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STUDIES OF RADIATION-DRIVEN AND BUOYANCY-DRIVEN FLUID FLOWS AND TRANSPORT

(NASA Grant No. NAG3-1653)

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ABSTRACT

It is well known that radiative heat transport influences many types of buoyant flows due to its effect on the temperature and thus density field in the fluid medium. It is of interest to study gaseous flows driven solely by radiation in the absence of buoyancy, particularly because of its application to astrophysical flows that are well known from astronomical observations and numerical simulation. However, no laboratory-scale experiments of this phenomenon have ever been conducted. To study the possibility of obtaining such flows in the laboratory, an apparatus was built to produce large temperature differences (ΔT) up to 300K in a gas confined between flat parallel plates. SF_6 was used as the radiatively-active gas because its Planck absorption length is much shorter than that of any other common non-reactive gas. The NASA-Lewis 2.2 second drop tower was used to obtain reduced gravity in order to suppress buoyancy effects. To image the resulting flows, a laser shearing interferometer was employed. Initial results indicate the presence of flow that does not appear to be attributable to the residual flow resulting from buoyancy influences before the drop. For $\Delta T > 70K$, slight deformations in the interferometer fringes seen at lower ΔT became large unsteady swirls. Such behavior did not occur for radiatively-inactive gases, suggesting that a flow driven solely by radiation was obtained in SF_6 and to a lesser extent in CO_2. This was more pronounced at higher pressures and plate spacings, consistent with our scaling predictions.

INTRODUCTION

Radiation-driven flows occur in many gases and liquids that are neither completely transparent nor completely opaque to electromagnetic radiation. This effect of importance to many practical problems including glass and semiconductor processing; oceanographic or atmospheric flows with application to global climatic change; astrophysical flows; plasma physics; combustion systems; solar energy collection; nuclear explosions and heat transfer in inhabited enclosures.

We have proposed that flow driven solely by radiative effects without imposed hydrodynamic or hydrostatic pressure gradients may be possible for the following reason. If a parcel of gas receives slightly more heating than the surrounding gas, its temperature increases. In gases with a strongly temperature-dependent Planck absorption length (l_p) such as SF_6, this temperature increase results in a significant decrease in the absorptivity, which in turn causes an increase in the radiative conductivity. For SF_6 the radiative conductivity is roughly proportional to T^5. The local increase in temperature would encourage further heat transfer throughout the gas and upon coupling with thermal expansion effects, may produce a flow. Evidence of this instability has been found in μg combustion experiments (ref. 1). In combustible CH_4-O_2 and H_2-O_2 mixtures diluted with SF_6, a flame structure characterized by the sudden fingering of an evolving front has been observed, particularly at high pressures. The fingering occurred in SF_6-diluted mixtures but not N_2-, Ar- or CO_2-diluted mixtures, which is to be expected if the proposed instability mechanism is present because $\partial l_p/\partial T$ is much larger for SF_6 and because at the conditions tested only SF_6 is optically thick. For the current study, we examined radiative flow instability in a non-reacting gas at μg with an imposed heat source of known character, rather than a chemical reaction whose heat release characteristics are intimately coupled to the thermal field.

Many theoretical and computational studies of radiation-driven flows appear in the astrophysical literature (refs. 2 - 4) because of its relevance to solar flares, the formation of galaxies, etc., yet no experimental studies of analogous flows have been conducted in a laboratory setting. Scaling analyses indicate that at earth gravity, this flow would be overwhelmed by buoyant convection even in a highly radiatively-active gas such as SF_6. Depending on the orientation, buoyancy would either suppress the instability or would be overshadowed by Rayleigh-Benard convection. Consequently, microgravity conditions are needed for an experiment test for the existence of this type of flow. The intent of the current experimental study is to explore aspects of radiation-dominated fluid flows which cannot be studied at earth gravity.

