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Technical Notes

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Application of Laser Holographic Interferometry to Temperature Measurements in Buoyant Air Jets

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Introduction

THE present work is concerned with the temperature measurements on a heated, round, air jet-like or plume-like flow using a real-time holographic interferometry. Buoyant jets and plumes occur in many environmental problems, from the discharge of thermal effluents into lakes or oceans, to the emission of hot gas in the atmosphere through chimneys. The study of jet- and plume-like flows has been a subject of investigation for almost a half-decade. In most previous investigations of buoyant air jets and plumes, temperatures were measured using intrusive apparatus, for instance, thermocouples[1] and the two-wire probes.[2] However, temperature distributions typically encountered in these kinds of flows are spatially and temporally variant and require measurements with high spatial and temporal resolution. Recognition of this need has resulted in a considerable effort toward development of a wide range of diagnostic techniques. Owing to current significant progress in the laser optical diagnostics, nonintrusive temperature measurements can be made by many techniques such as holographic interferometry, Mach-Zehnder interferometry, light-scattering thermometry,[3-5] and so forth. Among these nonintrusive techniques available for the experimental study of air jets and plumes, holographic interferometry has the capability for less expensive, in situ, planewise temperature measurements with high spatial and temporal resolution. It is this technique that is employed in the present work.

Experimental Facility

The test apparatus consisted of an air-injection nozzle pointing vertically upward within a screened enclosure (one layer of 24-mesh screen 500 mm square and 800 mm in height) to reduce the effect of room disturbances. The air was electrically heated and then passed through, in turn, a mixing chamber and a settling chamber before it was discharged into the still atmosphere to ensure the flow quality and temperature homogeneity at the exit of the nozzle. The inlet air temperature was measured at the exit end of the nozzle using a thermocouple. The flow rate of the discharge was measured by an area-type flowmeter.

The experimental setup for real-time holographic interferometry is shown schematically in Fig. 1. A coherent light (λ = 632.8 nm) was generated from a 5-mW He-Ne laser, and its intensity ratio of the reference beam to the objective beam was adjusted in a range from 1 to 4. A charge couple device (CCD) camera with exposure time of 30 ms was employed to record the holographic interferograms. A video digitizer with 512 × 512 resolution was used to digitize the interferograms, and then the sectional distributions of fringe number were obtained. The optical system was placed on a vibration-damped optical table while the vibration level of the optical table was monitored by using a Michelson interferometer.

Temperature measurements were also made by means of a 50-μm-diameter, bare wire K-type thermocouple. The thermocouple was mounted on a two-dimensional traversing gear that allowed it to be moved both horizontally through the flow to obtain the sectional profiles of air temperature, and vertically through the flow in the axial direction. The time response of this small-size thermocouple is not expected to play an important role in the temperature measurement. An effective integrating time of approximately 90 s was used to obtain time-mean values of the measured thermocouple temperatures. Repeatability tests showed that the errors were within 0.5% of the thermocouple temperatures. Temperature drops due to radiation loss over the temperature range of interest were negligibly small (less than 1 K or 0.2%); no corrections were made in the thermocouple measurements. These time-mean values obtained by the thermocouple are taken as a basis for comparison with the interferometric temperatures.

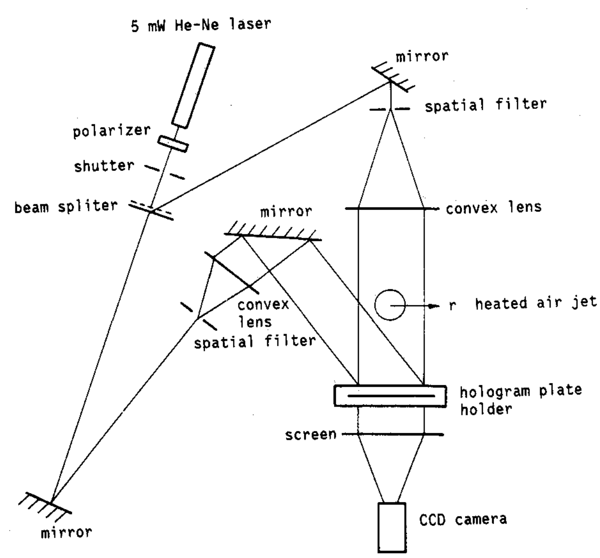

Fig. 1 Schematic of optical system of real-time holographic interferometry.

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Results and Discussion

The technique used to calculate the axisymmetric distribution of temperature from the planar interferogram can be found in Ref. 3, and is omitted here. The numerical method of Nester and Olsen[6] was employed for solving the Abel's inversion equation.

A fluid motion whose primary source of kinetic energy and momentum flux is a pressure drop through a nozzle is defined as a jet, whereas a fluid motion whose primary source of kinetic energy and momentum flux is from body forces is defined as a plume. Two test cases, one for plume-like and the other for jet-like flow, were selected to accomplish the purpose of this study and are summarized in Table 1.

