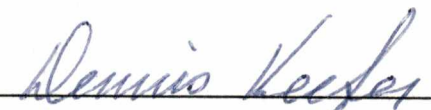


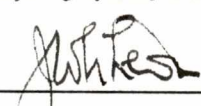
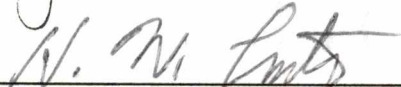
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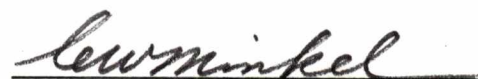
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HOLOGRAPHIC INTERFEROMETRY OF A CYLINDRICAL TUBE

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Heung Cheon Paik

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An experimental and analytical study has been conducted to determine whether holographic interferometry methods can be used to determine the index of refraction of an object contained within a cylindrical containment tube.

Numerical simulation and an experiment on the cylindrical tube are presented and results are reconstructed using Abel inversion with cubic spline fitting. Numerical Simulation showed that there exists about 4 % error at the edge of the hologram if the gases are assumed to be non-refractive.

Analysis of the numerical simulation and the experimental data are presented and reconstructions are compared to the expected values. Reconstructions result in less than 1 % error for the numerical simulation and less than 5 % error for the experiment. The results indicate that the technique can be applied to a phase object contained in a cylindrical tube if an imaging system is used, and the index of refraction distribution can be reconstructed with less than 5 % error.

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CHAPTER I

INTRODUCTION

Holographic Interferometry has been applied to temperature measurement of a phase object such as a flame [1]¹ or a wind tunnel [2]. When the phase object is protected by a cylindrical tube, an object beam that carries phase information from the object can be affected by this enclosure and interference of the object beam and reference beam, which is related by the phase difference is also influenced. Reuss [3] at the General Motors Laboratory has used double exposure holographic interferometry on a acrylic tube and reported reconstruction errors less than 1 %. However, that experiment used no imaging system, which is necessary in many situations in order to direct the object beam onto the hologram plate. When an imaging system is used, the object beam must pass through many optical components, and the resulting refraction influences the interference of the object and the reference beam on the hologram. Therefore, this study aims to investigate the effects of an imaging system combined with a cylindrical tube which contains the phase object on holographic interferometry.

¹Numbers in brackets refer to similarly numbered references in the Bibliography.

The study took the following approaches to investigate the problem. First, a holographic interferometry experiment was performed with homogeneous gases having a known index of refraction in a cylindrical tube. Next, a numerical simulation of the experiment was performed using a ray tracing program, OPTEC II, and the reconstructed results were compared to the known index of refraction difference values.

Several questions relating to refraction of light-ray paths, are raised when interferometrically probing a phase object surrounded by a cylindrical tube. The first question concerns how to determine the symmetry axis of the tube to correct for ray refraction by the tube. The problem is particular to this kind of investigation where the object of study is confined by a tube. The second question involves the difficulties of probing interferometrically adjacent to the inside of the tube wall. The cylindrical geometry of the tube is such that every ray undergoes refraction except the ray that passes through the center. The refraction becomes severe as the ray probes the tube close to the wall. The third question concerns the errors which may result from the effect that the tube has on the interferogram quality. The refracted rays are diverging after passing through the tube. Thus, the rays require some kind of focusing device to interfere on the hologram.

The first problem concerns mainly the alignment. Using a tube holder and an optical system that is sophisticated enough to allow adequate alignment, and is mounted on an optical table, the error can be reduced

significantly. For uncorrected errors, which appear on the hologram, fringe spacing analysis can be used to find the center of the interference pattern.

The second problem requires an accurate optical ray tracing of the tube and the related system. Numerical simulation of the tube and the related system was performed using an optical ray tracing program called OPTEC II. OPTEC II is available to the APRG/CLA group at UTSI and performs ray tracing and optical design problems based on paraxial and real ray tracing.

The third problem can be investigated in several ways. The main concern is the imaging of the rays on the hologram plane. An optical system that directed the refracted diverging object beam onto the hologram plane was designed with the aid of the OPTEC II.

The assumption of non-refractive medium that has been used in previous work is investigated and discussed in Chapters III and IV. [4] The assumption is based on the fact that the index of refraction of the compared media differ only in small amounts from each other. Therefore, the object ray path is considered to be the same throughout the system regardless of the medium chosen. However, with a different index of refraction the ray paths are not exactly the same. This difference can be considered small, but as the beam refracts through many surfaces, the beam path can be affected and the result may be different.

Although the complete theoretical model of holography based on diffraction phenomena is beyond the scope of this work, a simple model of holographic systems is discussed in Chapter II. Emphasis has been placed on holographic interferometry in the latter part of Chapter II.

In Chapter III the imaging system designed for the cylindrical tube is discussed. Also, the relationship between the y coordinate of the hologram and the radial coordinate of the tube is described.

The experiments were conducted with a glass tube which has a 30.2 mm i.d. and 38.4 mm o.d. The index of refraction of the tube is not known accurately. In numerical simulation of the experiment, the index of refraction of the tube is assumed to be 1.5 which is a typical value of glass material. The errors caused by this approximation are discussed in Chapter VI. The tube was filled with room air during the first holographic exposure and carbon dioxide (CO_2) or helium (He) during the second exposure. The gases are homogeneous at room temperature and pressure. The gases contained by the tube during both exposures are regarded as non-refracting and have a known refractive index.

Interferograms resulting from these conditions were determined both from numerical simulations and laboratory experiments. The numerical simulations were obtained using the OPTEC II ray tracing program and masscomp computer to provide a comparison with which the accuracy of the laboratory experiments could be assessed. The laboratory experiments

were conducted to demonstrate the methodology for interferometric probing of a cylindrical tube. In Chapter IV the numerical simulation of the experiment is discussed. In Chapter V the experiment and reconstruction of the index of refraction change is discussed.

In Chapter VI the reconstructions from the experiment are compared to the numerical reconstructions. The conclusion of the study is drawn from the comparison and other related investigations. This will be presented along with the discussion of the possibility of using holographic interferometry for the investigation of a plasma confined to a cylindrical tube.

CHAPTER II

BACKGROUND

Holography

Holography was originally proposed by Gabor [5] in 1948 to improve the resolution of the electron microscope. Although it was first concerned with electron optics, later it made great contributions in applied optics with the aid of lasers which supply a coherent light source.

In the early 1960's Leith and Upatnieks [6] established holography as a method of obtaining excellent three-dimensional images of objects. Following this, there was much interest in holography and its applications to this and to other fields.

When an object is illuminated by a coherent light source, the light is reflected or refracted. Holography is an interference method of recording these light waves. The refracted waves from the object are caused to interfere with a phase-related reference wave. If the waves are highly coherent, the relative phase between object and reference waves remains constant in time producing an observable effect on the intensity distribution of the resulting interference pattern. The photographic record of this pattern, the hologram, contains sufficient information about both the phase and

amplitude of the refracted waves to permit their reconstruction. Wavefront reconstruction takes place when the hologram is illuminated with the reference wave. The reconstruction is the unlocking process of the hologram to display the object light intensity with both amplitude and phase information.

Preservation of relative phase information is the unique characteristic of the holographic process. The method of holography applies to all waves, for example, electron waves, X rays, microwaves, acoustic waves and seismic waves, providing the waves are coherent enough to form the required interference patterns.

In the mathematical treatment that follows, a simple holographic system in which light from a laser is divided into two beams is considered; one beam is termed the reference beam and is reflected from a mirror onto a hologram, the other beam is called the object beam and is reflected (or transmitted) from an object onto the hologram plane.

Since only the electric field interacts with the recording medium, only the electric field component is considered in the treatment.

The electric field can be represented in the form

$$\vec{E}(\vec{r}, t) = \frac{1}{2}(\vec{A}e^{-i\omega t} + \vec{A}^*e^{i\omega t}) \quad (2.1)$$

The intensity is given by

$$I = \langle E^2 \rangle \quad (2.2)$$

where $\langle \rangle$ denotes a time average of the quantity inside.

Since in the holographic process, there are object and reference beams,
let

$$\vec{E} = \vec{O} + \vec{R} \quad (2.3)$$

where

$$\begin{aligned} \vec{O}(\vec{r}, t) &= \frac{1}{2} (\vec{O}(\vec{r}) e^{-i\omega t} + \vec{O}^*(\vec{r}) e^{i\omega t}) \\ \vec{R}(\vec{r}, t) &= \frac{1}{2} (\vec{R}(\vec{r}) e^{-i\omega t} + \vec{R}^*(\vec{r}) e^{i\omega t}) \\ I &= O^2 + R^2 + 2 \langle \vec{O} \cdot \vec{R} \rangle. \end{aligned} \quad (2.4)$$

The interference is described by $\langle \vec{O} \cdot \vec{R} \rangle$ and this term contains information about phase and amplitude.

Now consider the interaction of two beams,

$$\begin{aligned} \vec{O} \cdot \vec{R} &= \frac{1}{4} (\vec{O} e^{-i\omega t} + \vec{O}^* e^{i\omega t}) \cdot (\vec{R} e^{-i\omega t} + \vec{R}^* e^{i\omega t}) \\ \vec{O} \cdot \vec{R} &= \frac{1}{4} (\vec{O} \cdot \vec{R} e^{-2i\omega t} + \vec{O}^* \cdot \vec{R}^* e^{2i\omega t} + \vec{O} \cdot \vec{R}^* + \vec{O}^* \cdot \vec{R}) \end{aligned} \quad (2.5)$$

Therefore,

$$2 \langle \vec{O} \cdot \vec{R} \rangle = \frac{1}{2} (\vec{O} \cdot \vec{R}^* + \vec{O}^* \cdot \vec{R})$$

If

$$\vec{O}(\vec{r}) = o e^{i\delta_1 \iota}, \quad \vec{R}(\vec{r}) = r e^{i\delta_2 \iota}$$

then

$$2\langle \vec{O} \cdot \vec{R} \rangle = \frac{1}{2} (ore^{i(\delta_1 - \delta_2)} + ore^{i(\delta_2 - \delta_1)})$$

$$2\langle \vec{O} \cdot \vec{R} \rangle = or \cos(\delta_1 - \delta_2) \quad (2.6)$$

If the light is coherent, the interference occurs and the complete interference equation becomes

$$I = \langle E^2 \rangle = I_R + I_O + \frac{1}{2} \vec{O} \cdot \vec{R}^* + \frac{1}{2} \vec{O}^* \cdot \vec{R} \quad (2.7)$$

$$I = I_R + I_O + or \cos(\delta_1 - \delta_2)$$

where

$$I_R = \langle R^2 \rangle$$

$$I_O = \langle O^2 \rangle.$$

To describe the reconstruction, the amplitude transmittance of the hologram is assumed to be proportional to intensity.

$$T \approx I$$

If the reference beam is used for reconstruction, then

$$\vec{R}T \approx \vec{R}I = \vec{R}(I_R + I_O) + \frac{1}{2} \vec{R}(\vec{R} \cdot \vec{O}^* + \vec{R}^* \cdot \vec{O}) \quad (2.8)$$

$$or \cos(\delta_2)I = or \cos(\delta_2)(I_R + I_O) + or^2 \cos(2\delta_2 - \delta_1) + or^2 \cos(\delta_1).$$

This transmitted light contains an undiffracted zero order wave and two first order diffracted waves. The third term in the equation, $or^2 \cos(\delta_1)$, is a reconstruction of the object wave, and it is diverging from the virtual image of the object. The second term is the conjugate image which is found on the opposite side of the hologram. The first term is the undiffracted original beam or the reference beam.

Holographical Interferometry

From this perspective, the holographic interferometry process is considered. When a hologram storing more than one wave is illuminated with coherent light, the reconstructed waves can interfere with one another. A wave recorded in a hologram is effectively stored for future reconstruction and use. Holographic interferometry is concerned with the formation and interpretation of the fringe patterns which appear when a wave, generated at some earlier time and stored in a hologram, is later reconstructed and caused to interfere with a comparison wave. It is the storage or time-delay aspect which gives the holographic method a unique advantage over conventional optical interferometry.

In the case of a cylindrical gas tube where gases are changed inside to create phase differences, two holograms are taken on the same plate. The holograms interfere with each other to create an interferogram representing the gas change. The interferogram is caused by the optical path difference between the two exposures.

Since the optical components used in the process are the same for both exposures, imperfections in the components do not contribute to errors because they are subtracted from each other. This is another advantage of holographic interferometry since it permits use of poorer quality equipment

to achieve the same results.

If the hologram constructed in the first exposure is developed without being moved from the original position where it was exposed, continuous laser illumination of the phase object through the developed hologram can construct real time fringe movements. Thus any displacements of the object or change in optical path length (OPL) can be viewed continuously as a developing fringe pattern.

With the assumption of a non-refractive medium inside the tube, the basic equation for holographic interferometry can be written. The origin of a system of cartesian coordinates is located at the center of the tube. The tube has a radius of r and the medium inside the tube has a known constant index of refraction. This is shown in Figure 2.1². With these conditions the information of the relative phase delay, i.e., the change in OPL is extracted. The reference gas index of refraction will be denoted by $n_1(r)$ and that of the comparison gas by $n_2(r)$. Let us define $f(x, y, z)$ by ;

$$f(x, y, z) = n_1(x, y, z) - n_2(x, y, z). \quad (2.9)$$

Let i indicate one of the possible paths through the tube, and let l_i measure the distance along the path.

²Figures are all in the Appendix.

The relative phase delay F_i is then given by the line integral along the path i :

$$F_i = \int_i dl_i f(x, y, z). \quad (2.10)$$

This is the basic equation of holographic interferometry. For reconstruction purposes, the equation can be inverted using various methods. [7], [8], [9] In the present investigation, the reconstruction algorithm developed by Limbaugh et al. using the Abel inversion technique and cubic spline fitting was used. [10]

The evaluation of the line integral (2.10) can be viewed in the following way. If the line integral is rewritten in a plane where z is constant, it becomes

$$F_i = \int_i dl_i (n_1(x, y) - n_2(x, y)). \quad (2.11)$$

This phase delay can also be written as a function of the tube radial coordinate.

$$F_i = \int_i dl_i (n_1(r) - n_2(r)). \quad (2.12)$$

Also

$$m_i \lambda = l_i \Delta n$$

where m_i is the fringe shift. Since $n_1(r) - n_2(r)$ is not an function of l_i ,

$$m_i \lambda = l_i (n_1(r) - n_2(r)), \quad (2.13)$$

$$m_i = \frac{l_i(n_1(r) - n_2(r))}{\lambda}. \quad (2.14)$$

Therefore the magnitude of the fringe shift at any one point in the x-y plane is directly proportional to the change in the OPL of the ray that passes through that point in the tube. Again, the assumption is that the rays travel the exact same path i , regardless of which gas is used.

CHAPTER III

IMAGING AND INTERPRETATION OF THE HOLOGRAM

Interferometric Probing of a Tube

In double exposure holographic interferometry, the hologram is first exposed to an object beam that carries the phase information of the object and to a reference beam, and the interference is recorded. The second exposure records the interference between the object and reference beams, but the object beam contains different phase information from the first exposure. When the hologram is developed and illuminated by the reference beam, the reconstructed field shows fringes that are due to interference between the two object beams. This pattern contains the information needed to reconstruct the change in the index of refraction that occurred within the tube between the two exposures.

Information about the index of refraction change is carried by the object beam. However, the object beam path is related to the geometry of the cylindrical tube. As the object beam passes through the tube, refraction occurs at each of the tube surfaces. There are four surfaces that the object beam must pass through in the tube and at each surface the beam is refracted. As a consequence, the beam paths are affected and the rays

must be traced individually. The tube diagram is shown in Figure 3.1 along with the refractions at the surfaces.

This refraction occurs because the angle between the ray exiting the tube and the x -axis increases as the rays get close to the tube wall. The refracted diverging rays present two problems for imaging. First, the diverging beam must be properly directed to the hologram since the hologram size is much smaller than the object beam size at the hologram plane. Second, the maximum radial position which can be probed is limited by the physical size formed by either the hologram or the imaging lens, whichever is smaller. Therefore, it is necessary to provide a system with an aperture as large as possible in order to probe as close to the tube wall as possible.

For the HC300 holographic camera, the width of hologram is about 30 mm which is smaller than the o.d. of the tube. Thus some consideration must be given to the aperture of the imaging lens to maximize the radial position that can be probed, and the lens must be cylindrical in order to preserve the cylindrical geometry of the tube.

The aperture size of a lens is limited by practical considerations such as cost. To image a diverging refracted beam from a tube of 38.4 mm o.d. and 4.1 mm wall thickness onto a 30 mm film plate about 100 mm away, a cylindrical lens of at least 70 mm minimum aperture and focal length on the order of 100 mm must be placed in front of the tube facing the hologram. Lenses of this type are commercially available and were used in

combination in the experiment.

Using the OPTEC II ray tracing software, a system was designed that provides probing to within 0.7 mm of the tube wall and at the same time imaging such that a 30 mm hologram can effectively record the interference containing phase information to within 2.7 mm of the tube wall, from a tube of 38.4 mm o.d. The system includes 3 cylindrical plano-convex lenses. The first lens has a width of 50 mm and a focal length of 150 mm and is placed 27 mm before the tube so that it works as a light collecting device for the tube. The second lens, of width 50 mm and 100 mm focal length, is placed 31 mm after the tube so that it effectively collects the refracted beam. The third lens, of width 50 mm and 70 mm focal length, is placed 100 mm from the hologram and 105 mm from the second lens and directs the object beam onto a hologram. All the components, including the tube, are mounted on rigid holders and an x - y mount. A schematic of the design is shown in Figure 3.2.

The real image reconstruction of the hologram was performed by illuminating the hologram with the same laser beam which was the reference beam used to record the hologram. To view the real image reconstruction of the hologram, a large white screen was placed behind the HC300 hologram camera.

Interference Interpretation

Any radial slice of the tube contains a medium that has a two-dimensional index of refraction distribution. When recorded by double exposure holography on a hologram, this axisymmetric phase object in a cylindrical tube is in the form of single 1-D interferogram observed in a plane normal to the object beam. The radial distribution of the index of refraction of the phase object implies the reconstruction integral which is given by the equation (2.10).

