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A SPECIAL DIFFERENTIAL INTERFEROMETER USED FOR HEAT CONVECTION INVESTIGATIONS

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Abstract—A special differential interferometer with achromatic $\lambda/2$ compensation has been used for measuring vertical- and horizontal convection density difference profiles in a rectangular box heated from below and cooled from above. The sensitivity of this type of interferometer when set at infinite fringe spacing can be chosen such that the flow configurations both in the test gas nitrogen and in the highly refracting silicone oil are visualized. The flow patterns and the density profiles have been evaluated quantitatively and compared with previously published results.

NOMENCLATURE

- e, beam separation;
- F, film;
- g, acceleration of gravity;
- h_z, height of the convection box;
- Δn, refraction index difference;
- O, objective;
- P, polarizer;
- Pr, Prandtl number (ν/κ);
- Q, light source;
- Ra, Rayleigh number $\left[\dfrac{g\alpha h_z^3(T_1-T_2)}{\nu\kappa}\right]$;
- S, width of the convection box;
- T_1, temperature at the lower horizontal plate;
- T_2, temperature at the upper horizontal plate;
- W, Wollaston prism;
- x, y, z, coordinates.

Greek symbols

- α, coefficient of expansion;
- $\Delta\Gamma$, optical path difference;
- λ, light wavelength;
- κ, thermal diffusivity;
- ν, viscosity;
- $\Delta\rho$, density difference;
- ρ_1, density at the lower horizontal plate;
- ρ_2, density at the upper horizontal plate.

1. INTRODUCTION

STEADY convection in a horizontal air layer was measured by Gille [1] and in water by Farhadieh and Tankin [2] using Michelson and Mach Zehnder interferometry. Mayinger and Panknin [3] applied holographic interferometry to investigate heat-transfer flows. A survey article was published by Hauf and Grigull [4]. But with these optical visualization techniques a comparative investigation of convection in different fluids within a wide range of Pr numbers is not possible using the same convection box. The optical path difference in gases ($Pr = 0.71$) is too small for flow patterns to be visualized especially in rectangular convection boxes of small depths. In the case of silicone oil ($Pr = 1780$) too many fringes are visualized and a quantitative evaluation of the interferograms is difficult. But the flow configurations in both fluids with increasing Ra number is up to this date still not well understood. We used, therefore, a $\lambda/2$ compensated differential interferometer for measuring steady convection in nitrogen and silicone oil. The sensitivity of this type of interferometer can be chosen such that good interferograms of phase objects having optical path differences down to $\lambda/30$ as well as up to more than 100λ can be taken. Both horizontal and vertical density profiles can be evaluated.

2. DIFFERENTIAL INTERFEROMETER

The optical set up of the $\lambda/2$ compensated differential interferometer is sketched in Fig. 1. It consists of the light source Q, two Wollaston prisms W_1 and W_2 (W_1 180° turned with respect to W_2), two objectives O_1 and O_2, two polarizers P_1 and P_2, the $\lambda/2$ plate and the camera objective O giving an image of the test section M on the film F. Without the $\lambda/2$ plate the ideal infinite parallel fringe spacing can not be obtained because of divergence of the light beam in the Wollaston prisms.

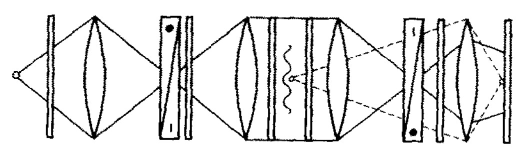

FIG. 1. Differential interferometer with $\lambda/2$ compensation.

