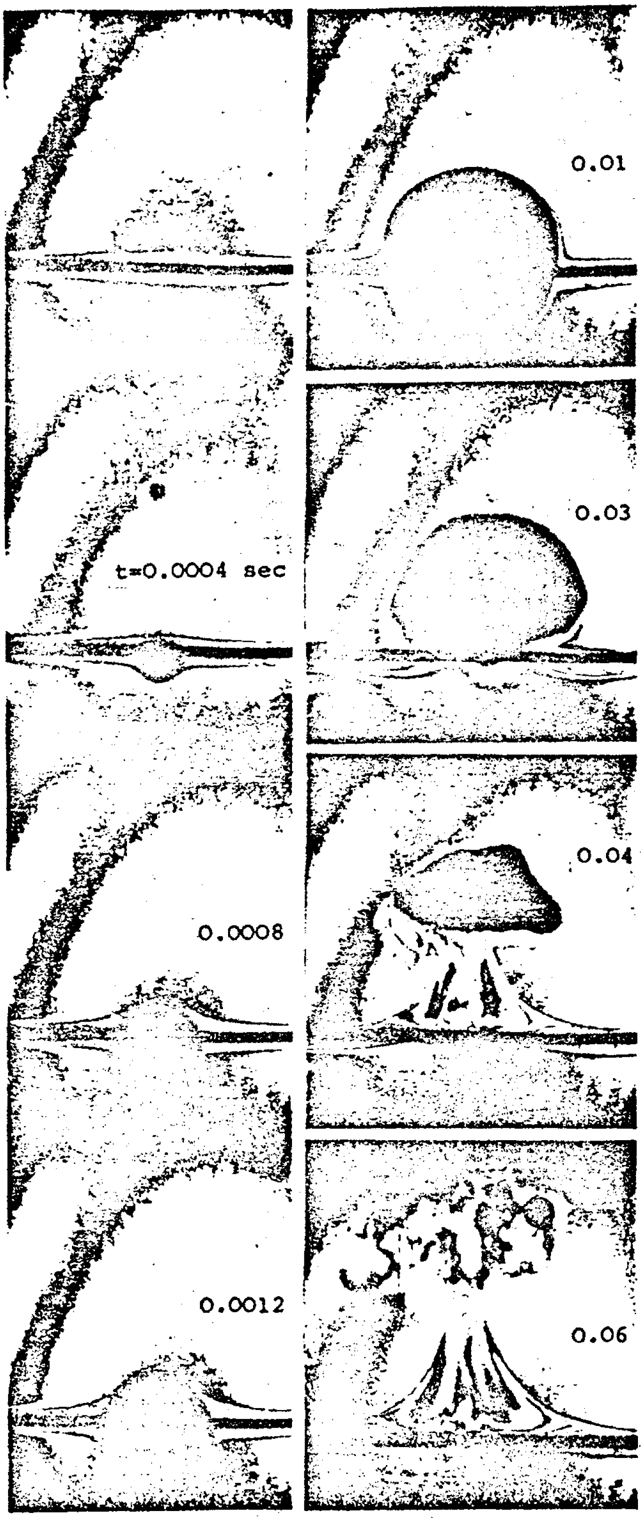


Fig. 22 High speed real-time interferometry. Growth and condensation of a steam bubble in water.

3.7 EVALUATION OF THE INTERFEROGRAMS

The evaluation of a holographic interferogram, made in an optical set-up with parallel object wave, is very similar to the evaluation of interference patterns recorded in a Mach-Zehnder interferometer /1/. Therefore only the basic equations will be given. In Mach-Zehnder interferometry the wavefront, which is distorted by the phase object in the test section, is compared to a plane wave. In holography the object waves, passing through the test section at different times are superposed, and therefore reveal the changes in optical path length between the two exposures. Expressed in multiples S of a wavelength, this change is calculated to

$$S(x,y)\cdot\lambda = l\,\{n(x,y)_2 - n(x,y)_1\} \qquad (1)$$

l is the length of the test section, in which the refractive index is varied because of temperature or concentration changes. The refractive index distribution n(x,y) during the recording of the two waves is assumed to be two dimensional (no variation in light direction). Equation (1) shows, that initially only local variationes 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 wave.

$$S(x,y)\cdot\lambda = l\,\{n(x,y)_2 - n_\infty\} \qquad (2)$$

To obtain absolute values for the temperature field, the temperature at one point of the cross section has to be determined by thermocouple measurements. This is usually done in the undisturbed region or at the wall of the test chamber. Equation (2) is the equation of ideal interferometry. It was assumed, that the light ray propagated in a straight line. Passing through a boundary layer, the light rays, however, are deflected because of refractive index gradients. This deflection, used for the various Schlieren- and Shadowgraph-methods, can be seen in fig. (23).

