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An investigation into the use of holography to measure temperature fields.

S. L. Tuli
University of Windsor

AN INVESTIGATION INTO THE USE OF HOLOGRAPHY TO MEASURE TEMPERATURE FIELDS

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S.L. Tuli

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P. H. Alexander

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ABSTRACT

For a number of years now, laser technology and consequently the science of holography have become very important in various research fields. Holography was chosen as a means of investigating bubble growth and temperature fields around a bubble growing in a pool boiler.

A hologram of a bubble growing on an artificial cavity was made in the present study. The interference pattern due to density differences around the boiling surface was obtained using double exposure technique under natural convection heat transfer conditions.

To obtain information on the temperature fields, a double exposure technique was employed using a pulse laser. This technique was not fruitful. Recommendations are given towards a suitable method to obtain the required information.

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I INTRODUCTION

For a number of years now, laser technology and consequently the science of holography have become very important in various research fields. In the applied sciences, examples of practical applications include the measurement and visualization of strain, real time observation of transient temperature fields and solutions to aerodynamic and shock wave phenomena problems. Since holography can detect growth and subtle changes associated with both microscopic and macroscopic events and since the associated equipment is simple to operate this technique was chosen as a means of investigating bubble growth and temperature fields around a bubble growing in a pool boiler.

The object of the present work was to measure the temperature fields associated with bubble growth from an artificial cavity in a pool boiler using water as the working fluid.

In this attempt to obtain information on the temperature fields a double exposure holographic technique was employed using a pulse laser. This technique was not fruitful but recommendations are given towards a suitable method to obtain the required information.

II LITERATURE SURVEY

The phenomenon of boiling heat transfer and particularly nucleate boiling, has received considerable attention in the past two decades. This is due mainly to the widespread occurrence of boiling heat transfer in practical applications such as nuclear reactors, rockets, heat exchangers etc.

Grief and Forester (1) studied the different mechanisms associated with heat transfer in nucleate boiling. All these mechanisms are primarily dependent on some form of bubble agitation. The mechanism of "Microlayer Convection" in the sublayer postulated by Gunther and Kreith (2), the mechanism of bubble agitation of Rohsenow and Clark (3) and the vapor-liquid exchange mechanism (4) are but a few of them.

The temperature drop at the surface due to bubble growth has been shown to be closely related to the bubble shape. Johnson and Mesler (5) attempted to explain the formation of different shape bubbles growing on a surface during nucleate boiling of water. It was found that some of the bubbles were spherical, while others closely approximated the hemispherical shape. In certain cases, it was found that the bubbles were oblate. A further realization was that the shape of the bubble is dependent on the relative magnitude of the surface tension forces and the inertia forces. Johnson and Mesler discovered that for spherical bubbles, inertia forces are small due to the slow growth rate.

Moore and Mesler (6) postulated the existence of a microlayer of liquid beneath the bubble. The vaporization of this microlayer removes heat from the metal surface efficiently, producing a rapid drop in surface temperature. Han Chi-Yeh (7) and Griffith (8) found that the temperature at bubble initiation on a given surface is a function of the temperature conditions in the liquid surrounding the cavity as well as the surface properties themselves.

Different techniques have been used to investigate the shape of the bubble and temperature distributions in a pool boiler. Optical methods have been found to be preferable in the field of fluid mechanics and heat transfer since they can be used to study rapidly changing processes. In addition they can be easily arranged in such a way so as to show in one picture the entire distribution of any quantity in which one is interested e.g. temperature fields around a growing bubble or velocity profile etc.

In order to measure the temperature distribution associated with natural convection heat transfer in fluids, four optical techniques have been used:

i. The Shadowgraph

ii. Schlieren Photography

iii. Interferometry

iv. Holography

A. The Shadowgraph Method: The shadow technique is a method of direct viewing of flow phenomena. It is a very simple optical tool, and its effects may be viewed in several every day phenomena using only the naked eye and local room lighting. One example is the visualization of the free convection boundary layer on a horizontal electric hot plate when viewed from the edge. This phenomenon is visible because of the density gradients which result from the heating of the air near the hot surface. It is almost fruitless to try to evaluate local densities using shadow photography; however, the shadowgraph is exceedingly useful to view turbulent flow regions, and the method can be used to establish the location of shockwaves with high precision.

B. The Schlieren Method: While the shadowgraph gives an indication of the second derivative of density in the flow field, the Schlieren method depends upon refraction of the narrowly defined edge of a light beam by gradients in the refractive index of the gas through which the beam of light passes. Thus, it receives its name "Schlieren", which is translated as "Optical inhomogeneity". In a typical system, a limiting diaphragm, usually a straight edge is so adjusted with respect to the edge of the light beam that refraction in one direction adds to the total illumination, and refraction in the other direction subtracts from it. Thus, an image is formed wherein the variations in brightness depend upon differences in the gradients of refractive index in the light path.

Figure 1 shows the simplest type of Schlieren system. Light from the source, which is preferably a line rather than

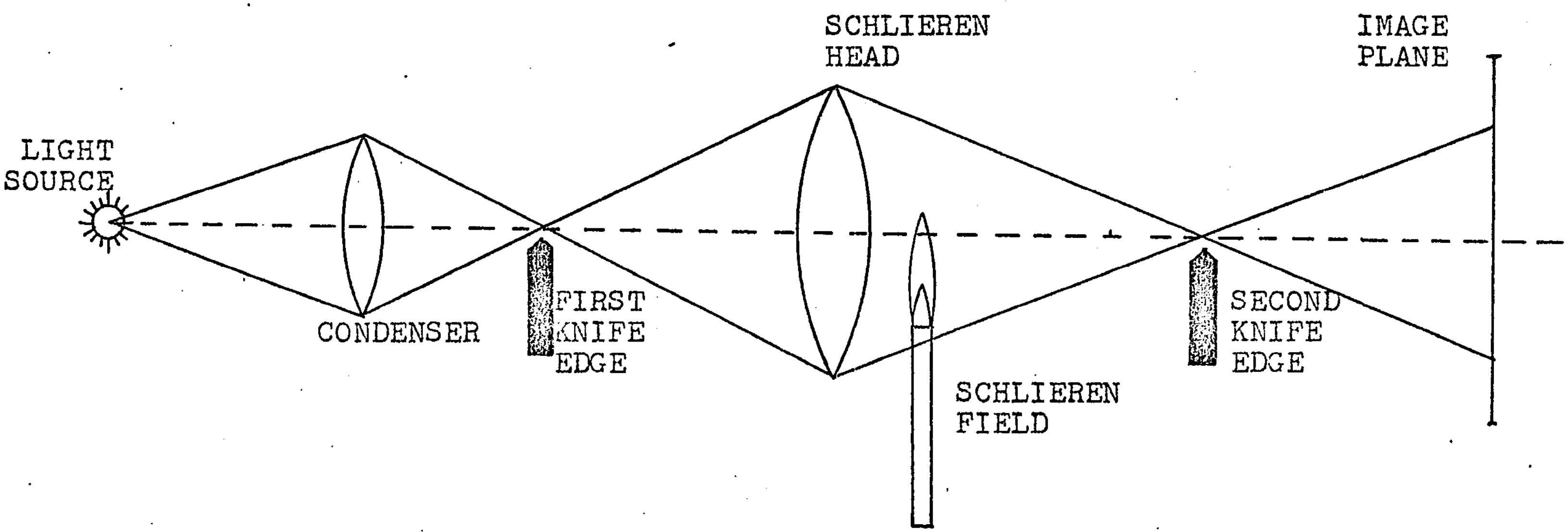


FIGURE 1 BASIC SCHLIEREN SYSTEM

a point, is focused by the condenser to form an image. A limiting diaphragm, generally straight rather than circular, is placed parallel to this image of the light source and intercepts part of it so that the resultant beam has a sharply defined edge. This beam then passes through the Schlieren Head, which focuses it through the schlieren field on to the second knife-edge. By adjusting the position of this second knife-edge so that it is exactly parallel with the first knife-edge, and by inserting it partially into the beam of light, a gate is provided that can intercept a large part of the luminous flux. This attenuated beam of light then passes to a photographic film where it can be recorded.

If there are no gradients in refractive index within the schlieren field, the amount of light reaching the film is fixed by the relative position of the two knife-edges. However, if a gradient normal to the plane of the knife-edges exists, the beam will be refracted so that it either adds to or subtracts from the light normally present on the screen. Thus, a Schlieren Field involving a pattern of gases is produced in various tones on the film. Opaque objects appear in silouette.

C. Interferometric Method: Kennard in 1931 (9) used an interferometric technique to study convection from vertical flat plates and horizontal cylinders. Similar investigations have since been made by Eckert (10), Soehngen (11) and others.

The principle of operation of the instrument is based on the phenomenon of light interference and change of refractive index with fluid density. A beam of collimated light is divided by a half silvered mirror, (Fig 2) . The two resulting beams of light travel different paths within the instrument and are recombined at a second half silvered mirror. One of the beams of light passes through a test section where models may be inserted. Considering the application of this technique to study heat transfer from a heated cylinder, the beam of light which passes through the test section is modified as a result of the increase in velocity of the light in the less dense air surrounding the heated model. Therefore, when this beam is recombined with the second beam which passes through the instrument undisturbed, the parts of the beam which pass through the heated air are out of phase with corresponding parts of the undisturbed beam. When these beams are projected on a screen, there are light and dark areas in the picture depending on whether the optical path lengths through the instrument differ by an even or odd number of half wave lengths. The resulting interference pattern may be evaluated quantitatively to determine the density distribution in the air surrounding the model.