In order to make a reconstruction, first the fringes were determined by assigning numerical values to the maximum intensity fringes, the bright fringes. The values are determined by the optical path difference (OPD) of the rays as described in equation (2.14). Then a correspondence is established between the geometrical path along which the object is probed by each ray and the position at which the ray is met in the interferogram. When a phase object is confined by a tube, as illustrated in Figure 3.2, the probing position, the probing radius, and the interferogram position are not the same. The relationship between these points is found by accurate ray tracing. Thus for the fringe shift equation (2.14),

$$m_i(y)\lambda = \sum_k (l_1^k n_1^k - l_2^k n_2^k)_i. \quad (3.1)$$

The subscript i refers to each ray considered and the subscript k refers to

the surface. Since the difference between the refractive indices of the gases is very small, and the gases are non-refracting, the interference is assumed to result from two rays propagating along the same path l during both holographic exposures.

Therefore, for a non-refractive medium

$$m_i(y)\lambda = l_i^5(n_1^5 - n_2^5), \quad (3.2)$$

where l_{i5} is the path length inside the tube, n_{15} is the index of refraction of gas in the first exposure, and n_{25} is the index of refraction of gas in the second exposure.

On the other hand, if the assumption of non-refractive gas is abandoned, the OPL of each surface for equation (3.1) needs to be calculated.

Note that the fringe shift is a function of the hologram y coordinate, and the fringe shift must be transformed into a function of tube radial coordinate. The transformation is simple if the relationship between the hologram y -coordinate and the tube radial coordinate r is found in terms of some known quantity. A description of the relationship can be obtained using the OPL, which is known for each ray and the tube radial coordinate r . From Figure 3.3, a simple relationship can be written for the path l .

$$2R \cos\theta = l \quad (3.3)$$

$$R \sin\theta = r \quad (3.4)$$

Therefore $\theta = \sin^{-1}(\frac{r}{R})$ can be substituted to give

$$2R \cos(\sin^{-1}(\frac{r}{R}))=l, \quad (3.5)$$

which can be written as

$$2R \sqrt{1 - \frac{r^2}{R^2}}=l, \quad (3.6)$$

and then gives

$$r=\sqrt{R^2 - \frac{l^2}{4}} \quad (3.7)$$

Therefore, using the above relationship, equation (3.2) and (3.1) can be written in terms of tube radial coordinate r .

$$m_i(r)=\frac{l_i^5(n_1^5-n_2^5)_i}{\lambda} \quad (3.8)$$

$$m_i(r)=\sum_k \frac{(l_1 n_1 - l_2 n_2)_i^k}{\lambda}. \quad (3.9)$$

Then, an Abel inversion is used to infer the refractive-index change that must have occurred along the probing ray path to result in the fringe number.

CHAPTER IV

NUMERICAL SIMULATION AND RECONSTRUCTION OF INDEX OF REFRACTION

The theoretical foundation which has been developed will now be applied to a tube of 30.2 mm i.d. and 38.4 mm o.d. containing the gases of interest. Before conducting the experiment, a numerical simulation of the experiment was performed and is presented in this chapter along with the reconstruction of the index of refraction distribution due to gas changes in the tube. The simulation was undertaken to make the comparison between the experimental reconstruction and the numerical reconstruction of the index of refraction field inside the tube. In addition to the comparison study, there is a discussion of the assumption of non-refractive medium.

Numerical Simulation

In order to model the optical set-up used for the experiment and simulate the interference due to the gas change, the OPTEC II ray tracing program on an IBM PC was used. The system configuration used in OPTEC II is shown in Figure 3.2. The initial rays were parallel to the x -axis and equally spaced. The glass tube of index of refraction 1.5 was used with the

laser wavelength $\lambda = 514.5$ nm. The index of refraction of the first two cylindrical plano-convex lenses is 1.523. The third cylindrical lens has an index of refraction of 1.5. The configuration includes the collimated parallel rays traced through the focusing system to the hologram plane. For given configuration parameters, OPTEC II generated path data for the system. The path data include optical path lengths between the surfaces of the optical components and the total optical path length for each ray. Since the gas change inside the tube is assumed to be the same everywhere, choosing a particular z -plane of the tube is not important. Therefore the chosen tube slice through which OPTEC II traces rays can be generalized over the whole z -axis.

The path data indicated that the tube was probed within 0.7 mm of the tube wall and that the hologram aperture limited the phase information to a 12.3 mm radius inside the tube. The missing information can not be obtained from the reconstruction.

Non-refractive and Refractive Gas

First, using the assumption of a non-refractive gas, the optical path length inside the tube for each ray is computed. The collimated parallel rays are generated by OPTEC II with equal spacing simulating the experi-

mental object beam and are incident upon the first plano-convex lens. The incident rays are refracted inward by the first lens and then are refracted outwards by the tube into the space inside the tube. The rays at the center region travel longer paths and those near the edge travel shorter paths inside the tube. The optical path length, therefore, is 30.2 mm at the center and decreases slowly as the rays probe toward the edge. Figure 4.1 shows the optical path length as a function of the hologram y coordinate.

For each ray the geometric path length is the same regardless of the gas used in the tube when using the non-refractive gas assumption. Thus the optical path difference is only due to the difference of the index of refraction between the comparison gas and the reference gas. The gas change in the tube is simulated by the subtraction of the optical path length of each ray in the comparison gas from the optical path length of the same ray in the reference gas inside the tube. The subtraction then results in the optical path difference. The fringes are then calculated by dividing the OPD by the wavelength used in the experiment, according to the equation (2.14). Figure 4.2 shows the fringe numbers corresponding to the hologram y coordinate for gas change of air-CO₂, air-He and CO₂-He. For the gas change of air-CO₂, the fringe value at $y=0$ mm is 9.39. Then the fringes are numbered subsequently and the fringe number given at $y=15$ mm is 5.36. The other fringes are similarly treated giving the fringe number of 14.96 at $y=0$ mm and 8.54 at $y=15$ mm for the gas change of

air-He. For CO₂-He, the fringe number at $y=0$ mm is 24.36 and at $y=15$ mm, the fringe number is 13.92. Since the number of fringes and the fringe number are dependent upon the index of refraction difference of the gases, there are more fringes in the CO₂-He change than in air-He and fewer in air-CO₂. Consequently the fringe number of the center ray of CO₂-He change is higher than the air-He change. The center fringe of air-CO₂ has the lowest fringe number among the three.

In order to reconstruct the index of refraction field inside the tube, the tube radial coordinate must replace the hologram plane coordinate according to equation (3.7). Since the process involved has already been described, only the result of the transformation is presented. Figure 4.3 shows the transformed positions.

So far, the assumption of non-refractive medium has been made, and since the gas is non-refracting, rays go through the same paths for all gases. This assumption can be investigated now using the total optical path length data and the equation (3.1).

Using OPTEC II, the optical path length for each surface is calculated for each gas. The total path length is determined from the sum of the surface OPL's. Figure 3.2 shows the surfaces under discussion. The total optical path length is plotted against the hologram plane coordinate, y , and is shown in Figure 4.4. The plot shows that the total optical path length is shorter near the center than the edges. This is because the rays that travel

close to the edge of the tube refract more through the system. In a similar manner, the fringe numbers are given for the gas changes without the non-refractive gas assumption according to equation (3.1) and the transformation to the tube radial coordinate is done according to equation (3.7). Figure 4.5 shows the fringe numbers as a function of the hologram y coordinate for air-CO₂, air-He, and CO₂-He. After the transformation, the fringe numbers are shown as a function of the tube radial coordinate in Figure 4.6.

This assumption of refractive gas medium can then be compared to the previous assumption for the non-refractive gas medium. In order to show the difference between the two cases, the fringe number for the non-refractive gas medium is subtracted from the fringe number of refractive gas medium. Then the relative error is computed and is shown in Figure 4.7. The errors are less than 1 % for $r < 11.5$ mm. At the edge region where $r > 11.5$ mm, the errors are increased to about 3-4 %. This large error was anticipated because of the aberrations which the lenses contribute at the edge.

So far, the simulation of the experiment by OPTEC II has resulted in the determination of the interference pattern of the gas change, and the patterns have been numbered and transformed. The fringe numbers can then be used for reconstruction of the index of refraction change.

Reconstruction of Numerical Simulation

When the object beam probes the tube, the tube is probed to the radius 14.3 mm. However, when the object beam interferes with the reference beam the hologram aperture limits the recording of the interference pattern to a maximum radius of 12.3 mm. The limit is calculated from the hologram coordinate transformation equation (3.7). The unprobed region of the tube does not contribute to the reconstruction. Thus, limiting the radius is necessary to measure the index of refraction difference distribution in the tube, and the inversion is limited to the radius 12.3 mm.

The reconstruction of the refractive-index distribution for the gas changes are computed using the Abel inversion algorithm with cubic spline fitting, as mentioned in Chapter II. Figure 4.8 shows the reconstruction of the index of refraction change for the gas change of air to CO₂. The Figure shows the index of refraction distribution for the gas change on the x -axis with the corresponding radial positions on the y -axis. For the gas change the Δn distribution for $r < 11.5$ mm is $1.6 \times 10^{-4} \pm 0.067 \times 10^{-4}$ and for $r > 11.5$ mm is $1.6 \times 10^{-4} \pm 0.52 \times 10^{-4}$ where maximum variation from the distribution are indicated after each index of refraction difference value. The reconstructed index of refraction distribution shows almost constant values, except in the regions close to the edge where large errors occur. The constant value for the distribution was expected since the gas change

of air-CO₂ is regarded as constant. The large error in the regions close to the edge are due to the cubic spline algorithm which encounters the slope of the distribution approaching infinity near the edge. [11] Figure 4.8 also shows similar reconstructions for gas changes of air-He and CO₂-He. The general trend is that the reconstructions show constant values up to about $r = 11.5$ and then oscillate with a large error beyond this point. For the gas change of air-He, the Δn distribution for $r < 11.5$ mm is $2.55 \times 10^{-4} \pm 0.1 \times 10^{-4}$ and for $r > 11.5$ mm is $2.55 \times 10^{-4} \pm 0.83 \times 10^{-4}$. For the gas change of CO₂-He, the Δn distribution for $r < 11.5$ mm is $4.15 \times 10^{-4} \pm 0.22 \times 10^{-4}$ and for $r > 11.5$ mm $4.15 \times 10^{-4} \pm 1.35 \times 10^{-4}$.

The index of refractions were compared to the expected value of the index of refraction distribution for each of the gas changes. The relative errors are computed and are shown in Figure 4.9. The average relative error for air-CO₂ is 1.63 %, for air-He, 1.45 %, and for CO₂-He, 1.43 %. The average relative error for $r < 11.5$ mm is considerably lowered because the large error at the edge are not taken into account. For $r < 11.5$ mm, the relative error of air-CO₂ is 1.24 %. Similarly, the average relative error of air-He is 1.14 % and of CO₂-He is 1.12 %.

CHAPTER V

THE EXPERIMENT

In the numerical simulation discussed in Chapter IV, rather complete fringe information was determined for the three gas changes considered in the study. With this information available, the holographic interferometry experiment on the cylindrical tube and the reconstruction of the experimental data are now discussed.

Optical Systems

The optical system, illustrated in Figure 5.1, includes a holographic interferometer, the imaging system, the HC300, and the Vicom image processor. The holographic interferometer includes an Argon ion laser as a light source and optical components such as mirrors, a beam splitter, and attenuators. The imaging system consists of the collimator and the imaging part which includes the cylindrical lenses, the tube, and the mounting devices. Part of this imaging system has been described in Chapter III. The HC300 holographic camera contains a thermoplastic hologram film plate which is about 30 mm by 30 mm and records a hologram. This camera is

capable of developing a hologram in minutes without being moved. Lastly, the Vicom image processor uses a video camera to record the hologram and handles image processing of the hologram.

Experimental Preparation

The argon-ion laser was operated at 0.125W at a wavelength of 514.5 nm with an etalon for increased coherence length. The polarization rotator was used to orient the direction of the linearly polarized light. The tube and thermoplastic film plate were centered on and normal to the x -axis of the object beam

The laser beam is split into the object and reference beams, by a beam splitter. The object beam passes through the attenuator and neutral density filter to the mirror which then reflects the beam into the collimator. Before the collimation, the object beam is spatially filtered and expanded by the 5 micron pin-hole and 50x microscope objective. The resulting collimated object beam is parallel to the x -axis and is 3 inches in diameter. The object beam is then directed to the tube and the imaging system. The reference beam is also spatially filtered and expanded by a 25 micron pin-hole and 10x microscope objective. The reference beam is diverging at an angle of 13 degrees from the center axis.

The manufacturer recommended intensity ratio of the object to the reference beam for the thermoplastic film used in the HC300 holographic camera is 1 : 9. However, the irradiances of the two beams were not uniform. Prior to the experiment, the intensity of the object and the reference beam were measured and adjusted to the recommended ratio, but the two different shapes made it difficult to obtain the exact ratio. The plot of the intensity distribution is shown in Figure 5.2. The peak of the reference beam reached about $1000 \mu w$ at $y=9.3$ mm. In contrast the object beam had $110 \mu w$ at about $y=6$ mm. The ratio was approximately 1 : 9 at the center region and decreased slowly towards the edge. This resulted in some minor blurring of the hologram at the edge.

The scattered light was controlled by a flat screen which blocks the light that might fall on the hologram. This also prevented the scattered light from interfering with the hologram light. The shutter speed was controlled by the electronic shutter placed in front of the polarizer and was set for a 1 second exposure time, which had been selected from a prior test of the HC300 camera. All the systems were mounted on the optical table which was supported by compressed air.

Experiment

Before making the hologram, the position of the tube holder was adjusted, tightened and then maintained stationary throughout the experiment. The first step taken was for the tube to be vented and filled with room air, and the first exposure was made at this time and developed. While the hologram was being developed the tube was vented and filled with a comparison gas (CO_2 or He). The second exposure was made about 1 or 2 minutes later after the comparison gas has settled. The plates were exposed for 1 second and developed by the HC300. The plate was then illuminated without leaving its position to create the reconstructed real image. A video camera was placed to capture the image of the interferogram at an angle of about 24 degrees normal to the viewing screen. The camera then sent the image data to the Vicom image processing computer, and the image was stored in memory. A photograph of the hologram imaged in the Vicom is shown in Figure 5.3.

Five holograms of each gas change, air- CO_2 , air-He and CO_2 -He, were taken in the experiment, and recorded in the Vicom processor. For reference purposes, pictures of the background and the calibration were also taken. The calibration picture contains an image of 1/8 inch grid graph paper pasted on the hologram viewing screen.

Reconstruction of The Experimental Data

After the experiment, all data were stored in the Vicom memory in binary numbers. Using the Vicom image processing capabilities some enhancement of the quality of the image has been made. The contrast between the dark fringes and the bright fringes was increased using high and low pass filtering, fast fourier transforms and inverse fourier transforms, and the hidden fringes were brought out. Figure 5.4 shows the enhanced hologram for a gas change of air-CO₂.

For the reconstruction of the index of refraction difference the images were eventually moved to the Masscomp to improve the image evaluation technique. The interferogram is contained in an image of 512 x 512 pixels.

In order to reconstruct the index of refraction change, the fringe numbers were found from the interference relation of the fringe patterns described in equation (2.14). To do this each data row was analyzed. Each row contains irradiance information and corresponding positions. The peaks were visible along with small amounts of background noise. Figure 5.5 shows the irradiance distribution for row 200 of a hologram as a function of pixel position. In order to distinguish the fringes the background

information was subtracted from the irradiance distribution before passing through the low pass filter, and its intensity distribution is shown in Figure 5.6. The background subtracted irradiance distribution has clearly distinguished peaks. The noise was removed by low pass filtering. The filter uses a variable cut-off frequency so that the filter can be varied depending on the spectrum of the noise to be removed. The filtered irradiance distribution is shown in Figure 5.7.

The filtered image of the hologram is now ready for determination of the maximum and minimum irradiance position. Because of the axisymmetric geometry of the cylinder, the interferogram contains the fringe information from each half of the tube. The first peak appears according to the calculation made by equation (2.14). The second peak usually appears with larger spacing than the rest of the fringe spacing. The fringes are symmetrical about the center of the tube. The fringe spacing plot can be seen in Figure 5.8. Using this peak information the center of the hologram corresponding to the tube center was determined and found to be 228 on the pixel coordinate for the row 200.

Then the peaks were numbered according to the equation (2.14) in Chapter II. At the center the fringe number can be specified using the tube diameter given. Then the adjacent peaks can be numbered sequentially. The peaks take on integral values. Another way of assigning the fringe numbers is to start at the edge giving the edge the fringe number 0 and

number them inward in sequence. For this method of assigning the fringe numbers, problems arise since some fringes are missing at the edge portion of the tube. This is due to the refraction of the tube and the fact that the object beam was not able to probe the region adjacent to the tube wall. To use this method equation (2.14) can be used to calculate the missing fringes and the both methods results in the same values for the fringes.

The above method is valid only if the index of refraction at the center and the tube diameter are known accurately. However, the index of refraction information can not be known until the experiment is performed. Therefore some other approach must be used to assign the fringe number for the center in the case where the index of refraction is not known.

After the fringe numbers were determined, the hologram plane coordinate was transformed to the tube radial coordinate. This was accomplished by the mathematical treatment described in Chapter III.

Before reconstruction, adjustments on the fringe spacing were needed. The calibration curve was determined from the calibration image data which is shown in Figure 5.9. In steps similar to those taken for the interferogram, the background image was subtracted from the calibration image and the image was processed by the low pass filter. Spacing between two adjacent peaks corresponds to $1/8$ inch on the viewing screen and to 1.32 mm on the hologram y -coordinate. The calibration curve was then found by plotting the peaks as a function of the corresponding hologram y

coordinate and is shown in Figure 5.10. The adjustment of the fringe spacing according to the calibration was done by fitting the fringe positions to the calibration curve. The fringe number distribution as a function of the tube radial coordinate for the gas changes are shown in Figure 5.11.

The reconstruction of the refractive-index distribution for the gas changes on the holograms uses the Abel inversion algorithm with cubic spline fitting introduced in Chapter II. In the numerical simulation the problem of the missing fringes was avoided by reducing the tube radius to 12.3 mm. In the experimental reconstruction, the missing fringe presents the same problem and the same method used in the numerical simulation was used to take the missing fringes into account.

