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SHORTER COMMUNICATIONS

HEAT TRANSFER TO A GAS FROM A SPHERICAL ENCLOSURE: MEASUREMENTS AND MECHANISM

B. J. TYLER and A. F. TUCK

Department of Chemistry, Faculty of Technology, University of Manchester, Manchester, 1

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NOMENCLATURE

g, acceleration due to gravity;
r_o, vessel radius;
t, time;
ΔT_m, maximum difference between gas and vessel temperatures at the centre of the vessel;
β, coefficient of cubical expansion;
α, thermal diffusivity;
ν, kinematic viscosity;
τ, $\alpha t/r_o^2$;

Ra, Rayleigh number, $= \dfrac{g\beta r_o^3 \, \Delta T_m}{\alpha\nu}$.

IN SEEKING to establish a method of calibrating fine-wire thermocouples *in situ* in experimental systems some unusual temperature fluctuations were observed in gases contained in spherical vessels after cooling by a rapid, adiabatic expansion. These effects are shown to be due to natural convection occurring whilst the gas temperature returns to that of the vessel, and the critical value of the Rayleigh number at which convective heat transfer becomes insignificant has been determined.

The gas temperatures were measured by 0·0025-cm diameter thermocouples and the thermocouple output recorded after amplification. The spherical vessels used were of 280- and 1100-cm^3 capacity with a fixed central thermocouple, 1100- and 5000-cm^3 capacity with a movable

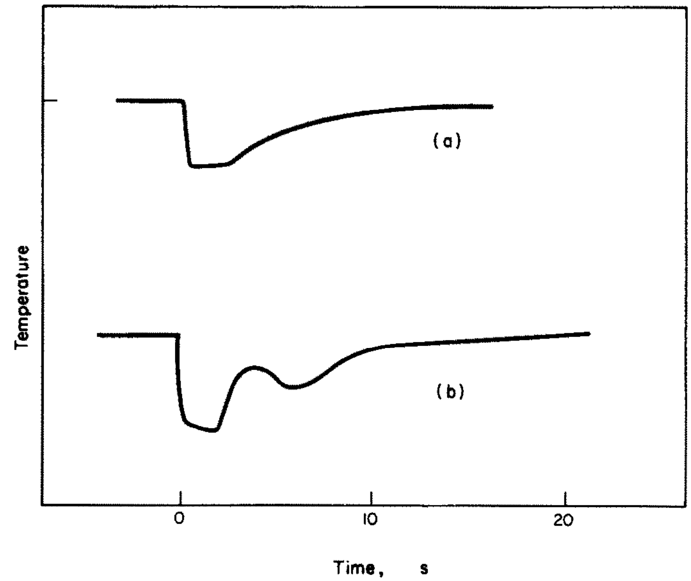

FIG. 1. Examples of the temperature variation observed at the centre of an 1100-cm^3 capacity spherical vessel after an adiabatic expansion.

(a) H_2, $\Delta T_m = 2{\cdot}1$ degC, $Ra = 1{\cdot}2 \times 10^3$.
(b) N_2, $\Delta T_m = 5{\cdot}2$ degC, $Ra = 1{\cdot}5 \times 10^5$.

thermocouple and one of 1100-cm^3 capacity with four junctions mounted along a radius. In each experiment the vessel was first filled with cylinder hydrogen, nitrogen or carbon dioxide to a measured pressure in the range 1–14 cm Hg above atmospheric pressure. After the gas had reached vessel (room) temperature the pressure was rapidly reduced to atmospheric by opening a tap of at least 0·6-cm bore in a short side-arm of the vessel.

The simplest pattern of temperature variation at the centre of the vessel was where the sharp fall in the gas temperature caused by the expansion was followed by a plateau, when there was little change in the gas temperature, and then a steady recovery to the vessel temperature (Fig. 1a). This behaviour corresponds qualitatively with that expected for purely conductive heat transfer [1]. Quantitative agreement was demonstrated in experiments in 280- and 1100-cm^3 vessels, using hydrogen, by detailed comparison of the experimentally observed variation of the centre temperature with the theoretical values, assuming only conductive heat transfer. This agreement was to better than 10 per cent for systems with Rayleigh numbers of less than 650 for times covering over 75 per cent recovery of the initial temperature drop. For the majority of the experiments the analysis was simplified to measurement of the time from the start of the experiment to the point where the centre temperature drop reached 0·5 ΔT_m. This recovery time, $\tau_{\frac{1}{2}}$, has a theoretical value [1] of 0·139 with only conductive heat transfer. The variation of $\tau_{\frac{1}{2}}$ with the Rayleigh number of the system is shown in Fig. 2. This semi-logarithmic plot covers experiments with all gases and with the three vessel sizes used.

The data indicate that up to Rayleigh numbers of about 650 the values of $\tau_{\frac{1}{2}}$ are in reasonable agreement with the theoretical value of 0·139, showing there is no significant contribution from convective heat transfer. Beyond this value there is a steady decrease in $\tau_{\frac{1}{2}}$ with increasing Rayleigh number, and the form of plotting the data provides a good correlation of the experiments with the different gases and vessels used. At Rayleigh numbers of 650 to about 2×10^4 the simple pattern of temperature rise previously described was still observed, but the recovery was always faster than predicted by conduction theory, so indicating the occurrence

