Reports

Heat Flow and Convection Demonstration Experiments Aboard Apollo 14

Abstract. *A group of experiments was conducted by Apollo 14 astronaut Stuart A. Roosa during the lunar flyback on 7 February 1971 to obtain information on heat flow and convection in gases and liquids in an environment of less than 10^{-6}g gravity. Flow observations and thermal data have shown that: (i) there are, as expected, convective motions caused by surface tension gradients in a plane liquid layer with a free upper surface; (ii) heat flow in enclosed liquids and gases occurs mainly by diffusive heat conduction; and (iii) some convective processes, whose characteristics are not fully known, add to the heat transfer.*

During vehicular space flight, heat transfer and fluid flow or convection occur for the most part without the aid of buoyancy forces. Other natural driving forces for convection include surface forces on free liquid surfaces generated by surface tension gradients and pressure forces generated by thermal volume expansions. The effects of these nongravity forces are generally unfamiliar and not well understood because buoyancy forces cannot be eliminated on the earth and thus either predominate or play a significant role in most practical situations. To obtain preliminary information on the nature of nongravity convection, astronaut Stuart A. Roosa carried out three experiments during the lunar flyback phase of the Apollo 14 mission. The experiments consisted of heating four different fluids (Krytox, carbon dioxide gas, water, and sucrose solution), each in containers of distinctive geometry, and noting resultant fluid flow or temperature changes.

The flow pattern experiment was designed to demonstrate convection driven by surface tension in the near absence of gravity. When a thin layer of oil, containing suspended aluminum particles to render the flow pattern visible, is heated on the ground, a pattern of hexagonal cells is observed (Fig. 1A). The cell centers are liquid upflows, and the cell peripheries are downflows. The cells in this hexagonal pattern are called Bénard cells after Henri Bénard who first studied the phenomenon in 1900 (*1*). Lord Rayleigh subsequently developed a theory of cellular convection which accounted for the Bénard cells on the basis of an unstable density gradient (*2*). Although Rayleigh's theory included a satisfactory explanation of some of the features of cellular convection when surface tension is not a factor, as in the case of a fluid layer contained between two rigid plates, the convection observed by Bénard was subsequently shown to be driven by surface tension, not gravity (*3*). A theory of cellular convection caused by surface tension gradients was subsequently developed by Pearson (*4*).

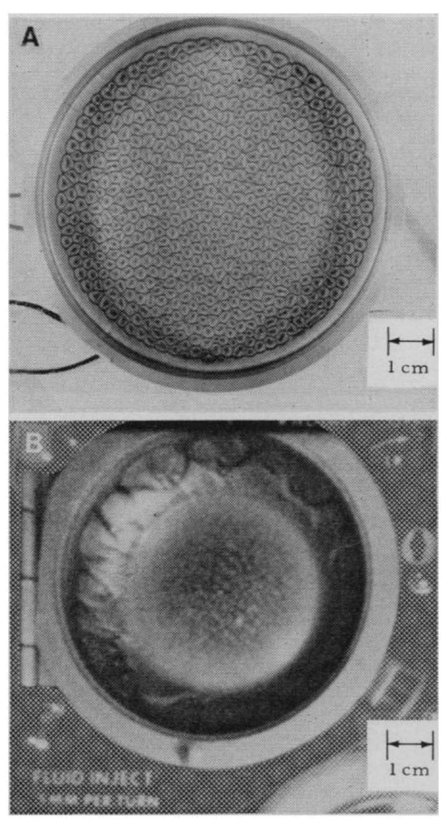

Fig. 1. (A) Bénard cells generated in the ground test (depth, 1 mm; heating rate, 7.4 watts). (B) Flow pattern in the flight test (heating rate, 7.4 watts).

An increasing number of recent papers (*5*) have been concerned with the roles of both gravity and surface tension in cellular convection. It is generally agreed that, in liquid layers thicker than about 4 mm, gravity is the chief determinant of such aspects of cellular convection as the thermal gradient at which convection begins and the shape of the resultant cells. Surface tension usually dominates in liquid layers less than 4 mm thick. The hexagonal pattern is generally associated with convection driven by surface tension and a roll pattern with convection driven by gravity. There exist, however, uncertainties concerning the magnitude of the thermal gradients required for the onset of convection and the resultant flow pattern when gravity and surface tension forces are of the same magnitude. There is also some question about the possibility that gravity somehow is a necessary ingredient in cellular convection. The existing uncertainties are difficult to clear up in experiments on the earth because, of necessity, they must always be conducted in 1*g* conditions.