The reconstructed plot of the hologram shows the index of refraction distribution for the gas changes inside the tube. Since the gas changes are regarded as constant the reconstruction was expected to be constant. The reconstruction of the fringe data for the gas change of air-CO₂ at $z = 200$ is shown in Figure 5.12. The reconstructed index of refraction is shown along the y -axis and the corresponding radial positions are plotted on the x -axis. As expected, the figures show large errors for the regions close to the tube wall. This was explained in the numerical simulation reconstruction by the abrupt change in slope of the distribution at the edge. The distribution is shown as a curve that closely follows the expected constant value distribution. The reconstructions at $z = 100, 300$, and 400 are shown in Figure

5.13. The figures are almost identical to $z=200$. The Δn distribution for $r < 11.5$ is $1.6 \times 10^{-4} \pm 0.11 \times 10^{-4}$ and for $r > 11.5$ is $1.6 \times 10^{-4} \pm 0.97 \times 10^{-4}$. Figure 5.12 also shows the reconstructions of gas changes of air-He and CO₂-He, where similar behavior is seen. For air-He, the Δn distribution for $r < 11.5$ is $2.59 \times 10^{-4} \pm 0.39 \times 10^{-4}$ and for $r > 11.5$ is $2.59 \times 10^{-4} \pm 1.83 \times 10^{-4}$. For CO₂-He, the Δn distribution for $r < 11.5$ is $4.18 \times 10^{-4} \pm 0.38 \times 10^{-4}$ and for $r > 11.5$ is $4.18 \times 10^{-4} \pm 2.81 \times 10^{-4}$.

The index of refraction distributions are compared to the expected value of index of refraction distribution of the gas changes and the relative error are computed and are shown in Figure 5.14. The average relative error for the gas change of air-CO₂ is 17.7 %. The average relative error for $r < 11$ mm is 3.7 %. Similar values are found for the other gas changes; for air-He the average relative error is 15.1 %, with 4.8 % for $r < 11$ mm and for CO₂-He the average relative error is 14.3 %, with 1.8 % for $r < 11$ mm.

CHAPTER VI

DISCUSSION

The reconstructions of the experimental data and numerical data have been presented without any comparison. In this chapter the potential sources of error are discussed in view of the experiment and a comparison of the reconstruction of the numerical simulation to the reconstruction of the experimental data is presented. The use of holographic interferometry for measuring the temperature distribution of a medium in a cylindrical tube is discussed and suggestions are made for future investigations.

Sources of Error

The index of refraction of the tube itself is known only approximately. In the numerical simulation the index of refraction of the tube was assumed to be 1.5 which is a typical value assigned for glass material. In a similar experiment on an acrylic tube by Reuss, [3] he reported the error in the reconstructed refractive-index distribution of the gas due to uncertainty in the refractive index of the tube material is less than 0.5 % for an index of refraction uncertainty of 0.2. For an uncertainty of 0.03, he reports less

than 0.1 % error. Therefore the use of an approximate value for tube index of refraction in the numerical simulation was assumed to contribute little error.

The experimental errors also include the inaccuracies of tube roundness and the tube wall thickness. Reuss points out that the average error due to inaccuracy in the tube roundness is less than .5 % for an out-of-roundness of 0.013-0.025 mm for a tube of 56.3 mm o.d. and 51.3 mm i.d., and the average error due to the tube wall thickness uncertainty is less than 0.15 % for 0.025 mm.

Other experimental error sources include the inaccuracy in positioning of the tube and related components, including the hologram plate and the unsteadiness of the gas inside the tube. The inaccuracies in the positioning of the set-up are estimated to be less than 2 %. The errors on the hologram due to this inaccuracy influence the fringe spacing and causes errors in the reconstruction. However, the magnitude of these errors is not well defined. The unsteadiness of the gas can be a major source of error in the study. Every effort was made to ensure the complete steadiness of the gas inside the tube. The tube was sealed at both ends and the gases entered through the plastic tubing connected to the upper end of the tube. The pressure of the flow was less than 1 psi.

The Abel inversion algorithm is more accurate for many data points than for a small number of data points. The number of fringes that are

contained for the gas change air-CO₂ is only 4, for air-He, 7, and for CO₂ is 11.

Comparison

The index of refraction of the gases are assumed, at 0 °C and 760 *mmHg*, to be 1.00029 ± 0.00002 , 1.00045 ± 0.00001 , and 1.000035 ± 0.000001 for air, CO₂, and He respectively and errors in the measurements are indicated after each values. [12] For the gas change of air-CO₂, the Δn is 0.00016 ± 0.00003 . Similarly for air-He, Δn is 0.000255 ± 0.000021 and for CO₂-He, Δn is 0.000415 ± 0.000011 .

The reconstructions of the experimental data are plotted with the reconstructions of the numerical data and is shown in Figure 6.1. The average relative error of the reconstructions of the numerical data are reported in Chapter IV and is 1.63 % for air-CO₂, 1.45 % for air-He, and 1.43 % for CO₂-He. For $r < 11.5$ mm, the average relative error of air-CO₂ is 1.24 %. Similarly, the average relative error of air-He is 1.14 % and of CO₂-He is 1.12 %.

The average relative error of the reconstructions of the experimental data are also reported in Chapter V. The relative error for air-CO₂ is 17.7 %, with 3.7 % for $r < 11$ mm. Similar values are found for the other gas

changes; for air-He the average relative error is 15.1 %, with 4.8 % for $r < 11$ mm and for CO₂-He the average relative error is 14.3 %, with 1.8 % for $r < 11$ mm.

Conclusion

The experiment using holographic interferometry showed that it can be used to measure the refractive-index distribution of a phase object contained in a cylindrical tube of 30.2 mm i.d. and 38.4 mm o.d. The imaging system consisting of a combination of plano-convex lenses was able to probe the tube to within 0.7 mm of the tube wall and the hologram was taken to include the index of refraction information up to about 12.3 mm radius. The experimental result has been inverted successfully within 5 % error using an Abel inversion with cubic spline fitting.

Successful application of holographic interferometry on a cylindrical tube is most dependent upon specification of a tube and the medium inside the tube. Each tube has different o.d., i.d. and wall thickness. The medium inside the tube can be homogeneous or inhomogeneous and can be non-refractive or highly refractive. All of these factors play a role in the refraction of the object beam through the tube. Therefore, in order to apply holographic interferometry to a cylindrical tube, each tube must be

considered as a different case.

In the experimental reconstruction, the fringe number was assigned based on the information of index of refraction and the tube diameter. The index of refraction at the center of the tube is not known in most of the cases. Therefore an investigation on determination of the center fringe is recommended for future study.

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BIBLIOGRAPHY

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APPENDIX

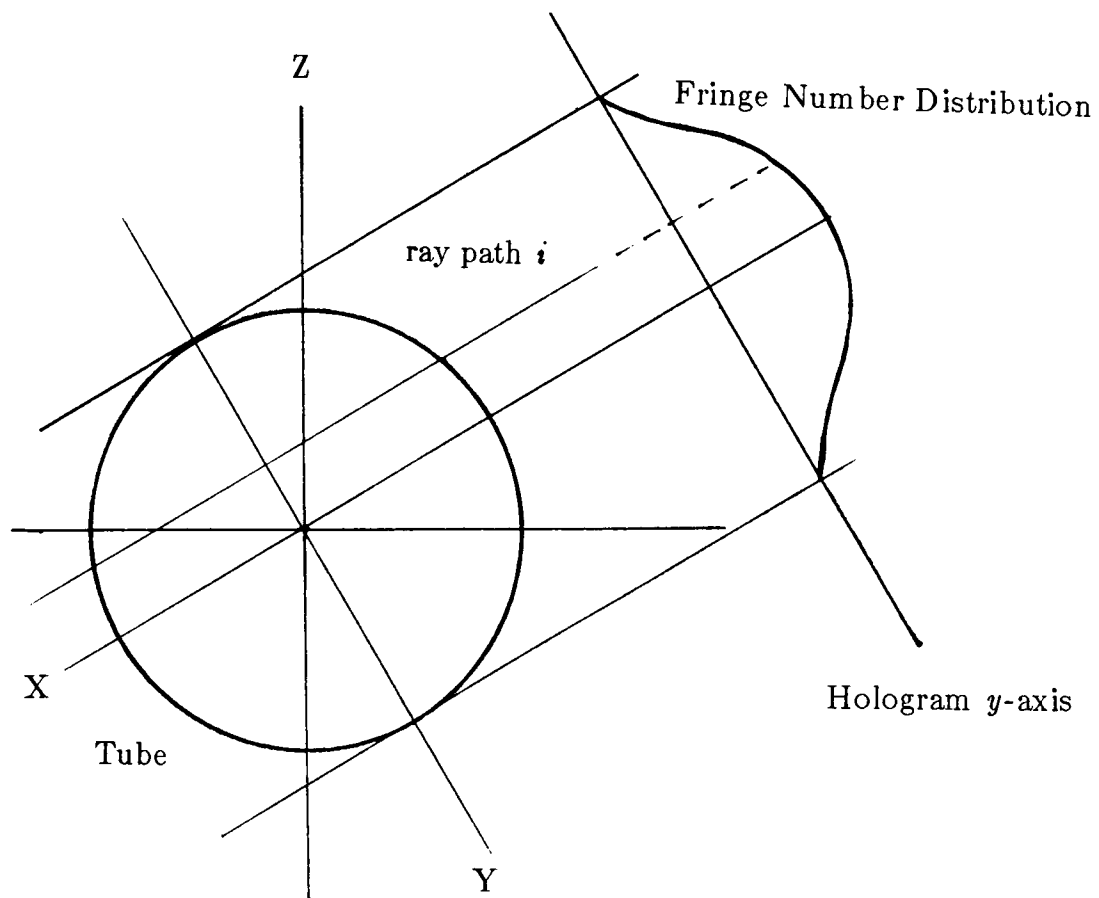


Figure 2.1. Cylindrical tube and Hologram coordinate : Ray paths are shown to relate both coordinates.

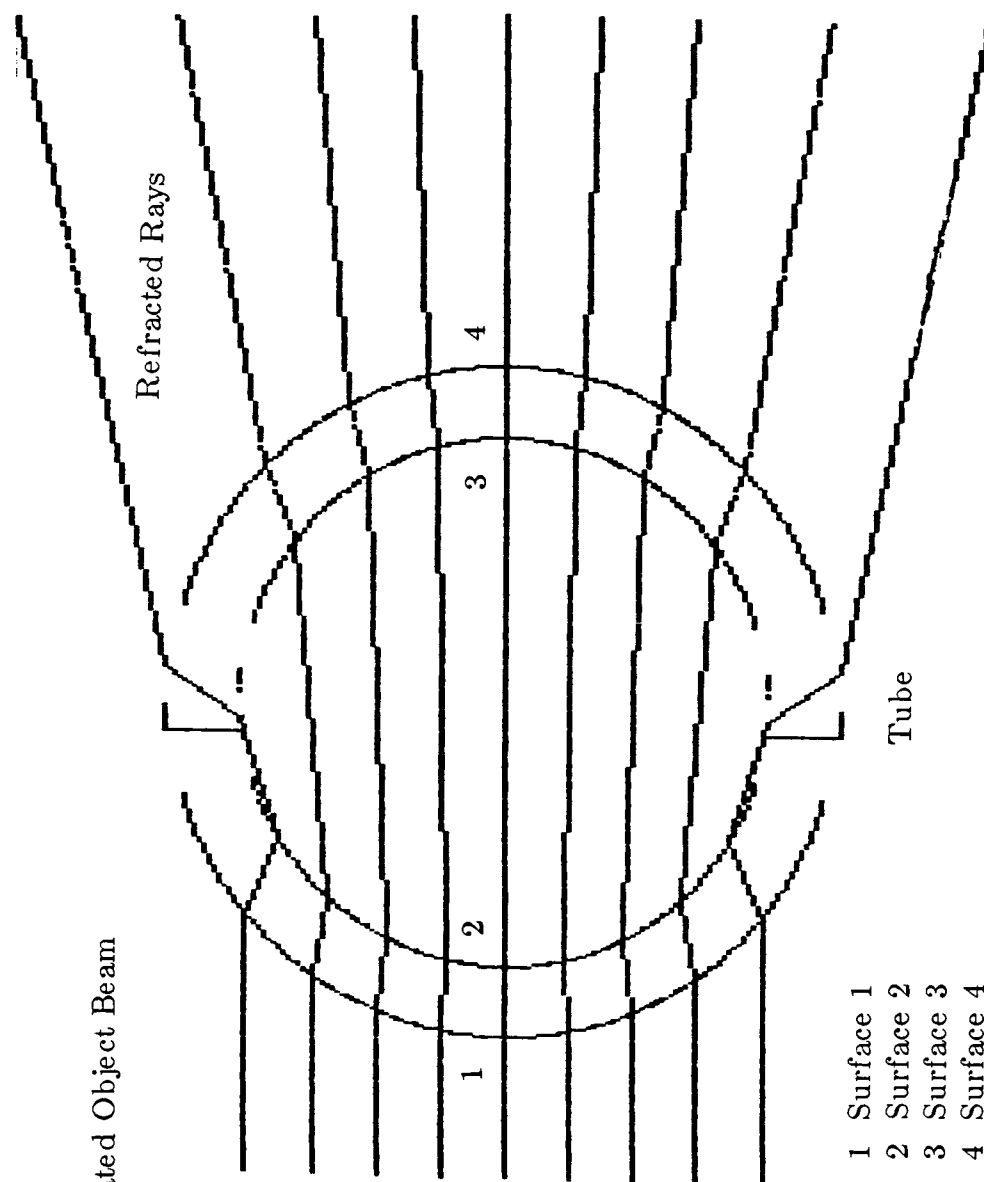


Figure 3.1. Tube diagram showing the refraction of rays on tube surfaces.

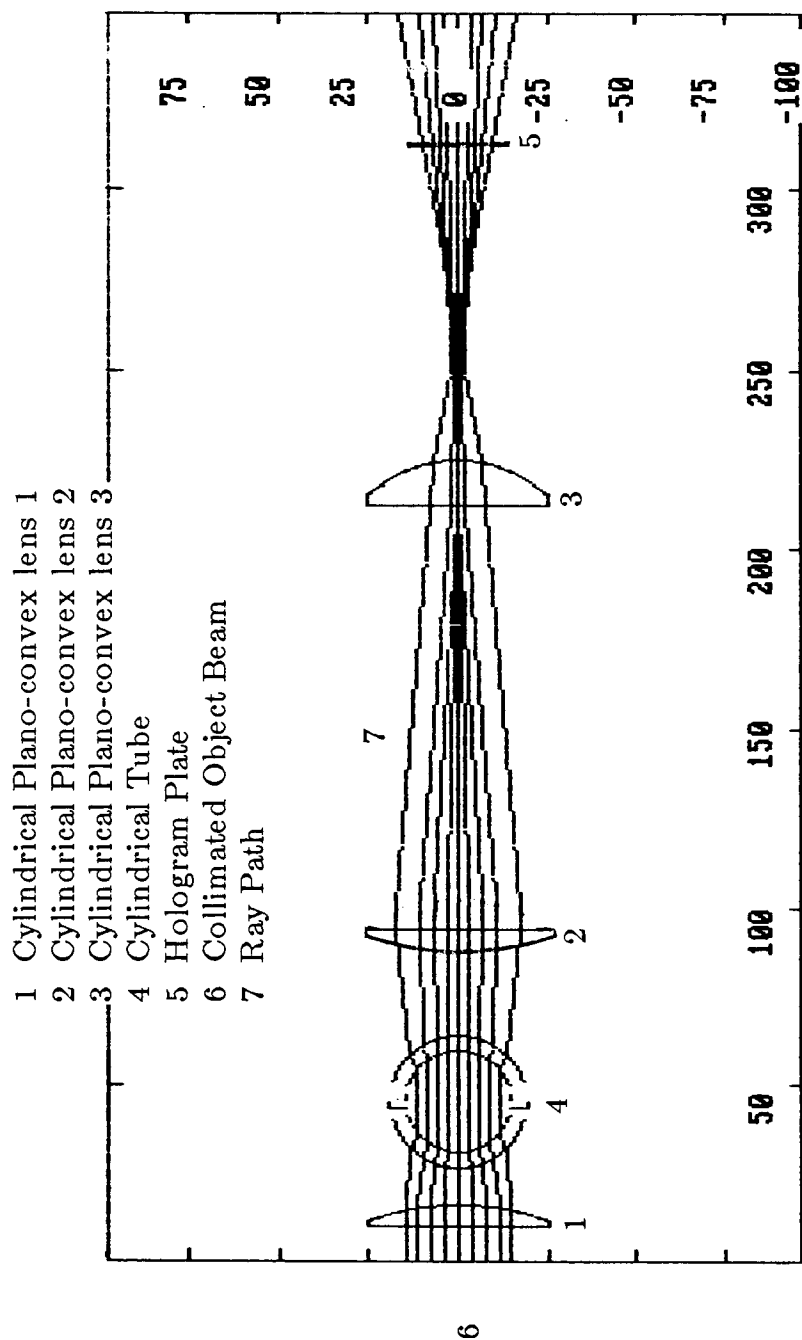


Figure 3.2. Schematic of Imaging System with ray paths.

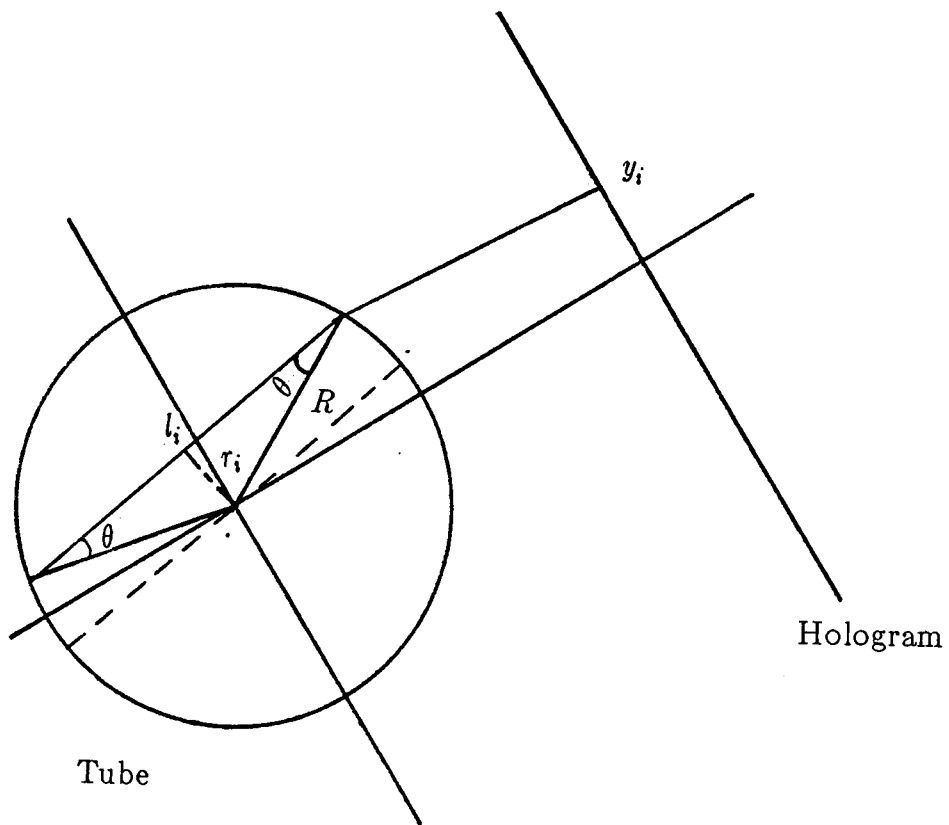


Figure 3.3. Relationship between the hologram y -axis and the tube radial coordinate, r .