With the $\lambda/2$ plate the perturbing effect of prism W_1 is compensated by that of prism W_2. In the first Wollaston prism W_1 each light beam is split into two perpendicularly polarized ones which are then made parallel by O_1 and traverse the test section of width S with a certain beam separation e. The components of the light beams in the plane of polarizer P_2 interfere on the film F. In this way the optical path differences $\Delta\Gamma = S\cdot\Delta n$ which are due to the refractive index difference

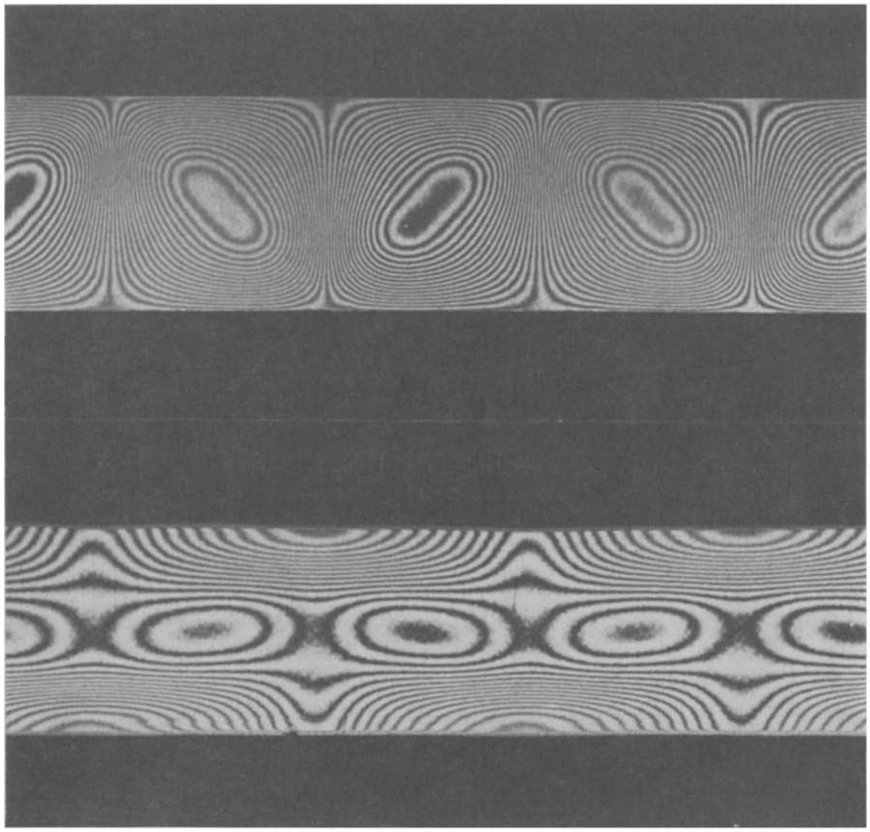

FIG. 2. Interferograms, silicone oil ($Pr = 1780$). (a) Horizontal density difference profile, $Ra = 3000$, $e = 3$ mm. (b) Vertical density difference profile, $Ra = 6270$, $e = 0.3$ mm.