EXPERIMENTAL APPARATUS AND PROCEDURES

Experimental Background

A modified Rayleigh-Benard type of apparatus was utilized for these experiments. It consisted of two parallel flat plates with a gap between them varying from 2 to 5 cm (see Fig. 1.) The upper hot plate was resistively heated and the lower cold plate was thermoelectrically or water cooled. 1-cm thick plates were used to ensure uniform temperature across the plate and to ensure that their thermal response time was very large compared to the low-gravity test duration. A large temperature difference (up to 300K) could be maintained between the two plates. Locating the hot plate on top of the cold plate minimized the buoyant flow in the test section before the drop, however, some buoyant flow within the test section was unavoidable because of the flow off of the top of the hot plate. This flow is undesirable because a finite amount of time is required for it to decay once buoyancy is removed, *i.e.*, when the drop begins. This makes it more difficult to determine whether flow observed during μg conditions is a result of radiative effects or decaying buoyant flow. A set of baffles and blocks of insulation was used to minimize this flow. Also, comparisons were made between tests conducted at similar earth-gravity Grashof numbers with radiative and non-radiative gases (see below). The plates and their supporting structure are housed in a well-insulated, sealed aluminum chamber. The NASA-Lewis 2.2 second drop tower facility was employed to obtain low-gravity conditions.

Measurement Techniques

Two types of measurements were made: thermal properties and imaging. The thermal properties are used to verify the 1-d transport equations, to quantify spatial and temporal deviations from steady and/or 1-d profiles (i.e., to identify instabilities) and to quantify the amplitude and spectrum of the disturbances. Thermal properties were measured by thermocouples and radiometers. Imaging provided qualitative information on the overall flow. Temperatures were measured with fine-wire thermocouples (50μm) were placed at several locations within the gas. Since their size was much smaller than the scales under consideration, their influence on heat transport can be considered negligible. To measure fluctuations in radiant energy flux, two thermopile-type narrow-angle shielded radiometers were placed in the gap between the plates. They were oriented parallel to each other, but separated by a horizontal distance of 8 cm, in order to obtain a relative measurement of fluctuations in radiant energy present at any given time during the drop test.

A shearing interferometer (Fig. 2) was developed for flow imaging in the drop tower, since the gases tested are transparent at visible wavelengths. A great deal of attention was given to its sensitivity as well as its ruggedness so that in the future, quantitative measurements as well as qualitative information may be obtained.

Radiative Media

The test gases were chosen based on their radiative properties. SF_6 and CO_2 were used in the bulk of the tests to represent strongly radiating gases. Although SF_6 has the smallest l_p and the most rapid decrease in l_p as T increases, initial drop tests performed with CO_2 also showed considerable radiatively-driven flow. N_2, a nonradiating medium, was utilized to determine if any flow would be encountered in the absence of radiative effects.

RESULTS AND DISCUSSION

At higher pressures and temperatures, flows were observed in SF_6 that did not appear to be a residual of the buoyancy-induced flow present prior to the drop tests. Drop tests performed with high pressure CO_2 also produced significant flow. The tests with N_2 did not produce any visual indication of the presence of fluid motion other than the decay of the buoyant flow present before the drop. Since N_2 is not a radiating gas, this is in accordance with the proposal outlined above.

Figure 3 shows an interferometer image of the flow in SF_6 at 2 atm taken near the end of the drop test. The large deformation of the fringes in the right half of the frame denote a sharp density gradient and the presence of flow. This is the most likely time frame for a radiatively-driven flow to materialize, since the estimated time scale for the onset of radiation at microgravity ranges from .5-5 seconds.

Although the CO_2 did not exhibit as much flow as SF_6, tests conducted at pressures above 2 atm. revealed a significant amount of fluid motion. In fact, CO_2 tests and N_2 tests performed at the same Grashof number were noticeably different. Figures 4 and 5 show interferometer images from CO_2 and N_2 drop tests, respectively, taken near the end of the drop. The CO_2 image shows several regions where fringe deformation is significant, while in the N_2 test only minimal fringe deformation is observed. It is significant that even though the earth-gravity Grashof numbers are nearly the same for these two cases, in the CO_2 case the flow persists throughout the drop whereas in N_2 the flow is steadily decaying, indicating that in the CO_2, radiatively-induced flow dominates.

