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OPTICAL TEMPERATURE GRADIENT MEASUREMENTS USING SPECKLE PHOTOGRAPHY

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Abstract—The grainy appearance of a diffusing object illuminated by a monochromatic source such as laser light is known as 'laser speckle'. This paper presents an optical method for measuring temperature gradients in liquids, based on this phenomena. Double exposure speckle photography is used to measure temperature gradients in liquids heated from below, in the Rayleigh number range 1.5–276 where the heat transfer is by conduction. Comparison with thermocouple measurements yields reasonable agreement. A few experiments illustrating the feasibility of using 'speckle' to study convection problems in the Rayleigh number range 4600–8957 are included.

NOMENCLATURE

- D diameter of laser beam at the diffuser [mm]
- L length of test section [mm]
- n index of refraction of medium
- n_a index of refraction of air
- ΔN fringe shift
- S distance between specklegram and screen [mm]
- T temperature [K]
- y coordinate direction [mm]
- Z distance from diffuser to photographic plate [mm]
- Z_{sc} distance from center of test section to photographic plate [mm].

Greek symbols

- α angular spacing, see Fig. 2
- δ fringe spacing [mm]
- ε speckle shift [mm]
- λ wavelength of light [nm].

INTRODUCTION

SCHLIEREN, shadowgraph, and interferometry are optical techniques which play a very important role in the non-contact measurement of temperature fields [1]. The first two techniques utilize the refraction of light rays to display a pattern related to the temperature profile. The third makes use of the principles of optical interference to produce fringe patterns related to the temperature field. This paper deals with the determination of temperature gradients using double exposure speckle photography; a technique which makes use of the displacement of optical noise (speckle) by refraction.

Speckle photography and interferometry have been widely used in measuring fluid velocities [2–4], displacements and strains [5, 6], and vibrations [5, 7]. In speckle photography, the information is obtained from the geometrical displacement of a speckle pattern generated by the interaction of a coherent light beam with a diffusing surface. The speckle displacement can be recorded photographically.

Relative to interferometry, speckle photography has the advantages of not requiring high mechanical stability, high quality optical instruments, or a reference beam; all of which are essential when using interferometric techniques. Further, the experimental arrangement is much simpler and lenses are not required. In application, speckle photography can measure larger temperature gradients.

EXPERIMENTAL TECHNIQUE

The grainy appearance of a diffusing object illuminated by a monochromatic light source such as a laser is due to the constructive and destructive interference of light scattered from the microroughnesses of the surface and is known as the 'speckle effect' [5]. A photograph of a laser speckle pattern is shown in Fig. 1. It consists of a multitude of bright spots where the interference has been highly constructive, dark spots where the interference has been highly destructive, and irradiance levels in between.

In the present experiments, the speckle pattern is generated by illuminating a ground glass plate with a collimated laser beam. The laser speckle is then passed through a transparent test section. A double exposure is taken of the resulting speckle pattern; one of the unrefracted pattern before heating and one of the refracted pattern after attaining a steady state. The resulting doubly exposed photographic plate (called a 'specklegram') acts like a diffraction grating, which when interrogated as illustrated in Fig. 2, produces fringes analogous to Young's fringes. These fringes are aligned perpendicular to the direction of heat transfer, and the fringe spacing is inversely proportional to the temperature gradient. Provided that the speckle displacements between the two exposures lie between 1 and 20 speckle diameters there is a region on the second exposure where its speckle pattern is well correlated to that of the first exposure. Beyond this, there is a loss of correlation between speckle patterns which result in the suppression of the fringe pattern [4].