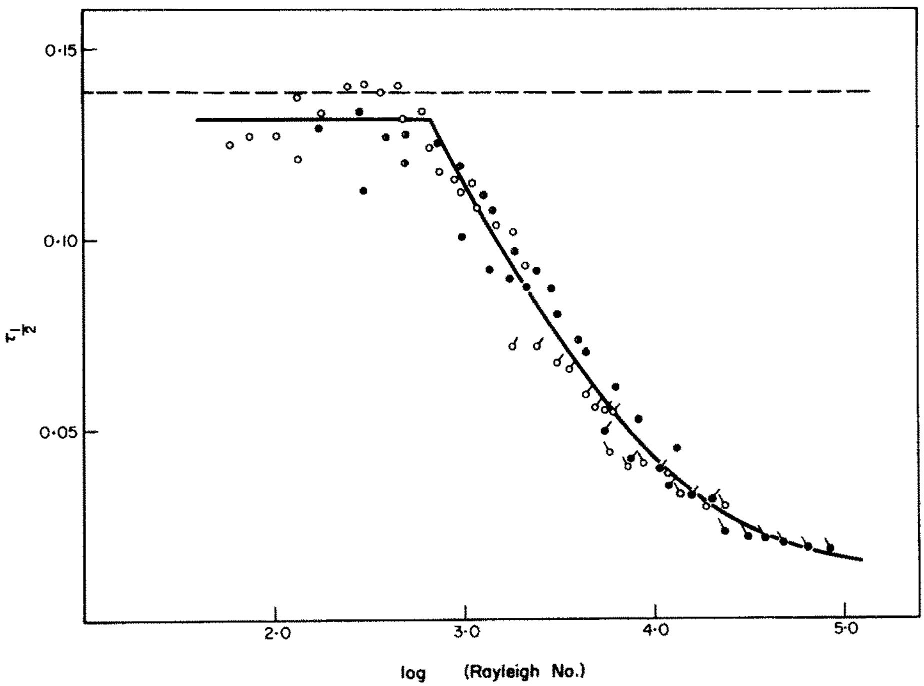

FIG. 2. $\tau_{\frac{1}{2}}$ vs. log (Rayleigh number).

H_2, 280-cm^3 vessel.
H_2, 1100-cm^3 vessel.
H_2, 5000-cm^3 vessel.
N_2, 280-cm^3 vessel.
N_2, 1100-cm^3 vessel.
CO_2, 280-cm^3 vessel.
CO_2, 1100-cm^3 vessel.

Broken line shows theoretical value for a purely conductive mechanism of heat transfer.

of natural convective heat transfer. At Rayleigh numbers greater than about 2×10^4 a new pattern of temperature rise appeared (Fig. 1b). The centre temperature still fell to the steady plateau, but this was terminated more sharply than at lower Rayleigh numbers and the temperature rose to a shallow maximum, and then fell again before rising smoothly to the vessel temperature. Under the most extreme conditions used three successive maxima and minima were recorded. That these effects were not induced by the method of expanding the gases was shown by altering the direction of the side-arm and by expanding the gases simultaneously through two side-arms: these changes did not affect the pattern of temperature variation observed. Some details of the movement of the gases in this region of mainly convective heat transfer were obtained using the 1100-cm^3 vessel with four thermocouples. These showed a brief period of conductive heating of the gas near the wall, establishing steep temperature gradients, followed by a downward movement of the colder gas near the centre of the vessel. This draws down warmer gas from the top of the vessel, so causing the rapid rise of temperature recorded on the centre thermocouple. The later cooling is caused by the downward movement of gas from regions in the upper half of the vessel, but not directly above centre. The technique available does not yield sufficient detail to permit the estimation of heat-transfer coefficients for these transient processes.

From these experiments it has been possible to identify the value of Rayleigh number below which there is purely conductive heat transfer in this situation of a spherical body of gas in contact with a vessel of much greater heat capacity. This value is extremely close to that obtained ($Ra = 600$) as the condition at which convection is first of significance in reacting gases in spherical vessels (2). In these circumstances the gas temperature is greater than that of the vessel for exothermic reactions, the temperature distribution across the vessel is approximately parabolic and changes only slowly with time in comparison with adiabatic expansions.

We wish to thank Mr. T. A. B. Wesley for undertaking the construction of the thermocouples used in this work.

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FILM BOILING OF A MIXTURE ON A HORIZONTAL PLATE

D. E. KAUTZKY* and J. W. WESTWATER

Division of Chemical Engineering, University of Illinois, Urbana, Illinois

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NOMENCLATURE

- g, acceleration of gravity;
- g_c, conversion factor;
- h, boiling heat-transfer coefficient;
- k_v, thermal conductivity of vapor;
- L', enthalpy change of vaporization plus sensible heat;
- Q/A, heat flux;
- ΔT, temperature difference driving force;
- x, y, mol fraction Freon-113 in liquid, vapor;
- μ_v, viscosity of vapor;
- ρ_L, ρ_v, density of liquid, vapor;
- σ, surface tension.

* Present address: Eastman Kodak Company, Rochester, New York.

Theoretical analyses exist for film boiling of pure liquids on horizontal cylinders [1] and horizontal flat plates [2, 3]. Experimental data [1, 4, 5] with pure liquids substantiate the equations. The only published data for a mixture in film boiling are the data of Dunskus and Westwater [6] who were examining the effects of trace amounts of high molecular weight, nonvolatile additives on the heat transfer to *iso*propanol. As little as 0·1 mol% of one additive, Igepal CO-880, caused the heat-transfer coefficient to increase by about 300 per cent. No data exist for miscible mixtures of two volatile components.

The goal of the new research was to obtain accurate film-boiling data for a miscible mixture of volatile liquids. It was of interest to show whether the results would agree with predictions based on the use of weighted physical properties in the existing equations for pure liquids.

The flat-plate geometry was chosen because the film