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Some applications of holography at the Idaho National Engineering Laboratory*

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Abstract

A project was recently completed that investigated possible uses of holography in the nuclear reactor safety program. A portable holographic camera which uses a pulsed ruby laser for illumination was constructed and used in various studies, including several designed to clarify the properties of steam/water mixtures that occur during loss-of-coolant accidents in nuclear reactors. The flexibility of the cameras's optical configuration also enables it to produce holographic interferograms, which have several advantages over conventional interferograms and which can be used to measure very small physical changes in a given environment.

Introduction

The Instrument Development Branch of EG&G Idaho, Inc., operating contractor for the Department of Energy's Idaho National Engineering Laboratory (INEL), recently investigated optical holography and related techniques to determine whether such techniques might be useful in characterizing various phenomena influencing nuclear reactor performance during accidents or other abnormal operating conditions. Many potentially severe accidents involve failure of the primary coolant system which leads to extremely complex two-phase (steam/water) flows and the resultant problems of heat and mass transfer between phases. We decided that useful data might be obtained from holograms in several areas:

1. Visualization of complex two-phase flow systems. The three-dimensional nature of holographic images coupled with the brief exposure times characteristic of pulsed lasers provides information not easily derived from more traditional imaging techniques.

2. Holographic interferometry. The possibility of using holographic interferometry to record the thermal environment near the steam/water interface[1] provides a tool to evaluate details of the heat transfer process. Such information would improve the basic understanding of phase change phenomena, and ultimately, would improve the reliability of computer codes which have been developed to evaluate reactor performance during loss-of-coolant accidents.

3. Nondestructive evaluation of various reactor components, such as fuel rods, piping, and pumps.[2]

In response to these considerations, we acquired the necessary expertise and equipment to produce holograms. A portable holographic camera was designed and built, incorporating a 750-mJ, double-pulsed ruby laser. This camera was subsequently used in several studies over the past two years. Some of the results of these studies are reported in this paper, and the equipment is briefly described.

The portable holographic camera

A portable holographic camera must have these basic features:

1. A suitable laser to create the highly coherent, nearly monochromatic light required to record the hologram; and associated optics required to expand the laser beams to whatever diameter required by the experimental arrangement.

2. A holographic plate holder which excludes most ambient light but permits the laser light to enter and strike the sensitive plate. Again, a certain number of optical components are required to control and position the light.

3. The system must be compact enough to be transported relatively easily and stable enough to maintain critical optical alignments during transportation.

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INEL's portable holographic camera system was jointly designed by J. D. Trolinger of Spectron Development Labs and staff members of EG&G Idaho, Inc. The camera incorporates a 750-mJ Apollo ruby laser capable of being pulsed twice per charge cycle with a maximum 1-s automatic delay between pulses. The camera consists of two parts: a light source containing the ruby laser and associated optics (Figure 1), and a receiver (Figure 2) which holds the holographic plate and any necessary optics. Both parts are built around appropriately sized optical breadboards with magnetic steel mounting plates drilled and tapped at regular intervals. Both units are covered by light-tight enclosures which have various hinged sections to provide access. This design permits great flexibility in modifying the optical arrangement to suit the particular application. At present, as many as three mutually coherent collimated beams, up to 150 mm in diameter, can be simultaneously produced. The hologram holder has a solenoid-operated shutter to limit plate exposure from extraneous light, and filters can be used to further restrict exposure to those wave-lengths near the laser line. A 10-mW HeNe alignment laser is used to correctly position experimental components in the laser beam and can also be used to reconstruct holograms in the field.