The initial Richardson number determines if the flow is jet-like or plume-like at the origin. The value of Ri_0 is zero for a pure momentum jet, while Ri_0 is approximately equal to 0.3 for a pure round plume.[7] Since Ri_0 for case 1 is less than 0.3, it is then known that the heated air flow is a turbulent buoyant jet (or force plume) at the origin. Kotsovinos[8] has shown that any round buoyant jet becomes a fully developed plume at a distance where

$$z\sqrt{Ri_0}/D > 12.5$$

This distance is equal to 28.2 D and 75.4 D for cases 1 and 2, respectively. It is thus clear that the flow type of case 1 at the measured plane of $z = 0.04$ m (1.3 D) was plume-like. In contrast to case 1, the flow type of case 2 at the measured plane of $z = 0.02$ m (0.84 D) was jet-like since Ri_0 is close to zero.

Figure 2a presents three radial distributions of mean fringe number in case 1 based upon the averaging information from 30, 60, and 90 frame images, respectively. The relative standard deviation of the fringe number is calculated by:

$$\sigma(r) = 100\% \times \sqrt{\sum_{i=1}^{N} [\bar{f}_i(r) - f(r)]^2/N/\max[|f(r)|]}$$

where max denotes the maximum value in a given radial section. The maximum values of the relative standard deviation for the three sets of 30, 60, and 90 frame images were 21.0%, 15.8%, and 15.3%, respectively. Clearly, the maximum value of the standard deviation has reached an asymptotic value when the mean quantities of fringe number were obtained with a basis of 90 frame images. Also, as can be observed from Fig. 2a, the mean profile of fringe number averaged from 90 frame images is nearly invariant. The radial distributions of mean interferometric temperature, which are separately calculated from the right- and left-half sections for each set of mean fringe number information recorded in Fig. 2a, are plotted in Fig. 2b. It is shown that the mean interferometric temperature profile obtained from 90 frame images does produce a nearly independent solution with respect to frame image number. Calculations of the mean interferometric temperatures in case 2 are, therefore, based upon the information averaged from 90 frame images.

Table 1 Test conditions

	Case 1	Case 2
Exit diameter of nozzle (D)	0.0307 m	0.0239 m
Axial position of measurement plane (z)	0.04 m	0.02 m
Mean velocity at nozzle exit (u_0)	0.675 m/s	1.486 m/s
Air temperature at nozzle exit (T_0)	450 K	423 K
Ambient air temperature (T_∞)	300 K	300 K
Froude number $Fr = u_0/\sqrt{[(\rho_\infty - \rho_0)/\rho_\infty]gD}$	2.13	5.68
Reynolds number $Re = \rho_0 u_0 D/\mu_0$	718	1297
Initial Richardson number $Ri_0 = \sqrt{\pi/4}/Fr^2$	0.196	0.0275

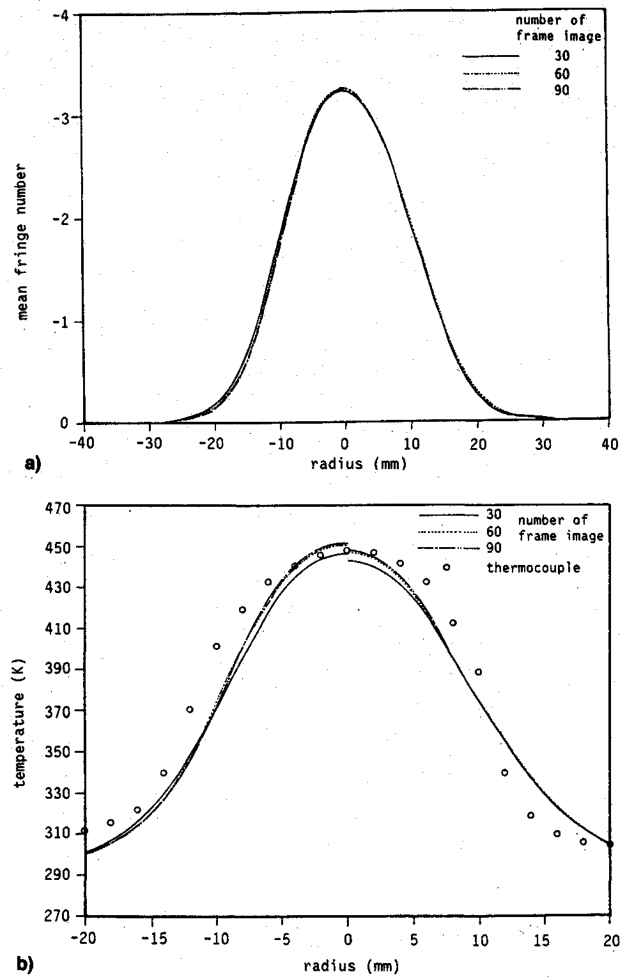

Fig. 2 Radial distributions of a) mean fringe number and b) mean interferometric and thermocouple temperatures at z = 40 mm for case 1.