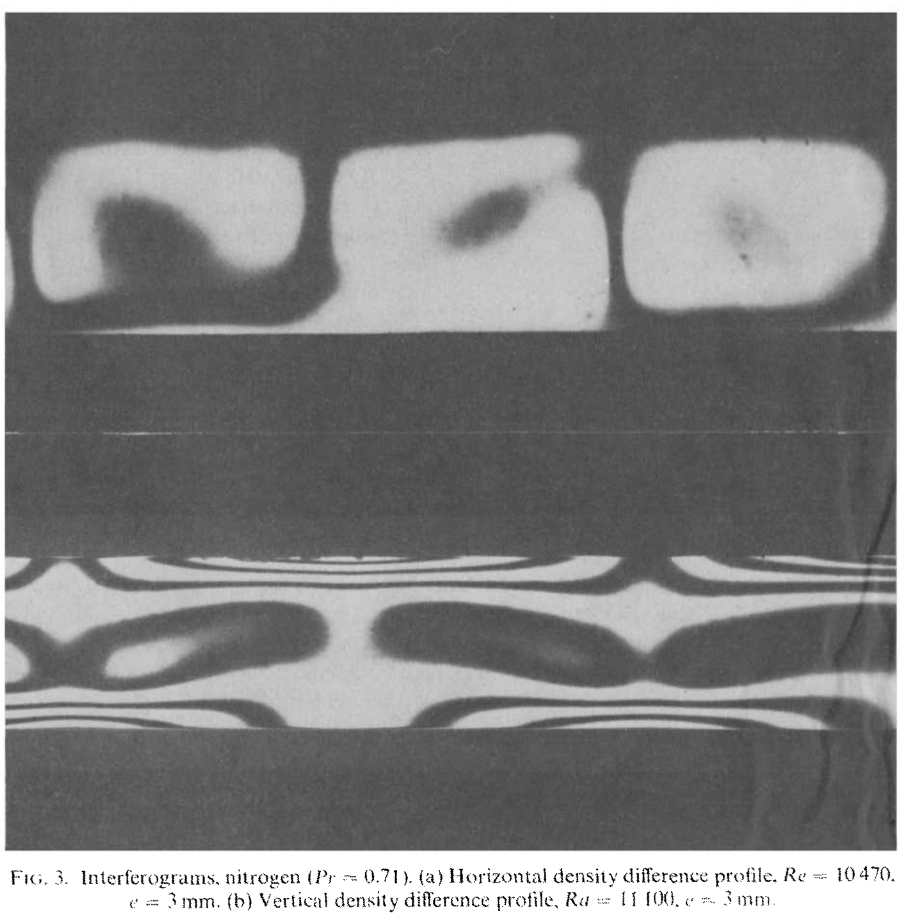

FIG. 3. Interferograms, nitrogen ($Pr = 0.71$). (a) Horizontal density difference profile, $Re = 10\,470$, $e = 3$ mm. (b) Vertical density difference profile, $Ra = 11\,100$, $e = 3$ mm.

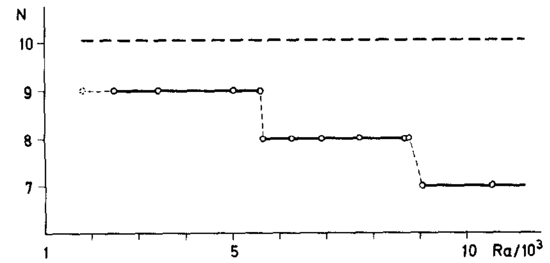

FIG. 4. Number of convection rolls: -----, silicone oil; ——, nitrogen.

similar to stream lines are visualized. Figure 3 shows the flow pattern in nitrogen. The optical path differences are significantly smaller and so the interferometer sensitivity is chosen correspondingly larger. Therefore, not density gradients, but density differences are measured.

In nitrogen seven convection rolls in the same convection box at a Ra number of 10470 were formed. This is due to the smaller Pr number of nitrogen compared with that of silicone oil. The number of convection cells N is plotted in Fig. 4 as a function of

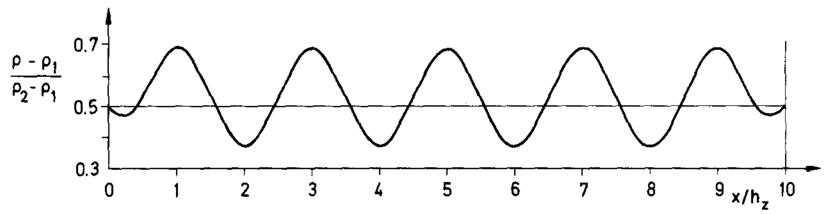

FIG. 5. Horizontal density profile, silicone oil, Ra = 4670.

Δn between the two interfering light beams in the test section can be visualized. The refractive index difference Δn is then related to the density difference $\Delta\rho$ using the dispersion equation. The differential interferometer therefore measures the components of density differences in the direction of beam separation e. If the beam separations are small the density gradients can be visualized. The sensitivity of the interferometer can be varied by using Wollaston prisms giving different beam splittings. It may be made sensitive to different components of the density gradients by simply rotating the prisms about the axis of the objectives. This offers the possibility of eliminating vertical heat conduction profiles.