Reconstruction system plate holder and positioner

A view of the reconstruction system appears in Figure 3. The holographic plate is held in a yoke which permits the long axis of the 4 x 5-in. plate to be vertical or horizontal, depending its orientation during exposure. This yoke can be rotated about two orthogonal axes while rotation about the third axis is performed by tilting the entire assembly. The plate holder can be translated both vertically and horizontally (along the image x and y axis) by stepping motors turning lead screws which engage nuts in the mounting stages. A third motor-driven slide carries an optical sensor or recording device such as a 35mm, 4 x 5, or video camera, which can be moved along the z axis to provide records of the various x-y planes in the three-dimensional holographic image. The x, y, and z axis positions are read from a linear optical encoder which is accurate to 0.00025 cm. The optical encoder readings are transmitted to a microprocessor which also controls the various positioning motors.

Applications

The portable holographic camera has been used in a number of studies, including two which required moving the equipment to field locations. These moves were made by truck over rough roads, but the equipment required only minor adjustment of the beam-directing optics. The laser oscillator cavity, the part most sensitive to misalignment, was unaffected.

Some of the recent applications of holography at INEL consisted of observation of non-equilibrium vapor generation in a nozzle, studies of the plasma surrounding a welding arc, studies of various two-phase flow regimes, and development of holographic interferometry for use in two-phase measurements. In this section, several of the applications of holography at the INEL are briefly described and some results presented.

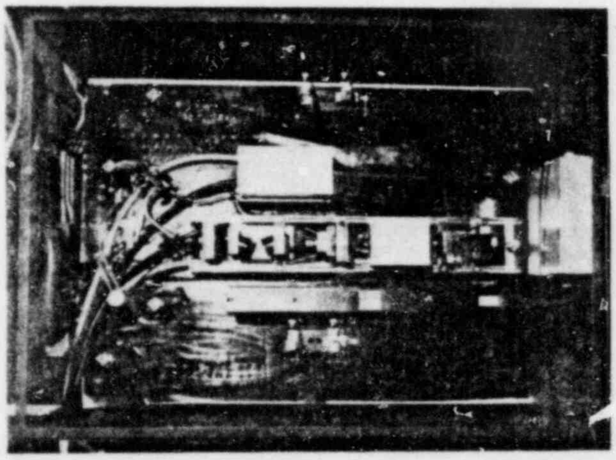

Figure 1. The transmitter assembly.

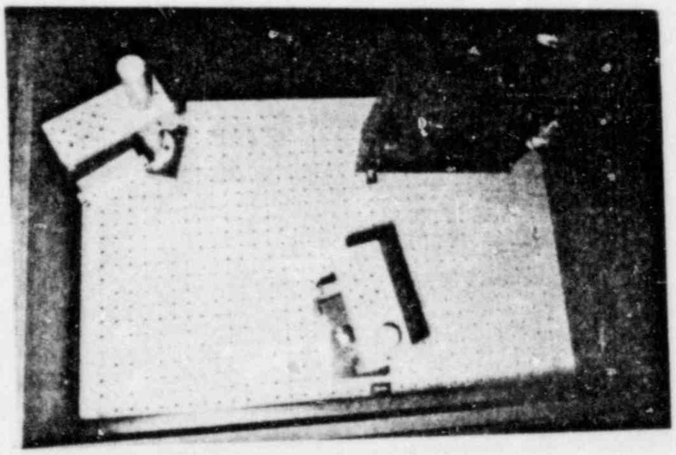

Figure 2. The receiver assembly.