The light deflection can be converted into an additional phase shift ΔS, if a linear distribution of the refractive index is assumed to be within this small area.

$$\Delta S = \frac{n_o\cdot\lambda\cdot l}{12\cdot b^2} \qquad (3)$$

b is the fringe width, n_o the average refractive index.

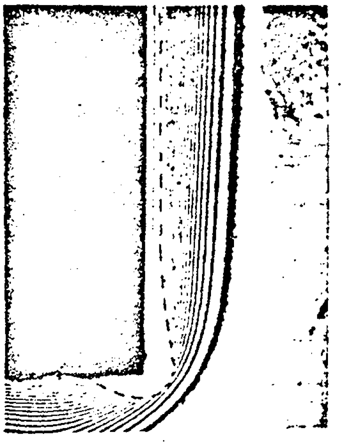


Fig. 23 Interferogram and light deflection of a thermal boundary layer

In many applications an ideal two dimensional field cannot be found. Often the boundary layer extends over 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 the molecular weight.

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

For gases with $n \approx 1$ this reduces quite accurately to the Gladstone-Dale-equation.

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

If there is only one component 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, one can use the equation of state, in order to obtain the following formula, which relates the fringe shift to the temperature.

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

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

$$\alpha = \frac{-k\left(\frac{dT}{dy}\right)_w}{T_w - T_\infty} \qquad (7)$$

The additional phase shift due to light deflection is usually small. In some cases, however, it can assume considerable values. Great errors can also occur, if the model is not properly alligned to the object beam or if the windows of the test chamber are deformed, e.g. by pressure. In the following example (fig. 24) the deformation because of the dynamic pressure of air was eliminated, by recording the comparison wave with flow.

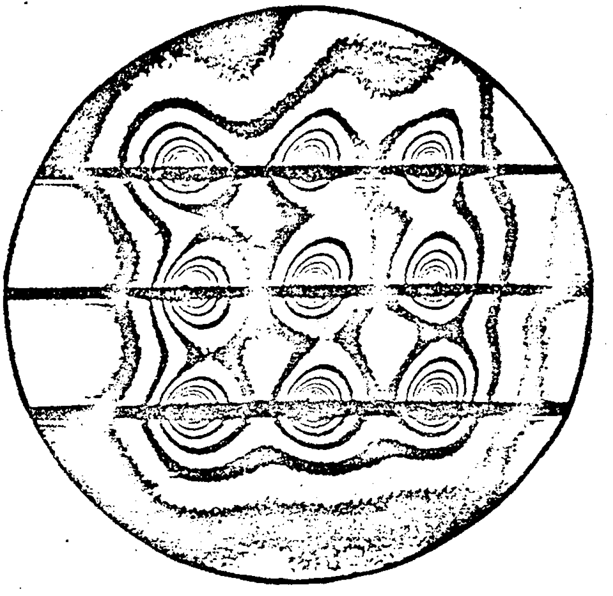


Fig. 24 Temperature boundary layer around thin wires

For the spinning of synthetic fibers, the heat transfer during the solidification phase is of special interest. Experiments were made for obtaining some information about the heat transfer in such a bundle. Instead of fibers thin metal wires were used, which could be heated electrically. One side of the test section was open, the other one was closed by a glass disk. The flow was established by drawing in the air from the surrounding. Because of this, the window was displaced slightly, resulting in an additional interference pattern. To eliminate this, both the comparison and the measuring beams were recorded with flow.

The three horizontal lines in the interferogram are copper bars, serving as electric connexion and for holding the wires. The spacing between the wires was 10 mm. The temperature boundary layer can clearly be seen. For manufacturing reasons it was difficult to adjust the wires exactly parallel to each other. Therefore the object beam could be alligned parallel to only one wire. For the other wires the evaluation of the interferograms was not possible, due to this improper alignment. Since at high air velocities the temperature gradient was so high that the light rays were deflected too much, only at low flow rates average heat transfer coefficients could be measured interferometrically. Nevertheless the pictures showed that the mutual influence of the boundary layers was very small. The temperature difference between two interference lines is about 2.1 K.