CONCLUDING REMARKS

Additional drop tests are being performed at NASA-Lewis in order to further isolate and eventually quantify the flows. In particular, we intend to measure the spectra of the temperature and radiative flux fluctuations and compare these to theoretical predictions from the astrophysical literature. The NASA-Lewis drop tower only provides 2.2 seconds of microgravity, so the long-term behavior of these radiatively-driven flows is unknown. The short time duration also prohibits the complete decay of the residual effects of buoyant flow at one-g. The interferometer images indicate that more microgravity time is needed to fully characterize and understand the phenomena of radiation-driven flows.

ACKNOWLEDGMENTS

We gratefully acknowledge the support of the staff at the 2.2 second drop tower at NASA-Lewis Research Center.

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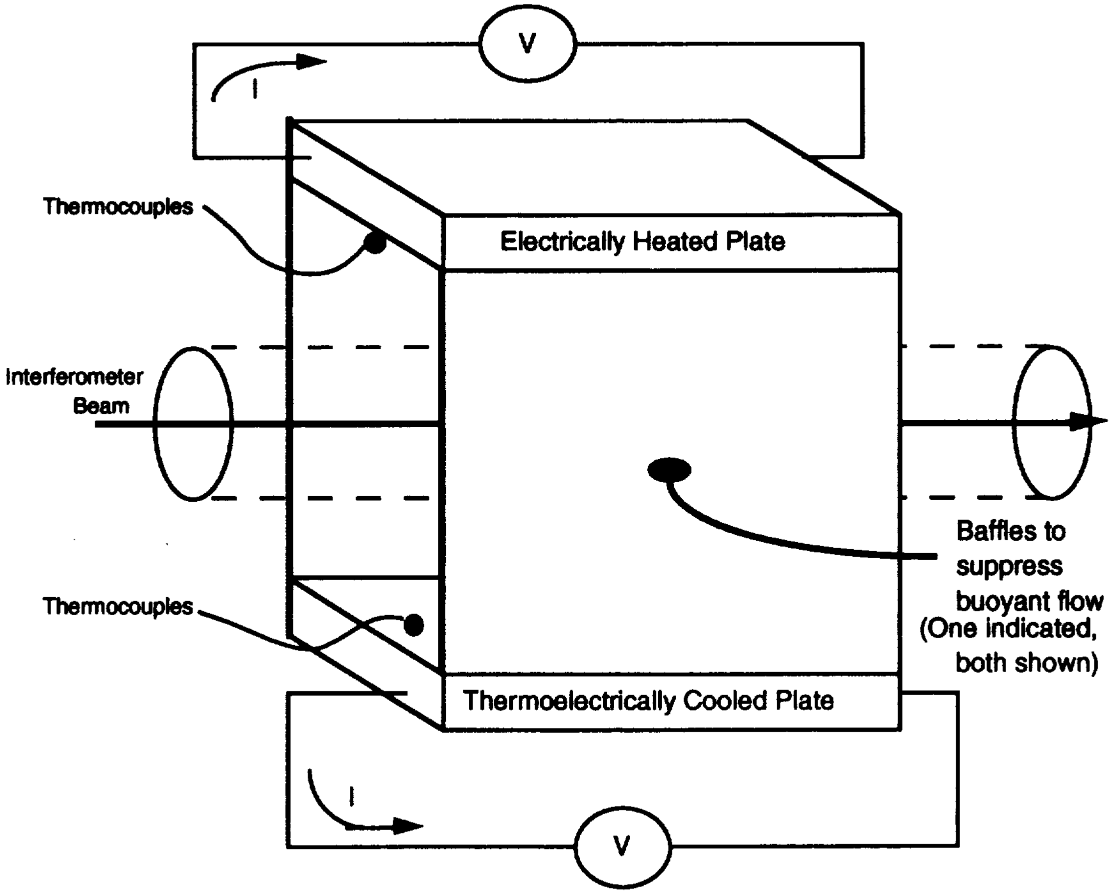