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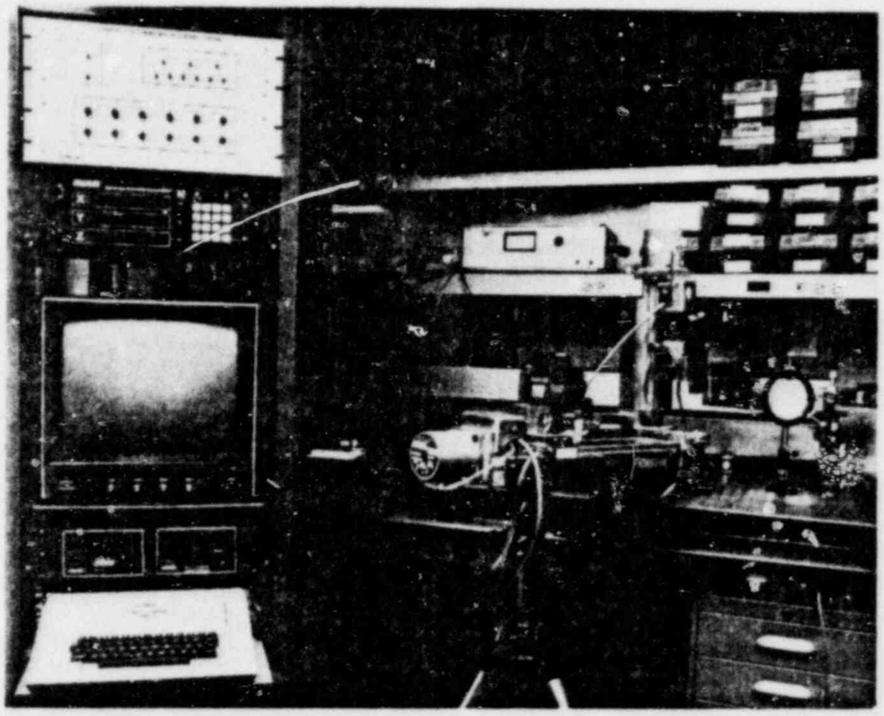

Figure 3. Hologram reconstruction system.

Nonequilibrium vapor generation in a two-dimensional nozzle

As part of a study of flow characteristics in nozzles similar to those used in Semiscale and LOFT,* a two-dimensional converging-diverging nozzle was constructed from transparent plastic. The upper and lower contours were similar to the Henry's nozzles used in Semiscale, while the front and back surfaces were flat. This design eliminated image distortions caused by vapor near the walls and by wall curvature. The object beam was directed through the flat sides of the nozzle while the reference beam passed around. Figure 4 shows the experimental setup and Figure 5 is a conventional photograph of the nozzle. Figure 6 shows an overall view of the nozzle and several details of the cavitation region. All of these views were photographed from the original holographic image with varying degrees of magnification. Figure 7 shows a short cavitation bubble which collapses just after leaving the throat. This work is fully reported in References 3 and 4.

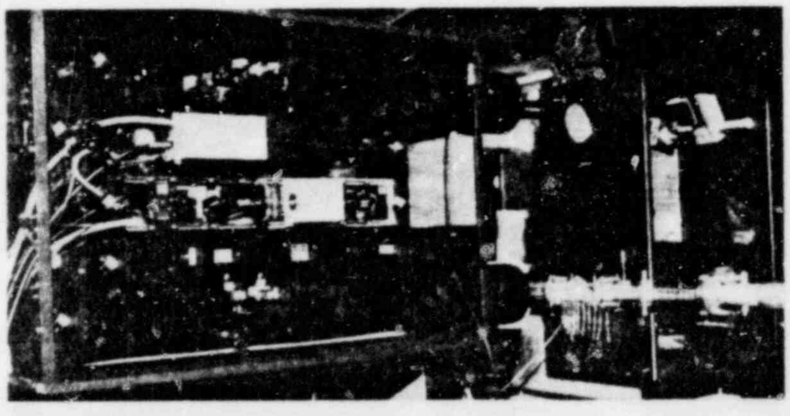

Figure 4. The holographic camera system.

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* The Semiscale facility is a small-scale, electrically heated reactor coolant-system simulator. The Loss-of-Fluid Test (LOFT) facility is a 50-MW test reactor. Both are located at INEL.

