Bubble shape and temperature gradient visualization

Burgain, P.G.J.P.

Published: 01/01/1989

Citation for published version (APA):
Final project report
of
P.G.J.P. Burgain

Bubble shape and temperature gradient visualization

March - June 1989

Report nr. WOP-WET 89.008

Faculty of
Mechanical Engineering
Eindhoven University of Technology
Contents
Abstract 2
Acknowledgements 3
1. Introduction and scope 4
   1.1 General outlines on two-phase flows 4
   1.2 Main topics of the EUT's two-phase flow group 4
2. Aims of the present investigation 5
3. Bubble shape visualization 5
   3.1 Principle of the used method 5
      3.1.1 General outlines on objective instruments 5
      3.1.2 Three dimensional investigation 6
   3.2 The studied experimental fitting under investigation 7
      3.2.1 The bubble 7
      3.2.2 The test section 7
3.3 The light source 8
3.4 Experimental results 8
   3.4.1 Two dimensional experiments without test section 8
      3.4.1.1 Expansion of the laser beam 9
      3.4.1.2 Bubble lighted with a parallel beam 10
         3.4.1.2.1 Formation of a shadow 10
         3.4.1.2.2 Formation of an image 11
            a. Required theory on image formation 11
            b. Deviation between theoretical and experimental results 12
            c. Image interpretation 13
   3.4.2 Two dimensional experiments with test section 14
      3.4.2.1 Penetration of the incident beam inside the test section 15
   3.4.3 Three dimensional experiments with test section 17
      3.4.3.1 General outlines 17
      3.4.3.2 Final set up 18
4. Visualization of temperature gradients 20
   4.1 General outline 20
   4.2 Heated test field as a refractive index field 20
   4.3 Disturbance of a light ray in an inhomogeneous refractive index field 21
   4.4 Interferometry 21
      4.4.1 Principle of two-beam interferometry [17] 21
      4.4.2 Mach-Zehnder interferometer (M.Z.I.) model 22
   4.5 Experimental results 23
      4.5.1 Observations 23
      4.5.2 Interpretation 24
4.6 Conclusions and future research: 25
   4.6.1 Conclusions 25
   4.6.2 Future research 25
Abstract

Progress in the field of bubble detachment behavior is critically dependant on a clear understanding of the nucleation phenomenon. The influence of the bubble shape and of the temperature gradient around it have been theoretically described. Experimental validations are now required. To accomplish this aim, an optical measuring strategy has been chosen. Therefore, the objective of the present survey which constitutes my final project before getting the french engineer diploma, is to design optical set ups to visualize:

1. The contour of a simulating glass bubble
2. The temperature gradient around a heated glass bubble

First, experimental steps and optical laws which have led to the realization of a set up allowing a three dimensional visualization of the bubble are presented.

Then, considering that the wave fronts of a parallel light beam are distorted in their passage through a region of variable temperature, we explain how to visualize a temperature gradient by means of a Mach-Zehnder interferometer.
Acknowledgements

Firstly, I want to express my a lot of gratitude towards Dr. C.W.M. Van der Geld for affording me the opportunity to carry out the present investigation within the Mechanical engineering department of the Eindhoven University of Technology.

Further, I would express my thankfulness to P.G.M. Boot for his continual assistance and moral support.

I also want to thank to J.W. Versteeg and to T. Wychers from T.N.O. at Delft for their instructive suggestions about image formation theory. Besides I would like to gratefully record my indebtedness to M.H. van Ooijen who has contributed considerably to the realization of this report.

Philippe Burgain
June, 1989
Eindhoven, The Netherlands
1. Introduction and scope

1.1 General outlines on two-phase flows

Two-phase flows, particularly gas-liquid and vapor-liquid flows have a manifold occurrence. They are of practical concern in engineering disciplines, including the petroleum, chemical and power industries. For instance, the study of boiling liquids is important in the context of safety in nuclear plants.

Two-phase flow situations have a great variety and certain classes of phase distributions can be delineated. They are commonly called flow regimes or flow patterns [1] (appendix 1). The understanding and delineation of flow patterns in general are particularly important in practical designs. Heating mode, outlet and entrance conditions as well as physical dimensions and the shape of a given design all influence flow conditions and tend to be flow regime dependent.

1.2 Main topics of the EUT's two-phase flow group

Two-phase flow investigations in the Eindhoven University of Technology (EUT), faculty of Mechanical Engineering concern the boiling, heat transfer and mass transport phenomena in the flow of a liquid-vapor mixture in a heated pipe. Their main topics are:

1. a contribution to the knowledge and understanding of phase distribution mechanisms in vertical evaporator tubes;

2. explanations for and measurement of the occurrence of some flow pattern transitions at high pressure;

3. numerical modelling of droplet impingement on solid surfaces including viscosity effects and prediction of interface distortion;

4. study of vapor bubble detachment in vertical tubes with forced convection, including the effect of wall geometry such as in rifled tube (appendix 2).

A Ph.D-thesis on topics 1 and 2 has been completed; Ph.D-thesis work on topic 4 is already started up. Topic 2 is still being investigated, with emphasis on the effect of the tube diameter and temperature. The Leidenfrost phenomenon was successfully simulated (topic 3), and a dynamic contact angle algorithm based on a semi-empirical correlation is currently being examined.

