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Observations of temperature jumps in liquid-vapour phase change

P N SHANKAR and M D DESHPANDE

Fluid Mechanics Division, National Aeronautical Laboratory, P.B. 1779, Bangalore 560017, India

Abstract. We have experimentally observed large temperature jumps at the interfaces during liquid-vapour phase change between plane surfaces. This settles an issue that has been controversial for the past few decades.

1. Introduction

Consider a pure vapour A confined between two infinite parallel surfaces of its own condensed phase which are at $\hat{T}_0$ (temperature of hot liquid phase) and $\hat{T}_1$ (temperature of cold liquid phase) respectively (see figure 1). As $\hat{T}_0 > \hat{T}_1$ the liquid will evaporate from the lower surface and condense on the top surface. It was Pao (1971) who first pointed out, from a kinetic theory analysis, that for a monatomic vapour the temperature would suffer large jumps at the interfaces; large enough, indeed, for the temperature gradient in the bulk of the vapour to possibly oppose the applied gradient. These remarkable results hold even in the continuum limit, though contamination by an inert gas and molecular internal energy can drastically reduce the effects (Shankar 1988).

Though Pao's results have since been theoretically confirmed by many others (for example, Sone and Onishi 1978; Aoki and Cercignani 1983) they have remained controversial. Serious doubts have been raised about the formulation and boundary conditions and even about whether the results violate basic physical laws (see Koffman *et al* 1984; Cercignani *et al* 1985; Hermans and Beenakker 1986). Surprisingly, although many investigators including Pao (1971) have suggested experimental tests of the theory no experimental results have been reported so far. We wish to briefly announce here our experimental confirmation of large temperature jumps at the interfaces.

2. Experiments and results

The idealized situation in figure 1 was simulated experimentally by evaporating and condensing suitable vapours in a cylindrical perspex chamber bounded by flat metallic plates. Provision was made for heating and cooling the end plates and a vacuum system was used to evacuate the chamber. The temperature in the chamber was measured by
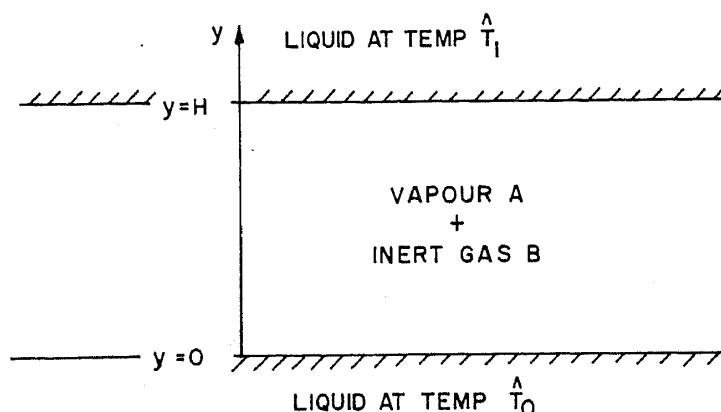
Figure 1. Liquid-vapour phase change between plane liquid surfaces.

10 chromel-alumel thermocouples epoxied into the chamber at various heights between the end plates. Several chambers were fabricated with an internal diameter of 105 mm and heights between the plates ranging from 17 mm to 40 mm. The tips of the thermocouples lay approximately on a helix about 40 mm from the chamber wall. The thermocouple outputs were read using an accurate digital multimeter. One may refer to Shankar and Deshpande (1988a) for more details regarding the apparatus and procedures.

The suitability of the apparatus was established by measuring temperature profiles in air over a range of Rayleigh numbers; the profiles so obtained agreed well with the temperature profiles expected over that range. For experiments with liquids, the chamber was first sealed, evacuated and isolated and the liquid then injected. Quasi-steady temperature profiles were then obtained as the system adjusted to the new conditions and to the increasing contamination. For experiments with mercury it was possible to evacuate with the liquid in place; thus, in this case the temperature profiles corresponded closer to 'steady state' conditions.

Typical results obtained from experiments with Freon 113 are shown in figure 2. The temperature profile in the contaminant air (at a pressure around 1 torr), prior to liquid injection, shows good linearity. The profiles in the vapour, after liquid injection, are steep, almost vertical, indicating uniform temperature. These profiles are what the theory predicts when the mass flux is high. For an organic vapour like Freon ($\gamma \approx 1.05$) theory predicts that only small jumps are likely at the boundaries (Shankar 1988). From the data shown in figure 2, and all our other data from water and Freon the temperature jumps at the boundaries were not large enough to permit resolution with our equipment.