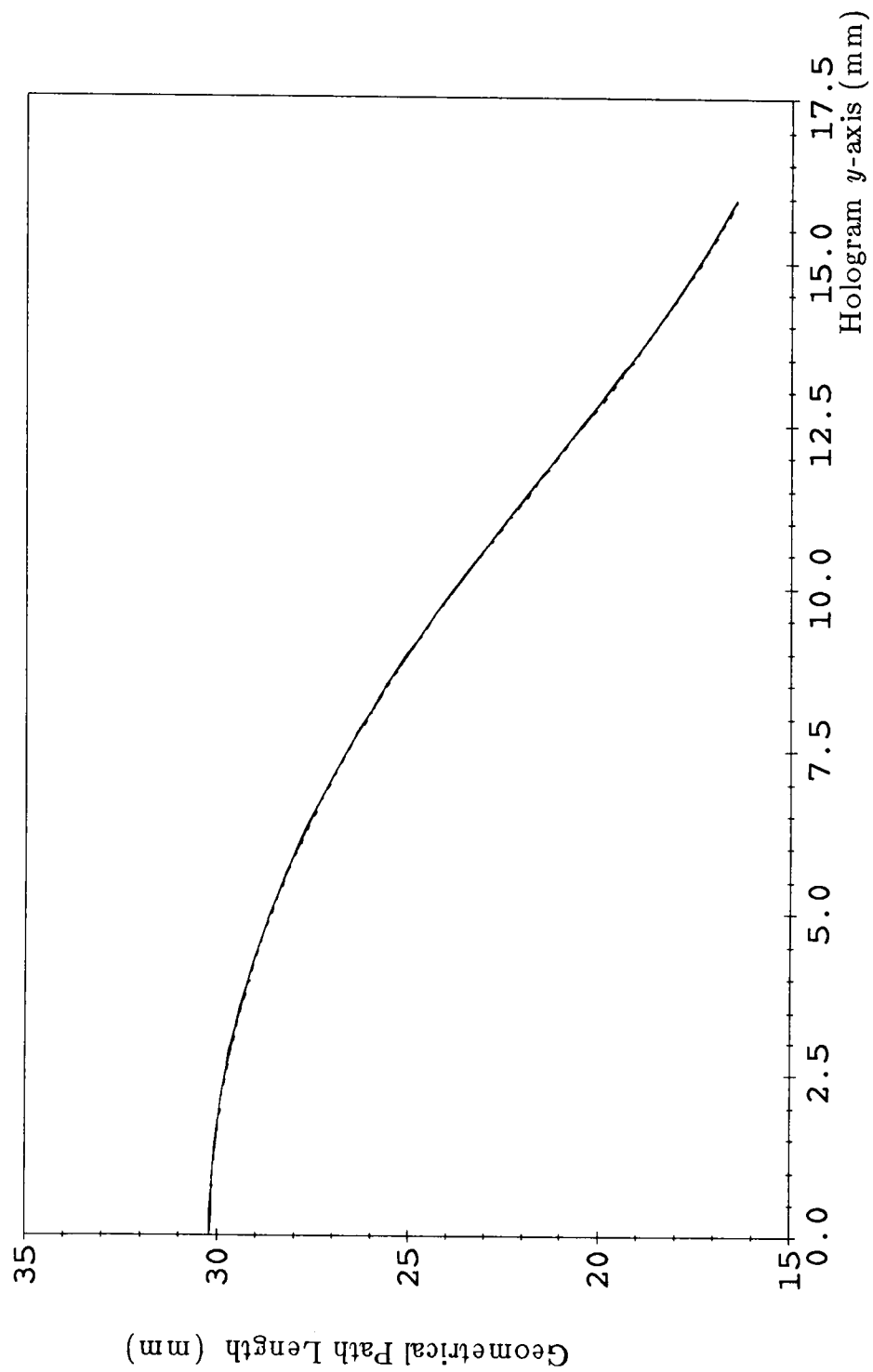


Figure 4.1. Geometrical Path Length plot as a function of hologram y -axis.

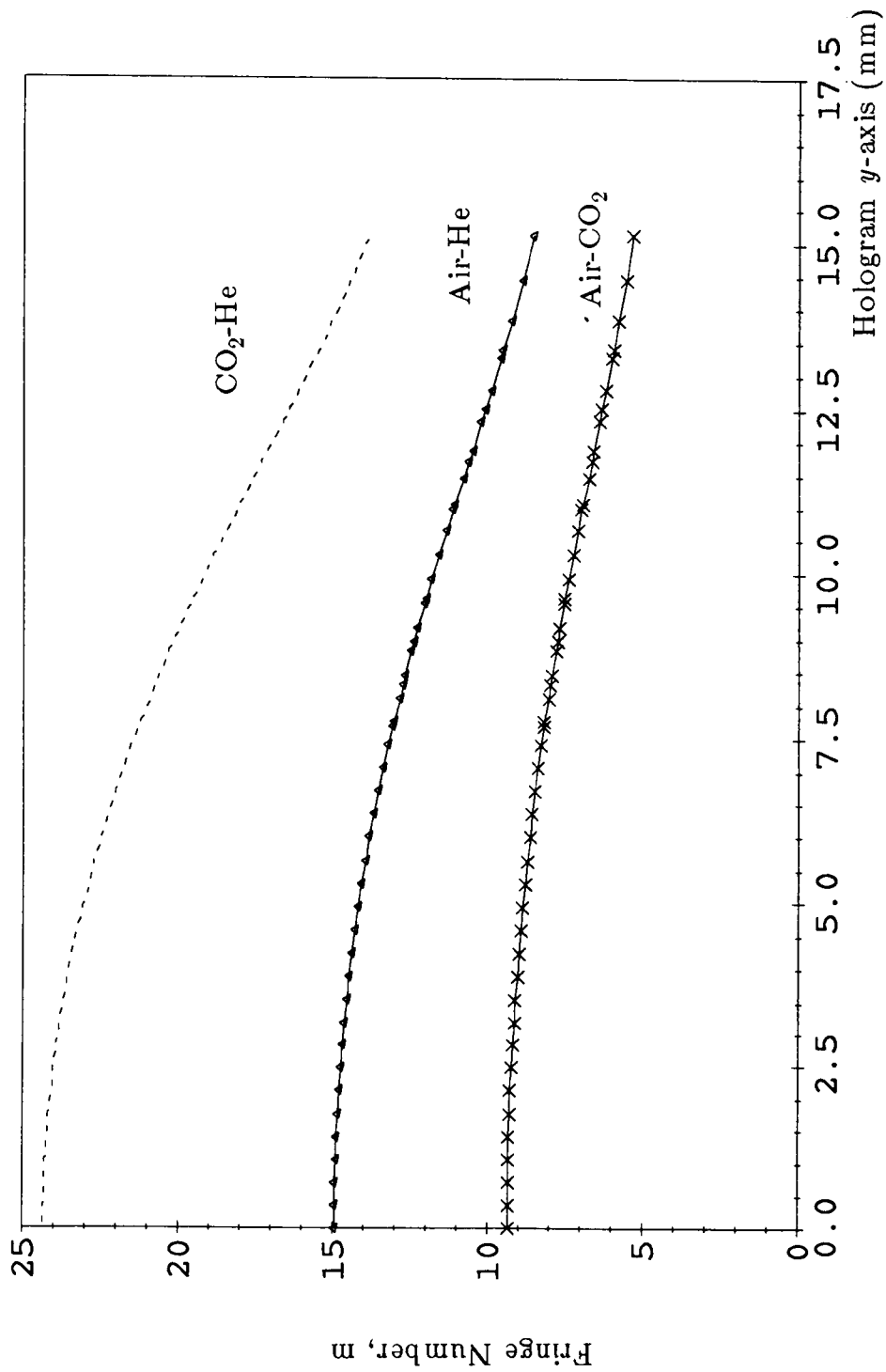


Figure 4.2. Fringe distribution as a function of hologram y -axis.

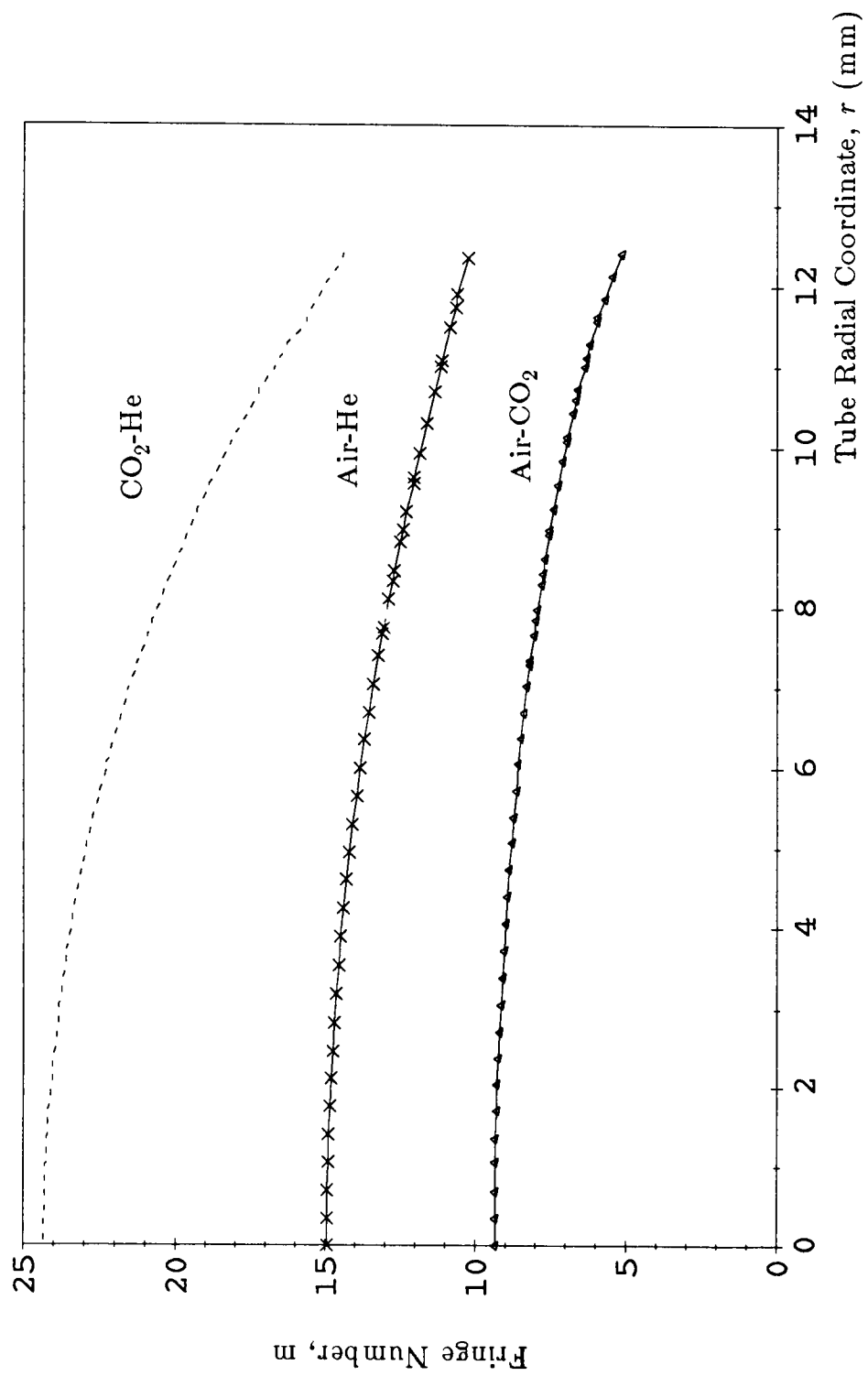


Figure 4.3. Fringe distribution as a function of tube radial coordinate.

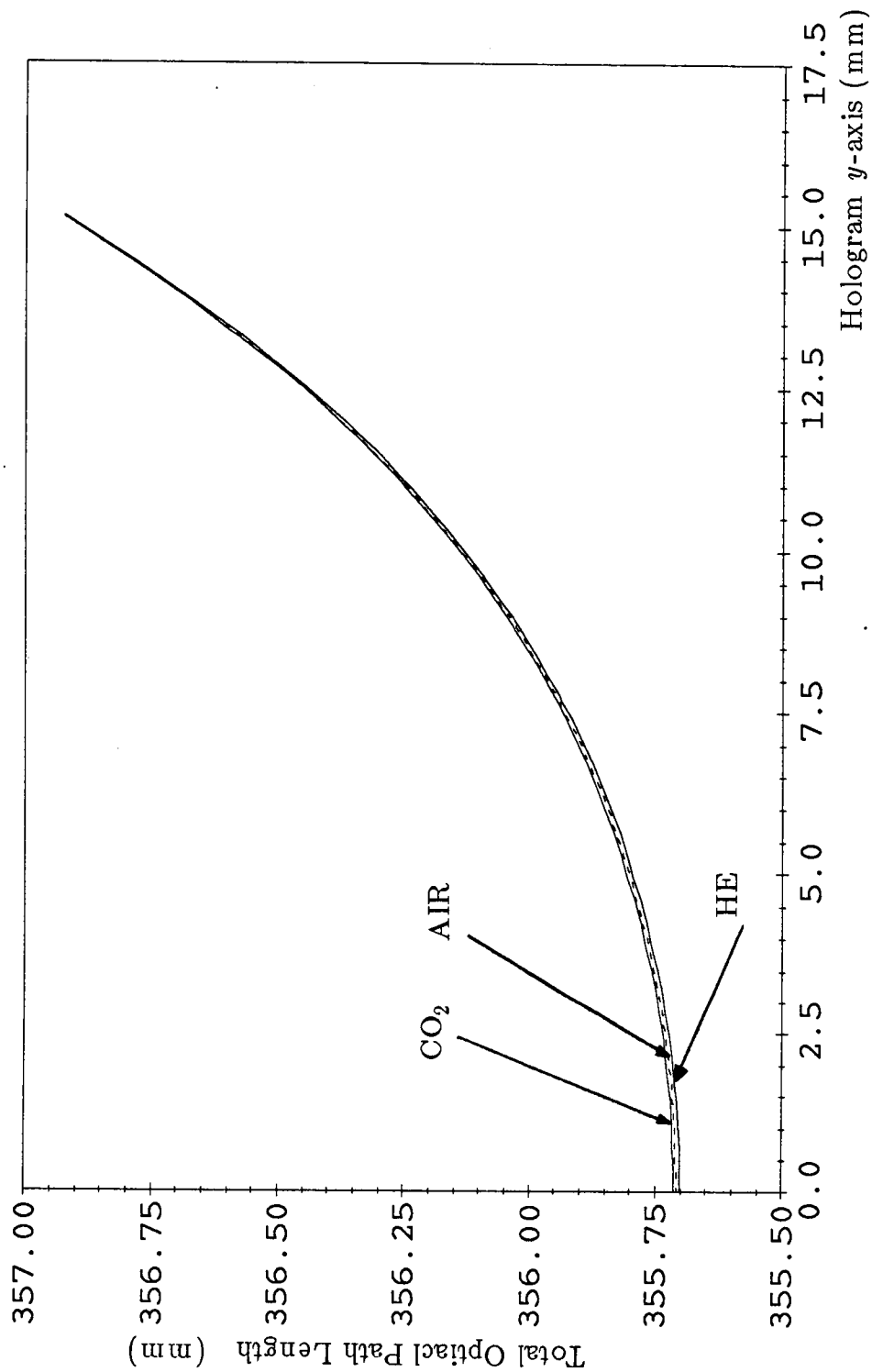


Figure 4.4. Total Optical Path Length plot as a function of hologram y -axis.

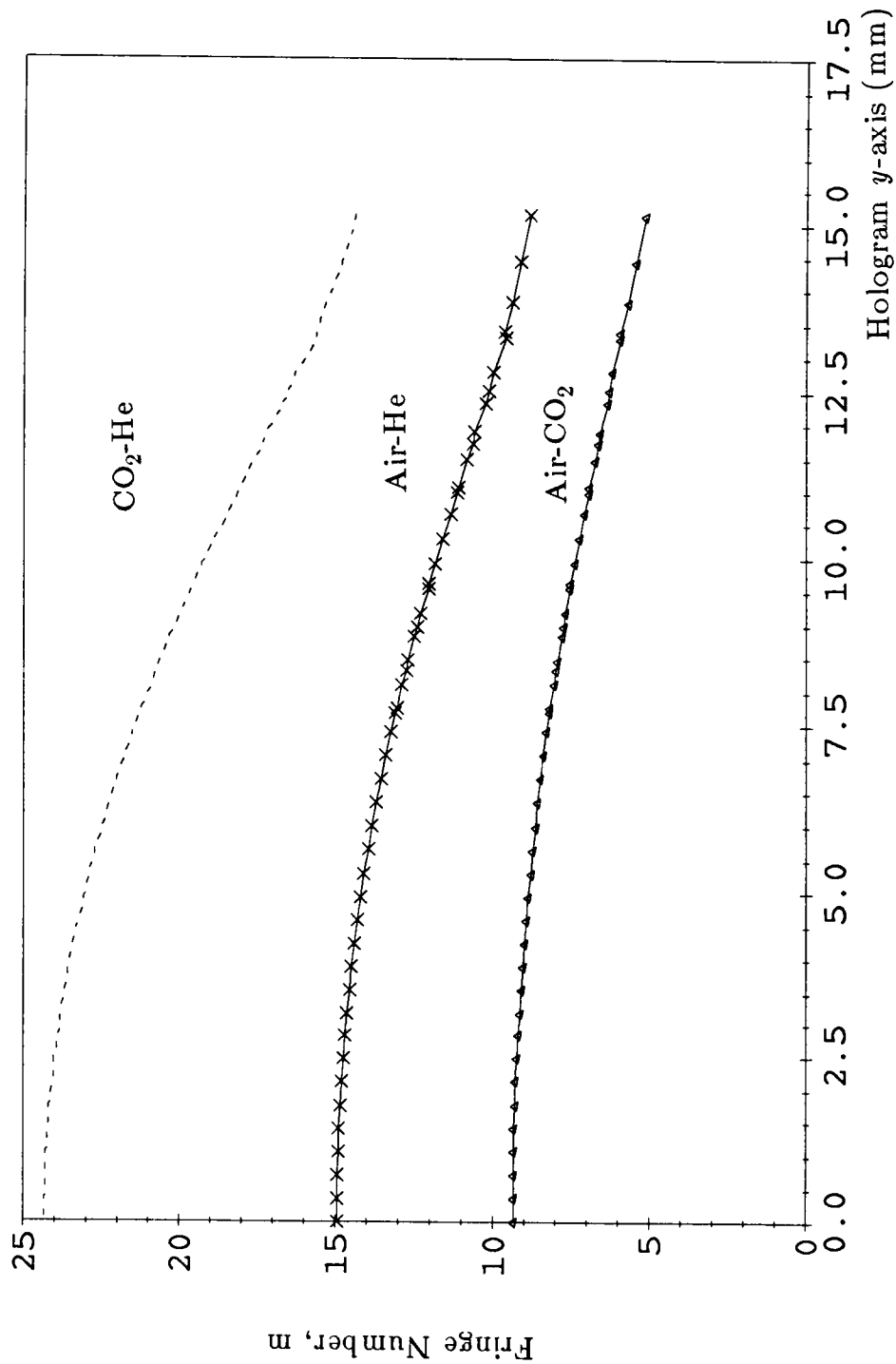


Figure 4.5. Fringe distribution as a function of hologram y-axis.