In the flow pattern experiment conducted aboard the Apollo 14 spacecraft a layer of Krytox 143 AZ oil 2 mm thick was heated electrically from below on a circular, uncovered dish with a diameter of 7.30 cm. The bottom of the dish was made of aluminum (high wettability), and the sides of the dish were constructed of an insulating plastic (low wettability). The flow pattern developed was photographed on motion-picture film. (Krytox 143 AZ, a perfluoroalkylpolyether, was used in preference to other oils because of National Aeronautics and Space Administration safety regulations. The viscosity of Krytox 143 AZ is 32.4 centipoise at 24°C, its surface tension is 15.4 dyne cm^{-1} at 21°C, and its temperature coefficient of surface tension is -0.1 dyne cm^{-1} $°C^{-1}$. Approximately 0.2 percent fine aluminum powder was added to the fluid, and a surfactant was added in order to suspend the aluminum powder. The gravity level at the time of the experiment, calculated from spacecraft rotation rates, was less than $10^{-6}g$.)

The pattern obtained during the Apollo 14 flight is shown in Fig. 1B. The less orderly and symmetrical arrangement observed in the flight test is the result of the fact that Krytox is positioned toward the container periphery and is not spread evenly over the bottom. In view of the greater wettability of the aluminum plate, it was expected that a flat, even layer of oil would be maintained. The wetting characteristics of the material of which the container side wall was constructed, however, apparently changed in the time interval between ground tests and the flight experiment. Nevertheless, convection cells with three to four sides are clearly visible in the fluid adjacent to the wall. A somewhat less distinct pattern is seen in the thin fluid layer (estimated to be about 0.2 mm) in the center of the pan. The cells in the thicker wedge appeared about 23 seconds after the cells in the center layer, in general contradiction with the theory which predicts that cellular convection occurs at lower temperature gradients in thick fluid layers than in thinner fluid layers (*4*). The later appearance of the cellular pattern in the liquid at the cell walls therefore indicates that the cellular flow pattern developed during an earlier noncellular flow caused at the pan walls by a radial temperature gradient. Furthermore, an underlying steady flow distorts a regular cellular pattern (*6*). The irregular pattern actually observed, therefore, is in keeping with the postulation of an undercurrent. Close scrutiny of the photographic data also indicates a wall or edge-type flow. This noncellular type of convection apparently originated at the wall of the pan because the plastic liner was not a perfect insulator.

The Krytox experiment provides information on three important aspects of cellular convection driven by surface tension: (i) surface tension alone can drive cellular convective flow of visible magnitude; (ii) a critical value of the temperature gradient must be exceeded before cellular convection is initiated; and (iii) a polygonal cellular pattern is preferred in a thin liquid layer of uniform thickness.

The radial heating and the zone heating experiments were designed to provide information on convection in confined gases and liquids. In the radial heating experiment a dish of carbon dioxide gas, initially at a pressure of slightly more than 1 atm, was heated by means of a center post heater. In the zone heating experiment two glass cylinders, one containing gas-free distilled water and the other containing a 20 percent (by weight) sucrose solution, were heated by centrally located band heaters. Temperature changes were followed by means of liquid crystal indicator tapes. Such tapes change color reversibly with temperature, each color corresponding to a particular temperature. The color changes are from red to yellow to green to blue with temperature increase. An observed color band, therefore, represents an isotherm. The propagation of the isotherms was recorded on color film once each second. In the radial cell the liquid crystal tapes formed a dish cover, 0.6 cm from the center post heater. In the zone heating experiment liquid crystal tapes were attached both to plastic rods which ran through the center of the cylinders longitudinally and also to the inside walls of the glass cylinder. The dimensions of the two experimental cells were as follows: radial heating cell, 6.43 cm in diameter and 2.38 cm high; zone heating cell, 2.54 cm in diameter and 12.7 cm high. The center band heaters in the zone heating cells were 3.81 cm wide.