D. Holography

Holography or wavefront reconstruction is a method of storing information concerning the three dimensional nature of an object. It is a form of common path interferometry where the test and comparison beams are separated in time. This method has advantages over these previously available

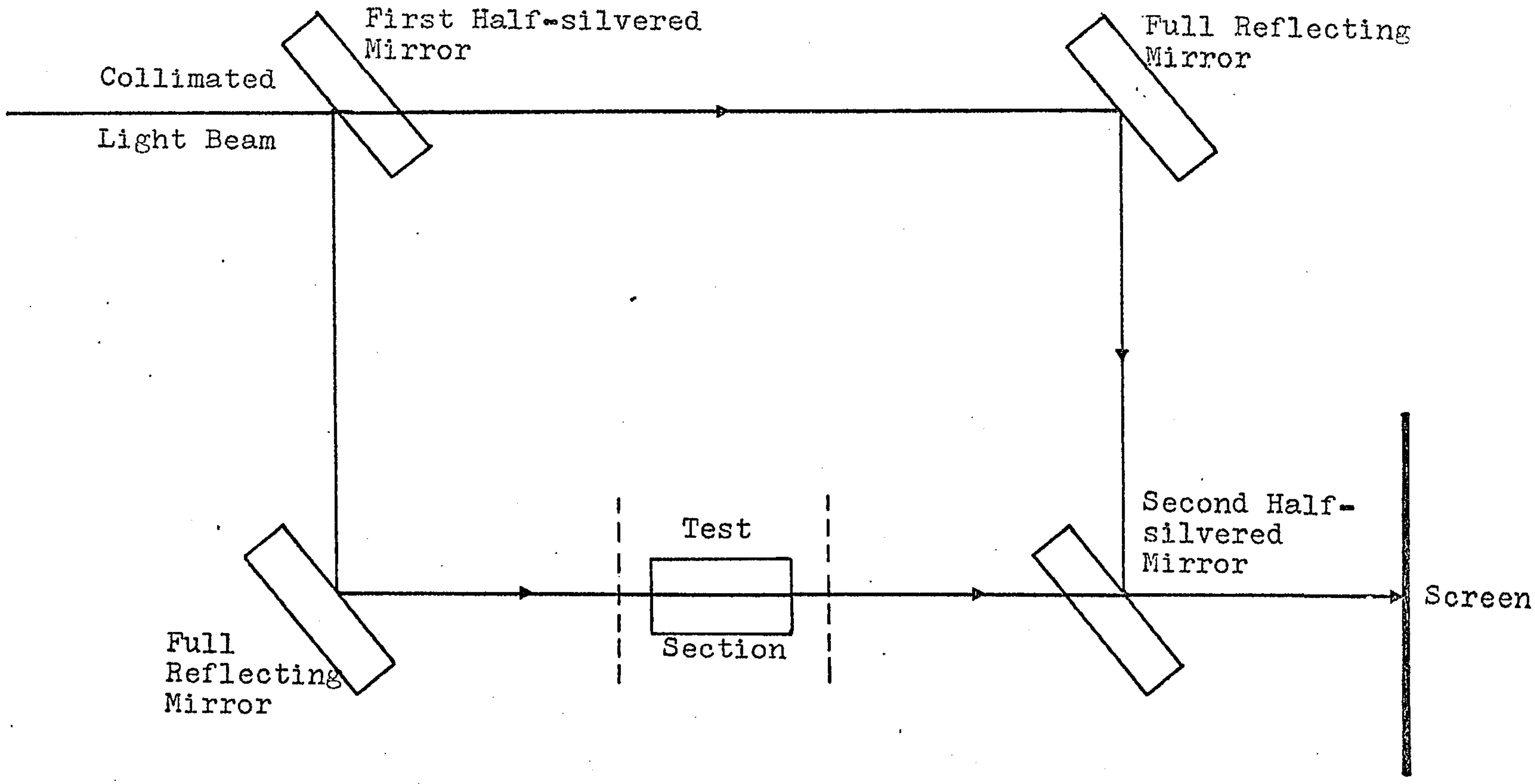


FIGURE 2 BASIC OPTICAL SYSTEM

in that measurements can be made instantaneously over the whole surface of the object and prototype models do not have to be used.

Furthermore, because hologram interferometry is a null method of measurement, the quality of the lenses and mirrors used in the optical arrangement is unimportant, since any aberrations will be automatically subtracted in the double hologram. The name 'hologram' is derived from the Greek word holos which means the 'whole' , because it contains the whole information on amplitude and phase.

There are innumerable applications of holography in engineering research e.g. the distortion of a structure under load can be studied, effects of creep, fatigue or thermal distortion can be examined on the actual component and not on the model. Modes of vibration of a surface are examined by observing the line interference fringes obtained by hologram interferometry; fluid flow patterns in wind tunnel experiments can be examined. At the National Physics laboratory in London (12) the technique of holography is being used to compare the shape of an irregular object with a master shape. The newest application of holographic technique is in the field of dentistry where holograms of teeth are made for an effective three dimensional view. Holographic images possess all the visual properties of parallax and depth of field of the original scene and, in fact, no visual test can distinguish between the two.

Live fringes are obtained by recording the hologram of an object using coherent laser light and afterwards replacing the processed hologram plate in its original position in the same apparatus. One then sees the reconstructed image of the object superimposed on the object itself. Any slight changes in the surface contours for example due to mechanical strain or thermal expansion, will give rise to interference effects between corresponding points on the object and its holographic image.

Holography was discovered in 1947 (12) by Dennis Gabor of the Imperial College of Science and Technology in London. But due to the lack of an adequate source of coherent light, that is, light whose waves are all in phase, it did not prove to be of much importance at that time.

In 1960 the advent of the laser opened a new door for easy visualization of rapidly changing phenomena which can be viewed and investigated at leisure.

The use of holography for interferometry was first suggested by Horman (13). Later work pertaining to holographic interferometry was carried out by several authors such as Hildebrand and Haines (14) and Burch (15) etc. One type of hologram interferometry performed on vibrating objects was carried out by Powell and Stetson (16). In that application the developed hologram was replaced in the original set up and the fringe patterns examined as the object was vibrating.

The type of interferometric measurement in which the plate is replaced in the very same apparatus in which it was recorded is known as "stored beam" holographic interferometry

(17). It has the disadvantage that the measurements must be made in the same apparatus used to record the hologram.

The technique of double exposure holographic interferometry was discovered quite by accident by Heflinger (18). It is explained in terms of two separate holograms recorded on the same plate. Small differences in the scene between the two exposures result in a reconstruction with fringes. The advantage is that the two holograms are locked permanently in the same emulsion, and can not be destroyed, as with the stored beam hologram.

Pulsed holography has been the object of a considerable amount of research largely because a very short exposure time may be obtained with laser devices. Buges and Terneand (19) developed a multiple exposure holographic camera in the nanosecond range. Several objects were recorded on a single hologram and reconstructed from it without interference by using reference beams at different angles to the holographic plate. Authors intend to apply this method to plasma diagnostics.

Williams and Dorothy (20) used holographic interferometry to study concentration changes and diffusion coefficients in a Cu-$CuSO_4$ Cell.

III EXPERIMENTAL EQUIPMENT

The experimental equipment used in this study consisted essentially of a pool boiler (with an artificial cavity in the boiling surface) having optical windows and the laser and associated optics for making holograms.

A. Pool Boiler

The pool boiler design was as simple as possible. Major consideration was given to the optical windows through which one of the laser beams had to pass for obtaining holograms of the bubble during its growth. A diagram of the pool boiler is given in Figure 3.

The pool for the boiler was constructed using a $4\frac{1}{4}$-inch I.D. by 6-inch high section of a glass pipe. The glass pipe was supported on a 5/8 inch thick aluminum plate (No.I, Fig 3) which had a 3-inch diameter hole in the centre. A second 5/8-in thick aluminum plate (No II, Fig 3) with a 17/8-in diameter hole at the centre supported the boiling surface. Grooves were cut in the aluminum plates to hold the optical window section.

1. Boiling Surface

The boiling surface (Fig.4) was fabricated from a 7/8-i diameter by 4-in long stainless steel cylindrical rod. The top end of the stainless steel rod was polished successively with 240, 320, 400 and 600 grit papers. When the top surface