4. INTERFEROMETRIC TECHNIQUES FOR THE STUDY OF SIMULTANEOUS HEAT AND MASS TRANSFER

All interferometric methods at first only allow the measurement of variations in the refractive index within the test section. When they are caused either 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 directly be evaluated. Therefore coupled heat and mass transfer processes can be examined by interferometric methods only if one of the two fields is obtained by calculation or additional measurements. For the study of simultaneous heat and mass transfer several authors have combined optical with non-optical measurements. For example Adams and Mc Fadden /10/ measured the temperature profiles with thermocouples, and could thus evaluate the interference patterns, El-Wakil et al. /11/ assumed identical temperature and concentration profiles and could thus evaluate the interferograms without additional measurements.

4.1 TWO-WAVELENGTH INTERFEROMETRY

There have also been some attempts to apply the dependence of the refractive index on the wavelength of light to determine the temperature and concentration fields by means of separate interferograms taken at different wavelengths. Ross and El-Wakil /12/ used this two-wavelength interferometry in a modified Mach-Zehnder interferometer for the study of the vaporization and combustion of fuels. The accuracy obtained was, however, not satisfactory. This was partly due to the fact that the two interferograms could not be superimposed accurately enough.

The peculiarity of holography, allowing the recording of different interference patterns on one plate, promised to overcome some of the difficulties involved in this technique. Therefore we again tried to put this principle into practice and succeeded in getting quite good results. The experimental set-up for the holographic two-wavelength interferometry is shown in fig. (25).

It very much resembles 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 (λ_j = 6328 Å) and of the argon laser (λ_k = 4579 Å) intersect, 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 object and two reference waves at the different wavelengths.

For the experiments a vertical heated plate was chosen, which was coated with

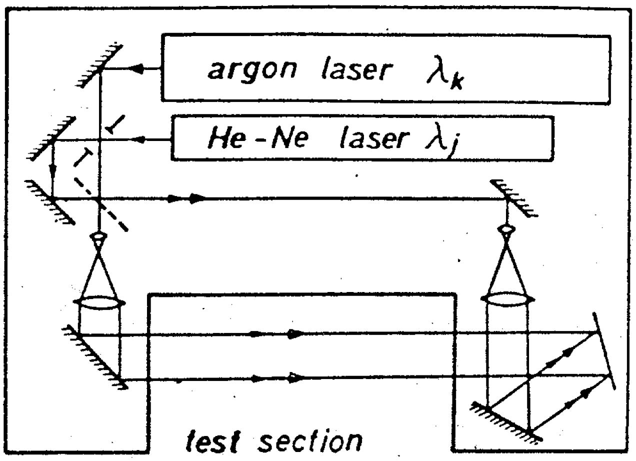


Fig. 25 Optical set-up for holographic two-wavelength interferometry

a thin layer of naphtalene. The plate was 300 mm long. The interferograms were made using the double exposure technique and a modified real-time-method. Instead of the undisturbed comparison wave, only the measuring waves were recorded on separate holograms. This has the advantage that a set of holograms could be made one after the other without having to establish the comparison wave in between the exposures. In the reconstruction stage the undisturbed comparison waves were superimposed onto the recorded measuring waves.

It may be mentioned that not only the object wave λ_j is reconstructed by the reference wave λ_j , but that also a false object wave λ_k is obtained. This unwanted wave, however, emerges at a different angle from the hologram and can therefore easily be separated from the original waves.

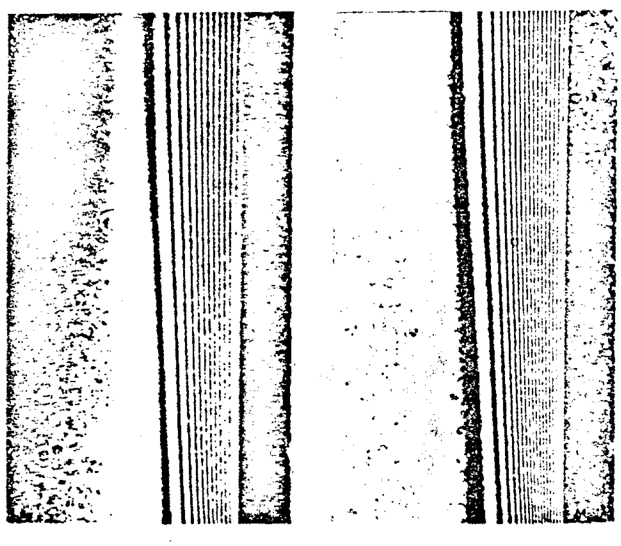


Fig. 26 Dual interferograms of a temperature and concentration boundary layer
λ_j = 6328 Å, λ_k = 4579 Å

The interferograms taken simultaneously at two different wavelength are presented in fig. (26).

They show the boundary layer formed due to heat and mass transfer from a vertical plate at free convection.