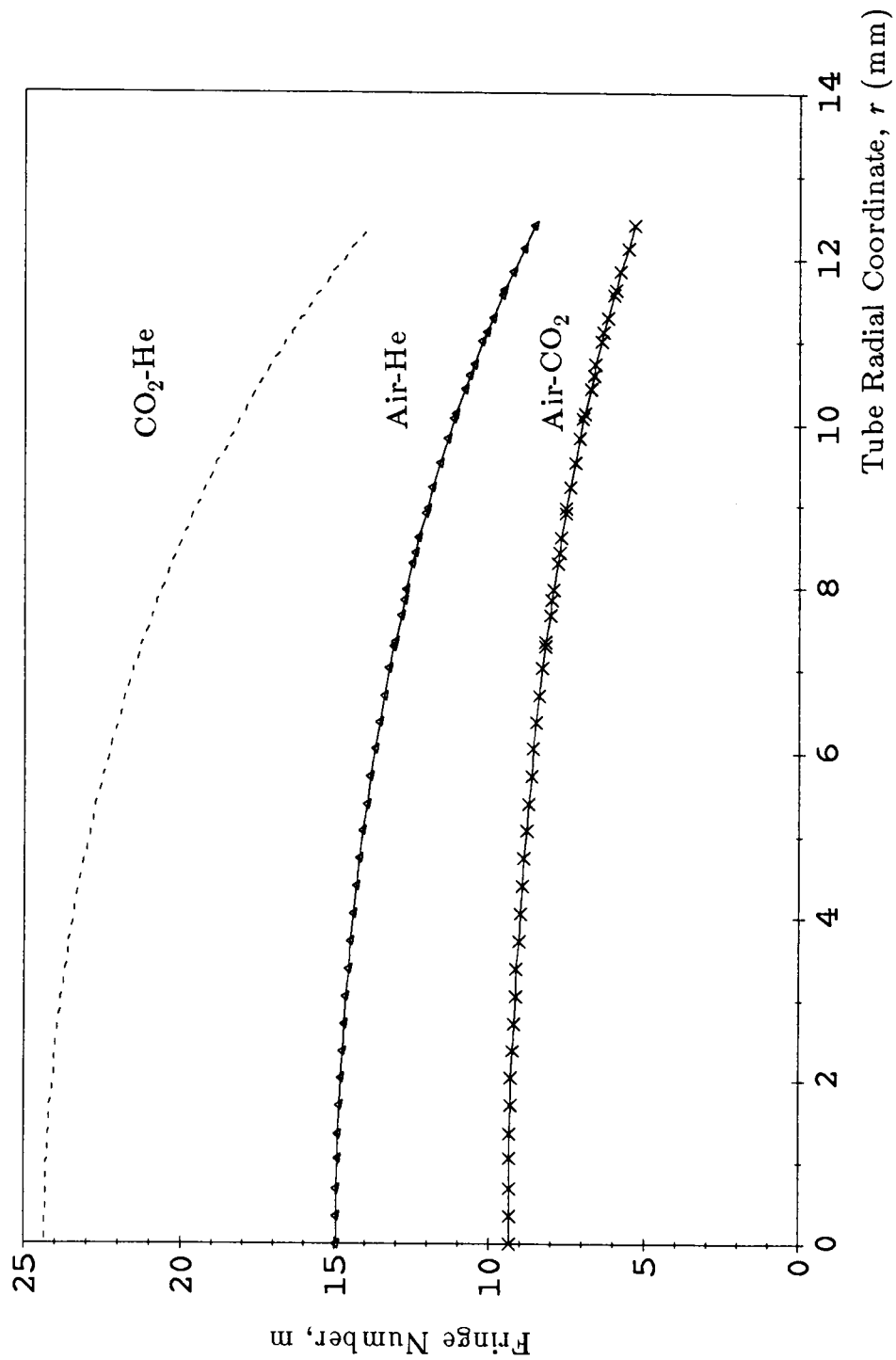


Figure 4.6. Fringe distribution as a function of tube radial coordinate.

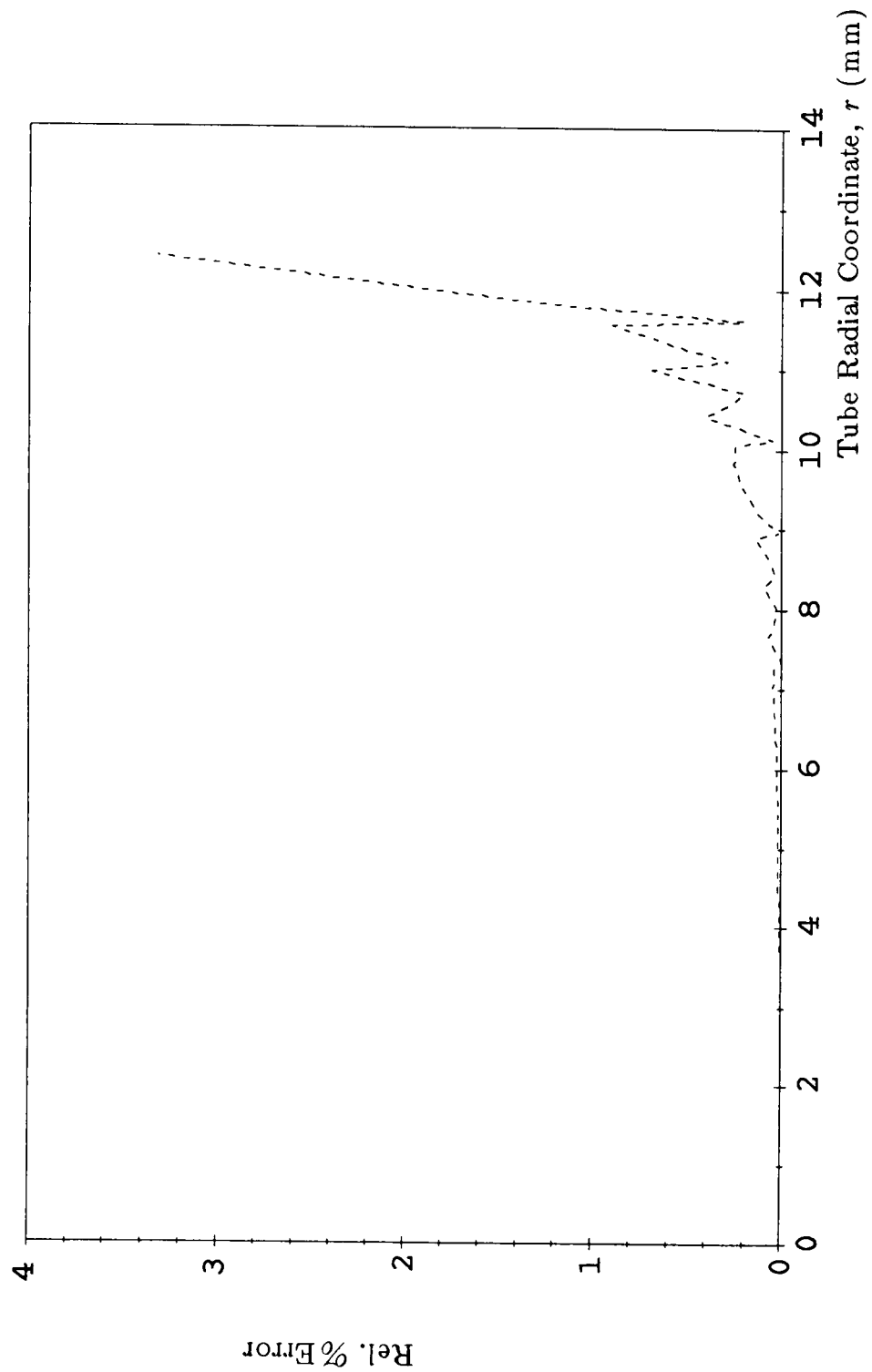


Figure 4.7. Relative error distribution as a function of tube radial coordinate.

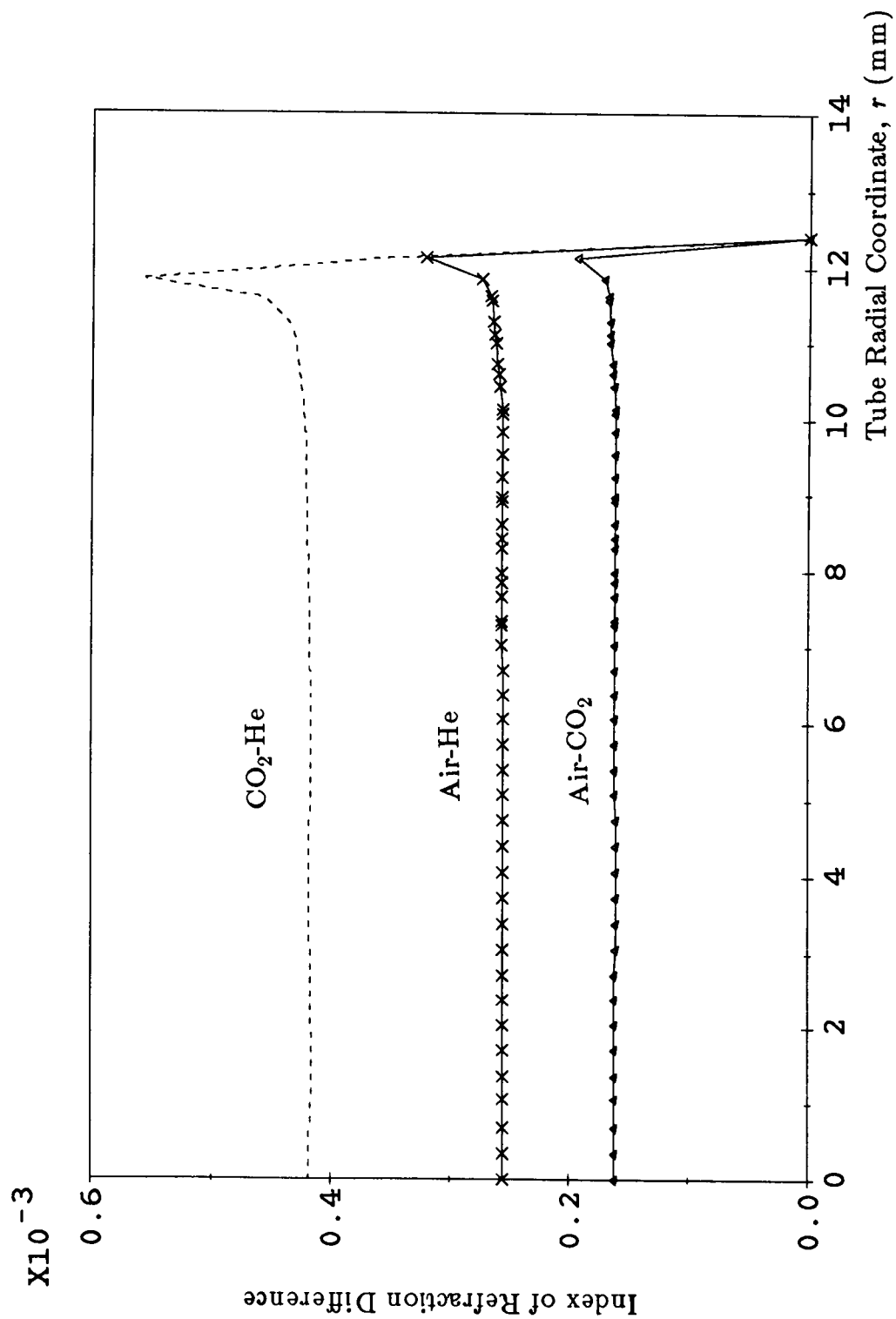


Figure 4.8. Reconstruction of index of refraction change as a function of radial coordinate.

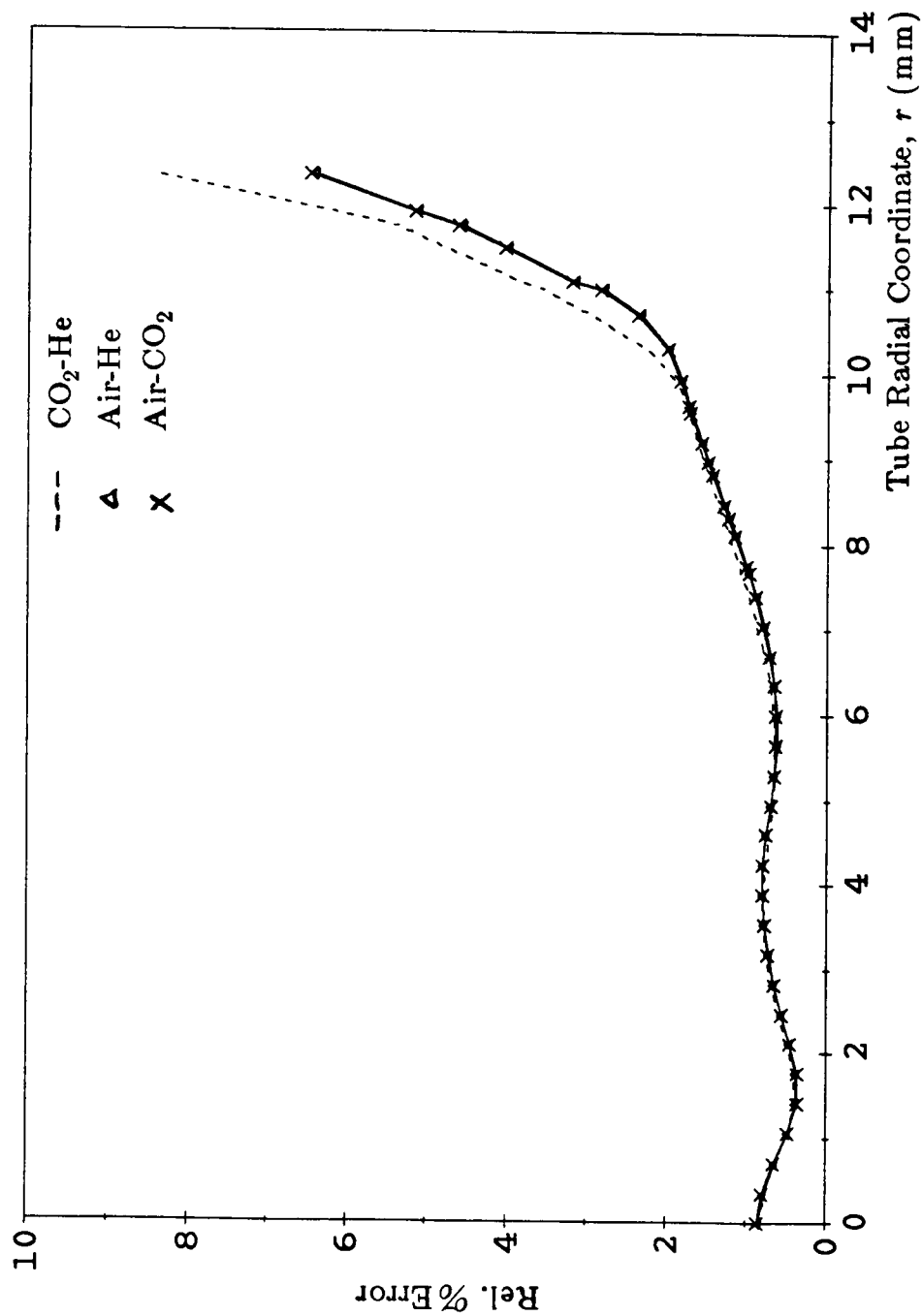
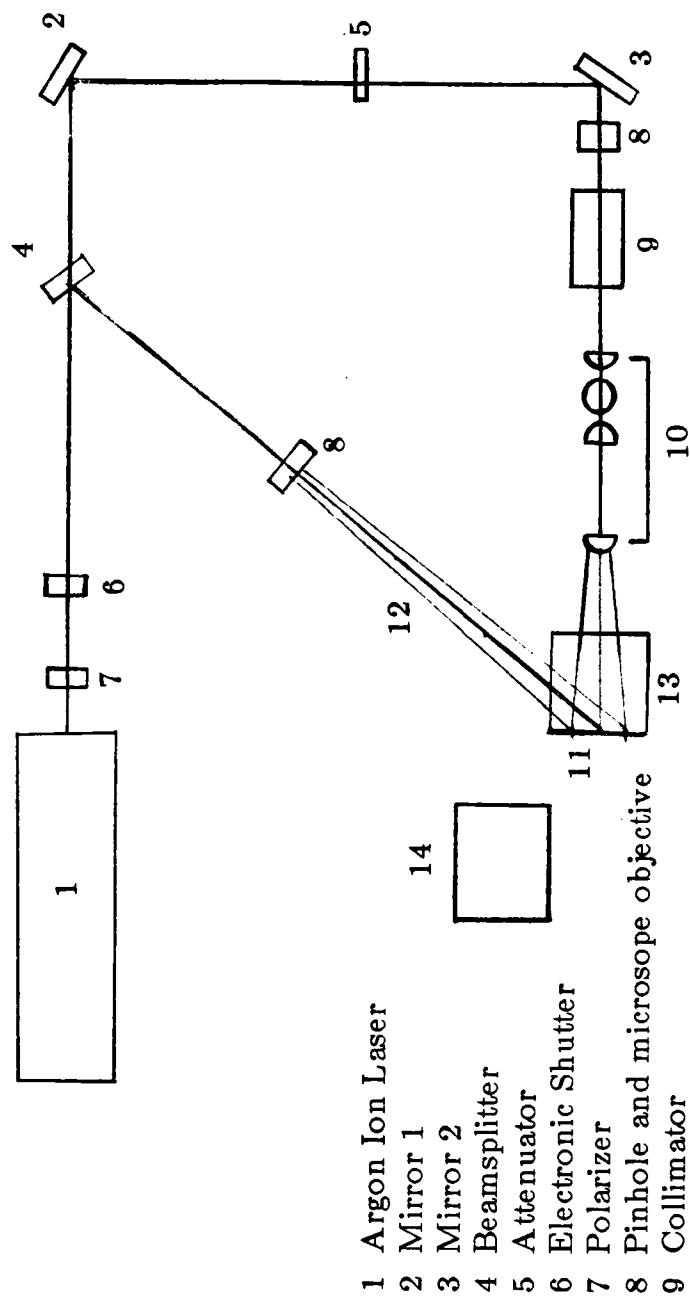


Figure 4.9. Relative Error Distribution of Numerical Simulation.