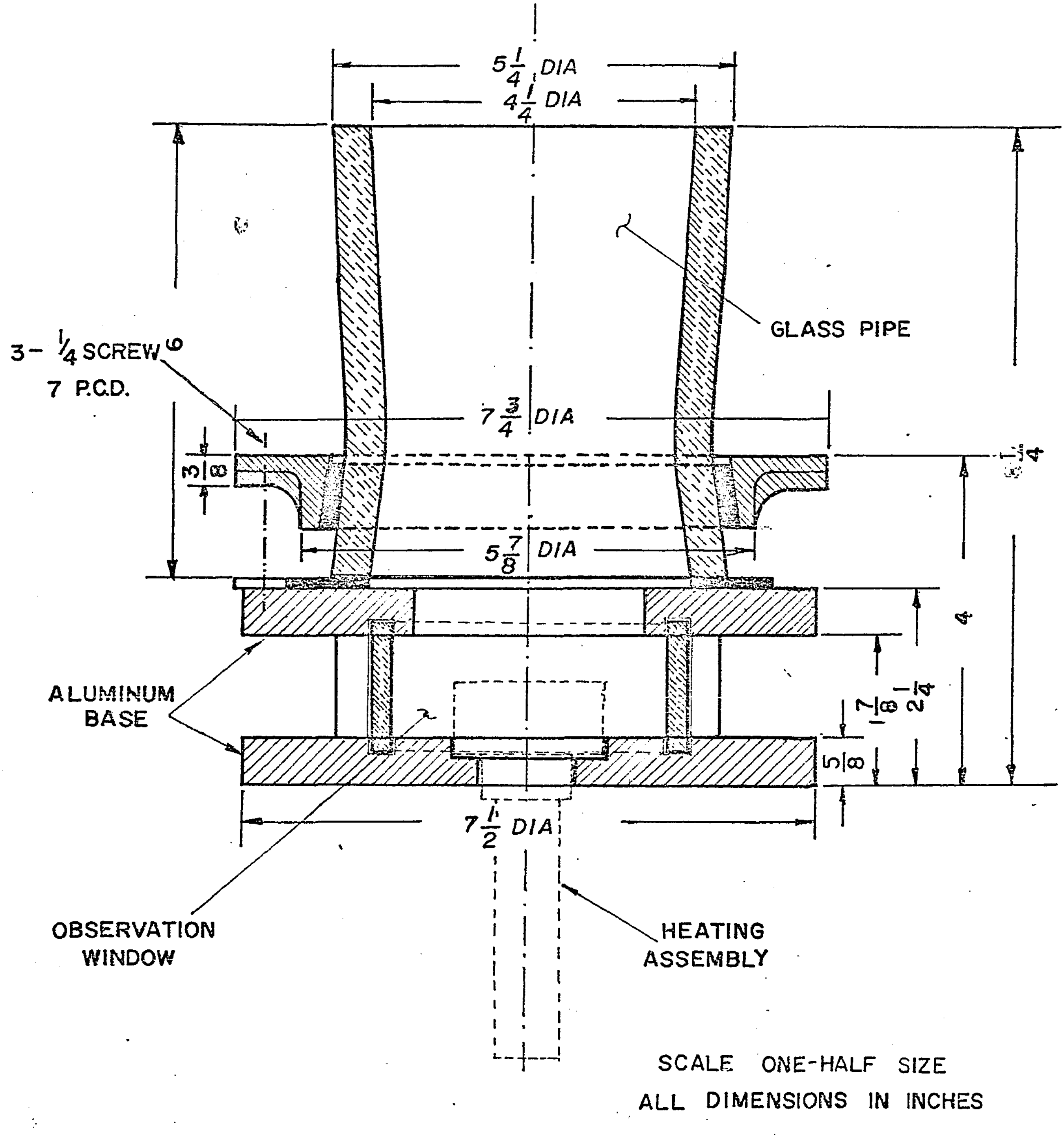


FIGURE 3 SECTION OF POOL BOILER

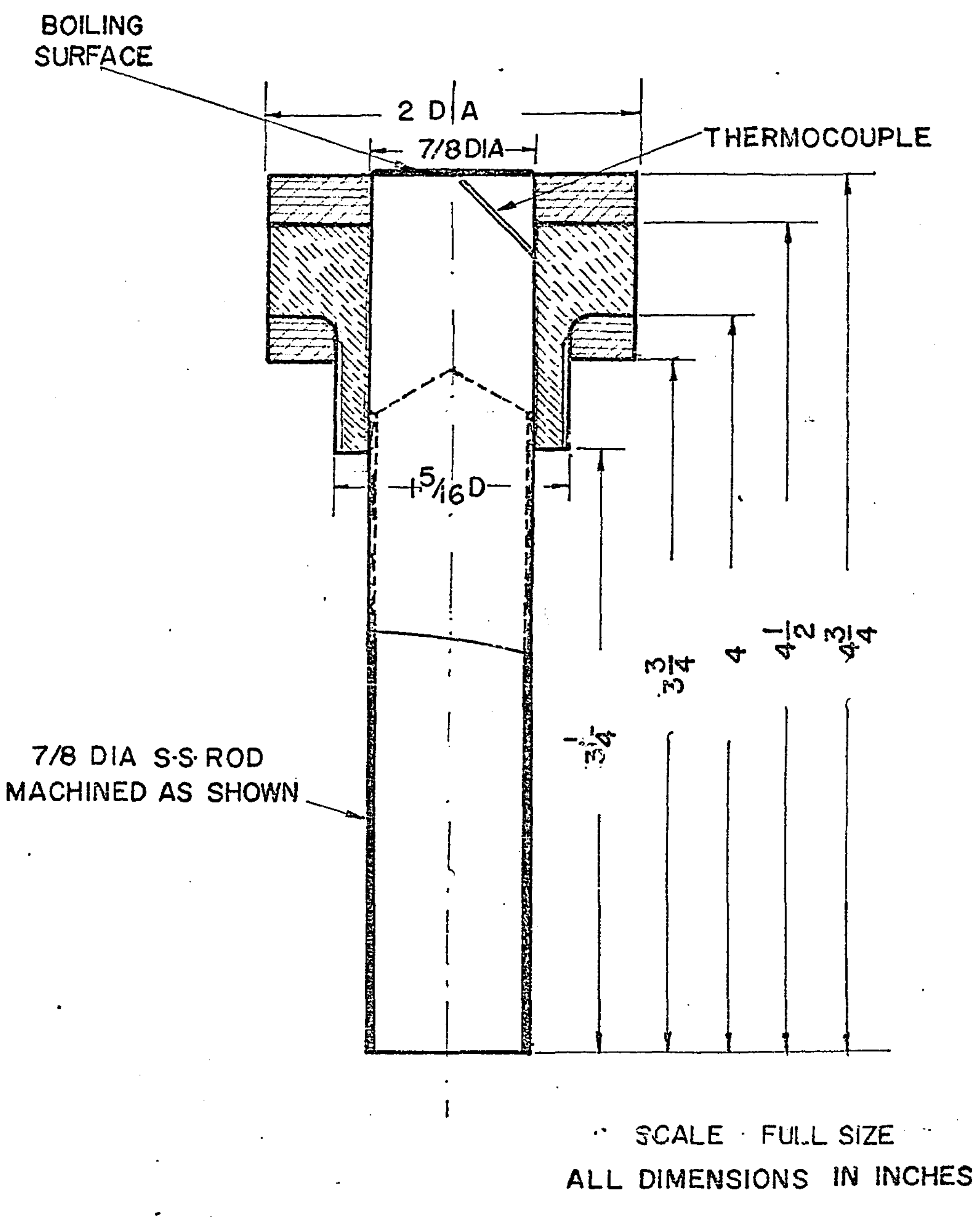


FIGURE 4 DETAILS OF BOILING SURFACE

was free of any scratches and sufficiently smooth, it was polished with 0.5 micron (μ) alumina, until a mirror like surface was obtained. This polishing operation was performed on a polishing wheel and then the surface was washed successively with distilled water and alcohol.

At the centre of the boiling surface, an artificial cavity with a diameter of approximately 0.03-in by 0.02-in deep was made using a 0.02-in diameter drill. At the bottom end of the stainless steel rod a hole 3/4-in diameter by 3 -in deep was drilled to hold a cartridge heater. The details of the boiling surface are shown in figure 4.

A 7/8-in diameter hole was drilled in a teflon rod (1 -in in diameter by 2-in long), to contain the stainless steel rod. The rod, with the polished surface facing up, was fixed in such a way that a 5/16-in length of the rod remained above the teflon surface. A 1/4-in thick Neoprene rubber washer was fitted tightly to the bare surface of the rod above the teflon piece. This was done to eliminate nucleation around the periphery of the rod. A high temperature resistant glue was used to cement together the rod, the neoprene rubber and the teflon piece.

The temperature of the boiling surface was measured with a 10 mil diameter copper-constantan teflon coated thermocouple having a .001-in junction. The thermocouple was fixed approximately 1/16-in below the boiling surface. To measure the temperature of water, two subminiature thermocouple probes of immersion length 6-in and .02-in sheath diameter were used. The thermocouple probes were placed at a distance of approximately 1/8-in and 1/4-in above the boiling surface.

2. Power Supply

Two different kinds of heaters were used in this study. A cartridge heater 3/4-in diameter by 3¼-in long with a power rating of 250 watts was used to supply heat to the boiling surface. A Variac (0-140 volts) was used to regulate the heat input to the boiling surface. The second heater (with the power rating of 1500 watts) was of the immersion type. This heater was suspended in the water and used to keep the water in the pool at a selected temperature. Another Variac (0-140 volts) was used with this immersion heater to regulate the heat input to the liquid. The power supplied to the boiling surface was measured using a voltmeter, ammeter and wattmeter.

B. Holographic Equipment

1. Optical Table

The diffraction pattern being formed on the photographic plate has a spacing of the order of the wave-length of the light being used. Therefore, the relative motion of the various items is limited to values less than this spacing.

In order to achieve this, a system consisting of 40x78x2 inch honed granite work table, supported by a steel cabinet and hardwood table assembly with an intermediate air suspension was used. This form of optical table effectively isolated the floor vibrations from the holographic system.

2. Gas Laser

The continuous wave gas laser built by Jodon (Model HN 1060) had a power output of 10 milliwatts in a uniphase mode. This laser was used for alignment of the pulse laser and for viewing of the holograms.

3. Ruby Laser

A ruby laser (Model K-1 QH) marketed by Union Carbide was used for making holograms. The performance specifications of the ruby laser system are as follows :

Coherence length	> 100 cm.
Pulse energy (TEM_{00})	2 joules
Pulse width	15-25 Nano seconds
Wavelength	6943 Å.
Pulse repetition rate	0-2 PPM.

The ruby laser system had the following main components :

i. a K-1 water cooled laser head with a helical flash lamp, reflector, and 3/8-in by 4inch flat/flat, holographic quality ruby crystal AR coated at both ends.

ii. a Pockels cell Q-switch with an interface between the windows and an active crystal, reference polarizer, resonant maximum reflector and power supply, timing circuitry and trigger electronics.

iii. Two selectors: a transverse mode selector with

1 and 2 mm apertures in a precision calibrated X-Y positioning mount and longitudinal mode selector, used as the output reflector. This is a three surface, temperature tuned resonant system with sapphire optics.

iv. a mounting base for the above providing adjustable spacing of optics (lengths up to 4 feet).

v. a laser power supply with, 0-5 KV, 5KJ energy storage banks, solid state trigger and logic electronics, castor mounted electronics enclosure (25-in by 26-in dia. by 56-in height).

vi. a K-WC 3, refrigerated heat exchanger.

4. Accessories for Optical set-up

The pin-hole Spatial Filter assembly had two micrometers for easy vertical and lateral movements of the pin hole. The pin-hole had interchangeable 10 and 25 micron holes to arrest all the undesirable modes of laser light. There were three 4-in by 5-in front surface mirrors and a few 2-in by 3-in front surface mirrors for reflection of reference and object beams to the holographic plate and alignment of the ruby laser respectively.

The purpose of the beam steering was to adjust the beam up and divert it horizontally or vertically in any desired direction.

Two different kinds of beam splitters were used. A prism-type beam splitter consisting of two right angle prisms cemented to form a cube. In this type of beam splitter there is 30% transmission of light, 30% reflection and approximately

40% of the light is absorbed by the reflectance coating. The mirror type beam splitter is non-absorbing. It reflects approximately 33% light and transmits the remainder.