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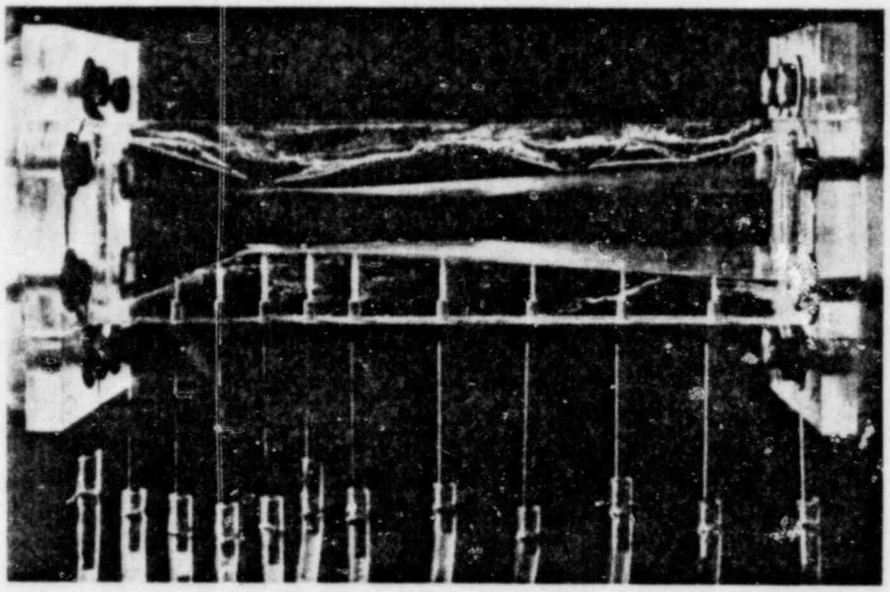

Figure 5. The two-dimensional nozzle showing vapor generation on top and bottom nozzle contour surfaces.

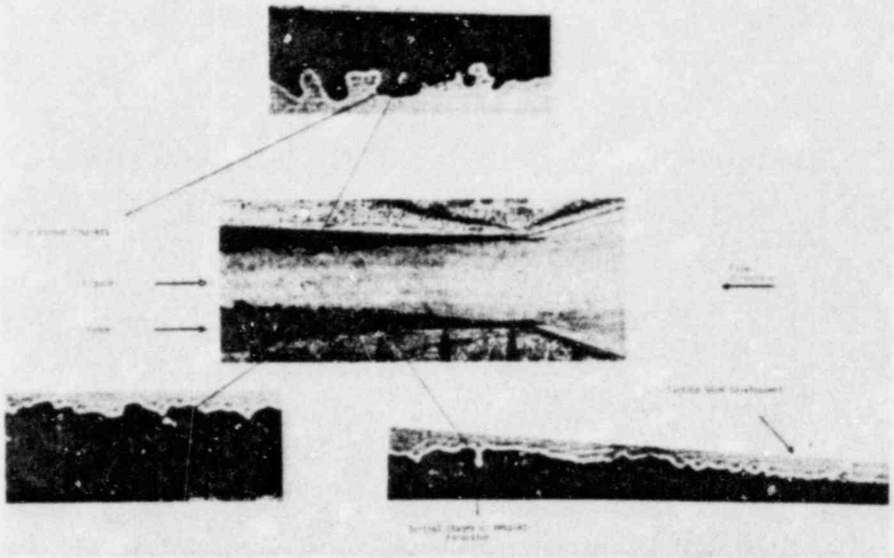

Figure 6. The full cavitation bubble with details.

Holography of air/water two-phase flows

An early application of holography in this program involved making pulsed ruby-laser holograms of air/water mixtures flowing in a rectangular plastic pipe. A holographic camera rented from Spectron Development Labs and operated by Dr. Trolinger was used in this study. We were interested in determining bubble shapes and distributions for various flow regimes as well as which flow conditions might prove to be too optically opaque to make usable holograms. Figure 8 shows photographs of a typical air/water mixture. For dispersed bubble flows up to a maximum void fraction of 0.2, image quality was satisfactory. Above 0.2, image quality was unsatisfactory, except for bubbles close to the near wall. This image degradation was due to multiple reflections from bubble air-water interfaces. Figure 9 shows the results of double-exposing a hologram with a 50-μs delay between exposures. The double image permits the velocity of each bubble to be measured since the bubble displacement can be directly measured, and the time interval is known.