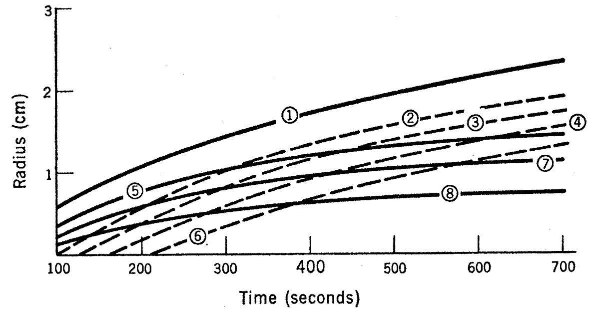

Fig. 2. Curves of isotherm position versus time for the radial heating experiment (heating rate, 5.73 watts). (Solid lines) Flight data; (dashed lines) analytical model. Colors: ① and ②, amber (29.8°C); ③ and ⑤, yellow (31.0°C); ④ and ⑦, green (32.7°C); ⑥ and ⑧, blue (35.2°C).

Figure 2 shows a set of observed curves of isotherm position versus time. In these curves the radial distances shown are from the center of the liquid crystal cover. The dashed curves in Fig. 2 are the theoretical curves, calculated on the assumption that conduction and radiation are the only modes of heat transfer admitted. The colors in the flight data appear sooner than predicted by the analytical model, and the slopes of the flight curves are not as steep as those of the analytical model. Both of these observations indicate an increased heat flow above that predicted on the basis of pure conduction and radiation. The shape of the curves, furthermore, is typical of convective heat transfer. It is estimated that the inferred convection increases the heat flow above that predicted on the basis of pure conduction and radiation from 10 to 30 percent. The convection just discussed is called first-order to distinguish it from an oscillatory kind of convection called second-order, also indicated by the results. Low-frequency temperature oscillations appear in the data when high-frequency oscillations corresponding to random measurement error are "filtered" out. The filtering procedure used consisted of a numerical technique by which fluctuations of a frequency corresponding to identifiable measurement error are eliminated from a function which represents the observed data. The observed oscillations have a period of about 1 minute and an amplitude of about 0.5°C. They are not predicted from the calculated temperature distributions. The results of the zone heating experiment also indicate some first- and second-order convection, although the deviation of the observed from the calculated curves is much less than that obtained in the radial heating experiment. An estimate of the convective heat flow was not attempted because the error bands of the calculated and experimental curves of isotherm position versus time are large as compared to the total change. The lesser convective flow observed in the zone heating experiment as compared with the radial heating experiment may be the result of the lower temperature gradients utilized in the zone heating experiment. Lower temperature gradients were required in the zone heating experiment in order that the temperature be maintained below the boiling point of water. The results for pure water and for sucrose solution are almost identical, an indication that solute diffusion did not exert any appreciable effect. The short time for this experiment limited observation of any diffusion effects.

According to calculations based on current theory, gravity levels of $10^{-6}g$ are much too low to have caused the indicated first- and second-order convections. A gravity level of about $10^{-4}g$ is necessary to cause any noticeable convection in the test cells. Forces that could be responsible for the indicated first- and second-order convections include thermally generated volume expansions and intrafacial tension gradients. In one analytical study of the effect of volume expansions on heat transfer in an ideal gas under zero-gravity conditions Larkin concluded that the heat transfer was greatly increased over what would be predicted if such thermally induced motion were neglected (*7*). The term "intrafacial tension" is used to describe a developed tension arising in heated portions of a gas or liquid. Possibly the differences in physical properties between the hot and colder portions of a fluid can be large enough to result in an intrafacial tension. Evidence for this kind of tension has been discussed (*8*).

The demonstration of convection driven by surface tension in low-gravity environments suggests that in feasibility studies for a number of proposed space manufacturing processes in which sizable free liquid surfaces are in direct contact with a gas or vapor phase this sort of convection should be taken into account. The evidence obtained in the radial heating and zone heating experiments for still another form of low-gravity convection requires confirmation.

Further details of these experiments and the data analyses are given elsewhere (*9*).