For the evaluation of the interferograms the following equation is used. In conjunction with the Gladstone-Date formula and the ideal gas law, it relates the fringe shift to the temperature and concentration distribution in a heat and mass transfer boundary layer.

$$S(x,y)\cdot\lambda = \frac{3\cdot p\cdot l}{2\cdot R}\cdot N_m\left[\frac{1}{T(x,y)} - \frac{1}{T_\infty}\right] \qquad (8)$$

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

$$N_m = N_a\cdot C_a + N_b\cdot C_b \text{ with } C_a + C_b = 1 \qquad (9)$$

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 mixture. During the recording of the comparison wave the temperature distribution T_∞ in the test section is constant, and there is only one component a (air).

Combining equation (8) and (9) we obtain for each wavelength

$$S(x,y)\cdot\lambda = \frac{3\cdot p\cdot l}{2\cdot R}\left[\frac{1}{T(x,y)}\{N_a + C_b(x,y)\}\times \times\{N_b - N_a\} - \frac{N_a}{T_\infty}\right] \qquad (10)$$

Eliminating $C_b(x,y)$ the temperature $T(x,y)$ can be calculated:

$$S_j(x,y)\frac{\lambda_j}{N_{b_j} - N_{a_j}} - S_k(x,y)\frac{\lambda_k}{N_{b_k} - N_{a_k}} =$$

$$\frac{3\cdot p\cdot l}{2\cdot R}\left[\frac{1}{T(x,y)} - \frac{1}{T_\infty}\right]\left[\frac{N_{a_j}}{N_{b_j} - N_{a_j}} - \frac{N_{a_k}}{N_{b_k} - N_{a_k}}\right] \qquad (11)$$

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

Equation (11) shows that it is the difference between the phase shifts 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 dependance of $N(\lambda)$ is also very small and only assumes larger proportions in the vicinity of an absorption line, which, however, is usually not in the visible range. This, of course, limits the choice of liquids to those whose molar refractivities vary appreciably over the wavelengths used. Some test fluids, suitable for this technique, are naphtalene, carbon disulphide, benzene and hexan. 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 was recorded photometrically thus allowing a reading accuracy of $\pm$ 1 μm by use of a precision screw with digital output.

It should be noted that the additional fringe shift because of light deflection and edge effects has no greater influence on the accuracy obtained than in ordinary one-wavelength interferometry, since both interferograms are affected. An application example of the two-wavelength technique is given in fig. (27).

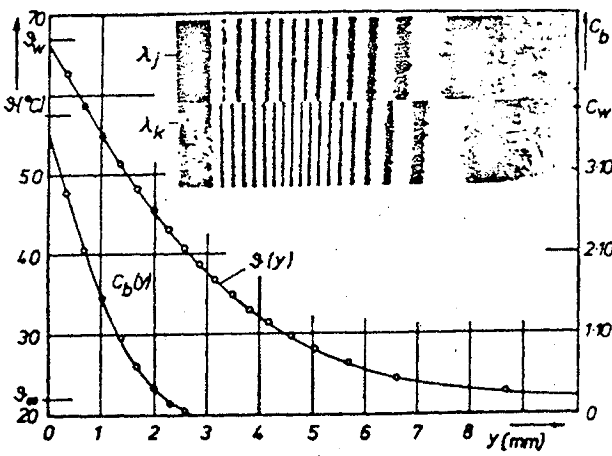


Fig. Temperature and concentration profiles in a laminar boundary layer

In order to demonstrate the differences in 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 at free convection.

The temperature in the undisturbed region was ϑ_∞ = 22°C. The temperature at the wall was measured by thermocouples, ϑ_w = 66,4°C. The theoretical concentration of the naphtalene vapor at the wall is C_w = 3,8 10^{-3}. The temperature and concentration profiles obtained are plotted in fig. (27). The temperature at the wall and in the undisturbed area evaluated from the interferograms exactly matches the values measured by thermocouples. Also the interferometrically determined concentration at the wall corresponds closely to the theoretical value. This holographic two wavelength interferometry is still at the development stage. The results obtained so far are however very encouraging. Under favourable operating conditions, similar accuracies as in one wavelength interferometry should be possible. Of course this can only be achieved by a relatively great experimental effort. In special cases it is possible to determine temperature and concentration profiles in coupled heat and mass transfer processes more easily.

4.2 EVALUATION TECHNIQUE, USING ONE INTERFEROGRAM ONLY

Under certain circumstances, simultaneous temperature and concentration profiles can be obtained of only one interferogram, when a special evaluation technique is used. This method can be applied in those cases where the thickness of the concentration boundary layer differs from that of the temperature boundary layer. To explain the principle, the interferogram λ_t = 4579 Å in fig. (27) is evaluated by the following technique. Because the naphtalene vapor increases the index of refraction, whereas the heating of the air decreases the index of refraction, the thickness of the concentration boundary layer can be determined by analysing the fringe density. In fig. (28) the phase-difference distribution S(y) and its first derivation dS/dy are plotted.