Comparison of the left- and right-half profiles of the mean interferometric temperature reveals that the flow asymmetry in case 1 may lead to a maximum error of 2.8% in temperature reconstruction. The image resolution in digitizing the holographic interferograms by the present frame grabber is about 0.3 mm, which represents the experimental uncertainty for fringe localization in the interferograms. A sensitivity study for case 1 shows that a change of 0.3 mm in determination of fringe position may result in the maximum temperature errors of 8.6% and 6.6% for the left- and right-half profiles displayed in Fig. 2b, respectively. The temperatures measured by a thermocouple are also presented in Fig. 2b. The temperature discrepancies, evaluated from Fig. 2b, between using two different measurement means are less than 7.9% (based upon the thermocouple temperature), which is about the same magnitude as the errors associated with the uncertainty in image processing.

Both mean temperatures measured by using the holographic interferometer and thermocouple in case 2 are displayed in Fig. 3. The uncertainties subject to the present image resolution were estimated to be at most 6.0% and 8.3% from the image information of the left- and right-half sections, respectively. The errors subject to the asymmetry of the heated airflow by comparing the mean interferometric temperature profiles presented in the left- and right-half sections are less than 3% and smaller than those stemmed from the limitation of image resolution.

A comparison of the mean temperatures measured by the two different means reveals that the temperature discrepancies become larger (about 3.2%, based upon the thermocouple temperature), particularly in the core region. Note that

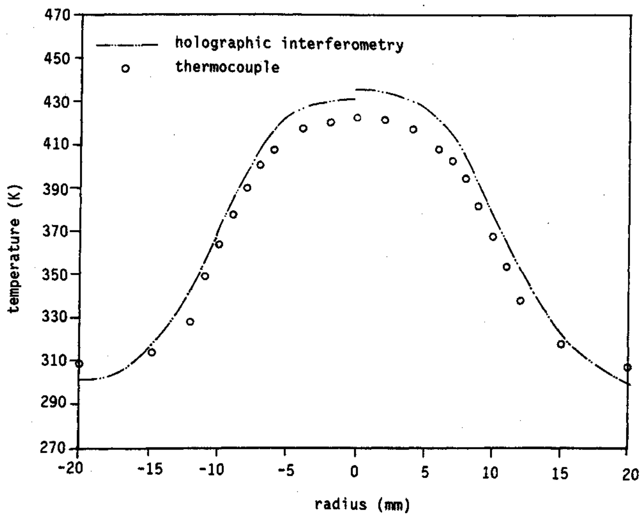

Fig. 3 Comparison of radical distributions of mean interferometric and thermocouple temperatures at z = 20 mm for case 2.

the inlet temperature of the heated air for case 2 is 423 K. As shown in Fig. 3, it is clear that the holographic interferometry overmeasures the mean temperatures, while the thermocouple measurements are quite consistent in the core region. The overestimations of the mean interferometric temperatures are attributed to the errors made in fringe interpolation/extrapolation. In case 1, there existed four dark fringes in the fringe pattern of each half-section and one dark fringe was located at the axis center (fringe order number to this dark fringe is $-3\frac{1}{2}$ as indicated in Fig. 2a). Therefore, the fringe number distribution in the core region can be interpolated by two neighboring fringes, i.e., $-2\frac{1}{2}$ and $-3\frac{1}{2}$. Consequently, the calculated mean interferometric temperatures agree well with the ones measured by the thermocouple in this region as shown in Fig. 2b. The nearly uniform mean interferometric temperature distribution in the core region for case 2 leads to a situation in which no dark fringe was formed around the axis center in the fringe pattern. This means that the fringe number distribution around the axis center was extrapolated from the data located in the outer flow region where the mean temperature gradients are much larger than those in the core region. This can explain why the mean interferometric temperatures in the core region were overestimated for case 2.

In summary, error analysis showed that the resolution limitation in the present image processing may cause as large as 8.6% and 8.3% uncertainties in the calculations of mean interferometric temperatures for the cases of plume-like and jet-like flows, respectively. These errors would be effectively reduced, provided a higher resolution capability of the image processing was employed in the experiment. The requirement of axisymmetry for the interest domain restricts these diagnostics applicable to measurements of mean temperature only. Nevertheless, our group has been developing a holographic tomography technique[9] capable of reconstructing a three-dimensional temperature distribution. It is believed that the instantaneously asymmetrical temperature distribution can be obtained by using such a holographic tomography technique. Another difficulty in the application of these diagnostics to thermal fields associated with high temperature gradient is due to ray bending of laser light while traversing these fields, and it remains to be studied further.

Acknowledgment

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Convective Flows in Enclosures with Vertical Temperature or Concentration Gradients

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Introduction

IN some crystal-growth techniques, the completely confined fluid phase is subject to vertical temperature and/or concentration gradients.[1,2] To gain insights on such flows, an experimental program was initiated to study flows in rectangular enclosures with vertical temperature or concentration gradients between horizontal end walls.

The present work for purely thermal cases is intended to give a comprehensive understanding of natural convection heat transfer in enclosures with thermally insulated vertical walls by systematically varying the parameters Ra (Rayleigh number) and Ar (aspect ratio). The fluid is tap water in these experiments.

An electrochemical system based on a diffusion-controlled electrode reaction is employed to create the vertical concentra-

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