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BY

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SUMMARY

The effects of condensation of the working gas (nitrogen) on pitot and static pressures in the R.A.R.D.E. hypersonic gun tunnel have been examined and the onset of condensation determined for flow Mach numbers of 8.4, 10.4 and 12.9. A large degree of supersaturation was observed at the two higher Mach numbers.

Symbols

M	flow Mach number
P	statio pressure
P_1	stagnation pressure
P_2	pitot pressure
T	static temperature
T_1	stagnation temperature

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*Replaces R.A.R.D.E. Memo. 24/66 - A.R.C.28 155.

1. INTRODUCTION

A comprehensive survey of condensation phenomena in high speed flows is given in [1]. The first investigations in this field wore concerned with the properties of superheated steam [2] but in 1934 tho condensation of water vapour in supersonic wind tunnels was investigated [3] and this topic has since been extensively studied [4]. In 1942 Wagner [5] recognised that the development of wind tunnels to operate at hypersonic Mach numbers meant that working section static temperatures could be sufficiently low to condense the working gas itself, e.g. if dry air at room temperature and pressure is expanded to a Mach number greater than about 5 both the O_2 and N_2 components will be supersaturated.

Since representative data cannot be obtained from a condensing flow it is necessary to dry the working gas in a hypersonic tunnel to eliminate water vapour condensation, and to raise the stagnation temperature, or reduce the stagnation pressure, to prevent the working gas itself from condensing. As the Mach number is increased these measures become increasingly more difficult and costly to apply but a useful gain results from the phenomenon of supersaturation, first recognised by Stodola [2] who discovered that steam expanding in a nozzle is cooled below its saturation temperature before appreciable condensation occurs. Supersaturation is an important factor in the operation of hypersonic wind tunnels since it implies that much lower stagnation temperatures can be tolerated than are theoretically necessary to avoid condensation. A considerable amount of experimental work has accordingly been-carried out on the condensation of air in hypersonic tunnels. This work has been summarised and extended by Daum [6] who shows that in general supersaturation is apparently restricted to static pressures less than about 4 mm. of Hg. and that as the pressure is reduced below this value an increasing degree of supersaturation can occur. Some recent data on nitrogen condensation in hotshot tunnels [7] confirm that supersaturation occurs with nitrogen to approximately the same extent as reported by Daum for air [6]. A theoretical treatment of the condensation of pure nitrogen in a hypersonic nozzle [8] leads to conclusions which are generally in good agreement with experimental results.

The object of the present work was to determine the apparent onset of condensation in the R.A.R.D.E. hypersonic gun tunnel with nitrogen as the test gas and to establish whether a useful degree of supersaturation can occur at typical operating temperatures and pressures. Various experimental techniques have been used to detect the onset of condensation. These include light-scattering to detect condensate fog [9], [10], schlieren photography of condensation shocks [1], measurements of wall static pressures [6], [7], model surface pressures [7], pitot pressures [6], [7], wedge shock angles [1], heat transfer rates [7] and recovery factors of thermocouple probes [11]. In the present tests the free stream pitot pressure and the wall static pressure were measured at fixed positions in the working section for a range of stagnation temperatures extending downwards from about the nitrogen saturation threshold and the onset of condensation was inferred from the variation of these pressures as the temperature was reduced.

Conflicting results have been reported from different hypersonic tunnels on the effects of condensation on pitot pressures, whereas static pressures have been found to give a more reliable indication of the condensation point [6]. On the other hand, in the present Mach number range the pitot pressure is about two orders of magnitude greater than the static pressure and can therefore be measured much more accurately. For these reasons both pitot and wall static pressures were used to indicate the onset of condensation in the present tests.

2. TEST PROCEDURE

The R.A.R.D.E. hypersonic gun tunnel [12] has a conical closed-jet working section of semi-angle 4^{o} and mean diameter 11 inches. "Oxygen-free" nitrogen containing over 99.9% N_2 and less than 0.01 grams of water vapcur per cubic metre is used for both driving and test gases. Three interchangeable nozzle throat inserts provide average flow Mach numbers of 8.4, 10.4 and 12.9 [13]. The stagnation temperature depends on the initial breech/barrel pressure ratio which is set according to a separate calibration in which stagnation temperatures were inferred from flow velocities measured by a streak camera method [14].