- 1 Argon Ion Laser
- 2 Mirror 1
- 3 Mirror 2
- 4 Beamsplitter
- 5 Attenuator
- 6 Electronic Shutter
- 7 Polarizer
- 8 Pinhole and microscope objective
- 9 Collimator
- 10 Imaging System
- 11 Object Beam
- 12 Reference Beam
- 13 HC300 Camera
- 14 HC300 Controller

Figure 5.1. Schematic of the experimental set up.

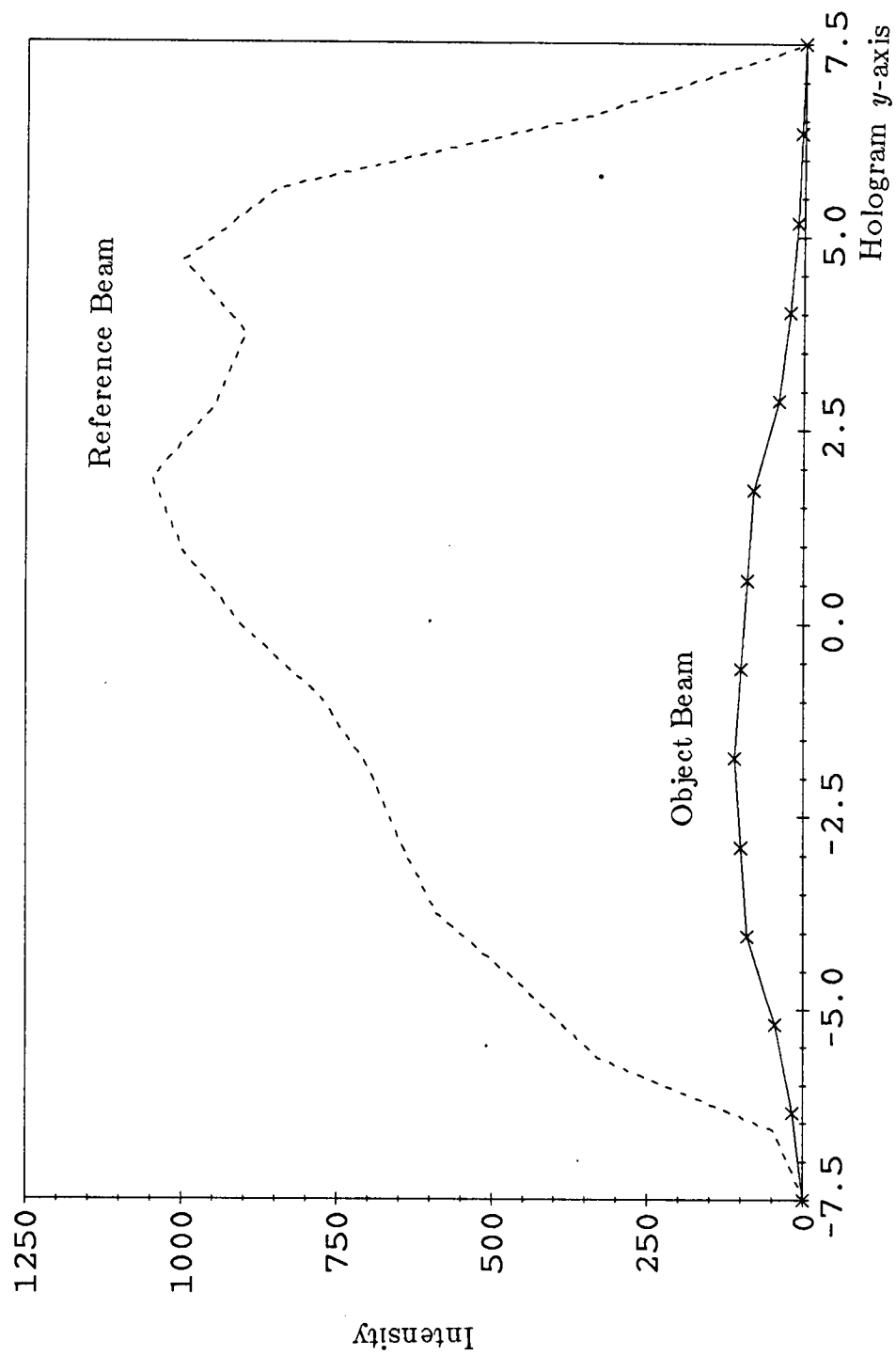


Figure 5.2. Intensity distribution of object and reference beam on the hologram plane.

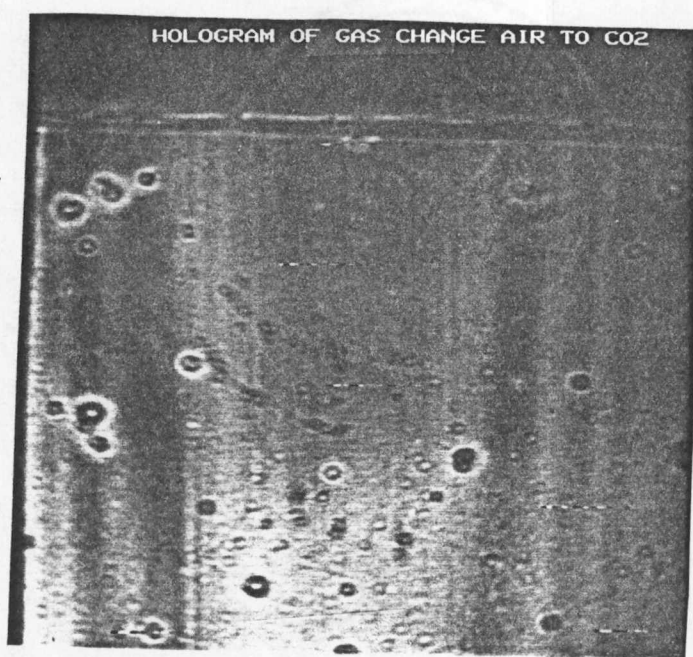


Figure 5.3. Photographs of Hologram.

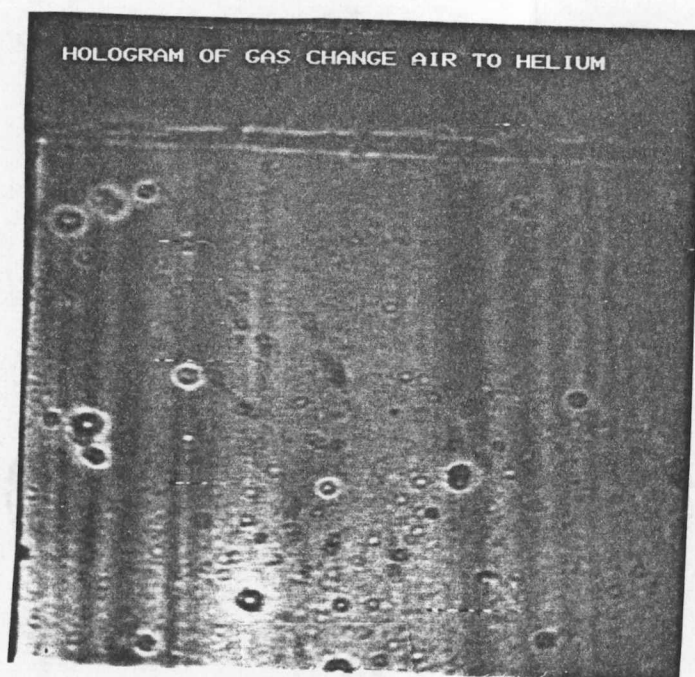


Figure 5.3. (Continued)

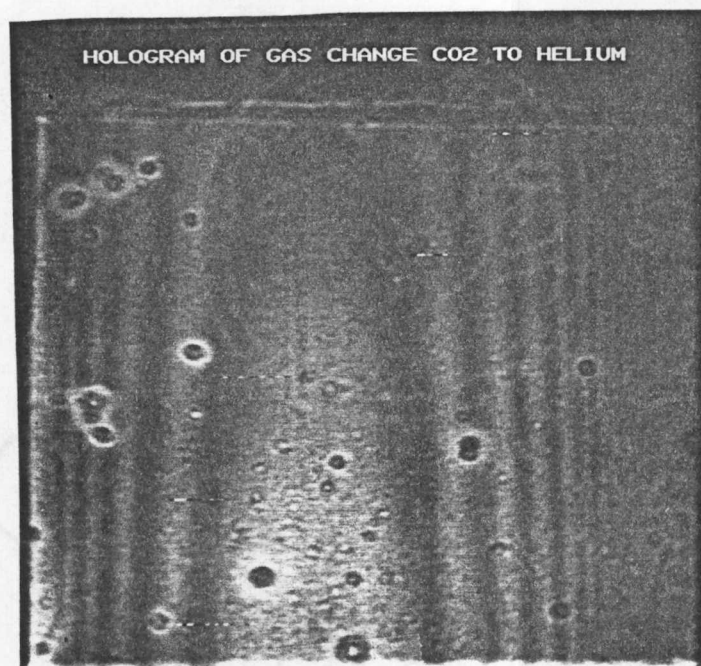


Figure 5.3. (Continued)

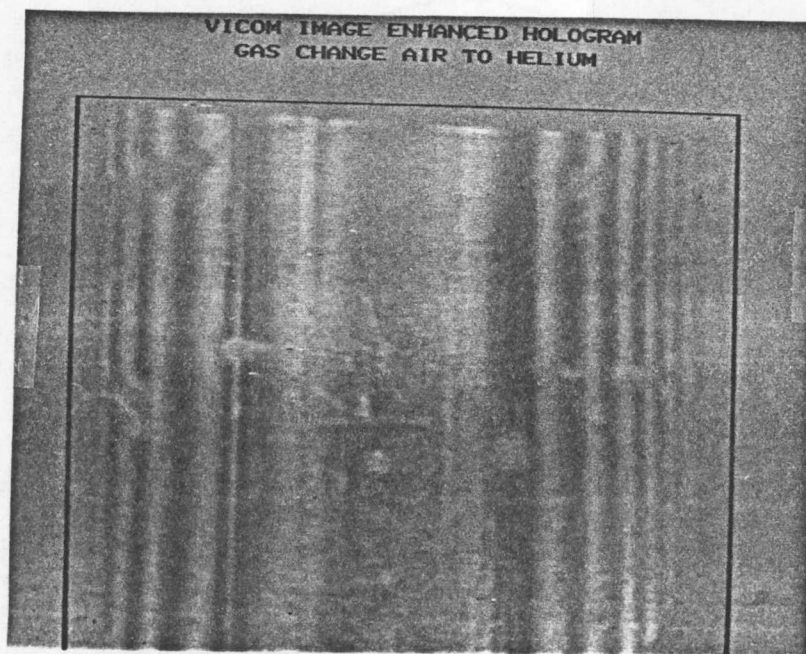


Figure 5.4. Image Enhanced Hologram.

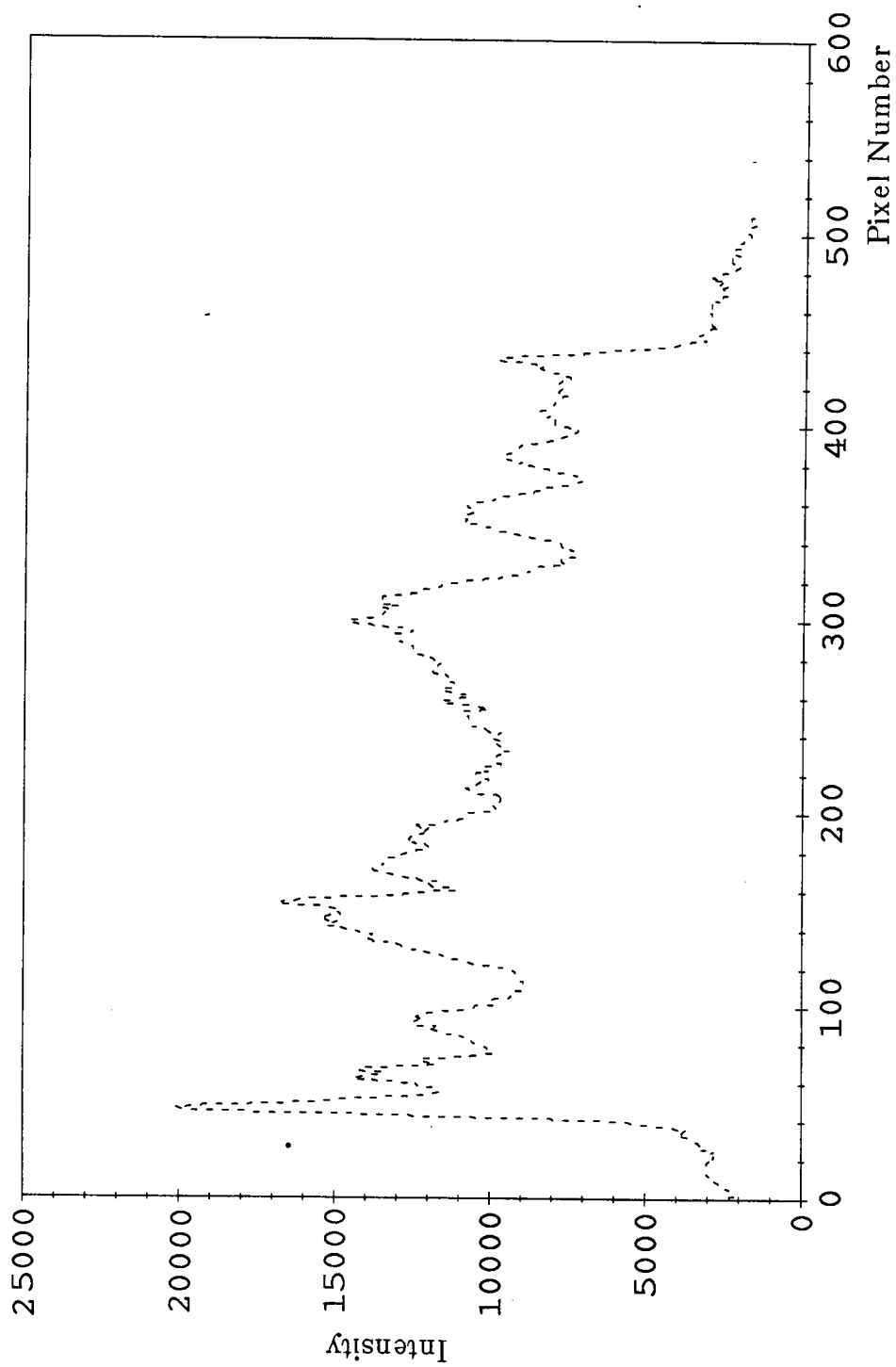


Figure 5.5. Intensity distribution of Row 200 as a function of pixel number.

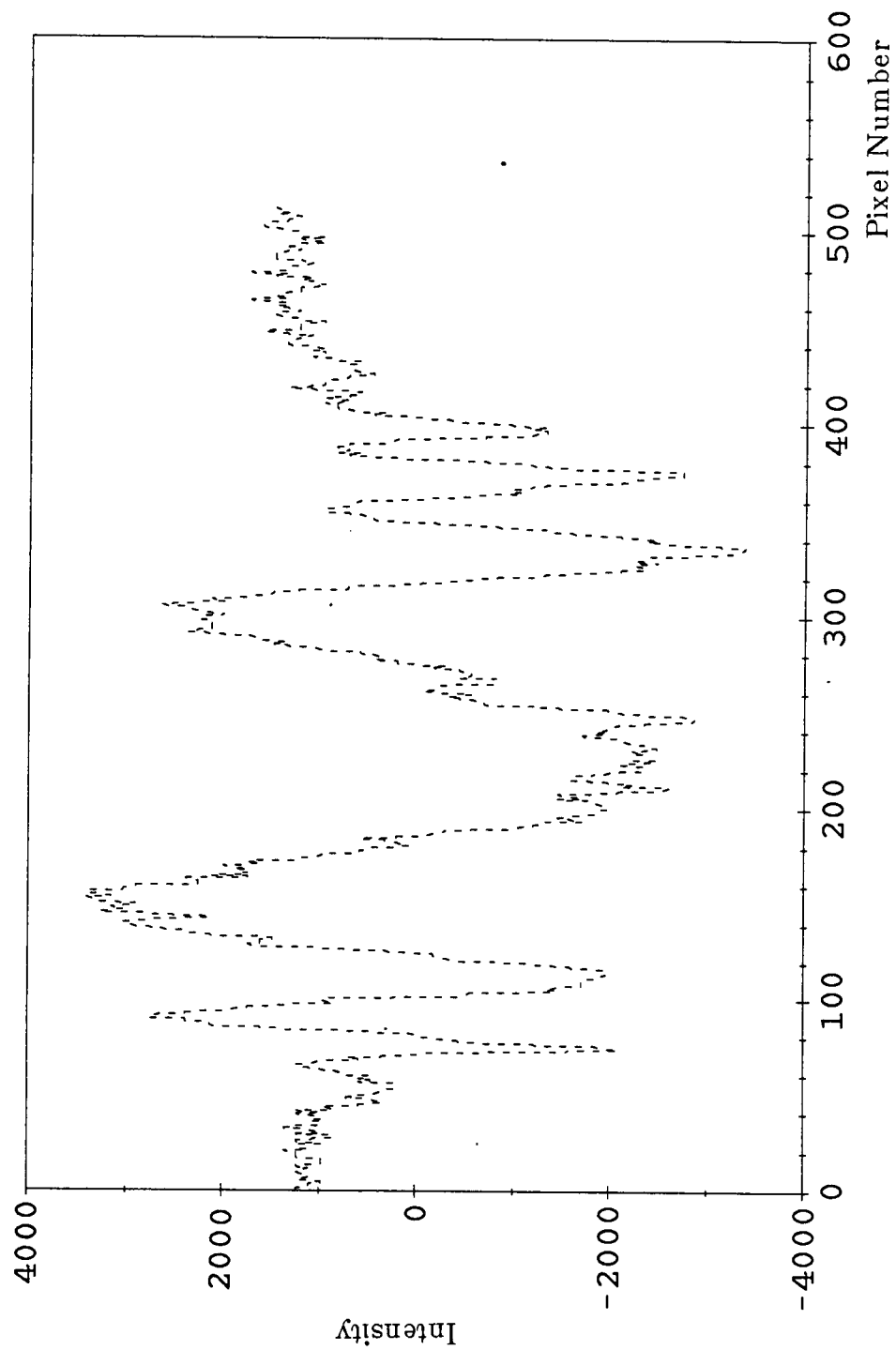


Figure 5.6. Row 200 of background subtracted hologram as a function of pixel number.