Different types of spectroscopic plates were tried for this work. For the pulse laser, Agfa 10E75 and Agfa 8E75 plates were used while Agfa 10E70, 8E70 and Kodak 649F plates were used for the gas laser. Their detailed specifications are given in Table I.

TABLE I

Specifications of Holographic Plates

	10E75 & 8E75	10E70 & 8E70	Kodak 649F
Resolving Power	2800 lines/mm & 3200 lines/mm	2800 lines/mm & 3200 lines/mm	Above 225 lines/mm
Thickness of emulsion	7 μ	7 μ	-
Color Sensitivity	694.3 mμ	632.8 mμ	632.8 mμ
Sensitivity	50 ergs/cm^2 & 200 ergs/cm^2	50 ergs/cm^2 & 200 ergs/cm^2	-

IV EXPERIMENTAL PROCEDURE

A. Hologram of the bubble

Before each experimental run, the heat transfer surface was polished on a rotating wheel with 0.5 micron alumina to ensure a smooth surface, and the cavity was reactivated by washing with alcohol. Distilled water was used as the test liquid. Approximately two liters of distilled water were used to obtain a water level six inches above the boiling surface. Both the auxiliary (immersion) and the cartridge heater were switched on to heat the water and the boiling surface respectively. Initially the voltages supplied to the immersion and cartidge heaters were 120 volts and 40 volts respectively. Three hours were required to obtain the desired temperatures at atmospheric pressure. At that time the voltage supplied to the immersion heater was reduced to 90 volts to maintain the water at the desired temperature. Simultaneously the voltage supplied to the cartridge heater was reduced to 30 volts. This was done to adjust the frequency of the bubble formation from the artificial cavity.

Care was taken to insure that the bubbles initiated only from the artificial cavity. In some instances bubbles started to originate from the sides of the boiling surface i.e. at the junction of the Neoprene rubber washer and the periphery of the stainless steel rod. Occassionally bubbles would also orginate from places other than the artificial cavity. In such cases, the water was first allowed to boil for a number of hours so as to degas the water completely. The undesired bubbles were also washed away manually from the boiling surface. When bubbles were departing from the artificial cavity at a steady rate, the variac settings were noted and left untouched for the remainder of the run.

A schematic of the apparatus used to produce the pulsed hologram is shown in Figure 5. The direct beam from the laser was made divergent by a negative lens. After passing through a glass beam splitter, the beam recombined at the film plane by front surface mirrors. The arrangement, as shown, has the feature that both beams undergo the same number of reflections, and that both beams are precisely superimposed on the hologram recording plane.

At this time all lights in the room, except a special light having a G-4 filter on it, were shut off. A holographic plate (Agfa 10E75) was put into the film holder. A few minutes were allowed for the plate to come to thermal equilibrium with its surroundings.

The plate was exposed by triggering the pulse laser. After the plate was exposed, it was developed via standard darkroom techinique; 4-5 minutes in fine grain high contrast developer Metinol 'U', stop bath, and 1-3 minutes in hypo. The plate was washed with running water and dried. Bleaching of the exposed plate was used to improve the brightness of holographic reconstruction.

After the plate is dried, it can be reconstructed and

B.S. Beam Splitter
F.S.M. First Surface Mirror

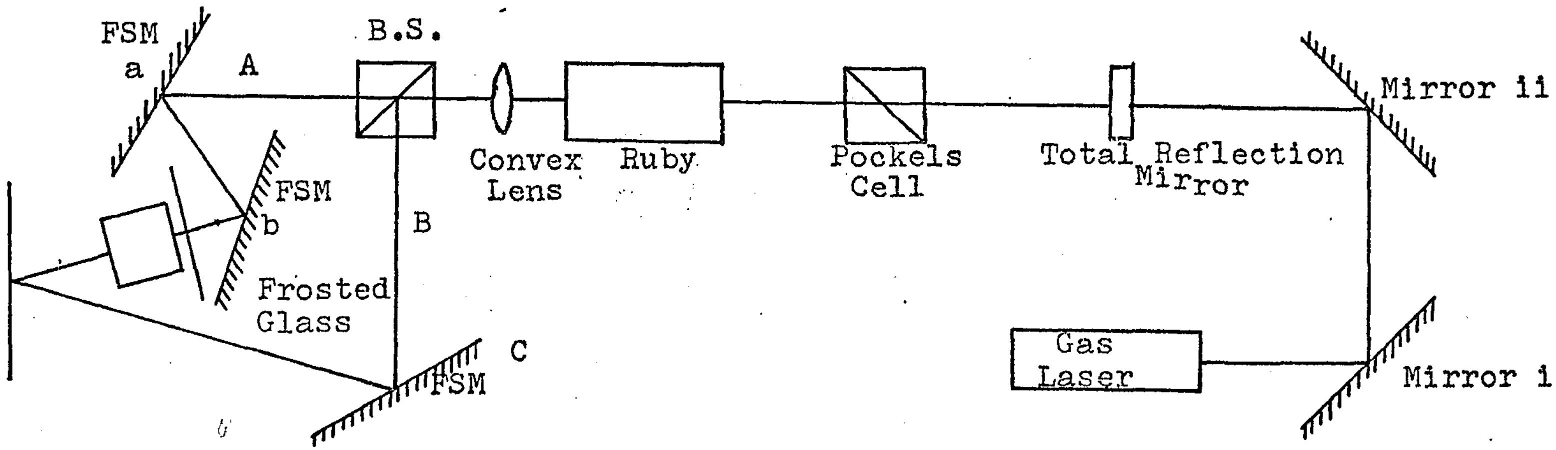


FIGURE 5 SCHEMATIC OF APPARATUS TO PRODUCE PULSED HOLOGRAM

the three dimensional image of the bubble viewed to obtain the desired information on the shape and size of the bubble. Photographs can be taken of the virtual image by simply using a lens in front of the hologram. At the same time a real image of the bubble can also be taken on a photographic film.

V RESULTS AND DISCUSSION

In 1967 when the laser and associated equipment for making holograms was purchased by the Chemical Engineering Department at the University of Windsor, the techniques for making holograms were new to the author. Therefore, it was necessary to go through a number of trial and error efforts before the final goal to obtain a hologram of a moving object (in this case a bubble growing on an artificial cavity) was achieved. Initially holograms were made of stationary objects (glass beads, toys etc) to develop the technique gradually. Then holograms were made of slow moving objects (growing water droplets on the tip of a burette) and finally holograms of a growing bubble.

A. Hologram of a stationary object

The known spectroscopic holographic plates at the time this work was initiated were Kodak 649F plates. These plates were of too low a speed for our work. The exposure time ranged from 2to 20 seconds depending on the size of the object. A few holograms of glass beads and small plastic toys were made using these plates.

Initially it was not known how to get the real image of the object from the hologram. Later it was discovered that if the object was put far from the holographic plate at the time the hologram is made, then the real image would form at infinity.

Also when the object was within approximately a foot of the plate, a real image could be obtained easily on a screen. The reconstruction of the real image depends partly on the radius of curvature of the reconstruction beam.

B. Holograms of moving objects

After holograms of stationary objects were made and reconstructed, attention was then focused on the major objective of making holograms of moving objects. There were two serious limitations blocking the achievement of this goal.

a. The power of the cw laser was much less than required. The 10mw power of the present cw laser was insufficient to make holograms of moving objects where power of the order of a few watts was needed.

b. Fast films or plates with high resolution were not available.

As a first step, it was decided to make holograms of water droplets growing at the tip of a burrette. The growth rate of the water droplets was very low (approximately one drop per minute). The beam diameters after divergence were in the range of one to two inches in diameter and the exposure time of 1/30sec was given. But due to the low sensitivity of the Kodak 649F spectroscopic plates, it was not possible to make holograms of the water droplets.

Eastman Kodak Co. of Canada was then contacted to enquire if films or plates suitable for our work were available. At our request, they forwarded two rolls of SO243 Aerial films. With this film it was possible to make a few holograms of growing water droplets. But due to the poor film resolution the reconstruction of the hologram was not satisfactory. In addition the only size of the film available was 35mm.

Fortunately Agfa Gevaert Co. developed films and plates having different speeds and resolving powers. Their 14C70 film was used to make holograms of water droplets growing at the rate of 10 drops/min, using 1/300 sec of exposure time. Although the 14C70 film was satisfactory with respect to speed, the resolving power of 1500 lines/mm was not satisfactory. Furthermore this type of film was not available in plate form. At the same time, Agfa 10E70 plates with a sensitivity of 200 ergs/cm^2 were tried but without any success. Only one choice remained ie. the film 14C70 requiring 3 ergs/cm^2 for optimum exposure. An attempt to make holograms with this film failed due to the convection currents , absorption of light by optics and reflection of part of the object beam by the window section. Obviously a desirable solution to the problem lay elsewhere.

It was decided to try a pulsed laser with more energy, at least of the order of a joule. A ruby laser was borrowed from the Mechanical Engineering Department. However the coherence length of this laser was not good enough for holographic work.

A hologram of a stationary object was first tried in the usual manner but by using the ruby laser. Care was taken to ensure equal path length for the object and the reference beams. Two types of holographic plates, such as 10E75 and 8E75 tailored to ruby laser of wavelength 6943 Å, requiring 50 ergs/cm^2 and 200 ergs/cm^2

respectively for optimum exposure, were used. It was found that a reflection type of set up, on reconstruction of the virtual image showed a few black spots. (For an explanation of the reflection type of set up, reference should be made to Appendix II). This might have been due to the poor coherence length of the pulse laser. Moreover the real image was also poor. In a trial using a transmission type set up, it was found that even with the poor coherence properties of the borrowed pulse laser, good holograms could be made.