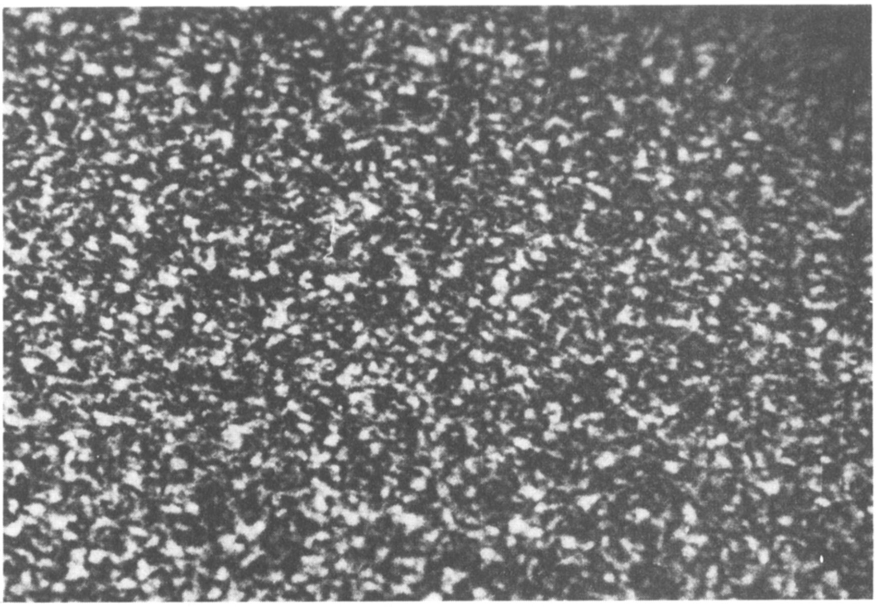

FIG. 1. Speckle pattern from ground glass plate.

Evaluation of the specklegram

There are two ways to analyze the specklegram, either by a whole field filtering technique or by a pointwise technique. With the former, an optical Fourier transform must be performed to determine the temperature gradient. This is done by inserting the specklegram in front of a lens with a convergent coherent beam [8]. The temperature gradient is then represented by a system of interference fringes over the entire image of the test section.

With the pointwise method illustrated in Fig. 2, only a small portion of the specklegram is illuminated with the laser beam. The resulting fringes will have an angular spacing α given by [4]

$$\sin \alpha = \lambda/\varepsilon, \qquad (1)$$

where all symbols are defined in the nomenclature. As α is generally small, equation (1) can be approximated as

$$\alpha = \lambda/\varepsilon. \qquad (2)$$

The fringe spacing and the speckle shift can be related by [9]

$$\alpha = \delta/S = \lambda/\varepsilon. \qquad (3)$$

Temperature gradients are calculated from the expression

$$\mathrm{d}T/\mathrm{d}y = 2\varepsilon[((L^2/n)+L(2Z_{sc}-L)/n_a)(\mathrm{d}n/\mathrm{d}T)]^{-1}, \qquad (4)$$

which results from an analysis of the speckle path deflection as it passes over a heated surface. The analysis is identical to that for the deflection of a light beam passing over a heated surface using the well-known Schmidt–schlieren system [1]. Equation (4) is valid only when the temperature variation is one-dimensional (1-D) and normal to the speckle path. If the temperature variation normal to the speckle path is two-dimensional (2-D), equation (4) must be extended to include the deflection angle ε in both directions [10]. Temperature variations in the direction of the speckle path [not accounted for in equation (4)] will result in an

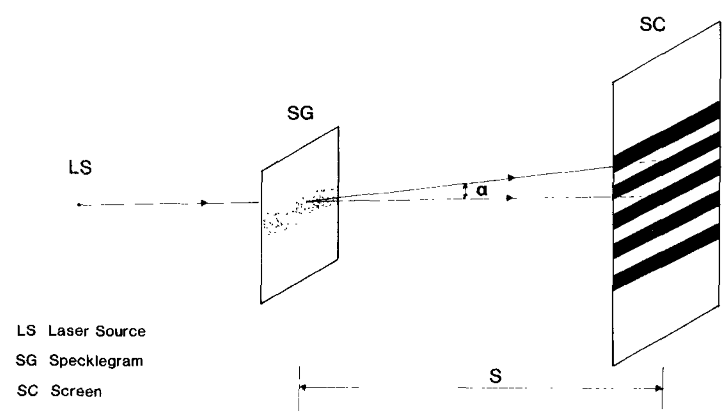

FIG. 2. Interrogation technique.