Flow conditions were monitored by measuring the stagnation pressure during each run. For this purpose a 0-3000 p.s.i. S.L.M. quarts piezoelectric transducer type PZ14 was mounted in a sampling hole near the end of the gun barrel and connected via an S.L.M. electrometer valve amplifier type PV17 followed by a Southern Instruments amplifier type MR514 to a multi-channel U.V. galvanometer recorder N.E.P. type 1050 using a galvanometer of 500 c/s natural frequency. The S.L.M. transducer was calibrated daily with a dead-weight tester and any variations in gain due to amplifier drift were detected by applying a standardmeasured voltage to the amplifier input terminals after the calibration and after each run. A constant breech pressure of 4015 p.s.i.a. was used during the tests but measured stagnation pressures ranged from about 4200 p.s.i.a. to 4700 p.s.i.a. according to the initial barrel pressure.

Pitot pressures were measured on the tunnel axis at the mid-point of the working section with a conventional total head tube connected to a 0-50 p.s.i.a. Statham strain gauge transducer type PA222TC, the output of which was applied to a galvancmeter of 250 c/s natural frequency through another Southern Instruments amplifier type MR514. The transducer calibration was known to be linear to better than ± 1% and the sensitivity of the system was checked after each run by measuring the recorder deflection when the pitot tube was connected first to a known vacuum and then to atmospheric pressure. Pitot pressures ranged from about 4 p.s.i.a. at M=12.9 to 28 p.s.i.a. at hL8.4.

Static pressures were measured with a 0 ± 1 p.s.i. Southern Instruments differential capacitance transducer type G247C connected to a 1/16 inch hole midway along the wall of the working section. The output was applied to a galvanometer of 250 c/s natural frequency through a Southern Instruments FM amplifier type MR220F. A calibration was carried cut before each run by reducing the working section pressure to 0.002 p.s.i.a. and then increasing it in small measured steps. Static pressures ranged from about 0.025 p.s.i.a. at M=12.9 to 0.3 p.s.i.a. at M=8.4.

An approximate value for the critical stagnation temperature corresponding to the saturation threshold for nitrogen in the working section was obtained from the nitrogen saturation curve [15] in conjunction with a previous tunnel calibration [13]. A more accurate estimate of the static temperature and pressure on the axis of the working section was obtained later by the method described in the following section but the average values in [13] sufficed to define the temperature range which was of interest. A range of stagnation temperatures was chosen, extending from about the critical nitrogen saturation temperature to well below this value to include the region of possible supersaturation. The tunnel was run at a number of stagnation temperatures within this range and records were obtained of the stagnation pressure (P_1), pitot pressure (P2) and static pressure (P) during each run. This procedure was repeated for each of the three Mach numbers.

3. RESULTS

Figures 1 to 3 show the ratios P_2/P_1 and P/P_1 for a fixed time of 15 milliseconds after the start of flow (as Indicated by the pitot record) plotted against the stagnation temperature T for each Mach number. A few points for a time of 40 milliseconds have been added to help to indicate the trend of the graphs; cooling corrections were applied to these latter points in accordance with [14] which shows that the stagnation temperature at 40 milliseconds is about 80^{o}K lower than at 15 milliseconds.

The nitrogen saturation threshold shown on each graph was obtained as follows. Since the free stream static pressure is difficult to measure accurately it was calculated from the measured pitot pressure and the flow Mach number. For this purpose the average value of P_2/P_1 measured at temperatures above the observed condensation point was used to define the ideal Mach number, then the data in [16] were used to calculate the real Mach number by a process of iteration and hence the theoretical free stream static pressure. The corresponding static temperature at saturation was obtained from the nitrogen saturation curve and converted to the threshold stagnation temperature, using the real Mach number already calculated.

The effects of condensation on the pitot pressure are shown in Figures 1(a), 2(a) and 3(a). As the stagnation temperature is reduced the ratio P_2/P_1 remains approximately constant down to a certain temperature below which it first increases slightly, then falls below the initial condensation-free value and later increases again towards the initial value. These changes in P_2/P_1 are rather small in relation to the estimated limits of error but they are sufficient to indicate the temperature below which the pitot pressure is no longer constant. This was taken to be the threshold of condensation.

Figures 1(b), 2(b) and 3(b) show the effects of condensation on the wall static pressure. As the stagnation temperature is reduced the ratio P/P_1 also remains approximately constant down to a certain temperature, below which a slight reduction in P/P_1 is followed by a substantial increase to well above the initial value. This increase in static pressure, which is due to release of the latent heat of condensation, provides a very definite Indication that condensation has occurred. The threshold of condensation was taken to be the temperature at which P/P_1 begins to deviate from a constant value.