To carry out these topics, the EUT's two-phase flow group supplied itself with a well developed measuring equipment [2]. For instance a high pressure test rig with dedicated instrumentation, is available. About 80 measuring stations exist in a tube length of about 5 meters. A photograph of a vertical evaporator tube allowing flow regimes and transitions surveys is given in appendix 2.
2. Aims of the present investigation

Concerning topic 4, many vapor bubble parameters such as bubble shape, bubble growth and surrounding temperature gradients have to be measured in order to validate theoretical descriptions [3], [4]. For this purpose, optical measuring strategies are highly suitable because they present the following characteristics:
- render information about local flow properties, in order to facilitate comparison with theoretical modeling, directly accessible to visual perception.
- non intrusive techniques providing reliable and accurate informations without physically interfering with the fluid flow.
- widely applicable at high temperature (ca. 300 °C) and high pressure (ca.220 bar) circumstances.

For the reasons above mentioned, the aims of this work are applying optical principles, to visualize:
- the bubble shape
- the surrounding temperature gradients.

On the basis of image formation and of interferometry theories, two optical measuring systems have been designed.

3. Bubble shape visualization

3.1 Principle of the used method

3.1.1 General outlines on objective instruments

To visualize a lighted object on a plane, as there are a screen or a photographic film; a basic optical design consisting of a so called "objective instrument" is suitable. The objective instrument consists of a combination of refracting or reflecting surfaces, that is, lenses and mirrors, usually plane or spherical. It gives in the receiving plane a real image of the object. This method gives a faithful two dimensional representation (projection) of a three dimensional object.

Here, the image formation can be treated in terms of the ray theory, that is, by using the laws of geometrical optics given in appendix 3. Moreover, since the studied object i.e. a bubble, is very small (radius less than 0.5 mm) in comparison with the dimensions of the optical equipment, Gaussian optics called paraxial optics, whose laws are given in appendix 5, can in first approximation be used to characterize the obtained image (size and location). Rigorous proofs of these laws are given in most optics books, for example [5], [6], [7].
3.1.2 Three dimensional investigation

The information to be recorded is the contour of the bubble. In order to obtain a three dimensional representation, the construction of an optical arrangement involving two imaging systems (constituted by a light source and an objective instrument) has been chosen (fig.1). These two imaging systems are placed perpendicular on each other. Consequently, if the bubble is exactly placed at the location where the two beams intersect, two pictures, each corresponding to one cross section of the bubble, are obtained.

**Fig.1**: Arrangement for a three dimensional representation

3.2 The studied experimental fitting under investigation

Experimental fitting is constituted by two elements:

- a bubble
- a test section

3.2.1 The bubble

As it is difficult to keep a real bubble in place, we decided to simulate it. The bubble with a diameter of about one millimeter is simulated by an ellipsoid of glass (refractive index of about 1.4) obtained by melting the extremity of a thin glass pin. Indeed, minimizing free energy, this glass extremity forms a perfect sphere. We need an image of an object with two different cross sections. This is realized by deformation of the sphere applying a pressure on it during the melting time.
This ellipsoid will hence for on be called bubble. It was placed inside a test section.

### 3.2.2 The test section

The flow tube with instrumentation is called test section. For our experiments we have built a mock-up, simulating the actual test section (see section 1.2). From now on we refer to our substitute as test section. It is filled with water. As shown in fig.2, it has a parallelepipedical shape. It is built with four glass plates (refractive index of 1.52) glued together. The parallelism of both sides of the plates plays an important role because the light rays have to enter the test section perpendicular on the axis of the latter.

![Fig.2: Test section with bubble](image)

### 3.3 The light source

For three dimensional imaging, two projections and hence two light sources are required. The two light sources used consisted of two continuous helium-neon lasers of 632.8 nm wavelength. They each emit thin parallel light beams (diameter ca. 1 mm) but have different powers (laser 1: 1 mW; laser 2: 5 mW). The laser sources gave satisfying results for the adjustment of the setup. But, in a definitive design, because only one recording plane will be included, each image must be linked with the source that has generated it. In order to meet with this requirement, the laser sources can be replaced by white point sources combined with different color filters. A color filter is featured by its curve transmission as a function of the wavelength. Hence, in order to obtain two images of the bubble sharply recognizable by their different colors, the two filters will have to cover two different parts of the visible spectrum. This combination (point source - color filter) is sketched on fig.3.
The light source is placed in the front focal point of a lens, thus forming a parallel beam.

Fig. 3: Association thermal point light source-color filter
3.4 Experimental results

3.4.1 Two dimensional experiments without test section

These experiments constituted the first stage of this survey, their purpose was to find the required optical components of the imaging system configuration, linking the light source (i.e. the laser), the test object (i.e. the bubble) and the recording screen together in order to obtain the most accurate picture of the bubble on the screen. The expression "two dimensional" used in the heading refers to the fact that only one projected section of the bubble was first studied.

3.4.1.1 Expansion of the laser beam

In order to expand the thin parallel laser beam for being used in the optical visualization system, a beam expanding optics system consisting as shown in fig. 4 of two lenses must be applied:

- a first lens (L1) of very short focal length f1 focusing the parallel laser beam on its back focal point.
- a second lens (L2) of focal length f2 placed so that its front focal point exactly corresponds to the back focal point of L1.

Hence, at the exit of this set up called the "beam expander" an expanded parallel beam destined to light the bubble, is obtained.

\[
\tan x = \frac{d_l}{2f_1} = \frac{d_2}{2f_2}
\]

is given by:
A proper illumination of the bubble is obtained by matching the ratio $\frac{f_2}{f_1}$ with 3 or 4. Indeed, such an illumination allows to obtain a relatively large observation field around the bubble. Hence, further recording with a camera of a moving bubble will be facilitated. For instance, with $f_1=10\text{mm}$ and $f_2=40\text{mm}$, the diameter of the expanded beam $d_2$ is 4mm.