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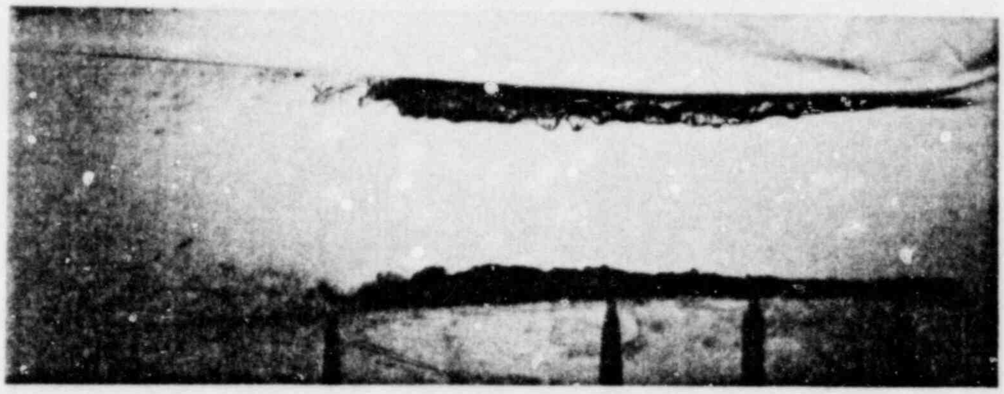

Figure 7. A short cavitation bubble showing bubble collapse.

Figure 8. Holographic view of air/water flow.

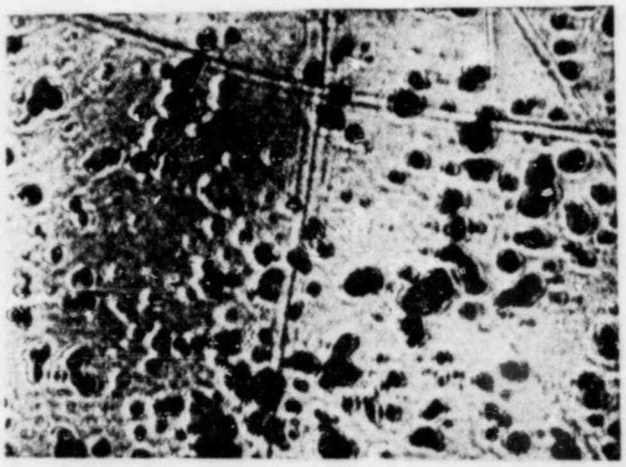

Figure 9. A double-exposed hologram of two-phase bubbly flow.

Steam bubble growth

Holograms were made of the early stages of steam bubble growth in superheated water as support for a bubble dynamics project.[5] The steam bubbles were generated on electrically heated, 75-μ-diameter platinum wires immersed in room-temperature water under reduced pressure. Figure 10 shows a double-exposed hologram of two steam bubbles, one still on the wire and growing, and a second which has released from the wire and is rising under buoyant forces. The interval between exposures was 50 μs. The technique permits a detailed study of steam bubble shape and growth due to the high spatial resolution of the image, the excellent time resolution of the 20-ns laser pulse, and the three-dimensionality of the image. Figure 11 is a holographic interferogram of a steam bubble growing on a 75-μ platinum wire. The fringes surrounding the wire indicate a local region with temperature greater than the bulk temperature. The lack of fringes near the bubble indicates that the bubble temperature differs by less than 0.5°C from the bulk temperature, consistent with the fact that the test cell was operating very near saturation.