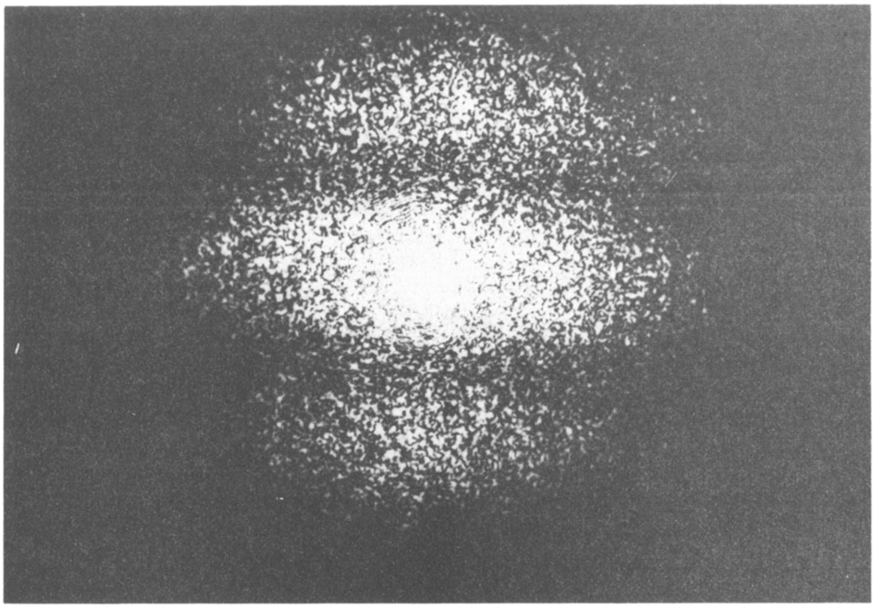

FIG. 3. Fringe pattern from interrogation of specklegram.

integrated average value of the temperature gradient through the test section. A photograph of a typical fringe pattern obtained using the pointwise interrogation technique is shown in Fig. 3. The spacing between the fringes gives the local temperature gradient and the orientation of the fringes gives the local direction of heat transfer. In this instance the area interrogated was 0.95 mm^2. As many points as necessary can be interrogated.

EXPERIMENTAL ARRANGEMENT AND PROCEDURE

A schematic of the experimental setup is shown in Fig. 4. The light source is a 15 mW He–Ne laser. The

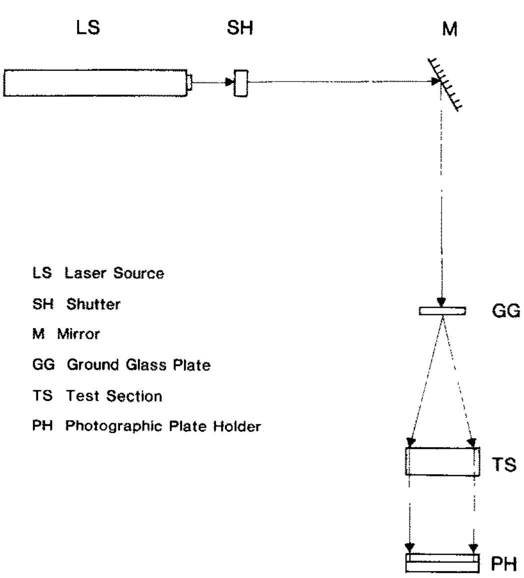

FIG. 4. Schematic of experimental system.

unexpanded beam is passed through a shutter and directed by a mirror to a ground glass plate. The resulting speckle pattern is passed through the unheated test section and recorded on a Kodak type 120-02 photographic plate. A second exposure is made once the heated test section has come to equilibrium. It is important to note that the optical path outside the test section must not change between the double exposures. Maximum fringe contrast occurs when the exposure times are equal. In this study, an exposure time of 0.1 s was used. The photographic plates are held in a special holder with side and top covers which allow development in place under room lighted conditions. After processing, the specklegram serves as a record which can be interrogated at any future time. All components are held magnetically onto a steel table supported by four inner tubes provided to minimize vibration.