### 3.4.1.2 Bubble lighted with a parallel beam

Having obtained a fitting parallel beam, the next task was to build a suitable objective instrument to faithfully image the bubble on a receiving screen.
3.4.1.2.1 Formation of a shadow

As shown in fig. 5, the bubble is directly lighted by the expanded parallel beam. According to the rectilinear propagation of light, a shadow of the bubble can be seen on the screen. This is explained by the fact that when a light source lights an object, beyond this object a shady zone can be observed. If a screen cuts this zone, an outline of the object can be visualized.

\[ \text{Fig. 5: Formation of a shadow as a result of the rectilinear propagation of the light} \]

3.4.1.2.2 Formation of an image

Now a convergent lens is inserted between the bubble and the receiving screen (fig. 6).

\[ \text{fig. 6: formation of an image with a lens} \]

a. Required theory on image formation

According to the general geometrical theory of optical systems (appendix 5), the locations of an object and its image through a thin lens are linked by the following fundamental equations which relate the
coordinates of conjugate points in the optical axis with the focal length (Fig.7):

- **Lens Maker's equation**:

\[
\frac{1}{12} + \frac{1}{11} = \frac{1}{f} \quad \text{(algebraic relation)}
\]

- **Newton's equation**:

\[FA \times F'A' = -OF' \quad \text{(algebraic relation)}\]

In addition, the obtained *lateral magnification* is given by:

\[M = \frac{12}{11}\]

![Diagram of lens with object space, image space, and optical axis](attachment:image.png)

\[\text{A': Image} \quad \text{A: Object} \quad \text{F': Back focal point} \quad \text{F: Front focal point} \quad \text{f: Focal length}\]

*fig.7: Conjugate points through a lens*

According to the position of the screen in comparison with the lens, included inside a luminous circle corresponding to the beam from the beam expander, either a reversed shadow or a reversed image of the bubble can be observed (Fig.8). Both with a certain lateral magnification.
b. Deviation between theoretical and experimental results

Given lens of focal length f, by fixing the distance 11, it is theoretically possible to foresee both the location and the size of the image. However, as shown by measurements given in appendix 6, a difference appears between the experimental values and those expected by the theory. The difference is even more important as 11 is closer to f. Several causes are responsible for such a difference:

- distance measurements done with a coarse rule involving important inaccuracies. An error of a few millimeters in the object space involves an error of a few centimeters in the image space.

- in calculations the thickness of the lens is neglected, i.e. 11 and 12 are measured in comparison with the same plane.

- optical aberrations introduced by the lens.

Accordingly, a sharp image of the bubble will be obtained by moving the receiving screen in comparison with the fixed lens.

C. Image interpretation

As shown on fig.8 and on the photograph presented in appendix 9, a sharp image of the bubble is featured by a dark contour bordering a bright area. Moving back the receiving screen in comparison with the lens, this
bright area extends and blurs the obtained image. This experimental establishment is based on the following statement: illuminated by a parallel beam the bubble behaves like a spherical lens, that is, it focuses the incident parallel beam on a "focal area" instead of a point (fig. 9). Therefore, the observed bright area corresponds to the image of this focal area through the lens.

Assume that the bubble is perfectly spherical and that the center of the bubble exactly coincides with the optical axis. Consider an incident light ray arriving on the bubble parallel to the optical axis. It is refracted by the first interface (point A). Since $n_1 < n_2$, according to Snell's law i.e. $n_1 \sin(i_1) = n_2 \sin(i_2)$ (appendix 3), it enters the bubble coming near the normal on the interface. At the second interface (point B), while $i_3$ is less than the critical angle (beyond which occurs the total internal reflection phenomenon explained in appendix 4), it undergoes a new refraction. In this case, as the refractive index of the second medium (air or water) is inferior to that of the first medium (glass), it leaves the bubble going away from the normal. Finally, it reaches the optical axis at F. Then in term of light rays, all the incident rays, except those for which total reflection occurs on the second interface and those which don't enter the bubble, converge to a small area (due to the astigmatism phenomenon) surrounding the F point. The calculation shows that in the air the distance from F to the bubble is given by [8]:

$$f = \frac{R \ast (2-n)}{2 \ast (n-1)}$$

**Fig. 9 : Bubble as a spherical lens**
Where R is the radius of the bubble (ca. 0.5 mm)
    n is the refractive index of the bubble (ca. 1.4)

Hence, in that case f= 0.4 mm i.e. the focus is very close to the bubble, as a result, its image appears matched with that of the bubble.

The dark contour is due, as previously mentioned, to the fact that part of the beam is totally reflected on the interface of the bubble and does'nt reach the screen.

3.4.2 Two dimensional experiments with test section

Now the bubble is placed inside the test section filled with water on the path of the light beam, the latter is exactly the same as the one used to perform the previously mentioned experiments without test section i.e. parallel light beam of about 4 mm diameter emerging from the beam expander.

The entering of the light inside the test section involves some modifications that one has to take into account in order to obtain a sharp image of the bubble, namely:

- reflection on the two crossed by light sides of the test section
- horizontal deviation of the beam
- refraction on the exit side of the test section.

3.4.2.1 Penetration of the incident beam inside the test section

If the incident beam enters the test section with two deviation angles (one vertical and one horizontal) in comparison to its entrance side, two phenomena are immediately observed

- a reflection on both sides of the light due to the vertical deviation angle (fig.10)
- the occurrence of a lateral deviated exit beam due to the horizontal deviation angle (fig.10).

To correct these flaws and to obtain an incident beam perpendicular to the test section side, the angular positions (vertical and horizontal) of the laser have to be slightly modified.
3.4.2.2 Test section face as a parallel-sided plate model

Considering a test section wall as a parallel-sided plate constituted by the association of two parallel plane surfaces, a refraction occurs on each of them. Then, as shown on fig.11, the lens placed behind the test section doesn't "see" the bubble through it but a virtual image of the bubble. Then, this virtual image will be the actual object for the lens and its location is calculated considering fig.11:
Consider:
A : object point (bubble)
A' : the image of A through the first refracting surface S1 (the second refracting surface S2 is neglected)
A'' : the image of A' through S2 and the definitive image of A through the test section face.

