Oscillatory and relaxation studies in the convection of supercritical ^{3}He

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Abstract

We analyze the observed temporal profile $\Delta T(t)$ of the temperature difference, measured across a very compressible supercritical ^{3}He fluid layer in the convective state. The experiments were done along the critical isochore in a Rayleigh-Bénard cell after starting the vertical heat flow q. For $q > q_{ons}$ ("convection onset"), the transient $\Delta T(t)$ under given conditions of q and $\epsilon \equiv (T_c - T_c)/T_c$ ($T_c = 3.318$K) shows a damped oscillatory profile with period t_{osc} modulating a smooth base profile. The latter forms the tail of the transient which relaxes exponentially to the steady-state $\Delta T(\infty)$ with a time constant τ_{tail}. The scaled times t_{osc}/t_D and τ_{tail}/t_D from all the data could be collapsed onto two curves as a function of the Rayleigh number over ~ 3.5 decades. Here t_D is the diffusion time.

Key words: critical phenomena; hydrodynamics; convection ; transients

While a substantial amount of recent research has dealt with pure fluid convection in a Rayleigh-Bénard cell in a quasi steady-state (See for instance[1]), comparatively little study has been done on the transient behavior after the heat flow q has been started across a fluid layer. Here we study the temporal profile of the temperature drop $\Delta T(t)$ across the fluid layer (thickness L=0.106cm, aspect ratio 57) of a very compressible fluid, supercritical ^{3}He, before the steady state value $\Delta T \equiv \Delta T(\infty)$ is reached. Here $\Delta T > \Delta T_{ons}(\epsilon)$, the convection onset value, and $\epsilon \equiv (T - T_c)/T_c$ where $T_c = 3.318$ K. The range along the critical isochore is $5{\times}10^{-4} \leq \epsilon \leq 0.2$.

Experiments on the convective behavior of ^{3}He, both transient and steady state, were recently reported[2] at Rayleigh numbers $Ra < 5 \times 10^8$. In the measurements of $\Delta T(t)$ at a given ϵ and heat flow q, the temperature of the upper plate was kept constant and that of the bottom plate was left floating. A detailed discussion of the fulfillment of the Boussinesq criteria in the experiments is given in ref.[2]. The present paper describes an analysis of some of the transients and their characteristic times, to be compared elsewhere with predictions by A. Onuki and his group[3].

Under certain conditions, to be described below, damped oscillations of $\Delta T(t)$ with a period $t_{osc}(q, \epsilon)$ were observed, following the initial sharp rise from zero after q is turned on. These result from a combination of density and high compressibility that leads to strong thermo-acoustic phenomena which have been shown responsible for very fast temperature homogenisation inside the fluid layer[4]. The mechanism involved for the accelerated energy transfer has been named "piston effect", which results from the hot (or cold) boundary layer that forms where a heat is suddenly applied (or withdrawn). This layer then acts as a piston that isentropically compresses (decompresses) the bulk of the fluid, thus raising (lowering) the temperature in a homogeneous way, as has been described in refs[5,6]. A sequence of hot and cold piston effects produces maxima and minima in $\Delta T(t)$ until a steady-state regime is reached.

After the heat flow is started, the observed $\Delta T(t)$

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profile is as follows: As q is increased beyond the q_{ons} needed for the convection onset, there is first an overshoot - or truncated oscillation, decaying to $\Delta T(\infty)$. This is similar to the observations in a liquid at constant pressure[7]. Further increase in q beyond a certain value produces damped oscillations with a period t_{osc} followed by a smooth base profile with a minimum, beyond which $\Delta T(t)$ tends exponentially from below to $\Delta T(\infty)$ with a relaxation time $\tau_{tail}(q, \epsilon)$. This is the exponential tail of the transient. The visibility and relative amplitude of these oscillations and the exponential tail is a function of ϵ and of q. For a given ϵ, both τ_{tail} and t_{osc} decrease with increasing q, where always $t_{osc} < \tau_{tail}$. When t_{osc} becomes comparable to the instrumental time constant of the thermometer circuitry, $\tau \simeq 1.3$ s., the oscillation amplitude and finally the first peak, the overshoot, become averaged out and only the smooth tail relaxation is observed.