Test section

A schematic of the test cell is illustrated in Fig. 5. It is rectangular and is constructed from 6 mm thick Plexiglas plates with interior dimensions 115 × 90 × 100 mm. The test cell has an aluminium base 19 mm thick and a copper boat 45 mm high at the top. There is a small clearance between the copper boat and the Plexiglas walls so that the spacing between the upper and lower surfaces can be easily varied. The upper surface temperature is maintained by passing cooling water from a constant temperature bath through the covered boat. The boat itself is supported by four rods which are connected to the base of the test section outside of the cell. The aluminium base is heated from its under surface by an attached flexible rubber heater. A copper–constantan surface thermocouple is fixed onto the top surface of the aluminium base and is referenced to the top copper boat. This differential

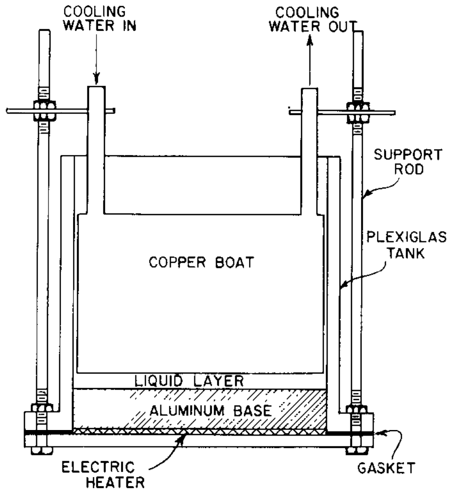

FIG. 5. Schematic of test cell.

thermocouple gives the temperature difference between the surfaces directly. Verification of the isothermal nature of the aluminium surface was obtained by holographic interferometric techniques.

RESULTS AND DISCUSSION

Experiments were carried out using Dow Corning series 200 silicone oils having viscosities of 12.5 and 1 Pa s and an aqueous solution of hydroxyethyl cellulose with a zero shear viscosity of 2 Pa s. A list of experimental parameters is given in Table 1. For each liquid, the Rayleigh number was varied by changing the depth of the liquid layer and/or the temperature difference across it. Because in each run the Rayleigh number is less than its critical value of 1708 [11], the mechanism of heat transfer is by conduction and the temperature profile across the liquid layer is linear.

Table 1. Experimental parameters

Liquid	Viscosity (Pa s)	Liquid depth (mm)	Temperature difference (K)	Rayleigh number
Silicone oil	12.5	16	0.188	5.5
			0.450	10.4
			0.715	17.8
		10	0.208	1.5
			0.465	2.9
	1.0		0.060	4.8
			0.240	18.5
			0.230	18.6
			0.412	32.6
		16	0.215	69.6
			0.302	98.0
			0.565	179.2
			0.825	275.8
Hydroxyethyl cellulose	2.0		0.463	13.3
			1.073	30.9
			1.332	38.3
			1.651	47.7
Silicone oil	0.05		0.560	4597
			0.668	5423
			0.723	5869
			0.779	6321
			1.100	8937

The specklegrams are analyzed using the pointwise interrogation technique. Fringe spacings were obtained by projecting the fringe pattern onto a screen and marking the positions of bright and dark fringes on graph paper. Figure 6 is a photograph of the Young's fringes obtained with a Rayleigh number of 1.5 and a temperature gradient of 0.02 K mm^{-1} using 12.5 Pa s silicone oil. The fringes are aligned perpendicular to the direction of heat transfer (and are therefore horizontal),