Applying formula given in appendix 7 at S1:
\[ \frac{S_1 A}{1.33} = \frac{S_1 A'}{1.52} \] (1)

Also applying at S2:
\[ \frac{S_2 A'}{1.52} = \frac{S_2 A''}{1} \] (2)

In fact, the calculation of A'' location is equivalent to calculate the displacement AA'' introduced by the test section face.

According to the Chasles relation:
\[ AA'' = S_2 A'' - S_2 A \] (3)

using (1):
\[ AA'' = \frac{S_2 A'}{1.52} - S_2 A \] (4)

using (2):
\[ S_2 A' = S_2 S_1 + S_1 A' - S_2 S_1 + \frac{1.52}{1.33} S_1 A \] (5)

Hence, inserting (5) into (4):
after calculation: 

\[ AA" = \frac{1}{1.52} \times (S2S1 + 1.52 \times S1A) - (S2S1 + S1A) \]

\[ 1.33 \]

Numerical example: \( e = 5 \text{ mm} \); \( AS1 = 50 \text{ mm} \)

\[ AA" = 14 \text{ mm} \]

This displacement has to be taken into account to adjust the imaging lens behind the test section. Practically, the bubble location inside the test section being fixed, the lens must be displaced away from the bubble of the calculated distance \( AA" \).

### 3.4.3 Three dimensional experiments with test section

#### 3.4.3.1 General outlines

As mentioned in paragraph 3.1.2, to visualize the bubble in three dimensions, an arrangement involving two imaging systems placed perpendicularly to each other is required. Moreover, in order to make a photograph of the final three dimensional image, the cross section investigated by the light source 2 (see fig.1) has to be projected on to the same plane as that used to visualize the bubble with the imaging system 1. As shown in fig.12, this is realized by using two flat mirrors (m) exactly inclined at 45° and a beam splitter (b.s.).
Each branch of the set up includes an imaging lens. When the location of the recording screen is fixed and the two mirrors are arranged in such a way that a light beam arriving from laser 2 is received by the screen, sharp images can be obtained by adjusting the location of the two lenses with respect to those of the bubble and the screen. In addition, to obtain the same magnification for both images, the ratios $11/12$ of the two branches have to be matched.

Where, $11$ = distance virtual object - lens (the object being located at bubble minus displacement $AA''$).

$12$ = distance lens - recording screen.

### 3.4.3.2 Final set up

The final set up sketched on fig.13 allows to obtain an extremely sharp three dimensional representation of the bubble with magnifications included between 8 and 9. To record it, a camera without lens can be used. In this way the image is directly formed on to the sensitive film which is exposed by opening of the shutter. Photographs of obtained images are presented in appendix 9.

The process used to adjust this device:

1. Suppress reflections occurring at the test section surfaces by properly orienting the two lasers.
2. Expand the two laser beams.
3. Adjust the two expanded beams at the same height.
4. Place the bubble at the crossing of the two beams.
5. Fix the location of the recording screen.
FIG 13
THE FINAL OPTICAL SETUP
6. Adjust the lens of the branch 1 such a way to obtain a sharp image with the wished magnification (i.e. ratio 12/11) on the screen.
7. Adjust the lens, the mirrors and the beam splitter locations of branch 2.

4. Visualization of temperature gradients

4.1 General outline

Using an optical method, the temperature distribution near a warm glass bubble (the system used to heat the bubble is sketched in fig. 14) submerged in water has to be visualized.

![fig.14: The heated bubble used for gradient temperature investigation](image)

4.2 Heated test field as a refractive index field

Temperature variations appearing in the test volume involve changes of the water density. And, according to the Lorentz-Lorentz relationship between liquids density and refractive index [9-10]:

\[ \frac{n^2 - 1}{n^2 + 2} = k * p \]

Where
- \( n \) = refractive index of the liquid
- \( p \) = liquid density
- \( K \) has the dimension of \([m^3/kg]\) and depends on certain characteristics of the liquid,
the variations of the water density cause changes of the refractive index. Accordingly, temperature differences in the liquid lead to refractive index gradient [11]. Thus, certain optical methods sensitive to changes of the refractive index has to be used to make visible temperature gradients in the field under investigation.

4.3 Disturbance of a light ray in an inhomogeneous refractive index field

The problem posed by the question how a light ray is disturbed in an inhomogeneous refractive index field is treated in terms of geometrical optics (i.e. excluding some physical phenomena like diffraction or dispersion) is well investigated in the references [12 -13]. The final result of such an investigation is that, with respect to the undisturbed case without temperature changes, the simultaneously occurring alterations are:

(1) The light is deflected from its original direction.

and

(2) The phase of the disturbed light wave is shifted with respect to that of the undisturbed.

While Shadowgraph and Schlieren techniques [14 -15] measure the deflection effect, the optical phase changes can be made visible by interferometry [16]. Indeed, in optical terms, a field with varying refractive index is a phase object, that is, a light beam transmitted through this object is affected with respect to its optical phase. But, the intensity (or amplitude) of the light remains unchanged after the passage of the object, for that reason the latter is invisible to the naked eye. In order to "see" the refractive index variations, a way of converting them in variations of intensity (maxima and minima of intensity) has to be achieved. This feat can be accomplished by causing the free-field light to interfere with the disturbance light.
4.4 Interferometry

4.4.1 Principle of two-beam interferometry [17]

As shown in fig.15, in two-beam interferometry, the phase of the disturbed light ray is compared with the phase of an undisturbed ray by causing the corresponding rays to interfere with each other.