Holographic interferometry

A major objective of INEL's holography project has been to exploit the unique advantages of holographic interferometry. A particular advantage of holographic interferometry is the relaxation of the stringent quality requirements for optical components compared with those used in conventional interferometry. Also, under certain experimental conditions, the density distribution can be constructed in three-dimensional form from the complex interference fringe structure recorded on the hologram. This technique is analogous to the computerized tomography used in medical and other applications. Until recently, inversion routines were not available at INEL to compute temperatures from interferometric data. However, a small subcontract was given to Dr. C. M. Vest at the University of Michigan to determine the most advantageous data conversion scheme for temperature measurements near a

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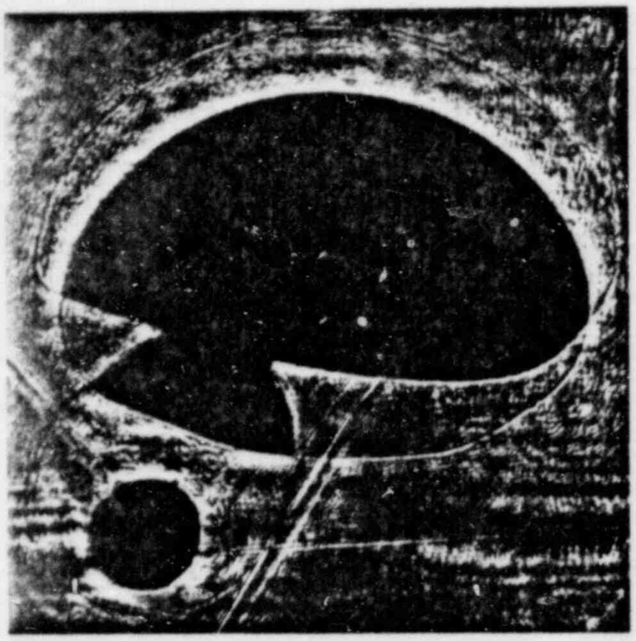

Figure 10. A double-exposed hologram of steam bubbles.

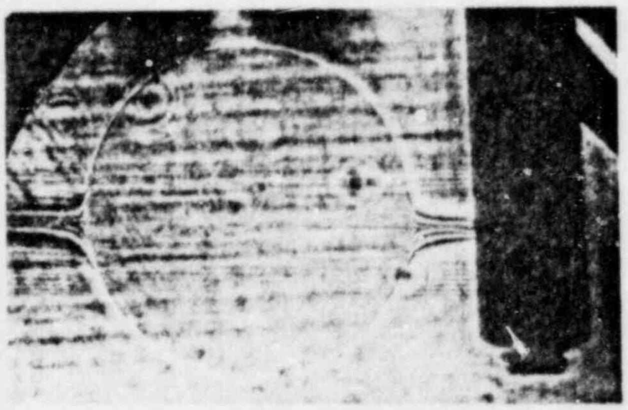

Figure 11. Holographic interferogram of growing steam bubble.

steam bubble. A scheme based on the Abel transform was developed for cases where the temperature distribution is nearly radially symmetric. Further work is necessary before a general asymmetric temperature distribution can be analyzed.

The portable holographic camera was also used in an effort to determine if holographic interferometry could be used to analyze the internal structure of a welding arc plasma. In this study, the intense light produced by the plasma was a significant problem. The solution involved shuttering to limit the time during which the holographic plate was exposed to ambient light; the actual exposure to make the hologram was only the 20-ns ruby pulse, but the plate was open to the plasma light for a far longer period of time. To further reduce the plasma light, a Schott colored glass edge filter was used which passes light with a wavelength near that of the ruby laser output (694.3 nm). A narrow-pass interference filter was also used. The equipment arrangement is shown in Figure 12 and an example of an interferogram is presented in Figure 13. Note that the plasma is almost transparent to the ruby light as evidenced by the relatively minor distortions in the