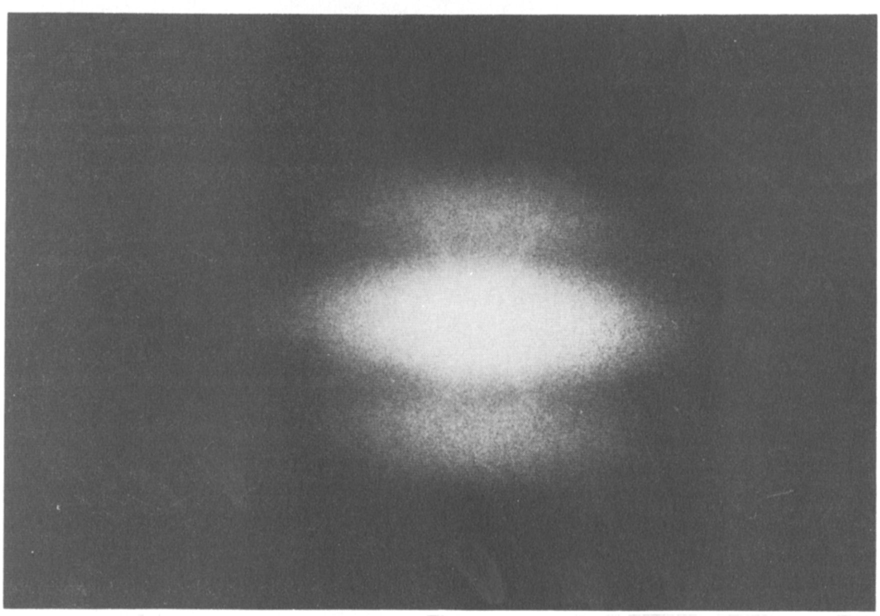

FIG. 6. A photograph of the Young's fringes for $(dT/dy) = 0.02$ K mm^{-1}, Rayleigh number = 1.5.

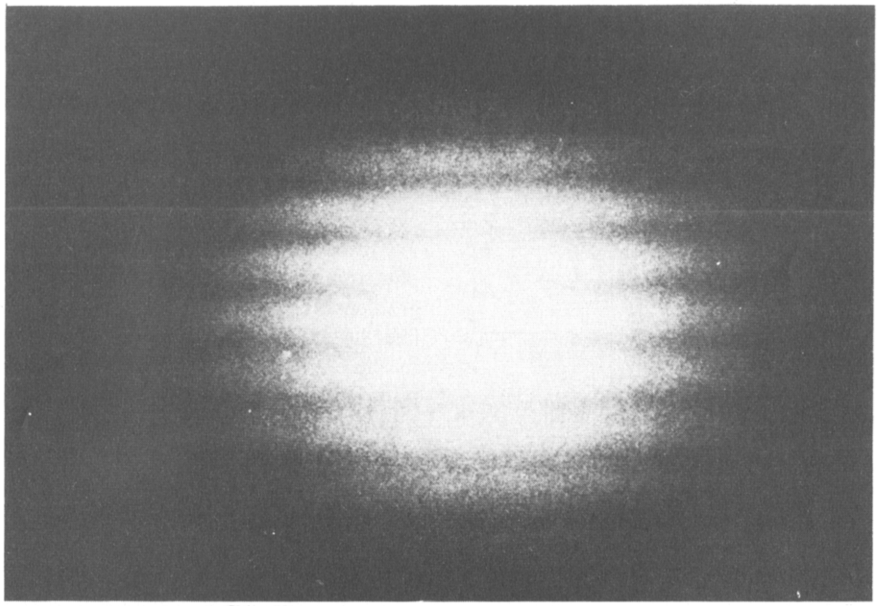

FIG. 7. A photograph of the Young's fringes for $(dT/dy) = 0.10$ K mm^{-1}, Rayleigh number = 45.6.

and are equally spaced. Figure 7 is a photograph of the Young's fringes for a Rayleigh number of 45.6 and a temperature gradient of 0.1 K mm^{-1} for a 1.4% by weight solution of hydroxyethyl cellulose in water.

The temperature gradients as a function of liquid depth for the above two runs are shown in Figs. 8 and 9. The continuous lines represent the temperature gradient calculated from the temperature difference measured by the thermocouple, and the thickness of the liquid layer. The dashed lines represent the least square average of the optically determined temperature gradients calculated from equation (4). The dash-dot line shown in Fig. 8 was obtained by interrogating the specklegram with an expanded and collimated laser beam. The resulting fringes thus represent an optically averaged value.