![Sketch of the two-beam interferometry principle](image)

The optical path lengths (OPL) in the two arms of the interferometer are different, and, this OPLD (optical path length difference) dL leads to a phase difference dS between the two beams given by:

\[ dS = \frac{2\pi}{\lambda} \times dL \]

\( \lambda \) is the wavelength of the illuminating light.

- The two beams interfere constructively i.e. a bright fringe is formed when dS is an integer multiple of \( 2\pi \), that is:
  \[ dS = k \times 2\pi \quad \text{thus,} \quad dL = k \times \lambda \]

- The two beams interfere destructively, i.e. a dark fringe is formed when dS is an uneven multiple of \( \pi \), that is:
  \[ dS = (2k+1)\pi \quad \text{thus,} \quad dL = (2k+1) \times \frac{\lambda}{2} \]
The basic requirement for two light rays of equal amplitude to interfere at a point where they intersect is that the phase relation between the rays at this point be constant during the time observation. This results in a condition concerning the spectral width of the emitted light (time coherence) and a second condition concerning the greatest allowable angle of aperture of an extended light source (spatial coherence). A laser light is highly monochromatic and coherent and therefore very suitable for use in interferometry.

4.4.2 Mach-Zehnder interferometer (M.Z.I.) model

The arrangement of the M.Z.I. we built is depicted in fig.16. A He-Ne (632.8 nm / 5mW) laser L is used as a light source. The essential components are the plane fully reflecting mirrors M1 and M2, and the plane semi-reflecting mirrors (beam splitters) BS1 and BS2 which are arranged to form a rectangle. The beam splitter BS1 separates the coherent light from the laser into two beams:

- the test beam which investigates the inhomogeneous distribution of refractive index surrounding the heated bubble.

- the reference beam which remains undisturbed.

After being rejoined behind BS2, the two beams can interfere and a certain interference fringes pattern appears on the screen.

The test section is brought into the path of the two beams. Thereby, when the four mirrors are exactly aligned in the "infinite fringe width" position, that is, without temperature variation the two beams travelling the same OPL, no fringes appear. Heating the bubble we create around it an inhomogeneous refractive index field yielding a certain phase alteration of the object beam which leads to the formation of interference fringes on the screen.
4.5 Experimental results

4.5.1 Observations

Fig. 17 shows the patterns observed on the screen applying the M.Z.I. previously described. The production of a "proper" band system requires an illuminating beam less or equal than the disturbed area. As this one is assumed to be very small (1 or 2 mm), because of the assumed low temperature variation (10 or 20°C) in the direct vicinity of the bubble, we directly use the laser beam (i.e. without expansion) whose diameter is about 1 mm.

(a) switch off

The two beams are adjusted to overlap. No fringes appear, only a luminous spot is observed.

(b) switch on

The test beam spreads, two fringe patterns appear:
1. interference between tb and rb
2. interference between the tb rays

(a) The supply (heating power) is switched off:

The M.Z.I. is adjusted so that only one luminous spot with a diameter of about 4 mm (i.e. magnification of 4) appears on the screen, that is, the test beam (tb) and the reference beam (rb) overlap without production of fringes.

The bubble is then set near the tb so that the diffraction phenomenon is just avoid.

(b) The supply is switched on:

Three effects occur:

1. The tb is slightly deflected from its original path, pointing out the existence of a refractive index gradient normal to the direction of the incident light.

2. The luminous spot corresponding to the tb spreads away from that corresponding to the rb. However, the spreading is limited since it has been evaluated to 7 mm on the screen from the initial situation. Then, according to the magnification we can state that the disturbance at the vicinity of the bubble is at maximum of about 2 mm.
3. Two fringe patterns appear on the screen:

(1) a thick (ca.2mm) dark fringe in the overlap area of tb and rb.

(2) a band system in the spread out area of tb.

4.5.2 Interpretation

Blocking the tb: (1) and (2) disappear, only the luminous point corresponding to the rb is still observed.

Blocking the rb: (1) disappears but (2) remains visible.

Consequently, both (1) and (2) are due to the temperature gradient: (1) due to interference of two beams, (2) due to one beam (the tb) being partly disturbed.

a. Pattern (1) occurs because of the interference between tb and rb, thus, it may be considered as a visualization of the temperature effect.

b. Pattern (2) may be considered as the result of the interference between an undisturbed part (i.e. which remains outside the disturbance) and a disturbed part of the tb. Indeed, consider $d_{TB}L$ the variation in the OPL (optical path length) $L(T)$ as a result of a change in temperature.

$$d_{TB}L = d_{TB}n_{water} \times l$$

where $d_{TB}n_{water}$ = variation in refractive index, $l$ = length of the disturbed region (1 or 2 mm).

This OPLD (optical path length difference) is responsible for the following phase lag:

$$d_{TB}S = \frac{2\pi \times d_{TB}L}{\Lambda}$$

For instance, for a phase lag of $D$ with $l = 2$ mm, $d_{TB}n_{water}$ should be equal to $1.58 \times 10^{-4}$. With help of the table $n_{water}$ vs. $T$ given in appendix 8, such a difference is obtained for a temperature variation of about $2^\circ C$. As the maximum temperature variations to be expected (10 or $20^\circ C$) in the surrounding of the heated bubble is at least ten times higher, much larger phase lags have to be expected. Finally, phase lags of $K \pi$ with $k$ increasing when approaching the hot bubble, occur. For $k=odd$: darkness; for $k=even$: light. As a result, the fringe pattern (2).
4.6 Conclusions and future research:

4.6.1 Conclusions

It was found experimentally, that M.Z. interferometry is a promising technique of temperature gradients visualization. With a fringes pattern it directly "images" the refractive index field surrounding the heated bubble. As a further step, a quantitative analysis of the obtained fringe pattern has to be performed to quantitatively map temperature variations.