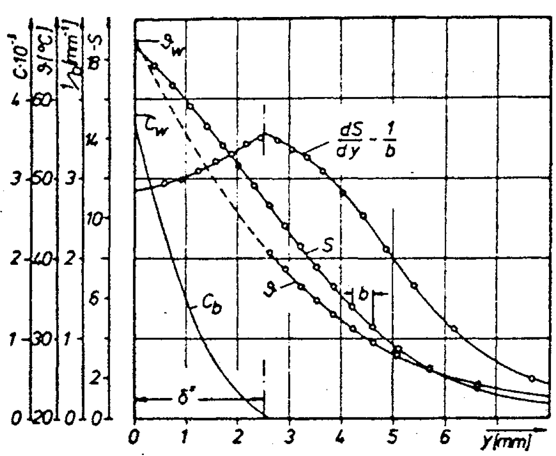


Fig. 28 Temperature and concentration profiles in a laminar boundary layer. Evaluation of only one interferogram

The bend in the curve dS/dy indicates the end of the concentration boundary layer. In the region of pure temperature field $\delta' \leq y \leq \delta'$ the temperature profile can be obtained by evaluating the interferogram according to equation (6). Within the concentration boundary layer the temperature has to be extrapolated to the wall temperature, which must be measured by thermocouples. This extrapolation can be done graphically or by a calculation procedure (e.g. least squares method). Using the estimated temperature distribution and the corrected phase shift distribution S(y), the concentration profile can be determined. In those cases where the concentration boundary layer was considerably smaller than the temperature boundary layer, fairly accurate results could be obtained. This was verified by additional measurements with a miniature thermocouple probe.

5. MEASUREMENT OF THREEDIMENSIONAL REFRACTIVE INDEX DISTRIBUTIONS

The evaluation of holograms discribed so far assumed a two dimensional refractive index field. For irregular threedimensional fields, the following integral equation has to be solved, where s is the way of the light beam.

$$\int_s \{n(x,y,z) - n_\infty\} ds = S(y) \cdot \lambda \qquad (12)$$

In the exceptional case of axial symmetric fields this equation can be converted into the Abel integral equation.

$$2\int_y^\infty \frac{n(r) - n_\infty}{\sqrt{r^2 - y^2}}\, r\, dr = S(y) \cdot \lambda \qquad (13)$$

There are several methods for solving it. In addition to a graphical method, a numerical procedure called zone method /13/ can be used. For increasing the accuracy and reducing the calculation procedure the equation can also be solved with the Laplace-transformation and by polynomials. For the measurement of arbitrary fields, the general integral equation (12) must be solved. In this case the information obtained by a single interferogram, giving only the integrate value of the twodimensional distribution is not sufficient. Additional information must be provided by making several interferograms from different angles. This can be done with little experimental effort using holographic interferometry.

The diffuse illumination of the test section allows to choose the angle of view in a certain range, depending on the size of the photographic plate and the experimental arrangement. Making a double exposure hologram, interference pictures can be photographed from different directions. The evaluation is simplified, however, if seperate parallel object waves are used, passing through the phase object at different angles.

Two methods for solving equation (12) are known. Maldonado and Olsen /14/ used orthogonal complex polynomials for the inversions of the integral equation. Collins /15/ uses orthogonal Fourier's series for the inversion, and thus reduces the mathematical effort considerably. This is, however, combined with a loss in accuracy. Collins demonstrated his method by the measurement of threedimensional shockwaves. Both procedures are still very complicated and therefore have not been often applied yet.

6. COMPARISON WITH CONVENTIONAL METHODS AND ADDITIONAL ASPECTS

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.

This 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 space 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.

Impuls holography has revealed further new prospects. Because of the extremely short pulses of about 30 nanosec., even the most rapid processes in supersonic flow, boiling and cavitation can be examined. Double pulse lasers allow a new type of short-time interferometry where the time between the two exposures amounts to only about 100 usec.

With this, even most rapid temperature changes, as for example occur in the phase boundary at subcooling boiling with very high heat flux, are interferometrically measurable. With continuously pulsed lasers holographic films can be made, in which the threedimensional information is not lost, in contrast to the highspeed films mentioned in paragraph 3.6.

By this, impuls holographs opens up a whole range of new prospects for the study of instationary rapid heat transfer phenomena.

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