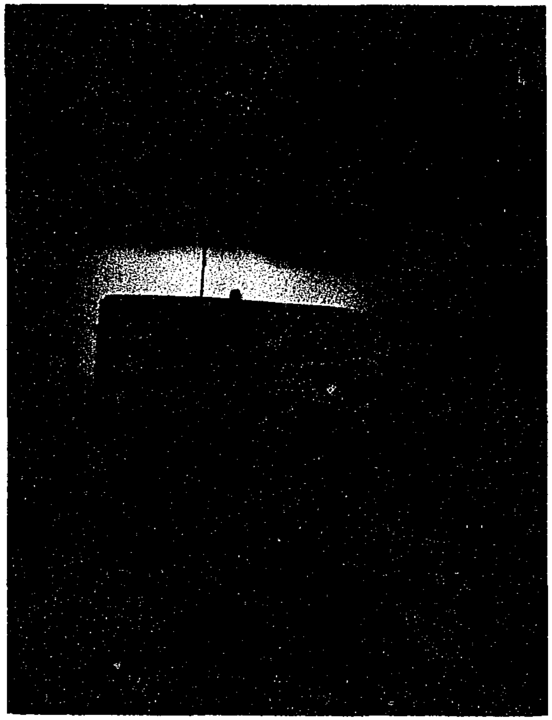
At this stage of development, it was decided to make holograms of the growing bubbles in the actual set up. A few holograms were made of growing bubbles. Their real and virtual images turned out to be satisfactory. By using different degrees of divergent beams, the size of the virtual image could be varied. It was found that if the hologram is viewed very near the pin hole, the size of the object is much smaller than the actual size. Viewing the hologram away from the pin hole increased the size of the object. Similarly for the real image, the size of the image in focus was dependent on the radius of curvature of the reconstruction beam.

Thus a hologram of a bubble was made. The three dimensional effect was visualized. Magnification was obtained with beams of different radii of curvature. Virtual and real images were photographed with the help of lenses and a polaroid camera back. It was found that the angle of incidence of the reconstruction beam is very important for reconstruction of real and virtual images. In certain cases two real and two virtual images were formed. It was also found that the real image opposite to the direction of reconstruction beam was far smaller than the real image in the normal expected direction. Photograph 1 gives the real image of the growing bubble.

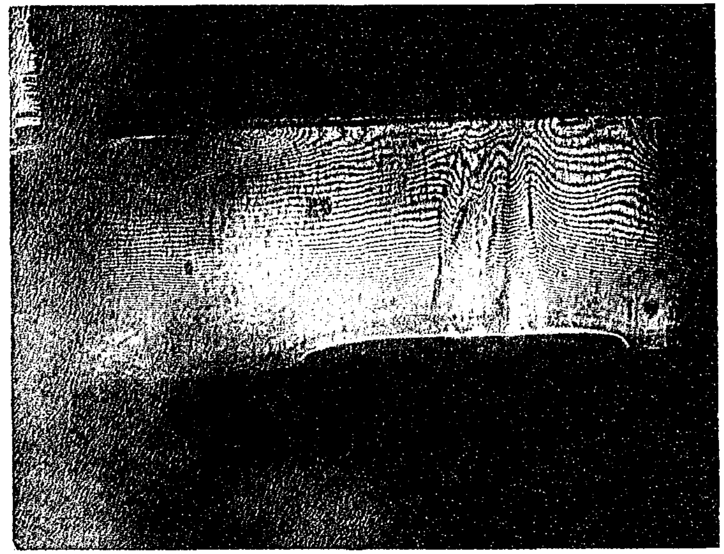
A double exposure technique was used to get an interference pattern of a changing phenomenon, such as convective currents created in a pool boiler.

Photograph 2 shows the interference pattern created due to convection currents. This particular photograph had a peculiar behavior of giving two real images in the direction of reconstruction beam. For some time it was thought that the aim of getting interference pattern was fulfilled but reconstruction of two real images was not clear. It was also found that the interference pattern was recorded on the plate itself as if it were a grating. Further more the virtual image did not contain any interference pattern.

Due to the uncertainty as to what these fringes represent, once again the set up was put together and a diverging beam from a cw gas laser was allowed to pass through the boiling water. It was found that the same kind of interference was there in the beam coming out of the window section. Hence it was established that the interference recorded as a grating on the plate was not due to the double exposure but due to the fact that some other phenomenon such as schlieren or shadowgraph was taking place. The set up used for this particular case



PHOTOGRAPH 1 Real Image of a Growing Bubble



PHOTOGRAPH 2 Real Image of Interference Pattern

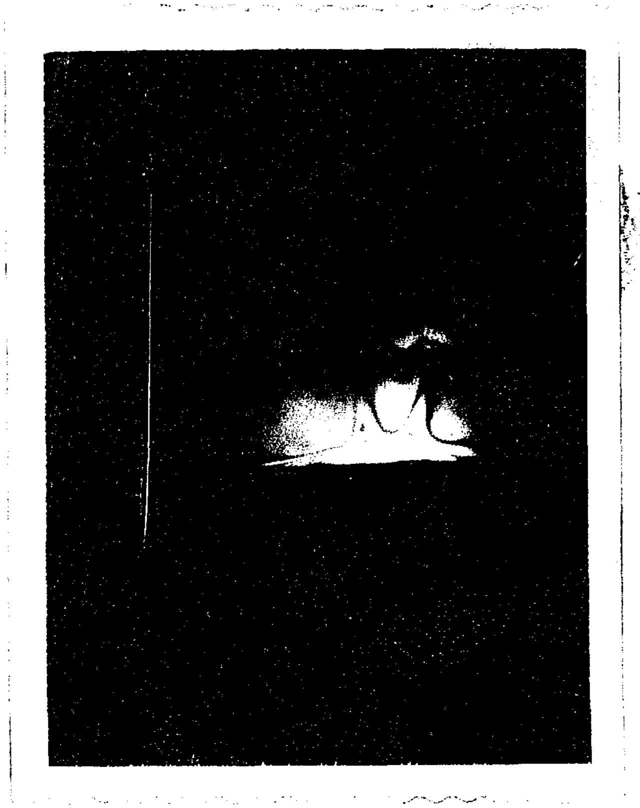
was such that the reference beam and the object beam made an equal angle to the plate. That might have been the reason for getting two real images in the same direction.

Now, perfection had been attained in making holograms of different objects, moving or stationary but the double exposure technique did not work all that well. Therefore, it was decided to use a frosted glass plate at the back of the window section so that the interference pattern due to some other mechanisms (such as in photo 2) could be avoided. This trial was a success and all the double exposed holograms were made by this method. The results obtained clearly show the interference pattern due to density differences created by natural convection currents.

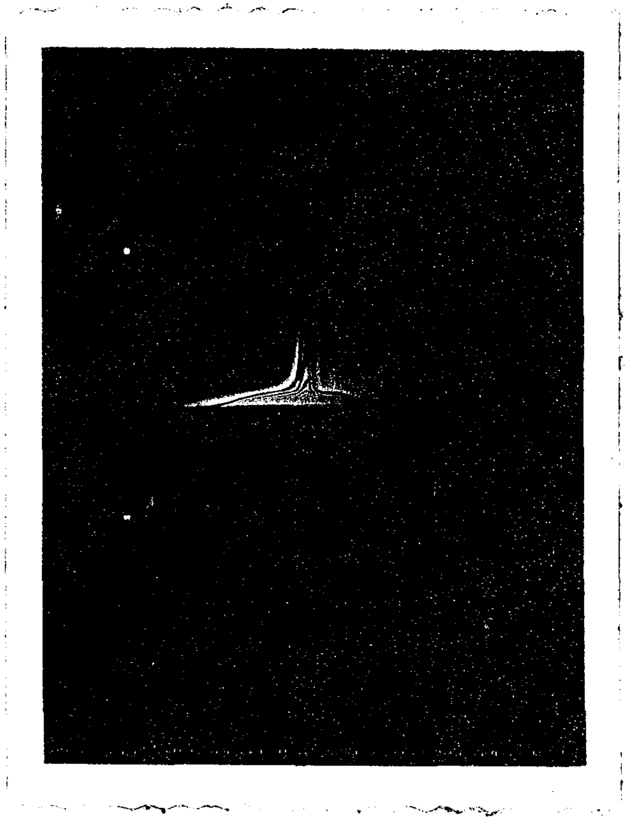
C. Analysis of Double Exposed Hologram

1. He-Ne Gas Laser: For the explanation of the double exposed hologram, reference should made to Appendix IV.

At the low heat flux of 16,800 Btu/hr.ft^2. The surface temperature at steady state conditions was 37.0^{0}C and the temperature of the surrounding water one-half inch above the heater was 25.7^{0}C. The fringe pattern (photograph-3) obtained is symmetrical around the heat transfer surface and very near to the boiling surface e.g. up to about 1/8-inch above the surface the fringe pattern is parallel to the surface. Fringes in this region are very fine and close together indicating that a rapid change of temperature is taking place in this region. Above this region the isotherms



PHOTOGRAPH 3 Interference Pattern Above the Boiling Surface
Heat Flux=16800 Btu/hr.ft^2



PHOTOGRAPH 4 Interference Pattern
Heat Flux=38800 Btu/hr.ft^2

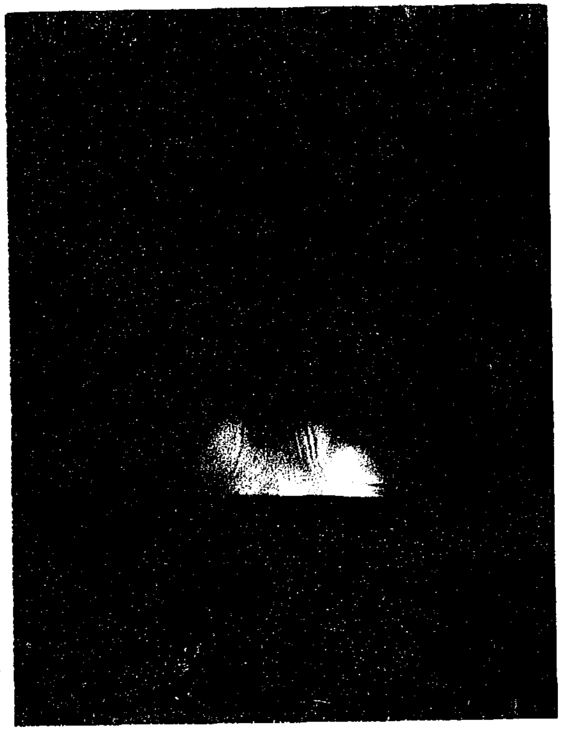
(fringes) rise at the sides and have a minimum at almost the middle of the heated surface. These interference fringes identify isotherms at different locations from the surface. This record called an interferogram provides an instantaneous picture of the density field surrounding the heated surface from which temperature gradient may be measured.