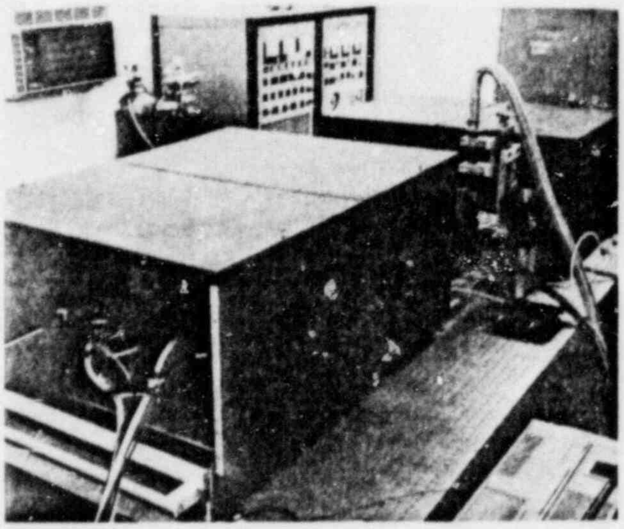

Figure 12. Experimental arrangement for holography of welding arcs.

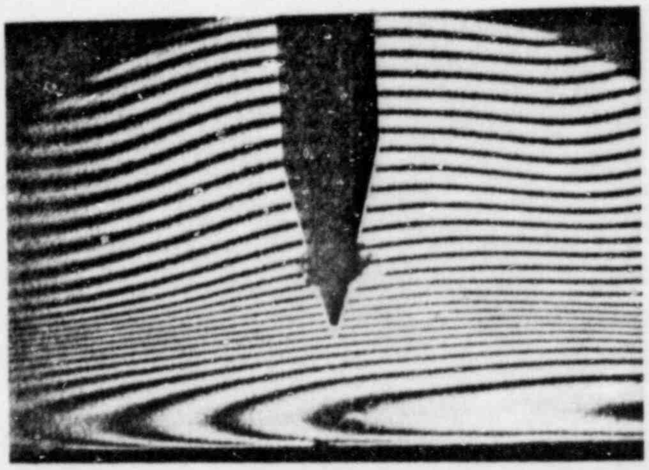

Figure 13. An interferogram of the welding arc plasma.

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normally parallel reference fringes, in spite of the several-thousand-degree temperature difference between the surrounding air and the interior of the arc plasma. As a result of these findings, it was decided to perform the measurements with the shorter wavelengths available from an argon ion laser, since sensitivity to density changes increases with decreasing wavelength. Also a technique known as double-pass interferometry, in which the light is directed through the test region twice along the identical path, can be utilized to double the sensitivity to density changes. This study is currently being pursued by the INEL's Materials Technology group.

Future work

At present, the holography effort at INEL is relatively inactive; one group is pursuing the study of welding arcs using holographic interferometry. A major problem with all optical techniques that require optical access to the reactor coolant system has been survivability of the window material. Considerable work has been done already at INEL on possible window materials; spinel (magnesium-aluminum oxide) and titanium dioxide have shown promise of long-term (hundreds of hours) survivability in high-temperature (350°C), high-pressure (15 MPa), chemical-laden water typical of reactor coolant systems.

The lack of available data on the refractive index of water at elevated temperatures has hindered full analysis of interferometric data taken at reactor operating conditions. Researchers at INEL are currently preparing to measure the refractive index of water at high temperatures.

Conclusions

A portable holographic camera has been built which produces high-resolution images of both quiescent and rapidly changing events. Such images are three-dimensional, allowing for more complete analysis. Additionally, the camera can make holographic interferograms which have several advantages over conventional interferograms and which can be used to measure very small changes in a physical environment; changes in temperature, density, and position, for example.

The camera is designed to be extremely flexible in optical configuration, thus permitting one to tailor the configuration to the particular experiment being conducted. The ruby laser, which is the heart of the system, produces 750-mJ pulses with a pulse duration of 20 ns. It is also possible to fire the laser twice during a single charge cycle for purposes of interferometry. The delay between pulses can be varied between 1 µs and 1 s.

The portable holographic camera has already shown its value in a number of applications at the INEL, including two-phase flow studies and studies of steam bubble growth and interferometry. Further work is necessary to fully implement these techniques; a suitable window material must be found and data on the refractive index of water at high temperatures must be obtained.

Notice

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