The optically determined temperature gradients are compared with those calculated from the thermocouple measurements, in Fig. 10. The solid 45° line represents exact agreement and the dashed lines represent the experimental uncertainty bounds as determined by the procedure in ref. [12]. As all of the data lie within these bounds, it is concluded that the measurements are in agreement.

The uncertainty associated with the fringe spacing measurements are estimated to be about $\pm 15\%$. When combined with estimated uncertainties for the other parameters which appear in equation (4), the overall uncertainty is about $\pm 20\%$ [13]. This uncertainty could be significantly reduced by the use of more sophisticated analysis equipment such as a microdensitometer or an image enhancement system. The thermocouple measurement itself is subject to uncertainties. However, even in the worst case, the calculated temperature gradient should be within $\pm 10\%$.

Comparison with holographic interferometry

In the introduction, it was stated that speckle photography can measure larger temperature gradients than is possible with holographic interferometry. For the latter, the temperature gradient can be expressed in terms of the sensitivity (fringes mm^{-1})

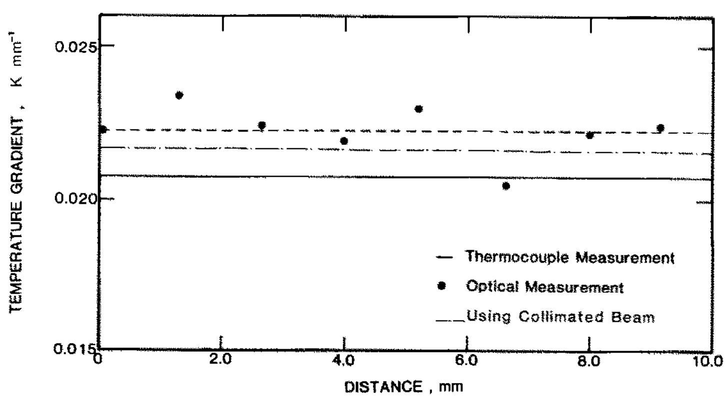

FIG. 8. Temperature gradients as a function of liquid depth, Rayleigh number = 0.5.

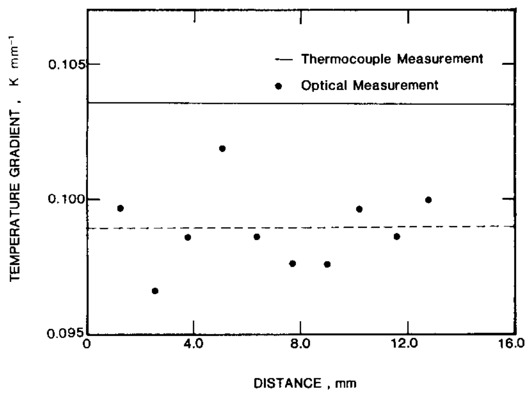

Fig. 9. Temperature gradients as a function of liquid depth, Rayleigh number = 45.6.

as [14]

$$\Delta T/\Delta y = (\lambda/L)(\mathrm{d}n/\mathrm{d}T)^{-1}(\Delta n/\Delta y). \quad (5)$$

Mclean *et al.* [14] reported being able to detect 20 fringes mm^{-1}. In a more recent paper, Panknin [15] states that serious evaluation problems can result if there are more than 30 fringes mm^{-1}. Thus for $\lambda = 632.8$ nm, $L = 100$ mm, $(\mathrm{d}n/\mathrm{d}T) = 3.865 \times 10^{-4}\ \mathrm{K}^{-1}$ and $(\Delta N/\Delta y) = 30\ \mathrm{mm}^{-1}$, the maximum temperature gradient which can be determined is found from equation (5) to be 0.49 K mm^{-1}.