In photograph 4 a different fringe pattern is obtained for a heat flux of 38800 Btu/hr.ft^2. The surface temperature was 42.0^{0}c and the water temperature one-half inch above the heater was 26.1^{0}C . The fringes here are almost symmetrical around the center of the boiling surface. Fringes are finer than the ones shown in photograph 3 due to the greater refractive index differences indicating a rapid density or temperature change at the higher heat flux. The thickness of the fine parallel fringes near the heater surface has diminished in this case.

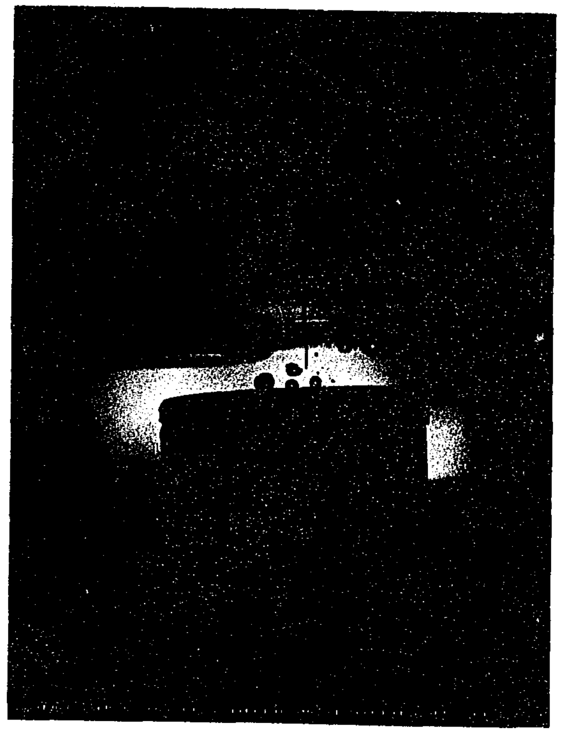
Photograph 5 illustrates the fringe patterns for a surface temperature of 43.7^{0}C and a heat flux of 51,000 Btu/hr.ft^2. As the heat flux was increased, the basic pattern of convection currents remained the same but the fringes became finer near the surface and the effective area of convection currents increased.

2. Pulse Laser

The pool boiler was reassembled for use with the new laser to determine if two pulses spaced over a time interval in the micro second range could give a record of temperature fields.



PHOTOGRAPH 5 Interference Pattern
Heat Flux=51000 Btu/hr.ft^2



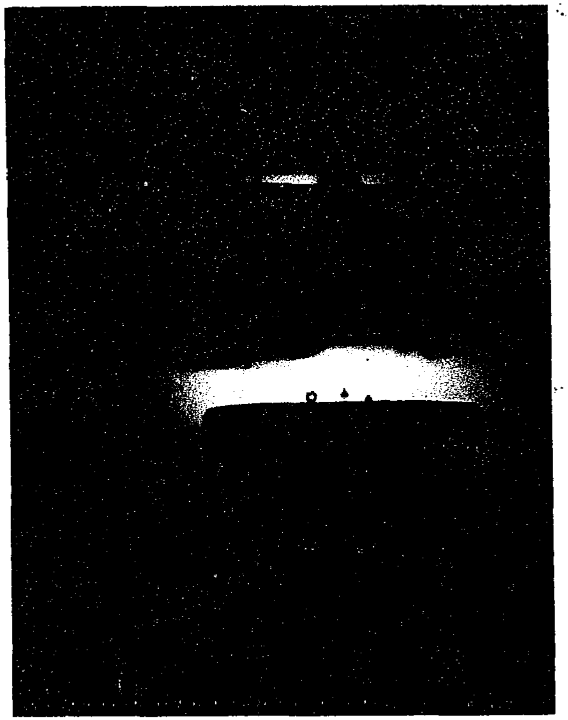
PHOTOGRAPH 6 Double Exposed Hologram with a 100 micro sec interval between two pulses

Photograph 6 was taken from a hologram which was double exposed with a 100 micro second interval between the two pulses. The heater surface was at a temperature of 121.0^{0}C and the bulk water temperature was 97.1^{0}C. No fringes are visible. The bubble which has already left the surface is eliptical in shape while the one sticking to the cavity is spherical in shape. The three dimensional effect was visualized by changing the position of the eye relative to the hologram in the same manner as a normal object is viewed.

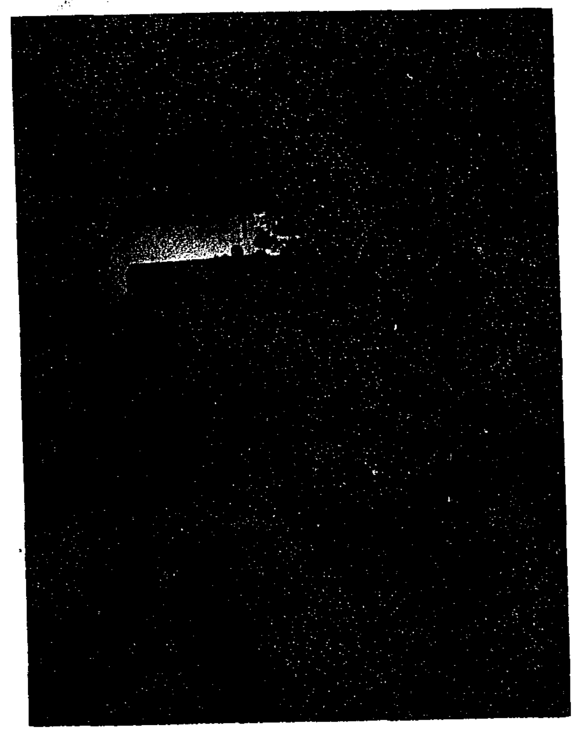
Photograph 7 was obtained from a double exposed hologram when time interval between two exposures was 250 μsec. At the cavity, bubble growth is initiating while one bubble has just left the cavity. The shape of the latter bubble is a very peculiar cone shape. The temperature of the surface was 121.6^{0}C and that of the bulk water 96.7^{0}C. Using this increased time interval between the two pulses no fringe pattern was obtained, indicating that the density change in such a short time is negligible and it could not be recorded.

One further attempt was made to record the interference pattern using a delay time of 1000 μsec between the pulses. Photograph 8 was obtained from the hologram. This photograph indicates that a fringe is begining to be recorded. There is a slight indication of fringes in the hologram but they were so dim and blurred, it was not possible to photograph them. Between the two bubbles there are visible black zig-zag lines which could be due to density differences.

One can conclude from photographs 6 through 8 that there



PHOTOGRAPH 7 Double Exposed Hologram with a 250 micro sec interval between two pulses



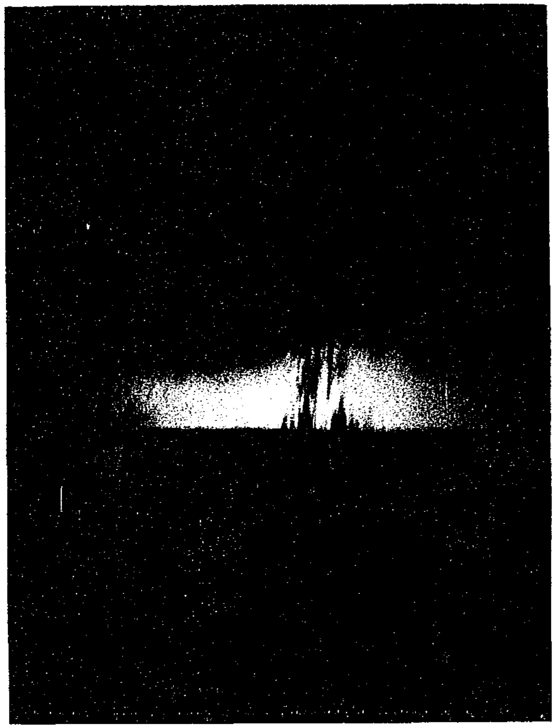
PHOTOGRAPH 8 Double Exposed Hologram with a 1000 micro sec interval between two pulses

appears to be an optimum time interval for obtaining the fringe pattern. With this in mind the 15mw gas laser was set up once more using the same arrangement as was employed for the pulse laser. The results obtained were encouraging and indicated that if a powerful gas laser or a pulse laser which can generate two pulses over an interval of greater than one milli-second were employed using atleast one micro second exposure time then there is a possibility of photographing fringes around a growing bubbles.

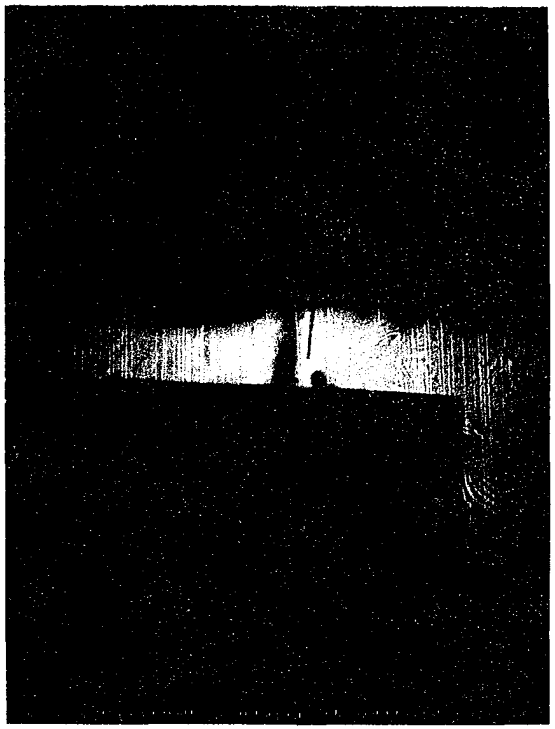
Photographs 9 and 10 are identical except that Fig. 9 was obtained from a single exposure hologram and Fig. 10 from a double exposure hologram. The exposure time used for both of the holograms was 1/125 sec for the double exposure hologram. There was approximately two seconds delay time between the two exposures.