A similar compensating differentialinterferometer has been applied by Oertel [5] using two $\lambda/2$ plates, within the two Wollaston prisms. Smeets and George [6] pointed out that one $\lambda/2$ plate outside the prisms may be sufficient. We tested this idea by applying it to convection visualization and found that the quality of interferograms is really much better than those taken without a $\lambda/2$ plate. With the $\lambda/2$ compensated differential interferometer a comparative investigation of convection in nitrogen and silicone oil is possible.

3. CONFIGURATION OF STEADY CONVECTION

Figure 2 shows the horizontal and vertical density difference profile of cellular convection in silicone oil. The rectangular convection box has a length of 15 cm, a depth of 6 cm (S) and a height of 1.5 cm. The lower horizontal plate is heated and the upper one cooled. The flow pattern consists of 10 convection rolls which are located along the shorter side of the box. The areas of upward and downward motion are periodically repeated. We find large vertical density gradients and therefore many fringes in the area of upward motion at the upper horizontal plate and in the area of downward motion at the lower horizontal plate. Using horizontal gradient sensitivity of the interferometer the vertical heat conduction is eliminated and lines

the Ra number. With increasing Ra number the number of convection rolls decreases. At a Ra number of 5650 the transition to eight and at 8900 to seven convection rolls were measured. In silicone oil 10 rolls were measured up to a Ra number of 8200. Up to this Ra number Koschmieder [7] found a significant increase of the wavelength of convection motions in an approximately infinite horizontal silicone oil layer. This demonstrates the influence of the vertical boundaries of the rectangular convection box which has, especially at large Pr numbers, a stabilizing effect on the flow configuration.

4. EVALUATED DENSITY PROFILES

The evaluated horizontal and vertical density profiles in silicone oil are compared in Figs. 5–7 with previously published results. Figure 5 shows the horizontal density profile in the middle of the convection roll. Areas of upward, density minima, and areas of downward motion are periodically repeated.

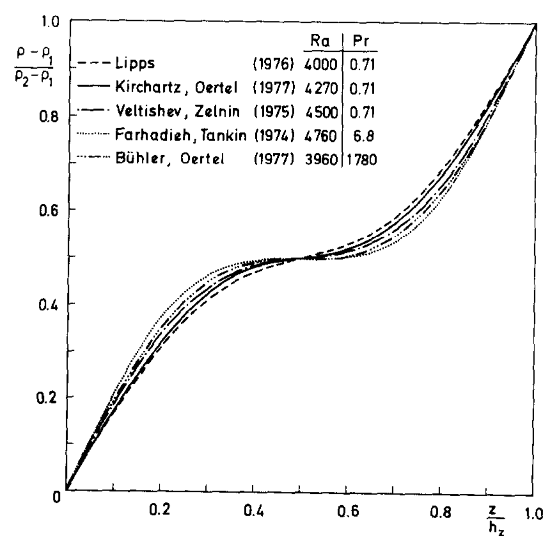

FIG. 6. Vertical density profile, middle of the convection cell.

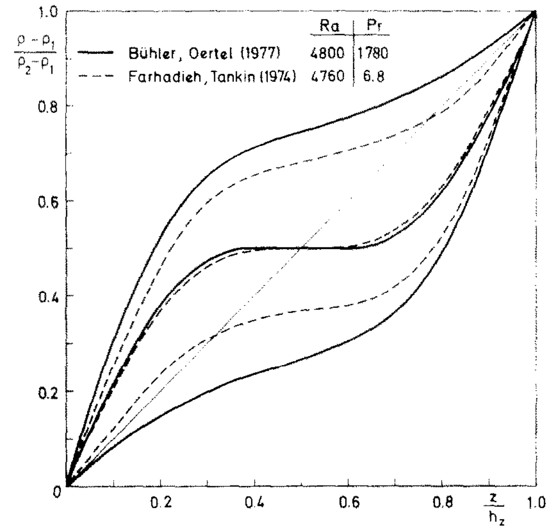

FIG. 7. Vertical density profile, zone of upward and downward motion, middle of the convection cell.