The choice of mercury as a working fluid was based on the need for a vapour with high γ (specific heat ratio for vapour C_p/C_v) and low vapour pressure at near room temperatures. For our experiments with mercury a new chamber was fabricated capable of achieving about 2 to 3 orders of magnitude better vacuum than in the earlier chambers. Figure 3 shows a set of profiles obtained in mercury vapour with the lower liquid at a temperature around 100°C. Note that thermocouples 1–3 are in the liquid while 10 is at the top surface; thermocouples 4 and 8 failed during the run. We observe the striking uniformity of the temperature in the vapour and the large jumps near the boundaries; the temperature jumps appear to be almost 50% of the applied temperature
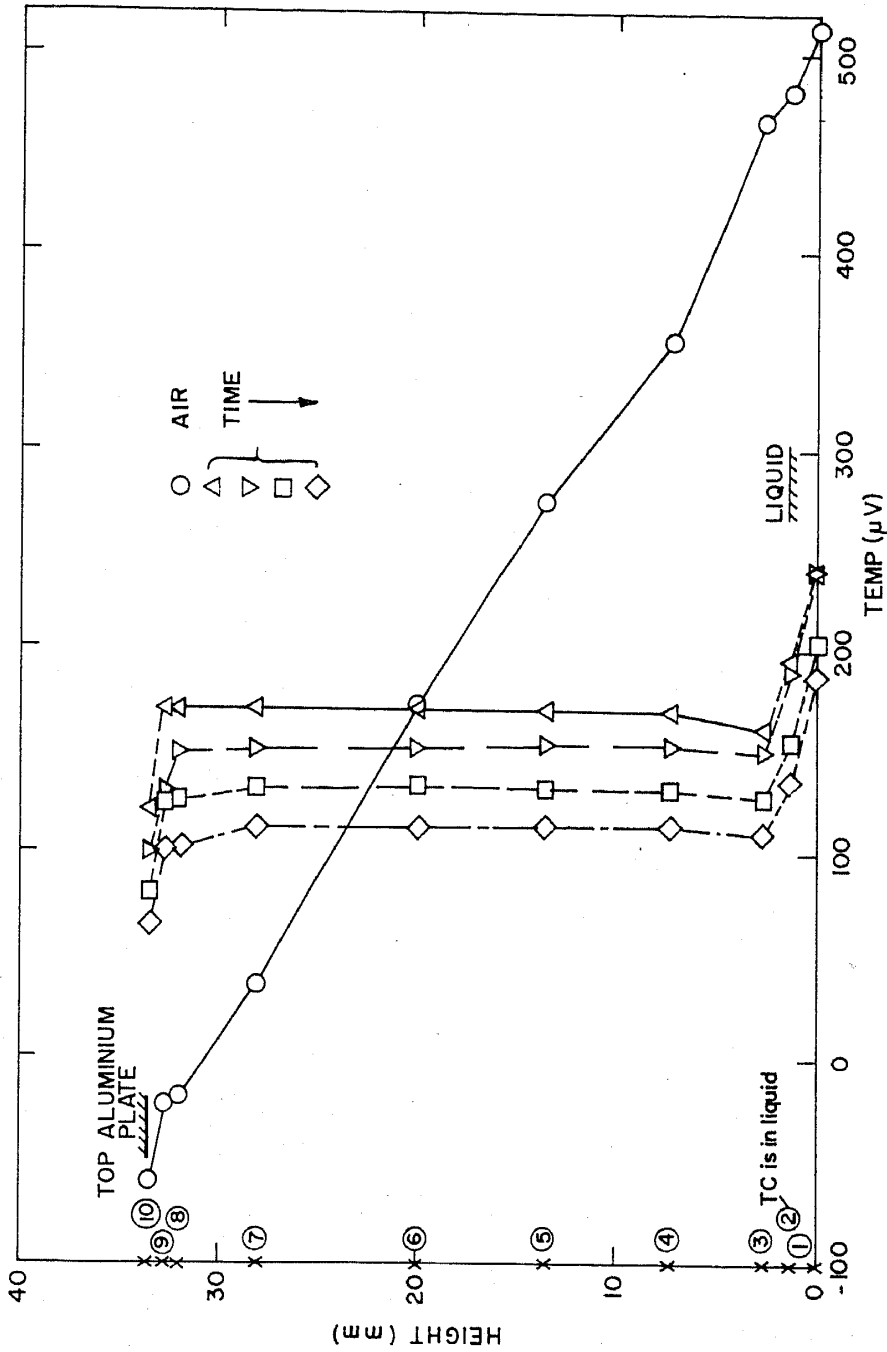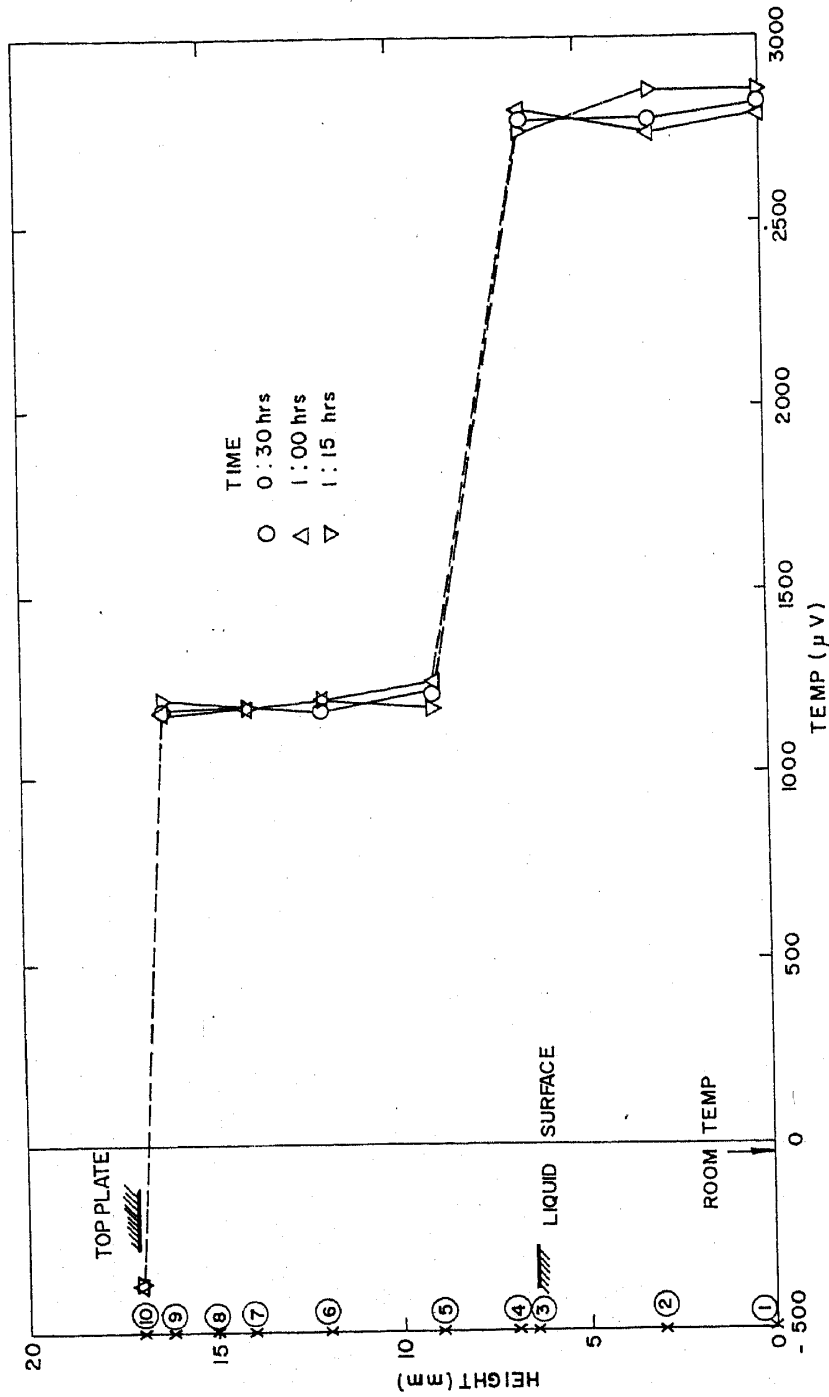
Figure 2. Typical results with Freon (39·8 μV = 1°C).

Figure 3. Temperature profiles in mercury vapour. $\hat{p}_0 = 0.27$ torr, mean free path $\hat{l}_0 \approx 0.17$ mm ($39.8\,\mu V = 1°C$).

difference. We have obtained data over a range of pressures $\hat{p}_0$ (saturation vapour pressure corresponding to $\hat{T}_0$) from 0·0024 torr to 0·27 torr and all of them show the jumps at the boundaries (Shankar and Deshpande 1988b).

3. Conclusions

We have, we believe for the first time, experimentally demonstrated the existence of large temperature jumps at the boundaries in liquid-vapour phase change. The important practical implication of this result is that in continuum calculations of the phenomenon (as in Plesset 1952) the jumps have to be taken into account. We have as yet not observed the anomalous temperature distribution; this may need even better control on contamination than we have so far achieved.

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