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Amplitude-Dependent Oscillations in Gases

O L de LANGE and J PIERRUS

School of Chemical and Physical Sciences, University of Natal
Private Bag X01, Scottsville, Pietermaritzburg 3209, South Africa

Abstract

We consider the following question: Suppose part of the boundary of a cavity containing a gas is set into oscillation, the damping in the boundary being small. What is the nature of the oscillations in the gas? We treat the low-frequency limit (wavelength much greater than dimensions of the cavity). Experiment shows that for small volumes of gas the oscillations are intermediate between adiabatic and isothermal extremes. As the volume of gas is increased, amplitude-dependent changes in the frequency are observed: one can plot a phase diagram (based on amplitude and volume) delineating three regions: intermediate, transition, and isothermal. The reason for the amplitude dependence is not clear.

We present experimental results relating to the following question: what is the nature of the oscillations in a confined gas if part of the wall of the container is set into motion? To perform the experiment, it is essential that the friction associated with motion of the wall be kept as small as possible. To this end, it is convenient to use for the mobile portion of the wall a smooth steel ball which fits closely into a precision-made glass tube. The motion (damped oscillation) of the steel ball is measured accurately using a linear voltage-displacement transducer [1]. The parameters of our experiment are such that the wavelength of the oscillations is much greater than the dimensions of the container.

Two useful physical quantities can be obtained from our measurements, namely the bulk modulus of the gas and the relaxation time associated with the damping. These two quantities enable one to deduce the nature of the oscillations. The experiments have been performed for a range of variables: volume of gas, amplitude of oscillation, type of gas. We find that the oscillations exhibit a variety of behaviour dependent on the above variables. Here we present a brief account of this behaviour, more details are published elsewhere [2, 3].

A typical plot of the measured position $x(t)$ of the steel ball versus t is shown in Fig. 1 for oscillations in a volume $V = 7.1\ell$ of $CC\ell_2F_2$. Three features are apparent from this plot. Firstly, an initial set of cycles (cycles 1 to 8) all have very nearly the same period, $T_m = 1.06$s. A second set of cycles (cycles 11 to 17) have a longer, nearly constant period $T_i = 1.26$s. The change between these two sets of cycles is accomplished quite rapidly, in cycles 9 and 10 (with periods 1.09s and 1.26s). The third feature is that the onset of the "tail" is accompanied by a decrease in damping: for cycles 1 to 8, $\tau_m/T_m \approx 5.1$, whereas for cycles 11 to 17, $\tau_i/T_i \approx 8.4$. These features are observed in all the gases we have studied (eighteen gases with atomicity ranging from 1 to 12).

We denote by A_L the amplitude of the last peak in the first set of cycles, and by A_1 the amplitude of the first peak in the tail (examples of these peaks are indicated by arrows in Fig. 1). Our measurements show that both A_L and A_1 increase with the volume of gas V.

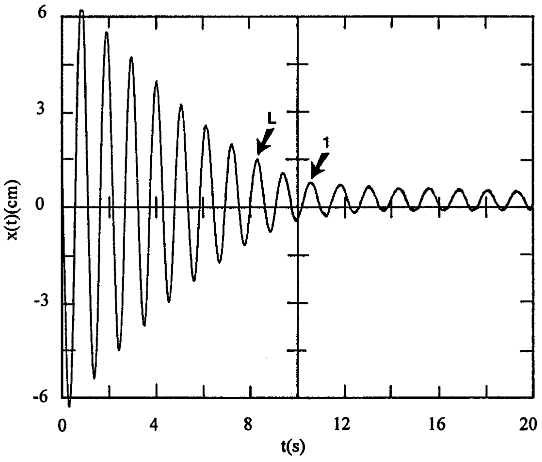

Figure 1. Oscilloscope trace for the displacement x of the steel ball versus t, for a volume $V = 7.1\ell$ of $CC\ell_2F_2$. The first 17 cycles are shown. The arrow L indicates the position of the last peak in the first set of cycles with constant period $T_m = 1.06$s. The arrow 1 shows the first peak in the cycles of the tail, which have constant period $T_i = 1.26$s.

See Fig. 2, where results are plotted for $CC\ell_2\ F_2$. The region marked I consists of initial oscillations with amplitudes $> A_L(V)$; these have period $T_m(V)$. Region III consists of oscillations in the tails (those with amplitudes $< A_1(V)$); these have period $T_i(V)$. Region II is a transition region where the periods are changing from $T_m(V)$ to $T_i(V)$. Thus plots such as Fig. 2 represent a "phase diagram" for the oscillations. Instead of the above method of defining region I (by constancy of the period), one can use constancy of the relaxation time. The amplitudes $\mathrm{A}_L(V)$ determined by the latter method are larger than those in Fig. 2. We mention that the numerical values of A_L and A_1 are sensitive to the container that is used. For small volumes of gas, the amplitude $A_1(V)$ for onset of the tail is too small to be observed in our experiments, and all the oscillations have period $T_m(V)$.

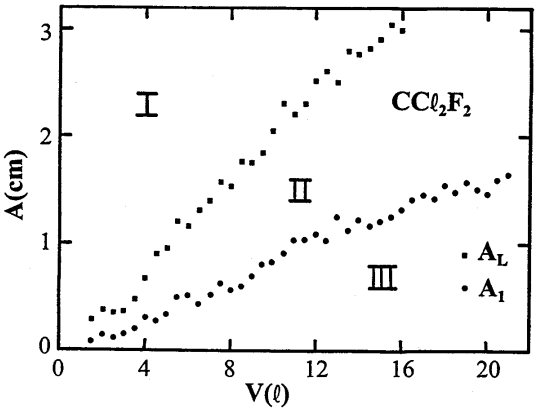

Figure 2. A phase diagram for oscillations in $CC\ell_2F_2$: a plot of the amplitudes A_L and A_1 versus the volume of gas. The amplitudes are determined from peaks such as those labelled L and 1 in Fig. 1. In Region I the oscillations are intermediate between adiabatic and isothermal. In Region III the oscillations are isothermal.

Analysis of the measured relaxation times of the oscillations in Region I leads to the conclusion that these oscillations are intermediate between the adiabatic and isothermal extremes [2, 3]: Due to the finite thermal conductivities of the gas and the walls of the container, there are heat flows into and out of the gas during the expansion and compression parts of the cycle. By contrast, the measured relaxation times τ_i of the oscillations in Region III indicate that these oscillations are isothermal (except for small volumes of gas (high frequency oscillations) where there is indication of residual thermal gradients in the oscillating gas [2]).

Measurements of the bulk moduli associated with oscillations in Region I are consistent with the interpretation that these are intermediate oscillations [2, 3]. For the oscillations in Region III the picture is more complicated: For monatomic and diatomic gases the measured bulk moduli are consistent with isothermal oscillations. However, for polyatomic gases the measured bulk moduli are all lower than the theoretical values for isothermal oscillations, and the disparity increases with the atomicity of the gas [2, 3].

The reason for the amplitude-dependence of oscillations in our experiments is not clear. Nor is it clear why the measured bulk moduli of oscillations in the tails (Region III) for polyatomic gases are all lower than isothermal values, in contradiction to the isothermal values of the relaxation times.

References

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[2] de Lange O L and Pierrus J, *Phys. Rev. E*, 1998, V.57, 5520.

[3] de Lange O L and Pierrus L (to be published).