At high enough values of q, an additional very broad maximum is observed before $\Delta T(\infty)$ is reached from above. The amplitude of this component is only at most 0.3 % of $\Delta T(\infty)$ and the corresponding relaxation time to steady state is estimated to be of order $5\tau_{tail}$. We will neglect here this additional component.

We have found that plots of both t_{osc} and τ_{tail}, when scaled by the diffusive time $t_D = L^2/4D$, and plotted versus $[Ra^{corr} - Ra_c]$, can be collapsed on two separate curves. Here D is the diffusivity, Ra^{corr} is the Rayleigh number corrected for the adiabatic temperature gradient [2] and Ra_c=1708 is the critical Rayleigh number. The range of scaling extends over about 3.5 decades in $[Ra^{corr} - Ra_c]$.

In Fig.1 we show this scaling plot where the various symbols indicate the reduced temperatures ϵ where the transients were recorded. There are some systematic deviations and scatter of less than ± 10% from the average curves. This is a remarkable result because with decreasing ϵ over the range for this plot, the compressibility and t_D increase by factors of 40 and 20 respectively, and the Prandtl number Pr increases from 2 to 42. Over approximately 2.5 decades of $[Ra^{corr} - Ra_c]$, the curves for t_{osc}/t_D and τ_{tail}/t_D can be represented by power laws with exponents of $\simeq$ -0.52 and -0.60. Hence both scaled times diverge as $[Ra^{corr} - Ra_c] \to 0$. There seems to be no clear dependence on Pr at these moderate values of Ra^{corr}, as shown by the collapsing of the data for various values of ϵ. We can therefore expect that the two sets of data in Fig.1 are independent of the fluid properties and hence they represent in a crude first approximation a universal set of curves.

For $\epsilon < 9 \times 10^{-3}$, no damped oscillations were detected, and the character of the transients seems to have changed (See ref[2]). An analysis of τ_{tail} at $\epsilon = 5 \times 10^{-4}$ showed the data to be inconsistent with an extrapolation from the curve in Fig 1 to the higher Ra numbers ($\sim 4 \times 10^8$) corresponding to these data.

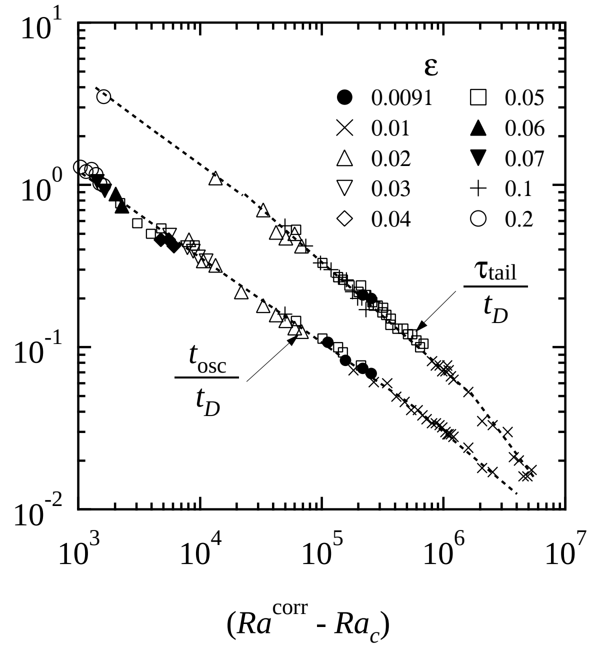

Fig. 1. Scaled plots of t_{osc}/t_D and τ_{tail}/t_D versus $[Ra^{corr} - Ra_c]$ for reduced temperatures $9 \times 10^{-3} \leq \epsilon \leq 0.2$. The two dashed lines are guides to the eye.

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