Vest [8] presents an expression for a typical speckle width as

$$b = 1.5(\lambda Z/D). \quad (6)$$

For $D = 1.1$ mm and $Z = 310$ mm (it should be noted that this distance was varied from run to run), the mean speckle size is 0.27 mm. From the criteria that $1 < \varepsilon/b < 20$ for fringes to be formed, the fringe shift will be in the range 0.27 mm $< \varepsilon <$ 5.4 mm. Substituting into equation (4) with $L = 100$ mm, $Z_{sc} = 145$ mm, $n = 1.4035$, $n_a = 1$ and $\mathrm{d}n/\mathrm{d}T = 3.865 \times 10^{-4}\ \mathrm{K}^{-1}$, the temperature gradients that can be measured range from 0.054 to 1.08 K mm^{-1}.

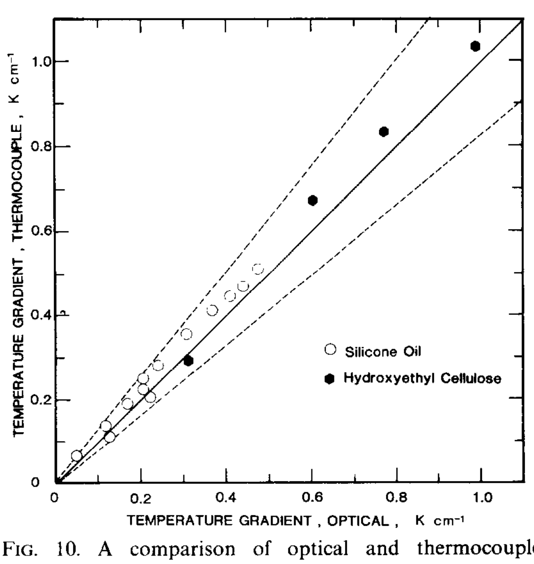

Fig. 10. A comparison of optical and thermocouple measurements.

The limiting temperature gradients calculated for each technique are of course only approximate, but it is worthwhile noting that those calculated for the speckle method using the parameters associated with these experiments, are of the order of those actually measured. The calculations illustrate that speckle photography can not only measure larger temperature gradients, but [from equation (6)] by expanding the laser beam to illuminate a larger area of the diffuser or by increasing the distance Z from the diffuser to the photographic plate, is capable of measuring gradients over a very wide range of values.

Convection experiments

Five experiments were performed with 0.05 Pa s silicone oil at Rayleigh numbers from 4600 to 8957. As all of these are above the critical value of 1708, convective motion exists in the system and the direction of heat transfer varies from position to position. Temperature gradients were not calculated from these experiments as equation (4) is applicable only to 1-D transport. However, the direction of heat transfer is normal to the orientation of the fringe pattern and this can be determined locally by pointwise interrogation of the specklegram. A fringe pattern typical of those found at different locations within the liquid layer is shown in Fig. 11. Unfortunately, the quality of the fringe pattern is rather poor. However, it is apparent after some study that the fringes at this location are nearly vertical and hence that the heat flow is locally horizontal.

Forced flow heat transfer systems can also be analyzed using the techniques described in this paper. As illustrated above for a natural convection system, a specklegram can be produced (independent of the motion of the fluid) which can be interrogated to yield Young's fringes; the spacing and orientation of which are related to the local temperature gradient and direction of heat flow. Again however, a 2-D analog of equation (4) is required for proper interpretation. The flow field itself can be determined in a separate experiment using the pseudospeckle technique known as speckle velocimetry and described by Meynart [16].

CONCLUSIONS

Double exposure speckle photography has been shown to be a simple and reliable means for measuring temperature gradients in transparent systems. Further, it is shown that the technique is capable of measuring higher temperature gradients than is possible with holographic interferometry.