The single exposure hologram does not have any trace of fringes in contrast to the double exposure hologram in which there are fine fringes away from the boiling surface. Near the boiling surface fringes were not obtained. Above the cavity where the bubbles are growing, the bubble is blurred showing that the exposure time must be reduced. The frequency of the bubble formation was kept very low in this case to ensure minimum density differences.

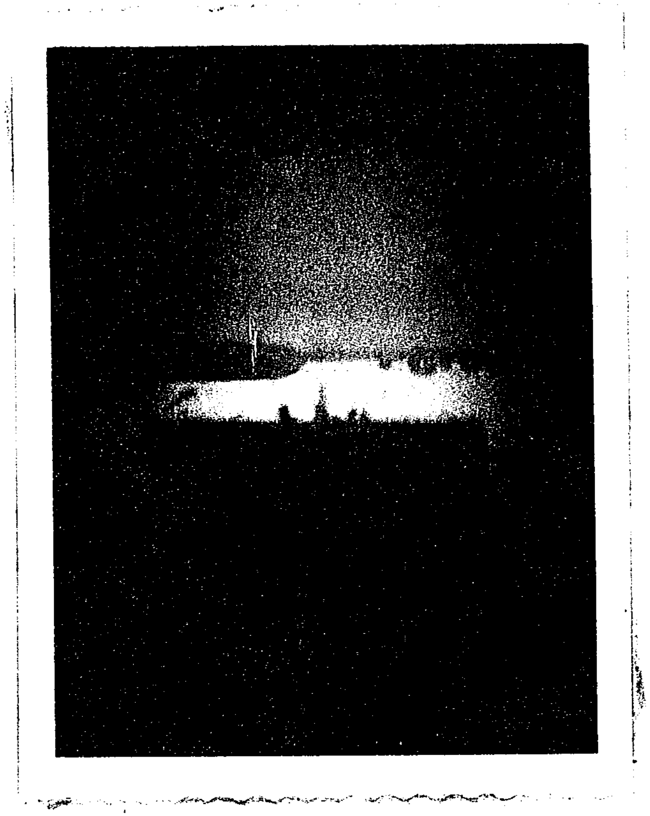
Photograph 11 and 12 were obtained under conditions identical to those used in obtaining Fig. 9 and 10 except that the exposure time was reduced to 1/250 sec. A similar effect is visible in these photographs but it appears that the blurring



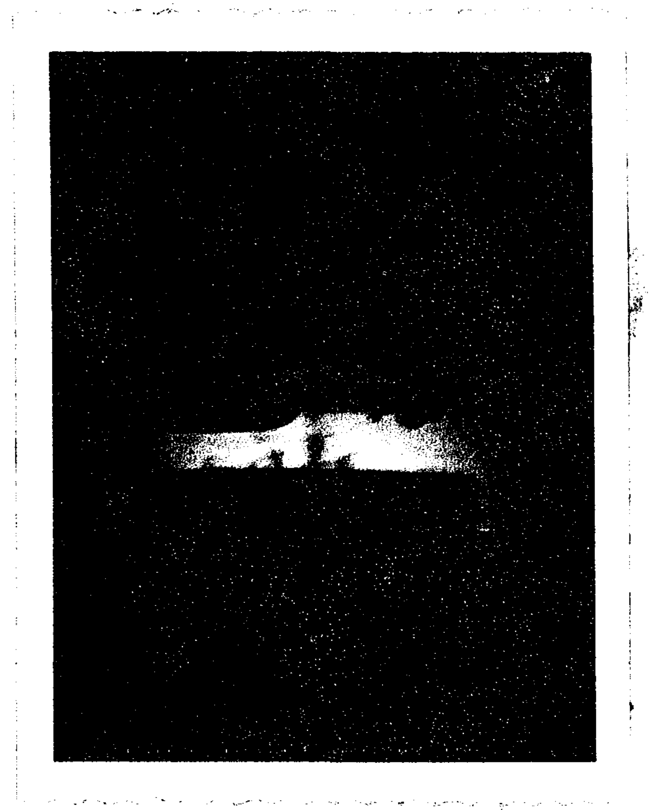
PHOTOGRAPH 9 Single Exposure Hologram
Exposure Time=1/125 sec



PHOTOGRAPH 10 Double Exposed Hologram with a 2 sec delay time between two exposures, exposure time=1/125 sec



PHOTOGRAPH 11 Single Exposure Hologram
Exposure Time=1/250 sec



PHOTOGRAPH 12 Double Exposed Hologram with a 2 sec delay time between the two exposures, exposure time= 1/250 sec

of the bubble has been reduced. This indicates that exposure time for this work should be smaller than 1/250 sec.

VI CONCLUSIONS AND RECOMMENDATIONS

The following is a summary of the observations and conclusions resulting from an analysis of the experimental data obtained in the present investigation.

i. A hologram of a bubble growing on an artificial cavity has been made. The virtual as well as real image can be easily viewed. A picture of real and virtual image of the bubble has been taken.

ii. The interference pattern due to density differences around the boiling surface has been obtained using double exposure technique under natural convection heat transfer conditions.

iii. Holograms made with pulse laser do not show any fringe pattern due to the insufficient time interval between the two exposures. The range of time intervals used between the two exposures were 100 μsec, 250 μsec, 1000 μsec and 1 minute. The 1000 μsec time interval between the two exposures was not great enough to record density changes. The time interval of one minute was too great as the change in density occuring in the interval was so great that the fringe pattern was washed out.

iv. The time interval of several seconds between the two exposures indicated a possible recording of an interference pattern. This record of interference pattern was obtained using a cw laser with 14C70 spectroscopic films.

The following recommendations are made for further studies.

i. This holographic study, using the double exposure technique should be continued using a time interval between two exposures of approximately 1 to 5 sec.

ii. Different cavity diameters and depths should be used to investigate if the shape and size of the bubble changes with cavity dimensions.

iii. The dimensions of the pool boiler should be reduced to a minimum if the pulse laser with a 1000 μsec time interval between two pulses is to be used.

iv. In order to allow reproducible measurements of temperature distribution during bubble growth, bubble growth should be initiated at a prefixed time. This objective can be achieved using a small voltage pulse across a thin film resistor.

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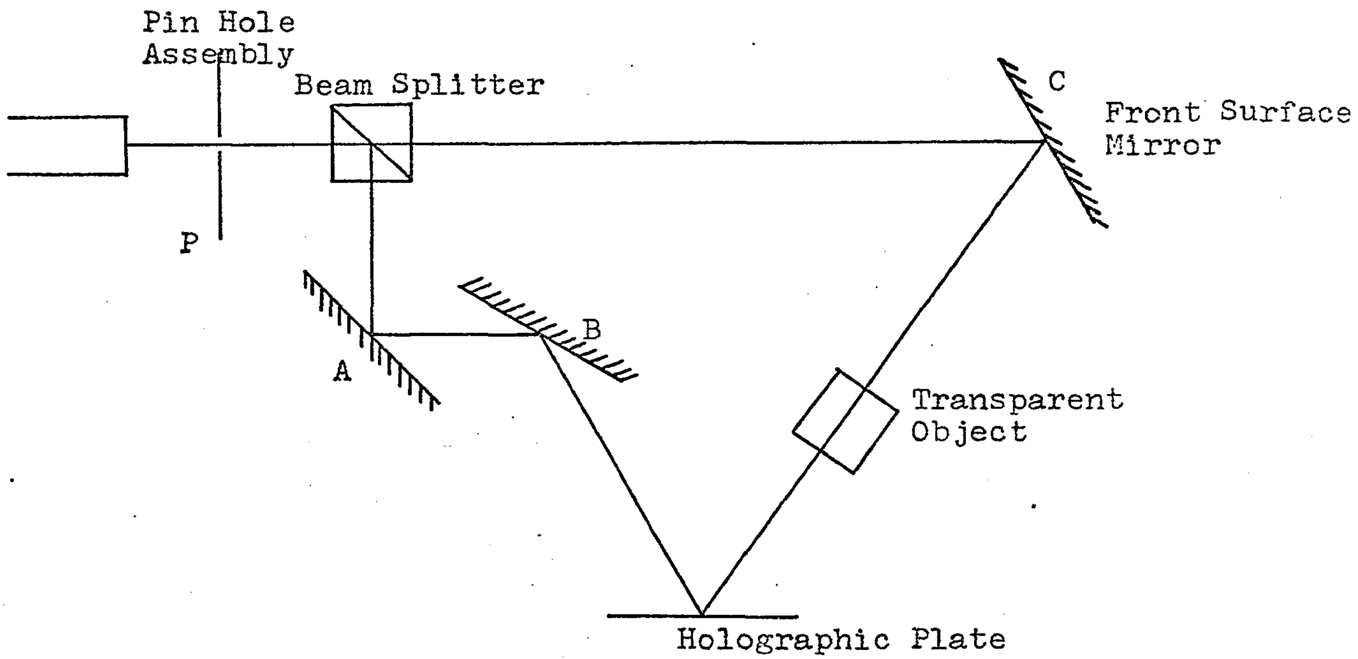
APPENDIX I