The degree of supersaturation appears in Figures 1 to 3 as the temperature difference between the nitrogen saturation threshold and the observed onset of condensation. At M=8.4 (Figure 1) very little supersaturation was detected, but a considerable degree was observed at M=10.4 and M=12.9 (Figures 2 and 3). These results are consistent with data from several other hypersonic tunnels, which have been summarised by Daum in [6]. Figure 4, which is reproduced from [6], is a pressure/

temperature diagram showing the saturation lines for air and nitrogen and also an empirical mean line representing the onset of air condensation in the various tunnels. This empirical line intersects the air saturation line at a pressure of about 4 mm. of Hg. For static pressures higher than this value the experimental points in [6] are scattered about the air saturation line, i.e. there is no supersaturation. For pressures below 4 mm. of Hg. the amount of supersaturation increases as the pressure is reduced, but the trend of the empirical condensation line suggests that a maximum value of supersaturation may be approached asymptotically at very low pressures.

Results of the present tests are also shown in Figure 4. Agreement between the oondensation thresholds indicated by pitot and static pressures respectively is good at M=8.4 (P=14.4 mm. of Hg) and at M=12.9 (P = 0.88 mm. of Hg) but less so at M=10.4 (P = 3.2 mm. of Hg) where the pitot threshold is lower than the static. A similar discrepancy has been noted by other workers [6], [7]. It is known from experiments on the condensation of water vapour in wind tunnels [17] that the pitot pressure measured in partially condensed flow is dependent on the diameter of the pitot tube, which determines the pitot shook stand-off distance and hence the relaxation time for re-evaporation to occur between the shook and the pitot tube. This relaxation effect may account for the discrepancy between pitot and static condensation thresholds in the present tests. It probably accounts also for the conflicting results which have been reported from different hypersonic tunnels regarding the extent to which pitot pressures are affected by condensation [6], for the data in [17] suggest that if the pitot tube is larger than some critical diameter condensation should have no effect on pitot pressures.

The present test results all fall to the left of the air saturation and condensation lines in Figure 4. Some displacement in this direction would be expected, because the working gas was nitrogen instead of air, but the main reason for the displacement is likely to be the comparatively small size of the R.A.R.D.E. tunnel. In previous work [18] a systematic variation of results has been traced to the different temperature gradients in the expansions used in different experiments. The rate at which temperature varies with distance along the nozzle is an important factor in delaying the onset of oondensation and in one extreme example when the temperature gradient was increased from 10°K/cm to 90°K/cm the supercooling increased from 50% to 90%. Similar results were found by Daum [6] and the dashed lines in Figure 4 refer to some measurements which did not fall on the main air oondensation line. These anomalous measurements were all made close to the nozzle throat (hence the transit time was short) whereas the main condensation line in Figure 4 refers to measurements in larger tunnels at a considerable distance from the throat. The R.A.R.D.E. results correspond to the "small tunnel" data.

In a hypersonic gun tunnel the benefits of supersaturation are realised both as a reduction in the minimum stagnation temperature to avoid oondensation and as an increase in the maximum flow duration for a given stagnation pressure. This is because the tunnel compression ratio determines both the stagnation temperature and the flow duration with 8 given nozzle throat. Results for the R.A.R.D.E. gun tunnel with a fixed breech pressure of 4015 p.s.i.a. may be summarised as follows. At M=8.4 (Figure 1) there is very little supersaturation and the minimum stagnation temperature is reduced only from about 880°K to 840°K, with a corresponding inoreaee in flow duration from 23 milliseconds to 26 milliseconds. At M=10.4 (Figure 2), taking the static condensation threshold as the more conservative, the minimum stagnation temperature is reduced from 1250°K to 1120°K and the flow duration correspondingly increased from 24 milliseconds to 36 milliseconds. At M=12.9 (Figure 3) the minimum stagnation temperature is reduced from 1640°K to 1280% and the flow duration increased from 24 milliseconds to 58 milliseconds.

These figures apply to the apparent onset of condensation as previously defined and Figures 1 to 3 suggest that even lower stagnation temperatures and longer flow durations might be used without changing the pitot and static pressures by more than a few percent from their condensation-free values. Provided the supersaturated flow is satisfactorily equivalent to an unsaturated flow it is clear that supersaturation can considerably extend the testing capacity of the R.A.R.D.E. hypersonic gun tunnel.