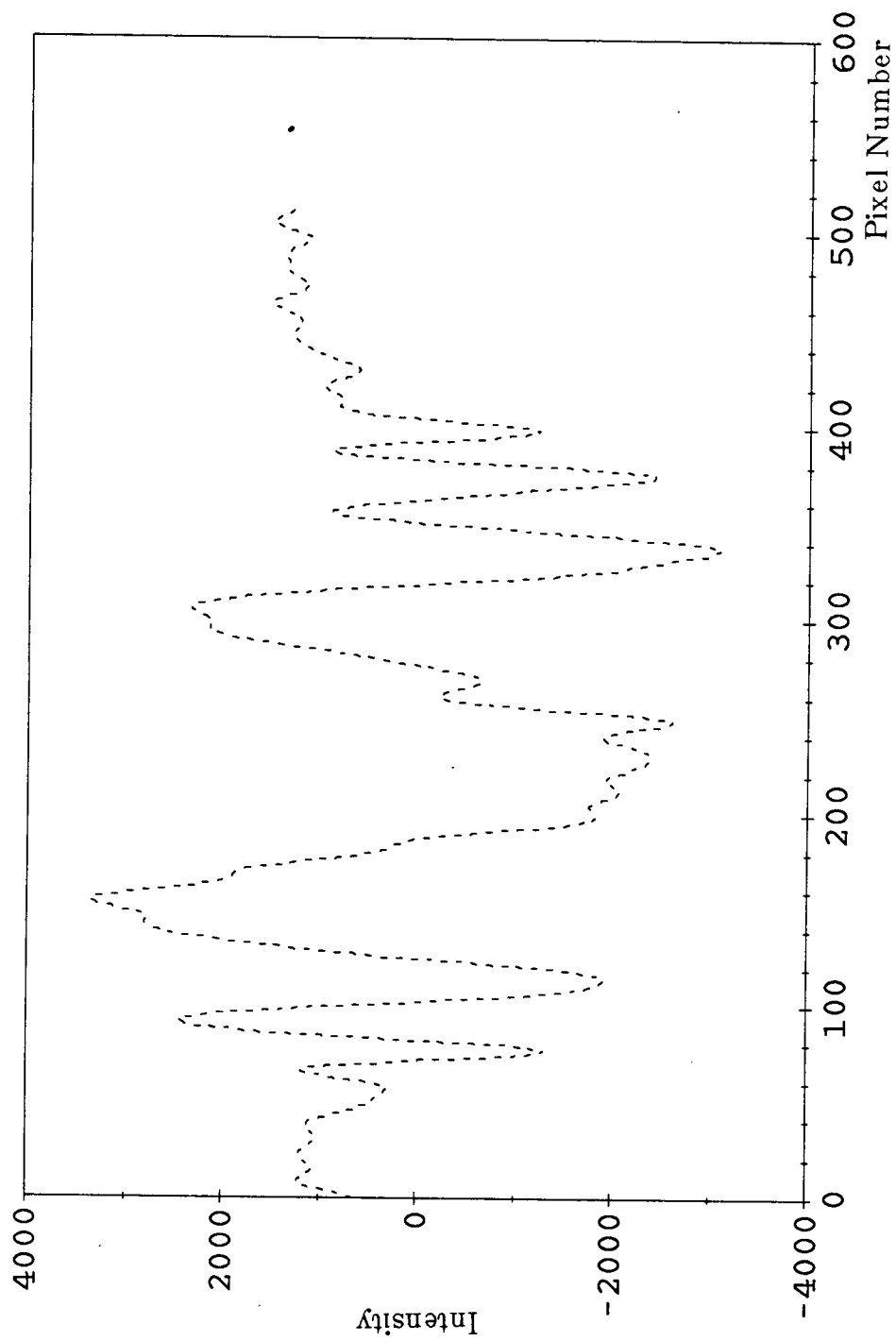


Figure 5.7. Row 200 of low frequency filtered hologram as a function of pixel number.

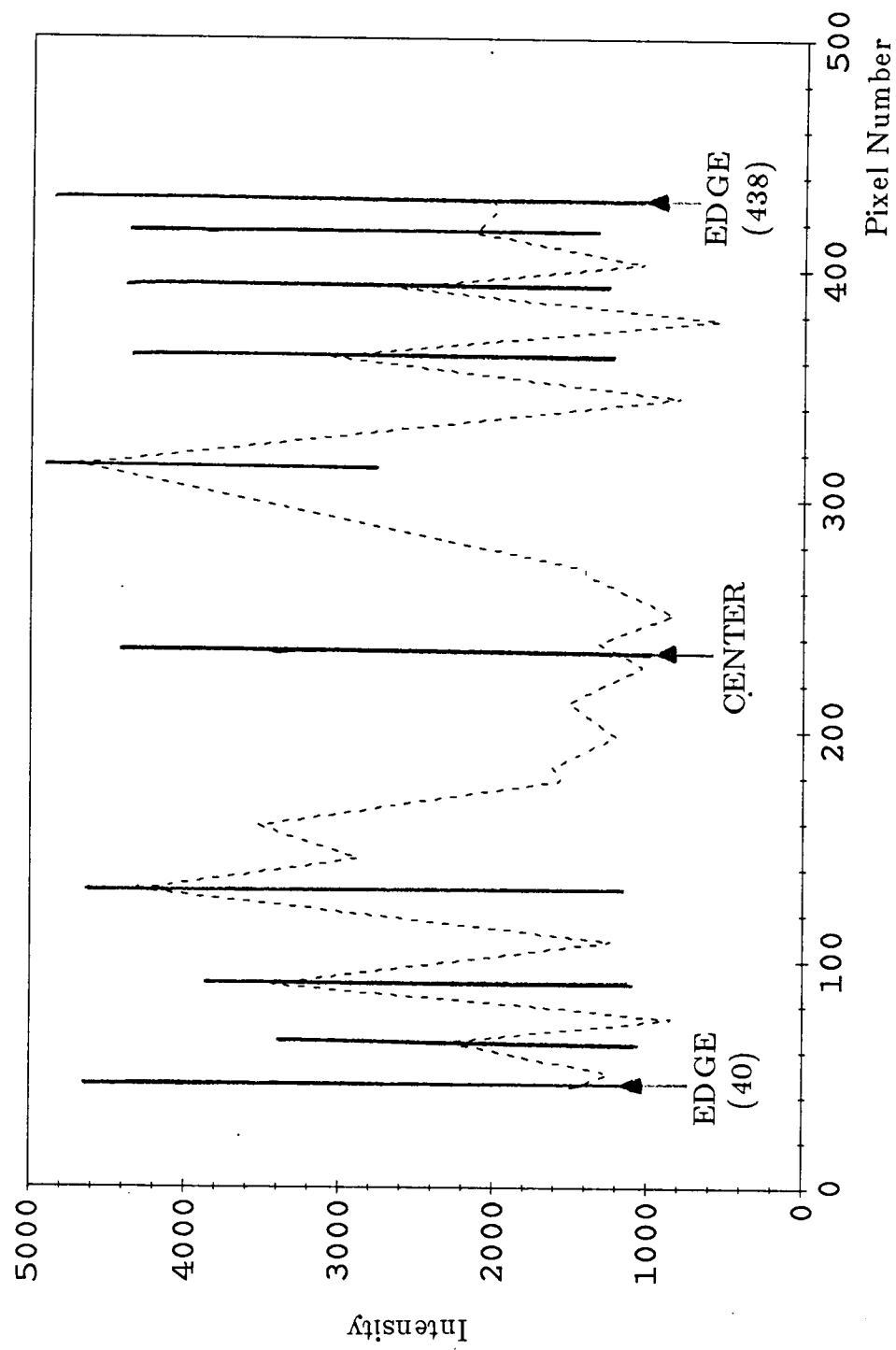


Figure 5.8. Fringe maximum points and fringe spacing plot

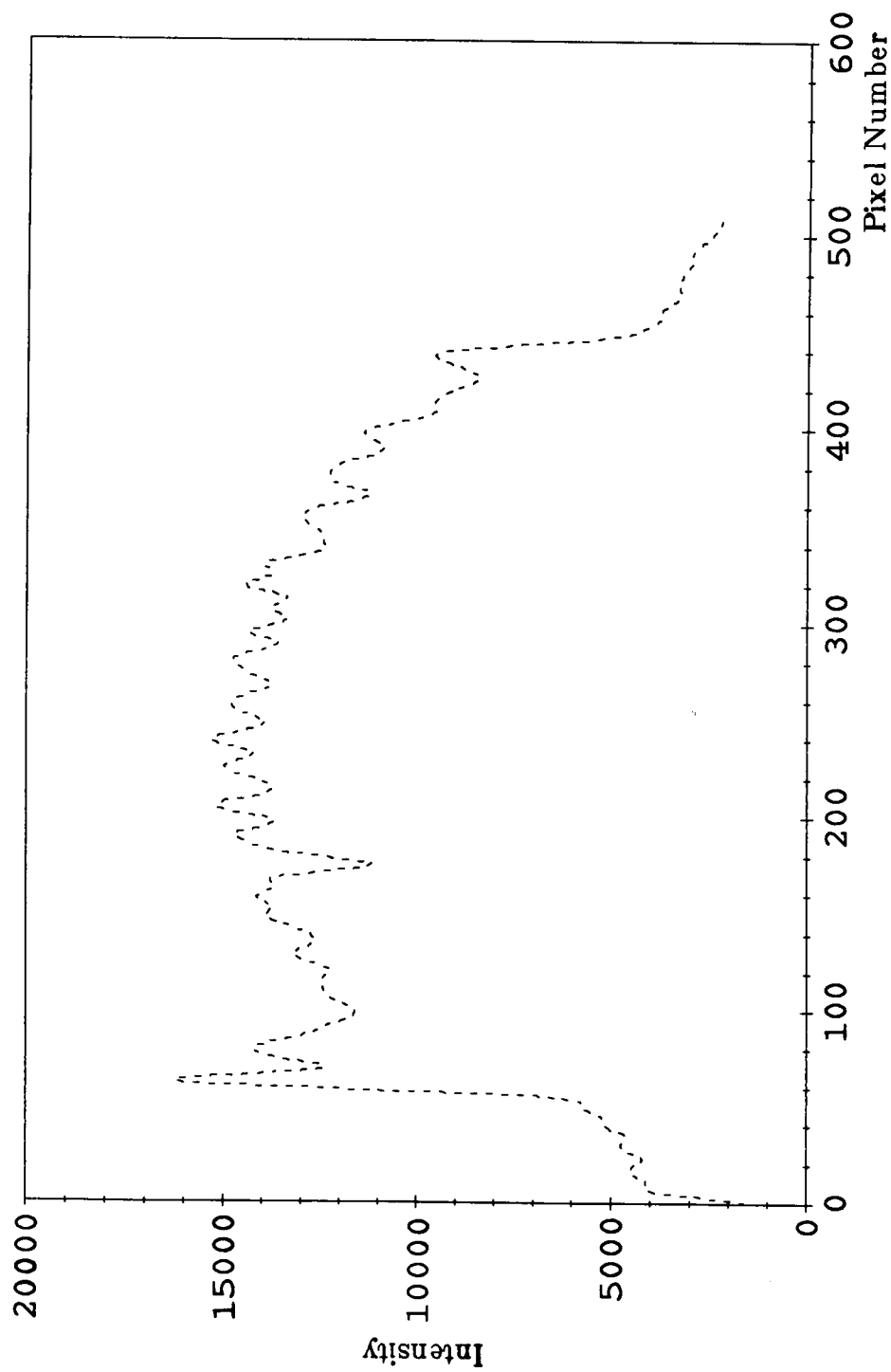


Figure 5.9. Calibration image as a function of a pixel number.

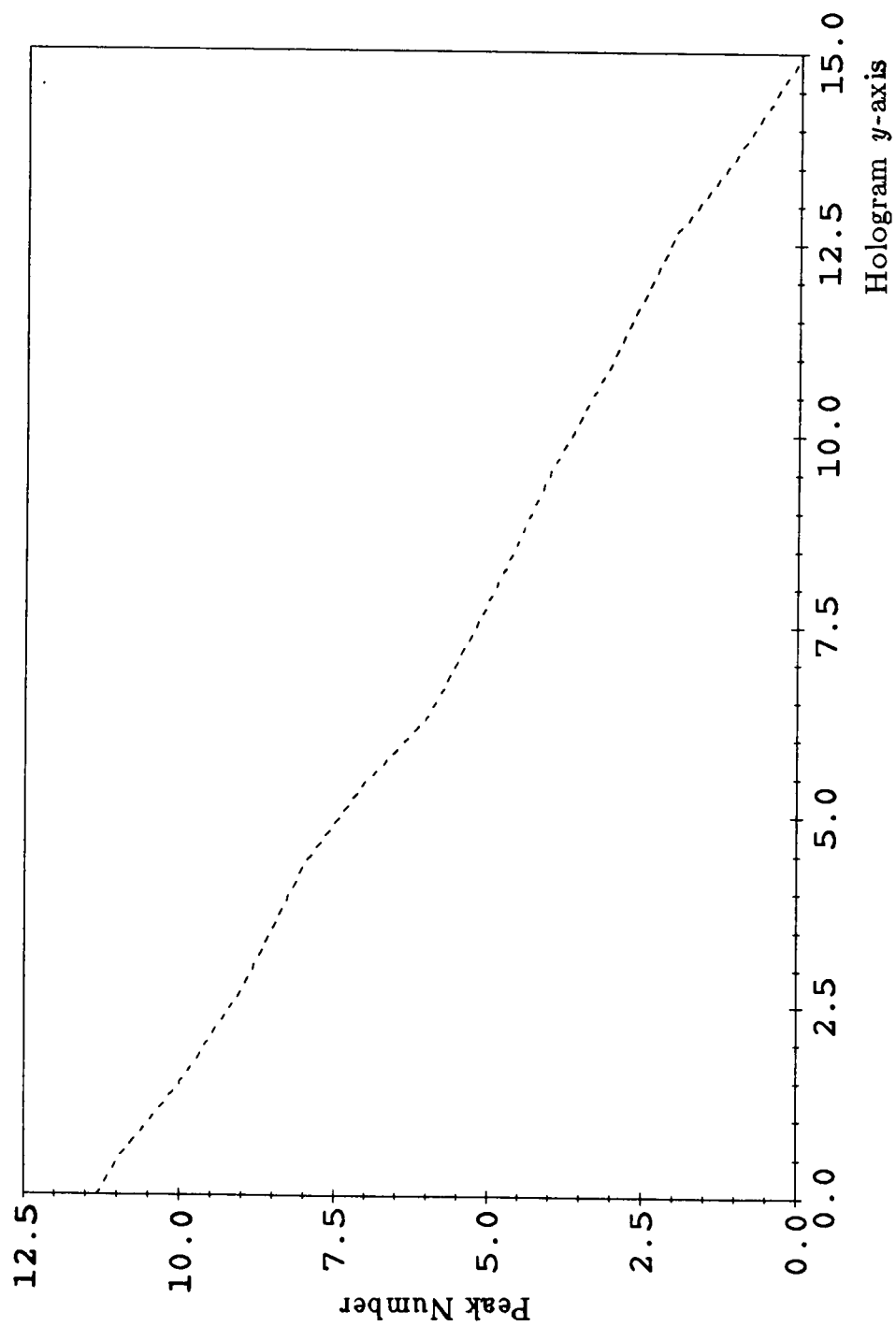


Figure 5.10. Calibration curve as a function of hologram y coordinate.