4.6.2 Future research

Future research must primarily include the following experimental steps:

- An enlargement of the fringe pattern is required, thoughts being directed towards the strategy of adjusting a lens and a screen behind the plane where the fringe pattern appear can be used.

- Values of temperatures around the bubble have to be obtained, for instance, by means of a very thin thermocouple. This measurement providing a first "idea" of temperature variations could lead to the statement of a required relationship between refractive index and temperature. Several relations (linear, quadratic, cubic) are available in the literature [18-19].

A next step in future research lies in surveying following (also theoretical) points:

1 The nature of the temperature field (i.e. two or three dimensions) taking into account:
   * the influence of the bubble geometry [12]
   * the importance of the beam deflection [12]

2 The meaning of the fringes:
   * are they curves of constant index of refraction ?
   * is the fringe spacing a function of the density dependence of the index of refraction, the wavelength and the optical path length in the disturbed area ? (i.e. for instance, can the spacing of dark bands be ascertained by \( dn = (k+1/2)*A \) ?)

3 The phase lag caused by the passage of the beam trough the temperature disturbance:

If the disturbance is two-dimensional such that \( n=n(x,y) \) (z being the axis of the light propagation), the OPL is \( n(x,y)*1 \). In a free-field where the index of refraction has the constant value \( n_0 \), the OPL is \( n_0*1 \). Hence when the free-field is used as a reference, the OPLD is given by

\[
[n_0 - n(x,y)]*1.
\]

Hence the phase difference is given by

\[
dS(x,y) = 2\pi * \frac{[n_0 - n(x,y)]*1}{\lambda}.
\]
We see that if \( n_0 \) is known and \( dS(x,y) \) could be determined, it would be possible to measure the refractive index at the point \((x,y)\) according to the relation

\[
n(x,y) = n_0 - \frac{dS(x,y)}{2\pi} \times \frac{A}{l}
\]

Hence, from a relationship between temperature and refractive index, the distribution of the temperature could be determined.
References .......................................................... XXVI

APPENDIX 1 FLOW PATTERN CONFIGURATIONS ...................... XXVIII

APPENDIX 2 PHOTOGRAPHS OF THE MECHANICAL DEPARTMENT
  EQUIPMENT .................................................... XXIX

APPENDIX 3 THE LAWS OF GEOMETRICAL OPTICS .................. XXXII

APPENDIX 4 TOTAL INTERNAL REFLECTION .......................... XXXIII

APPENDIX 5 GAUSSIAN OPTICS .................................... XXXIV

APPENDIX 6 EXPERIMENTAL RESULTS ............................... XXXVII

APPENDIX 7 REFRACTION AT A PLANE SURFACE .................... XXXVIII

APPENDIX 8 INDEX OF REFRACTION OF WATER VS. TEMPERATURE .. XXXIX

APPENDIX 9 PHOTOGRAPHS OF THE OPTICAL SET UP AND OF BUBBLE
  SHAPE VISUALIZATION RESULTS ............................... XL
References


[8] André Moussa and Paul Ponsonnet Cours de physique I

[9] H. Berr Interferometry and holography in nucleate boiling


[15] Norman F. Barnes and S. Lawrence Bellinger
Schlieren and shadowgraph equipment for air flow analysis
Journal of the optical society of America
Vol. 35, no8 August 1945

[16] Edward B. Temple
Quantitative measurement of gas density by means of light interference in a schlieren system
Journal of the optical society of America
Vol. 47, no1 January 1957

[17] Daniel Malacara
Methods of experimental physics, Vol 26

[18] H. Fiedler an K. Nottmeyer
Schlieren photography of water flow
Experiments in fluids 3, 145-151 (1985)

Schlieren interferometry. An optical method for determining temperature and velocity distributions in liquids.
Applied optics /Italy/965/Vol 4/ no7
Configurations simples

1 - Gouttes
2 - Bulles
3 - Film
4 - Poches et Bouchons

Configurations binaires

5 - Bulles + Gouttes
6 - Gouttes + Bulles
7 - Gouttes + Film
8 - Gouttes + Bouchons
9 - Bulles + Film
10 - Bulles + Bouchons
11 - Film + Bouchons

Configurations ternaires

12 - Bulles + Film + Bouchons
13 - Gouttes + Film + Bouchons
14 - Gouttes + Bulles + Bouchons
15 - Gouttes + Bulles + Film

Configurations quaternaires

16 - Gouttes + Bulles + Film + Bouchons
General view of the mechanical department building.
Ascendant evaporator tube
Rifled tube

Tube with sensors
APPENDIX 3  THE LAWS OF GEOMETRICAL OPTICS

The three laws of geometrical optics are usually stated in terms of light rays.

1. The law of rectilinear propagation:

Light rays, in homogeneous media propagate in straight lines. This basis of geometrical optics is verified only if all the considered dimensions of optical equipments are larger than the wavelength. The latter being inferior to the micron, this approximation is broadly available in current set ups.

2. The law of reflection:

At an interface between two different homogeneous, isotropic optical media, an incident ray is (partially) reflected, and the reflected ray is in the plane of incidence (the plane determined by the incident ray and the normal to the surface). The angle it makes with the normal (the angle of reflection $i_r$) equals the angle made by the incident ray with the normal (the angle of incidence $i_i$).