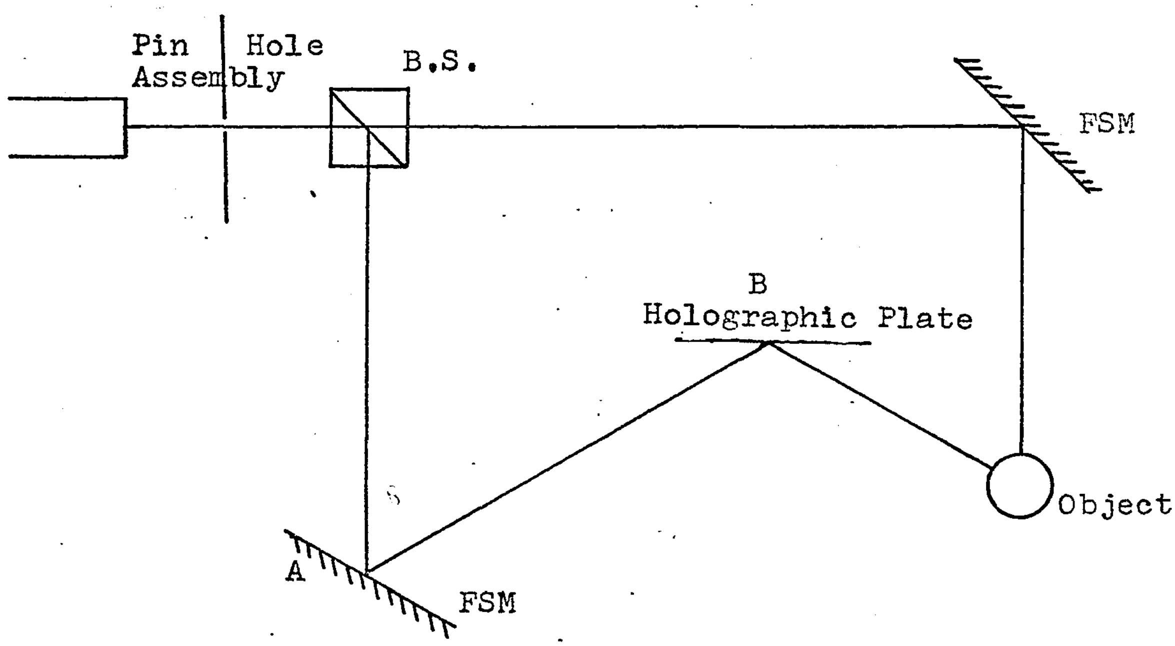
Recording and Reconstruction of Holograms

For a discussion of the mathematical details of the holographic image-forming process, the reader is referred to the original papers of Leith and Upatnieks(21-22) and to an interesting recent review paper by Ennos (23). However, it would be instructive to consider a simple apparatus for the formation of holograms and to describe some of the important properties of the reconstructed image.

Fig. I.1 shows one of the possible arrangements of making a hologram.



Set Up for Transparent Objects



Set Up for Opaque Objects

FIGURE I.1 RECONSTRUCTION OF HOLOGRAMS

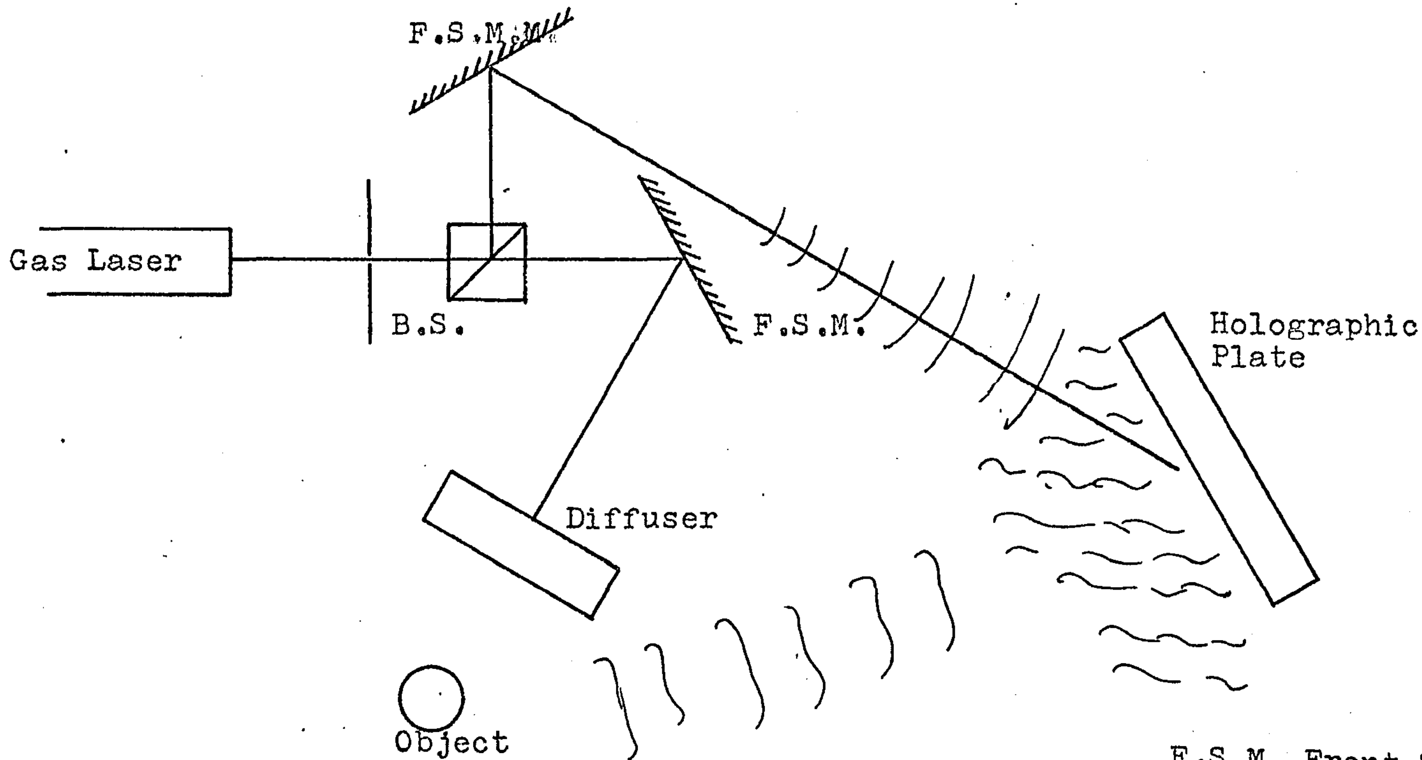
A laser light source is arranged to get two divergent light beam by using a pin hole assembly and a beam splitter. One ray, called the reference beam, is reflected from the front surface mirrors A and B onto a photosensitive emulsion on a transparent plate. The other ray is reflected from mirror C and gets scattered from the object onto the same point of the plate and is called the object beam. Due to the large coherence length of the light from the laser relative to the maximum difference between the length of the object and reference beams, a meaningful interference pattern will be formed at the photographic plate. This plate is developed in the same manner as any other photographic film.

The developed photographic plate, called a hologram, will appear as a granular gray pattern bearing no resemblence to the object when illuminated by white light. However, if the hologram is replaced back in the plate holder and reilluminated by the reference beam only, light will be diffracted from the grating. The zeroth order diffraction pattern will simply direct transmission of the reference beam through the hologram. The two first order diffraction patterns are of interest. One is an exact reconstruction in amplitude and the phase of the wave which emanated from the original object and will produce a virtual image of the object when viewed through the hologram. This image posseses all of the three dimensional properties of the original object. The other first order diffraction pattern produces a conjugate real image on the viewer's side of the hologram, and it can be taken on a screen or can be photographed with the help of camera back.

APPENDIX II

Reflection Type of Set Up

A typical arrangement for recording a "reflected light" hologram with gas laser is shown schematically in figure II.1. The coherent beam from the gas laser is incident on a microscope objective pin hole assembly and then filtered light falls upon a beam splitter which divides it into scene and reference components. The scene component passes through the beam splitter and is reflected from a mirror that directs it into a ground glass diffuser which disperse the light. The scattering makes the spatial coherence complicated, but does not destroy it. The scattered light is incident on the subject or scene in this case a toy. The toy further scatters the light. The light scattered in the direction of the photographic plate is light that constitutes the scene wavefront. The wavefront contains all of the information about the object-diffuser combination (i.e. the scene) The complex scene wavefront passes through the photographic plate. The reference beam component is that small fraction of light which is reflected from the front surface of beam splitter. This beam is incident upon a second front surface mirror which directs the light into the centre of the photographic plate. The hologram is a recording of any portion of this complex stationary interference pattern.



F.S.M. Front Surface Mirror
B.S. Beam Splitter

FIGURE II-1 HOLOGRAPHIC SET UP FOR RECORDING REFLECTED LIGHT HOLOGRAM

APPENDIX III

Alignment of the Pulse Laser

The term alignment can be explained with the aid of Fig 5. A cw gas laser was used for alignment. The gas laser was switched on and when it started lasing, the beam coming out of the laser was elevated with the help of a beam steerer to the same level as that of the back mirror in the ruby laser. Mirrors (i) and (ii) were adjusted in such a manner that the light beam was parallel to the granite base. The front mirror of the pulse laser was then removed and the laser assembly was adjusted in such a way that the cw beam from the gas laser passed through the pulse laser. A piece of paper with a small hole in it was put on the lasing end of gas laser so that the beam reflected from prism, pockel cell could be seen on the paper. In the beginning when the prism and pockel cell and ruby were not in the same axis, there were many reflections on the paper. Suitable adjustment was made to the screws provided so that the reflected beam from different components travelled the same path as that by the gas laser beam. Now the total reflection mirror was put back and was adjusted to bring the beam back to its own path. Once this is done the pulse laser would lase if trigerred.

A beam splitter was put in front of the beam coming through the pulse laser to get two beams A and B out of a single beam.

These two beams were perpendicular to each other. One mirror (a) was located so as to divert the beam A to mirror (b) which was adjusted in such a manner that the beam was directed to dummy plate in a plate holder after passing through the windows of the boiler. The other beam(B) was allowed to fall on mirror (c) and was diverted to the dummy plate. All the mirrors could be moved or rotated to get both the beams at the same spot on the dummy plate. Enough care was taken to insure equal path lengths for both the beams. The angle between the two beams was kept around 20°. Once this done, a 10x eye piece was placed, between the beam splitter and front of the pulse laser, to diverge the beam. The purpose of this was to have the plate fully covered by the two beams A and B, which can be checked by blocking one of the beams at a time.

Now the back mirror was put on the pulse laser assembly and was aligned with the help of screws provided so that the light reflected from the mirror retraces its own path.

The whole process of adjustment as described above is called Alignment of the pulse laser.

VITA AUCTORIS

1940	Born in Unnao, India
1964	Graduated from H.B.T.I., Kanpur, India with a B.Sc. degree in Chemical Engineering
1967	Accepted into the Graduate School of the University of Windsor
1970	A candidate for the degree of M.A. Sc. in Chemical Engineering at the University of Windsor