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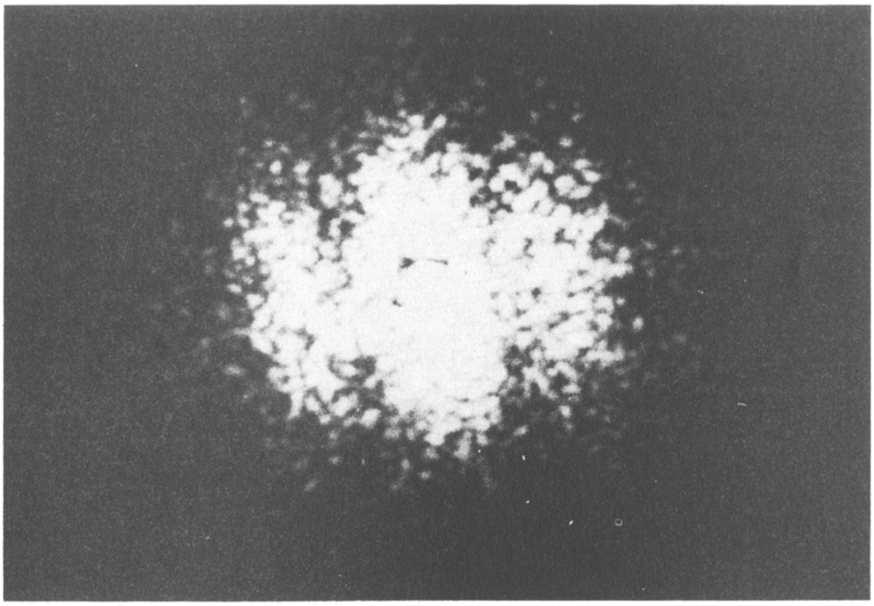

FIG. 11. A photograph of the Young's fringes at one location for Rayleigh number = 5423.

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MESURE OPTIQUE DE GRADIENT DE TEMPERATURE PAR PHOTOGRAPHIE "SPECKLE"

Résumé—L'aspect granuleux d'un objet diffusant éclairé par une source monochromatique telle qu'une lumière laser est connu comme "laser speckle". On présente une méthode optique basée sur ce phénomène pour mesurer des gradients de température dans les liquides. Une photographie "speckle" à double exposition est utilisée pour mesurer les gradients de température dans un liquide chauffé par le bas, dans un domaine de nombre de Rayleigh 1,5–276 pour liquel le transfert thermique se fait par conduction. Des comparaisons avec des mesures par thermocouple donne un accord raisonnable. On inclut quelques expériences qui illustrent la possibilité d'utilisation du "speckle" pour étudier les problèmes de convection dans le domaine du nombre de Rayleigh 4600–8957.

DIE OPTISCHE MESSUNG VON TEMPERATURGRADIENTEN MIT SPECKLE-FOTOGRAFIE

Zussamenfassung—Das körnige Erscheinungsbild eines streuenden Mediums, das mit einfarbigem Licht, wie z. B. Laserlicht, beleuchtet wird, ist als "Laserspeckle" bekannt. Die vorliegende Arbeit stellt eine auf dieser Erscheinung beruhende optische Methode vor, mit der man Temperaturgradienten in Flüssigkeiten messen kann. Zur Messung der Temperaturgradienten in von unten beheizten Flüssigkeiten bei Rayleigh-Zahlen zwischen 1,5–276, wo die Wärmeübertragung durch Leitung stattfindet, wird Speckle-Fotografie mit Doppelbelichtung verwendet. Der Vergleich mit Thermoelementmessungen liefert gute Übereinstimmung. Einige Versuche, die die Möglichkeit aufzeigen, Konvektionsprobleme im Bereich der Rayleigh-Zahlen von 4600–8957 mit Hilfe von Laserspecklen zu untersuchen, werden erwähnt.

ОПТИЧЕСКИЕ ИЗМЕРЕНИЯ ГРАДИЕНТА ТЕМПЕРАТУР МЕТОДОМ СПЕКЛОВ

Аннотация—Зернистое изображение диффундирующего объекта, освещенного таким монохроматическим источником света, как лазер, известно под названием "лазерного спекла". В работе предложен оптический метод измерения градиентов температуры в жидкостях, основанный на этом явлении. Фотографирование с двойным экспонированием используется для измерения градиентов температуры в нагреваемых снизу жидкостях в диапазоне чисел Релея от 1.5 до 276, где теплоперенос происходит за счет теплопроводности. Сравнение с результатами измерений термопарами дает приемлемые результаты. Представлены результаты экспериментов, иллюстрирующие возможности использования "спекла" для исследования конвекции в диапазоне значений числа Релея от 4600 до 8957.