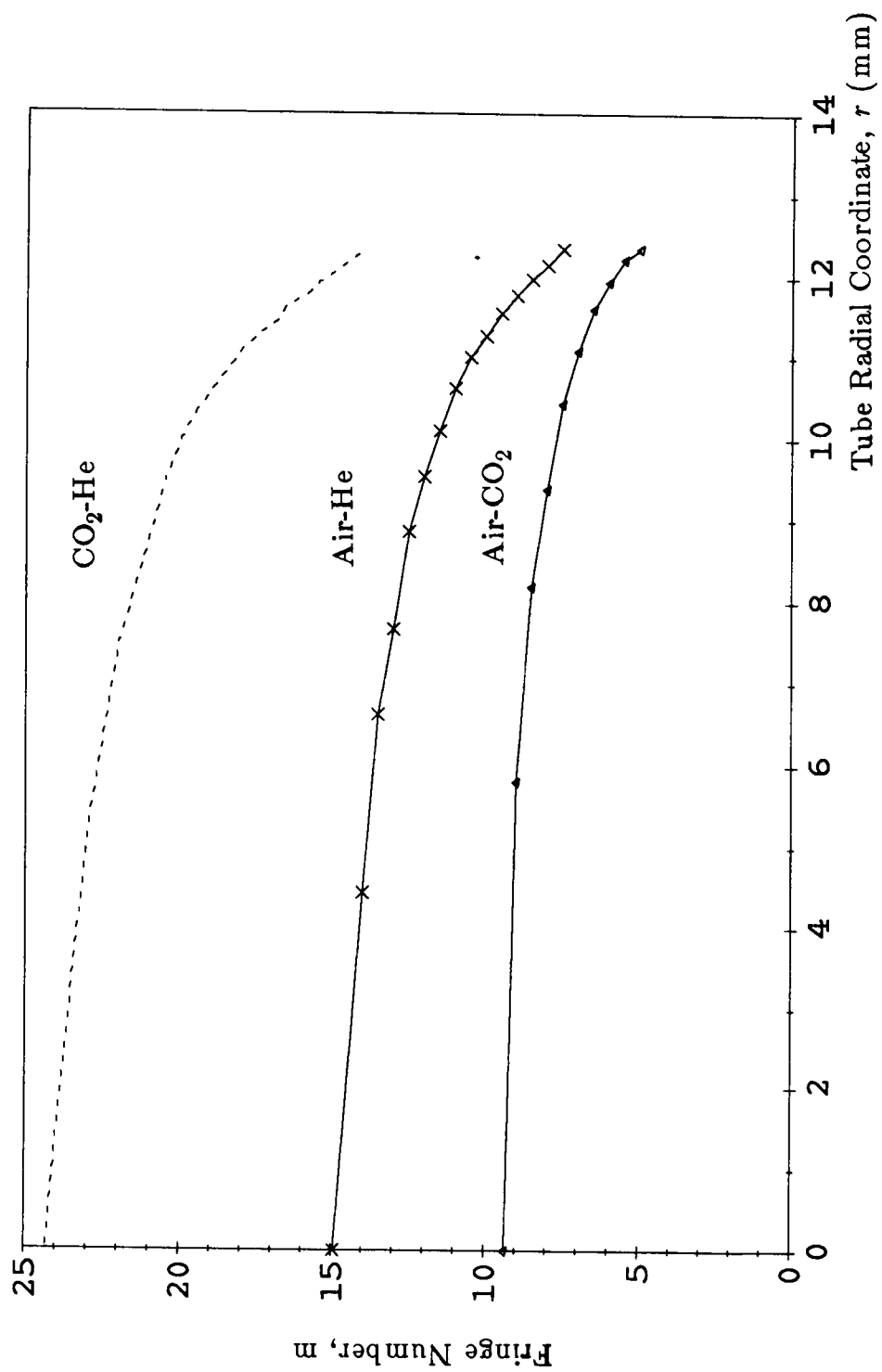


Figure 5.11. Fringe number distribution as a function of a tube radial coordinate.

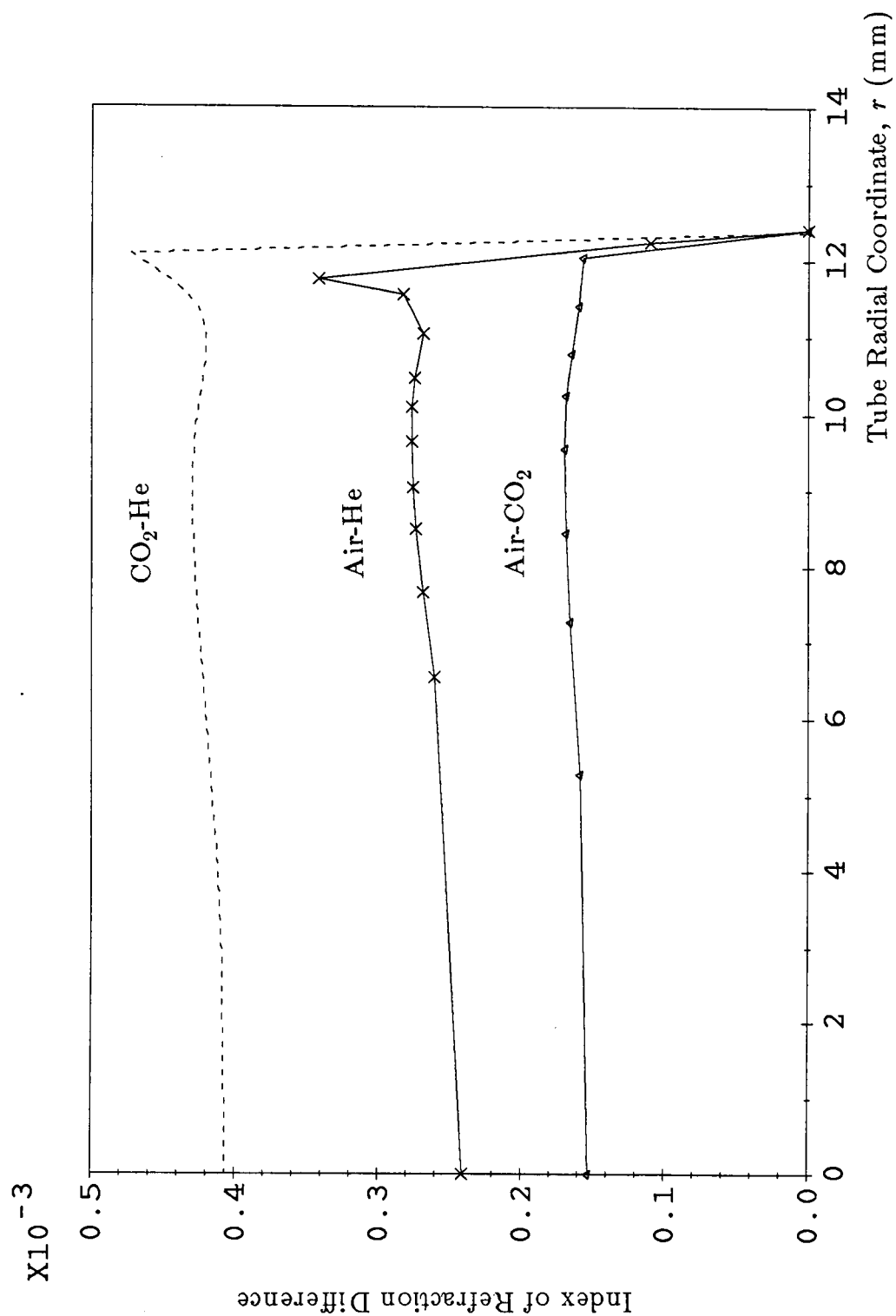


Figure 5.12. Reconstruction of index of refraction change as a function of radial coordinate.

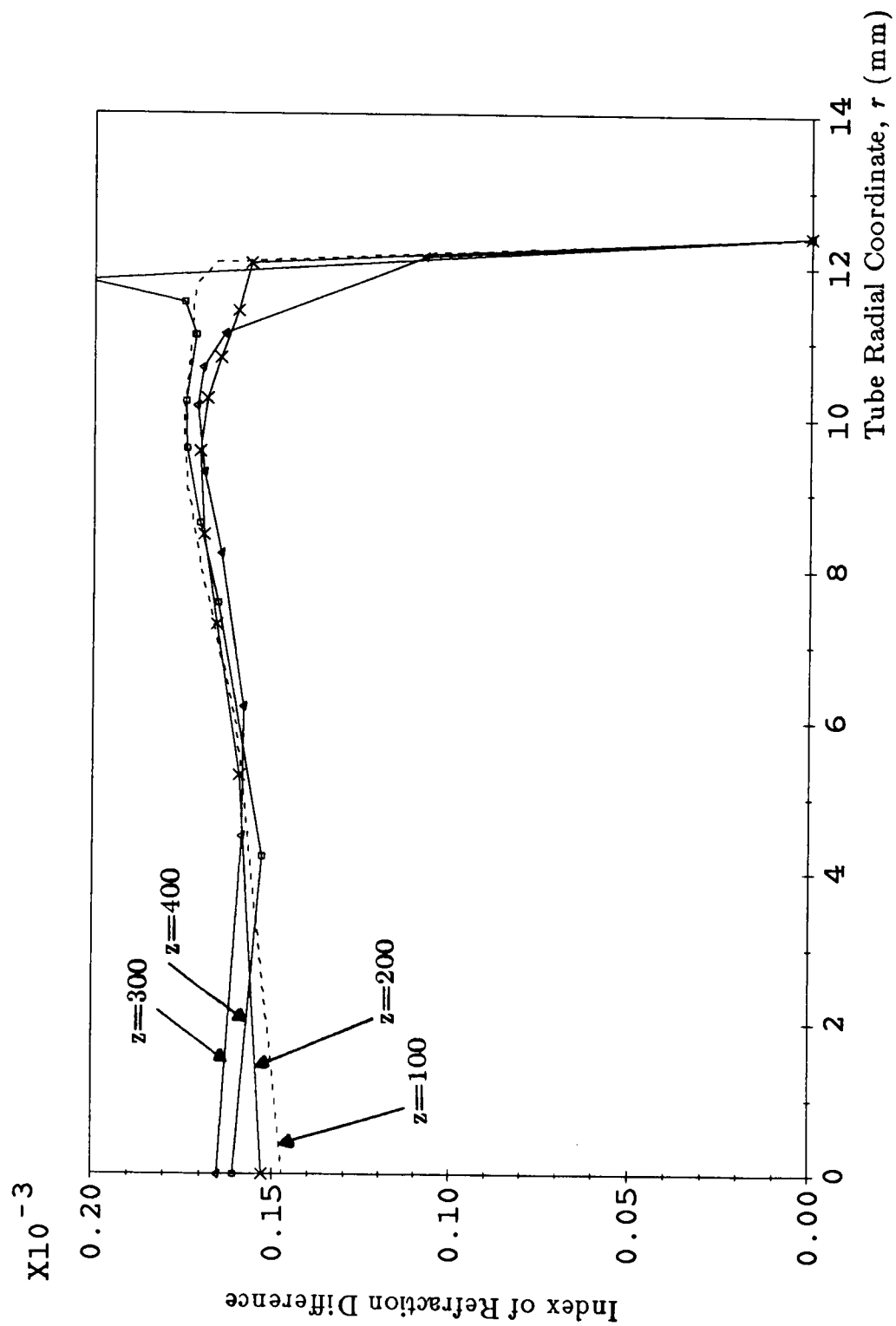


Figure 5.13. Reconstructions of the index of refraction change as a function of radial coordinate.

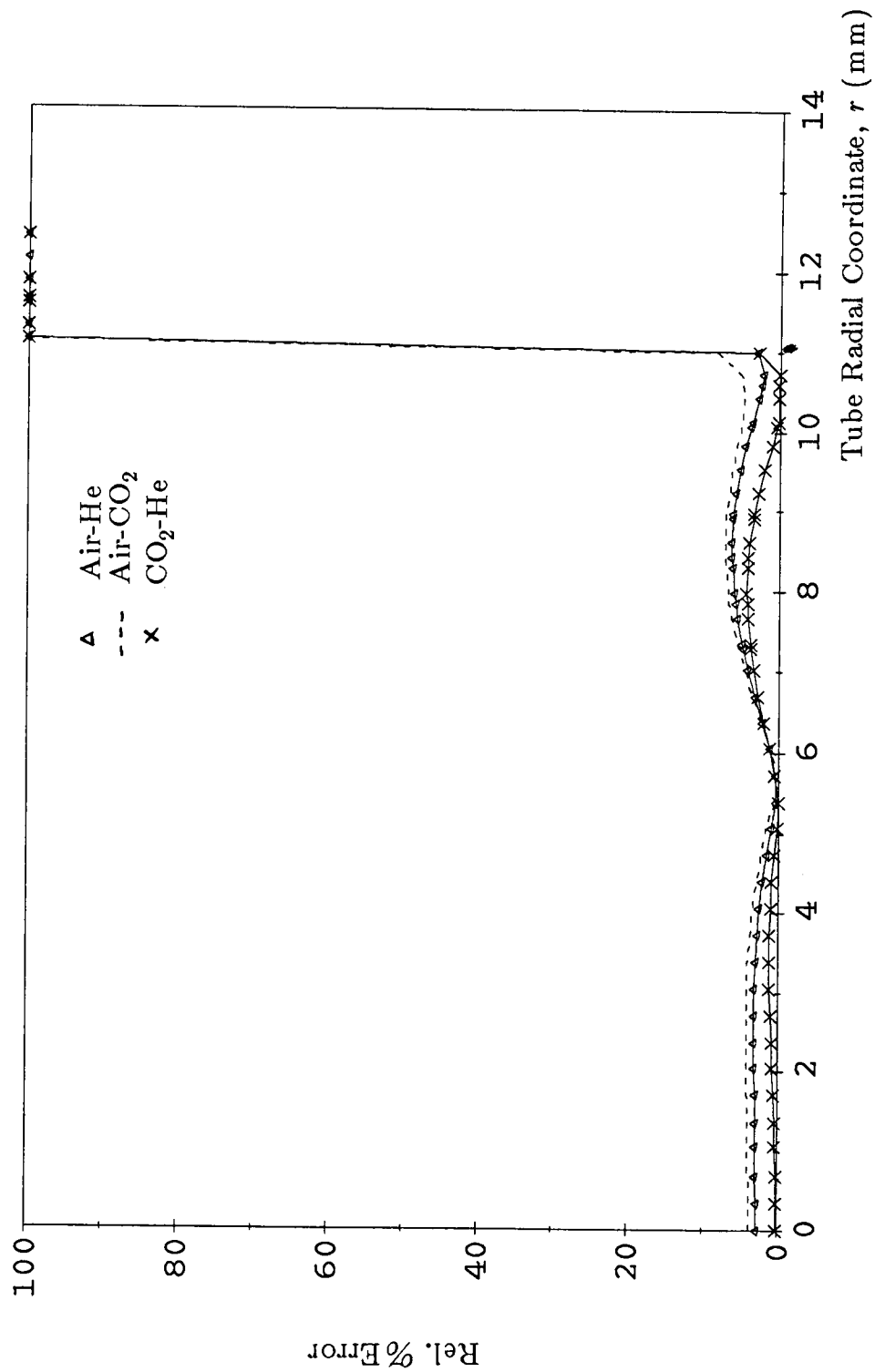


Figure 5.14. Relative error distribution of experimental reconstruction as a function of tube radial coordinate.

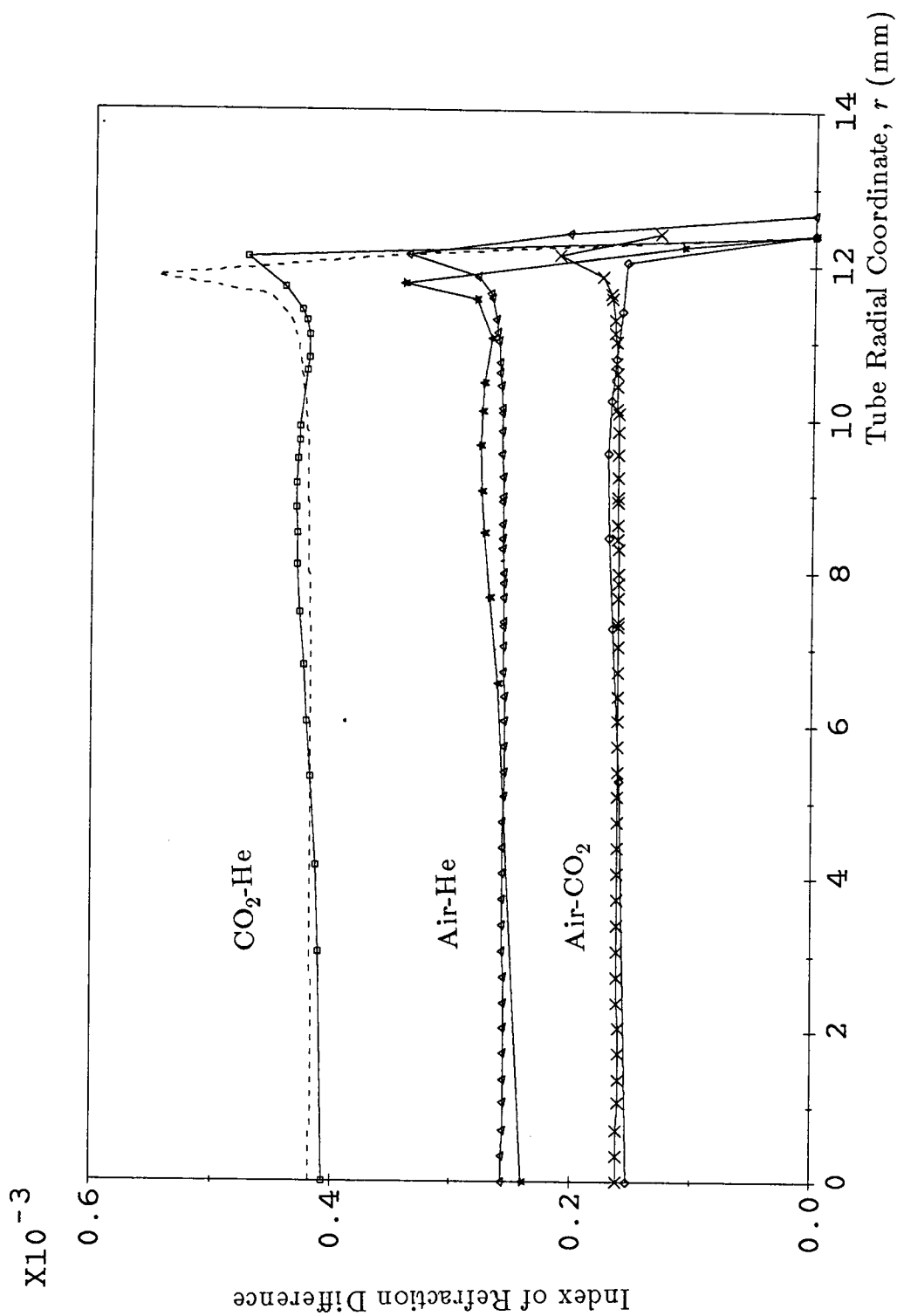


Figure 6.1. Reconstruction plots of Numerical Simulation and the Expected Value and the Expected Value as a function of tube radial coordinate

VITA

Heung Cheon Paik was born in Seoul, Korea, on December 14, 1961. After attending elementary and jr. high school in Seoul, he graduated from W. T. White High School in Dallas, Texas in 1980. He attended The University of Dallas until 1984, graduating with a Bachelor of Science in Physics. Mr. Paik continued his study of Physics at The University of Tennessee Space Institute, where he was awarded the Master of Science degree in Physics in August, 1986.