The vertical density profiles in the middle of the convection cell compared with previously published results in air, nitrogen, water and silicone oil are plotted in Fig. 6. The density profile in silicone oil is more curved than it is in nitrogen. This is due to the larger Pr and Ra number. In silicone oil at a Ra number of 4800 a density reversal in the middle of the convection box has been evaluated. The results are compared with the theoretical ones of Lipps [8], Veltishev and Zelnin [9] in air and the experimental ones of Farhadieh Tankin [2] in water in the middle of the convection cell. The discrepancies between the vertical density profiles are not significant and the influence of the Pr number seems to be small. This is different in an area of upward and downward motion as shown in Fig. 7. The measured vertical density profiles in silicone oil ($Pr = 1780$) are plotted and compared with those of Farhadieh and Tankin [2] in water ($Pr = 6.8$). Here, there are discrepancies of up to 35%.

5. CONCLUSION

The $\lambda/2$ compensated differential interferometer has proven to be a good method for comparative investigations in nitrogen and silicone oil. The convection flow configurations in both fluids within a rectangular convection box can be visualized. Different numbers of convection cells in silicone oil and nitrogen have been formed along the shorter side of the convection box. This is due to the different Pr numbers. The evaluated density profiles in silicone oil have been compared with previously published results in different test fluids. Discrepancies have been found, especially in the areas of upward and downward motion. The vertical density profiles in water are less curved than they are in silicone oil. At smaller Pr numbers the thermal energy transfer is large compared to the momentum transfer. Therefore the density profiles are more equalized.

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UN INTERFEROMETRE DIFFERENTIEL SPECIAL UTILISE POUR L'ETUDE DE LA CONVECTION THERMIQUE

Résumé—Un interféromètre différentiel spécial, avec compensation achromatique $\lambda/2$ a été utilisé pour mesurer les profils verticaux et horizontaux de densité différentielle dans une boite rectangulaire chauffée par le bas et refroidie par le haut. La sensibilité de ce type d'interféromètre réglé sur les franges à l'infini peut être choisie de façon que les configurations de l'écoulement peuvent être visualisées aussi bien dans le cas de l'azote que de l'huile de silicone. Les figures d'écoulement et les profils de densité sont évalués quantitativement et comparés avec des résultats antérieurement publiés.

EIN SPEZIELLES DIFFERENTIALINTERFEROMETER ZUR UNTERSUCHUNG VON FREIER KONVEKTION

Zusammenfassung—Ein spezielles Differentialinterferometer mit achromatischer $\lambda/2$-Kompensation wurde zur Messung senkrechter und waagerechter Dichteunterschiedsprofile infolge freier Konvektion eingesetzt. Die Messungen wurden in einem rechtwinkligen Behälter, der von unten beheizt und von oben gekühlt wurde, durchgeführt. Die Empfindlichkeit dieses Interferometertyps kann bei Einstellung auf unendliche

Streifenbreite so gewählt werden, daß die Strömungsmuster sowohl im Testgas Nitrogen als auch in dem stark brechenden Silikonöl sichtbar werden. Die Strömungsmuster und die Dichteprofile wurden quantitativ ausgewertet und mit bereits veröffentlichten Ergebnissen verglichen.

СПЕЦИАЛЬНЫЙ ДИФФЕРЕНЦИАЛЬНЫЙ ИНТЕРФЕРОМЕТР ДЛЯ ИССЛЕДОВАНИЯ ТЕПЛОВОЙ КОНВЕКЦИИ

Аннотация — Для измерения профилей плотности по вертикали и горизонтали при естественной конвекции в прямоугольной камере, нагреваемой снизу и охлаждаемой сверху, использовался специальный дифференциальный интерферометр с ахроматической ($\lambda/2$) компенсацией. Чувствительность данного интерферометра при настройке прибора на интерференционные полосы бесконечной ширины позволяет визуализировать картину течения как в исследуемом газообразном азоте, так и в силиконовом масле, обладающим большим показателем преломления. Проведена количественная оценка картин течения и профилей плотности, и дано сравнение с ранее опубликованными данными.