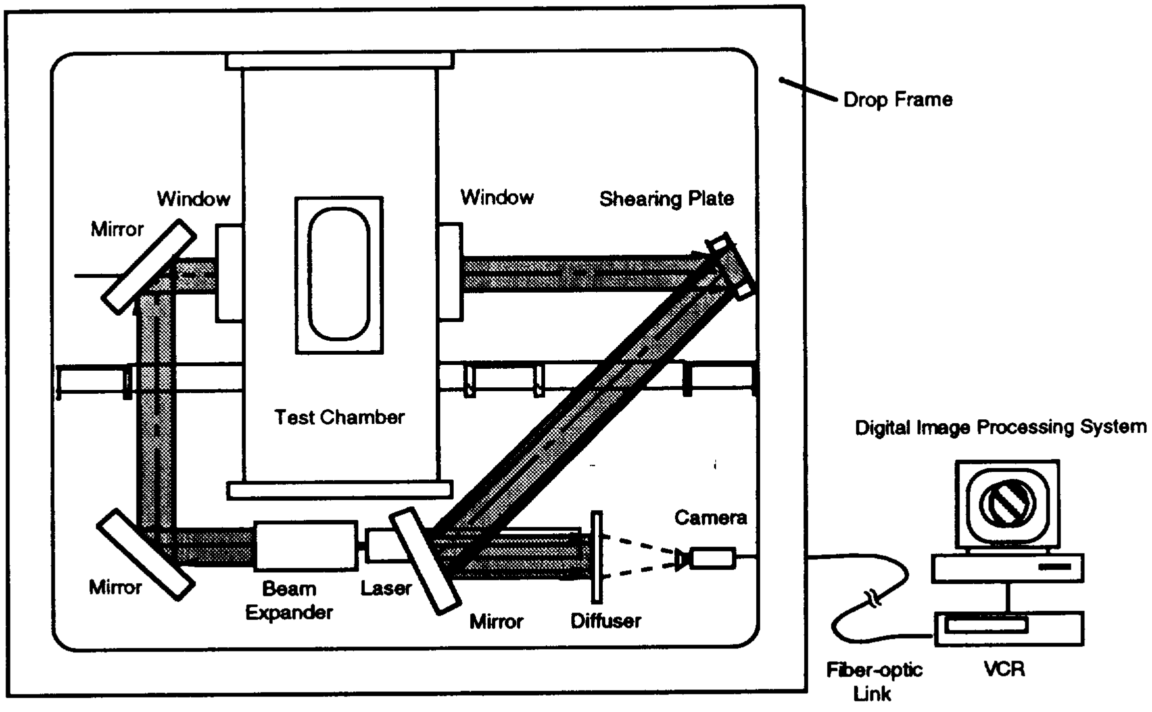


Figure 1. Test apparatus block diagram (expanded in vertical direction for clarity).



Side View

Figure 2. Interferometer and drop frame block diagram.

Figure 3. Interferometer image of radiation-driven flow at μg taken near end of drop period. Gas: SF$_6$; pressure: 2 atm; plate spacing: 2 cm; ΔT=105K. Note strong fringe deformation in fringes in upper right of image indicating density gradient. Fringes are parallel lines when no flow is present.

Figure 4. Interferometer image of radiation-driven flow at μg taken near end of drop period. Gas: CO_2; pressure: 3.2 atm; plate spacing: 2 cm; Grashof number at earth gravity: 1.4×10^6.

Figure 5. Interferometer image of decaying buoyant flow at μg taken near end of drop period. Gas: N_2; pressure: 4.6 atm; plate spacing: 2 cm. Grashof number at earth gravity: 9.2×10^5.