3. The law of refraction:

At an interface between dielectric media, there is also a refracted ray in the second medium, being in the plane of incidence, making an angle $i_t$ with the normal and obeying Snell’s law:

$$n_1 \sin(i_i) = n_2 \sin(i_t)$$

where $n_1$ and $n_2$ are the indices of refraction of the two media (if $v_1$ and $v_2$ are the velocities of propagation in the two media: $n_1 = \frac{c}{v_1}$, $n_2 = \frac{c}{v_2}$, $c$ is the velocity of light in vacuum. $v_1$ $v_2$
n2 < n1  total internal reflection

*Fig A4.1: Total internal reflection*

when n2 < n1, one has the well known phenomenon of total internal reflection for angles of incidence greater than the critical angle $i_c$ corresponding to a refracted angle $i_r$ matched with 90°.

For an interface:
- glass (n1=1.4) / air (n2=1)
  $$i_c = 45^\circ 35'$$
- glass (n1=1.4) / water (n2=1.33)
  $$i_c = 71^\circ 48'$$
This branch of geometrical optics assumes that all the rays are close to the optical axis. Such rays are known as paraxial rays, and one speaks of the region immediately surrounding the axis as the paraxial region. That is to say, within the paraxial region the angles may be equated to their sines or tangents. Gaussian (paraxial) optics gives an extremely useful approximation to explain the image formation theory in many applications.

1. Refraction at a spherical surface:

\[
\frac{n - n'}{SA} = \frac{n - n'}{SA'} \quad \text{(algebraic relation)}
\]

In terms of ray optics, the spherical refracting surface forms a point image of a point object. Moreover, for any plane object perpendicular to the axis a geometrically similar plane image is form perpendicular to the axis. There is said to be a colinear relationship between objects and images in the left- and right-hand spaces; the image is said to be conjugate to the object (they belong to conjugate planes). There is a certain transverse magnification associated with each pair of conjugate planes. This transverse magnification is denoted by \( M \) and given by:

\[
M = \frac{A'B'}{AB} = \frac{CA'}{CA} = \frac{n * SA'}{n' * SA} \quad \text{(algebraic relation)}
\]
2. **Image formation of thin lenses**

A thin lens consists of two refracting surfaces so that the separation between them may be neglected with respect to the object and image distances. The refractive index of the lens will be \( n' \), that of the surrounding medium will be \( n \).

### 2.1 Lens Maker's equation:

- \( A \) : Object point
- \( A' \) : Image point
- \( OF' \) : Focal length

#### Lens Maker's equation:

\[
\frac{1}{OA'} = \frac{1}{OA} = \frac{(n' - n)}{OC1} \cdot \frac{1}{OC2}
\]

\[
\frac{1}{OA'} - \frac{1}{OA} = \frac{1}{OF'} \quad \text{(algebraic relation)}
\]

*Fig. A5.2: Lens Maker's equation*

It is obtained by applying the formula of the image formation at a spherical refracting surface at each surface of the lens, and, assuming \( S1 = S2 = 0 \).

### 2.2 Determination of image position and size for a thin lens:

#### Newton formula:

\[
FA + FA' = -OF' \quad \text{(: algebraic)}
\]

*Fig. A5.3: Image position and size*
The image of an off-axis point A can be located by the intersection of any two of the following three rays:
- A ray parallel to the axis that is refracted through F'.
- A ray through F that is refracted parallel to the axis.
- A ray through the center of the lens that remain undeviated and undisplaced.

From the figure, one can obtain the Newton formula:

$$FA \times F'A' = -OF'^2$$
APPENDIX 6  EXPERIMENTAL RESULTS

Procedure of the experiment:

- a lens of f=40 mm is used.
- 11 location is fixed with respect to that of the bubble.
- 12 is adjusted so that a sharp image is observed on the screen. It will be called $l_{2\exp}$ and will be compared to $l_{2\th}$ given by the Lens Maker's formula, as a result $d_{12}$ is calculated.
- the experimental magnification $M_{\exp}$ measured on the screen is compared with the theoretical one $M_{\th}$ given by the ratio $l_{2\exp}/11$.

Table of measurements (distances given in mm):

<table>
<thead>
<tr>
<th>11</th>
<th>40.5</th>
<th>45</th>
<th>50</th>
<th>55</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l_{2\exp}$</td>
<td>454</td>
<td>243</td>
<td>162</td>
<td>132</td>
<td>111</td>
</tr>
<tr>
<td>$l_{2\th}$</td>
<td>3240</td>
<td>360</td>
<td>200</td>
<td>147</td>
<td>120</td>
</tr>
<tr>
<td>$d_{12}$</td>
<td>2786</td>
<td>117</td>
<td>68</td>
<td>15</td>
<td>9</td>
</tr>
<tr>
<td>$M_{\exp}$</td>
<td>10</td>
<td>5.2</td>
<td>3.2</td>
<td>2.3</td>
<td>1.4</td>
</tr>
<tr>
<td>$M_{\th}$</td>
<td>11.2</td>
<td>5.4</td>
<td>3.2</td>
<td>2.3</td>
<td>1.8</td>
</tr>
</tbody>
</table>
Consider a plane surface between two transparent media. We want to calculate the image location. Consider the ray AH, according to the Gaussian approximation the angle $i$ is small. Then, the angle $i'$ is also small.