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10. We are grateful to the many people who were involved in the fabrication, design, and data analysis of these experiments, especially Col. S. A. Roosa for his competent performance of experiments under space conditions. We also thank Dr. J. Bredt for suggesting the use of liquid crystals to track convection isotherms and Dr. E. L. Koschmieder for his many helpful suggestions on the writing of this report. Supported by NASA contract NAS8-25577.

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Pollution Monitor for Nitric Oxide: A Laser Device Based on the Zeeman Modulation of Absorption

Abstract. *The concentration of nitric oxide can be monitored by a new device in which the Zeeman effect is used to shift an absorption line of nitric oxide into coincidence with a laser line of carbon monoxide. The absorption is modulated by a small, oscillating magnetic field. This device is specific for nitric oxide and is not subject to interference from other gases.*

A new device, using the Zeeman effect, has been devised for the measurement of NO (and possibly NO_2) concentrations in gaseous samples. This device employs a CO laser source at a fixed infrared frequency and employs the Zeeman effect both to tune and to modulate the absorption. It is specific for a strongly paramagnetic substance such as NO and is not subject to interference from other contaminants in the sample, since other contaminants either have magnetic moments too small to modulate significantly (for example SO_2 and H_2O) or do not absorb infrared radiation (O_2). Because of the wide separation of the NO and NO_2 absorption bands, an excess of NO_2 does not interfere with the measurement of NO concentrations.

Kreuzer and Patel (*1*) have explained the need for an improved NO detector and have also outlined the problems involved in using infrared absorption to measure the concentrations of pollutants. They have shown how a tunable spin-flip Raman laser can be coupled with an optoacoustic detector to measure low concentrations of NO in the presence of other contaminants. Such continuously tunable laser devices are expensive and require skilled operators. Consequently, it is desirable to explore the possibility of developing simpler and cheaper measurement devices. Past attempts to utilize fixed-frequency lasers have not been notably successful because pressure broadening is usually required to achieve sufficient overlap of the absorption line of the pollutant and the laser line. This has two consequences: (i) measurements with a single laser line are no longer adequate to identify the pollutant, and (ii) moderate concentrations or long path lengths are required to obtain sufficient absorption. For NO we have overcome these difficulties by using the Zeeman effect to shift the absorption into near coincidence with a CO laser line and to modulate the molecular absorption line rather than the incident laser light.

Our device consisted of a continuous-wave CO laser oscillating only on the 1884.37-cm^{-1} line, an absorption cell placed between the pole pieces of an electromagnet, and an infrared detector to monitor the intensity of the laser radiation after it passed through the absorption cell. A d-c magnetic field was used to shift the Zeeman components of the NO absorption line into near coincidence with the CO laser line. The modulated magnetic field which was used to modulate the Zeeman components of the molecular absorption line in and out of resonance with the CO laser line was generated by using an audio amplifier to drive a set of small coils attached to the pole pieces of the electromagnet. The resulting modulated signal from the infrared detector was measured with a lock-in amplifier. In our experiments the field was modulated with the frequency 1 khz, and the amplitude of modulation was varied from 10 to 100 gauss. Measurements were made in the pressure range 1 to 30 torr. In the configuration described above the absorption cell is outside the laser cavity. With an intracavity configuration the device would be more sensitive to the presence of NO at very low concentrations but would probably be less able to quantitatively measure NO over a range of concentrations.

We now examine briefly conditions governing optimum values for the static and alternating magnetic fields. Qualitatively, one expects the intensity of the first-derivative spectrum to be greatest if (i) the sharp laser line lies on the steepest part of the much broader absorption line, and (ii) the modulating magnetic field shifts the line by half the line width in each direction. Quantitatively, the intensity of the first-derivative spectrum for low absorption (no saturation) and low pressure (Doppler line shape) is proportional to the Fourier coefficient of the $\cos\omega t$ term in the expression

$$\sigma^{-1}\exp\left[-1/2\left(\frac{d}{\sigma}+\frac{a}{\sigma}\cos\omega t\right)^{2}\right] \qquad (1)$$

where σ is the full width of the absorption line at half intensity in wave numbers (cm^{-1}) divided by the factor