Hence, $\sin(i) = \tan(i) = i$ and $\sin(i') = \tan(i') = i'$.

\[
SH = SA' * i' = SA * i
\]

\[
SA = i' \quad \quad \quad \quad \quad \quad SA' = i
\]

\[
n * \sin(i) = n' * \sin(i')
\]

Hence, $\frac{SA}{SA'} = \frac{n}{n'}$ (algebraic relation)

\[
SA = \frac{SA'}{n'} \quad \quad \quad \quad \quad \quad (algebraic relation)
\]

\[
SA = \frac{SA'}{n} \quad \quad \quad \quad \quad \quad (algebraic relation)
\]

\[
SA = \frac{SA'}{n} \quad \quad \quad \quad \quad \quad (algebraic relation)
\]
The molar refraction, \( R \), is defined as:
\[
R = \left( n^2 - 1 \right) \left( \frac{M}{d} \right)
\]
where \( n \) = refractive index; \( M \) = molecular weight; \( d \) = density in grams per cm\(^3\); and \( (M/d) \) is the volume occupied by 1 gram molecular weight of the compound. The units of \( R \) will then be cm\(^3\)g\(^{-1}\).

For a very large number of compounds \( R \) is approximately additive for the bonds present in the molecule. Using \( R \) based on \( n \) (sodium light), the following atomic, group and structural contributions to \( R \) are based on Vogel's extensive modern measurements published in the Journal of the Chemical Society, 1945.

### ABSOLUTE INDEX FOR PURE WATER FOR SODIUM LIGHT

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Index</th>
<th>Temperature</th>
<th>Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>15°C</td>
<td>1.33377</td>
<td>60°C</td>
<td>1.3754</td>
</tr>
<tr>
<td>20</td>
<td>1.33555</td>
<td>65</td>
<td>1.3852</td>
</tr>
<tr>
<td>25</td>
<td>1.33287</td>
<td>70</td>
<td>1.3757</td>
</tr>
<tr>
<td>30</td>
<td>1.33227</td>
<td>75</td>
<td>1.3735</td>
</tr>
<tr>
<td>35</td>
<td>1.33117</td>
<td>80</td>
<td>1.3723</td>
</tr>
<tr>
<td>40</td>
<td>1.33087</td>
<td>85</td>
<td>1.3728</td>
</tr>
<tr>
<td>45</td>
<td>1.33011</td>
<td>90</td>
<td>1.3736</td>
</tr>
<tr>
<td>50</td>
<td>1.32930</td>
<td>95</td>
<td>1.3739</td>
</tr>
<tr>
<td>55</td>
<td>1.32846</td>
<td>100</td>
<td>1.3719</td>
</tr>
</tbody>
</table>

### INDEX OF REFRACTION OF GLASS

<table>
<thead>
<tr>
<th>Variety</th>
<th>Wave length in microns</th>
<th>( n_0 )</th>
<th>( n_1 )</th>
<th>( n_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zine crowns</td>
<td>0.350</td>
<td>1.447</td>
<td>1.449</td>
<td>1.449</td>
</tr>
<tr>
<td>Higher dispersion crowns</td>
<td>0.350</td>
<td>1.447</td>
<td>1.449</td>
<td>1.449</td>
</tr>
<tr>
<td>Light flint</td>
<td>0.350</td>
<td>1.447</td>
<td>1.449</td>
<td>1.449</td>
</tr>
<tr>
<td>Heavy flint</td>
<td>0.350</td>
<td>1.447</td>
<td>1.449</td>
<td>1.449</td>
</tr>
</tbody>
</table>

### INDEX OF REFRACTION OF ROCK SALT, SYLVINE, CALCITE, FLUORITE AND QUARTZ

<table>
<thead>
<tr>
<th>Wave length</th>
<th>Rock salt</th>
<th>Sylvine, KCl</th>
<th>Fluorite</th>
<th>Calcite, ordinary ray</th>
<th>Calcite, extraordinary ray</th>
<th>Quartz, ordinary ray</th>
<th>Quartz, extraordinary ray</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.28</td>
<td>1.560</td>
<td>1.617</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
</tr>
<tr>
<td>0.30</td>
<td>1.540</td>
<td>1.617</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
</tr>
<tr>
<td>0.31</td>
<td>1.520</td>
<td>1.617</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
</tr>
<tr>
<td>0.34</td>
<td>1.500</td>
<td>1.617</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
</tr>
<tr>
<td>0.40</td>
<td>1.480</td>
<td>1.617</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
</tr>
<tr>
<td>0.45</td>
<td>1.460</td>
<td>1.617</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
</tr>
<tr>
<td>0.50</td>
<td>1.440</td>
<td>1.617</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
</tr>
<tr>
<td>0.55</td>
<td>1.420</td>
<td>1.617</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
</tr>
<tr>
<td>0.60</td>
<td>1.400</td>
<td>1.617</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
</tr>
<tr>
<td>0.65</td>
<td>1.380</td>
<td>1.617</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
</tr>
<tr>
<td>0.70</td>
<td>1.360</td>
<td>1.617</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
</tr>
<tr>
<td>0.75</td>
<td>1.340</td>
<td>1.617</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
</tr>
<tr>
<td>0.80</td>
<td>1.320</td>
<td>1.617</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
</tr>
<tr>
<td>0.85</td>
<td>1.300</td>
<td>1.617</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
</tr>
<tr>
<td>0.90</td>
<td>1.280</td>
<td>1.617</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
</tr>
<tr>
<td>0.95</td>
<td>1.260</td>
<td>1.617</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
</tr>
<tr>
<td>1.00</td>
<td>1.240</td>
<td>1.617</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
<td>1.567</td>
</tr>
</tbody>
</table>

**Example:** For \( \text{C}_2\text{H}_5\text{COOH} \): \( R_{\text{obs}} = 3(2.591) + 4(1.028) = 11.893 \), or 
\[ R_{\text{obs}} = 3.283 \]

For \( \text{C}_2\text{H}_5\text{NHCH} \): \( R_{\text{obs}} = 25.483 + 4.550 = 30.033 \), or 
\[ R_{\text{obs}} = 31.582 \]
Test section with bubble
General views of the final set up for the three-dimensional bubble shape visualization
Sharp three-dimensional bubble shape visualization