4. CONCLUSIONS

The effects of condensation of the working gas (nitrogen) on pitot and static pressures in the R.A.R.D.E. hypersonic gun tunnel have been examined and the onset of condensation determined for flow Mach numbers of 8.4, 10.4 and 12.9. It was found that a large and useful degree of supersaturation can occur when the static pressure is less than about 10 mm of Hg. Static pressures gave a more positive and reliable indication of the condensation point than pitot pressures, which were probably subject to relaxation effects depending on the diameter of the pitot tube. Results were in good agreement with condensation data reported for other types of hypersonic wind tunnel of comparable dimensions.

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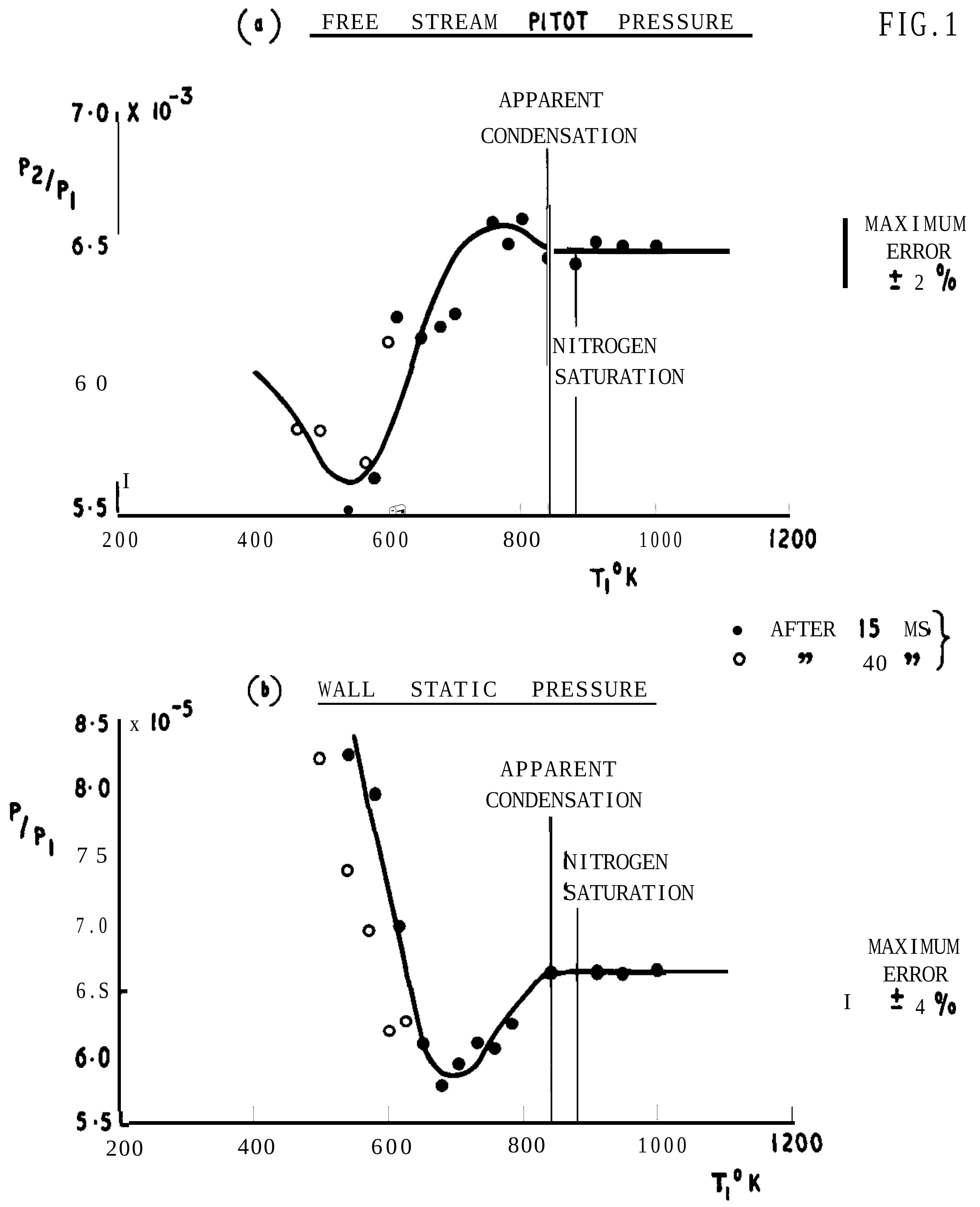

FIG. I EFFECT OF CONDENSATION ON PITOT AND STATIC PRESSURES : $M = 8 \cdot 4$

FIG. 2

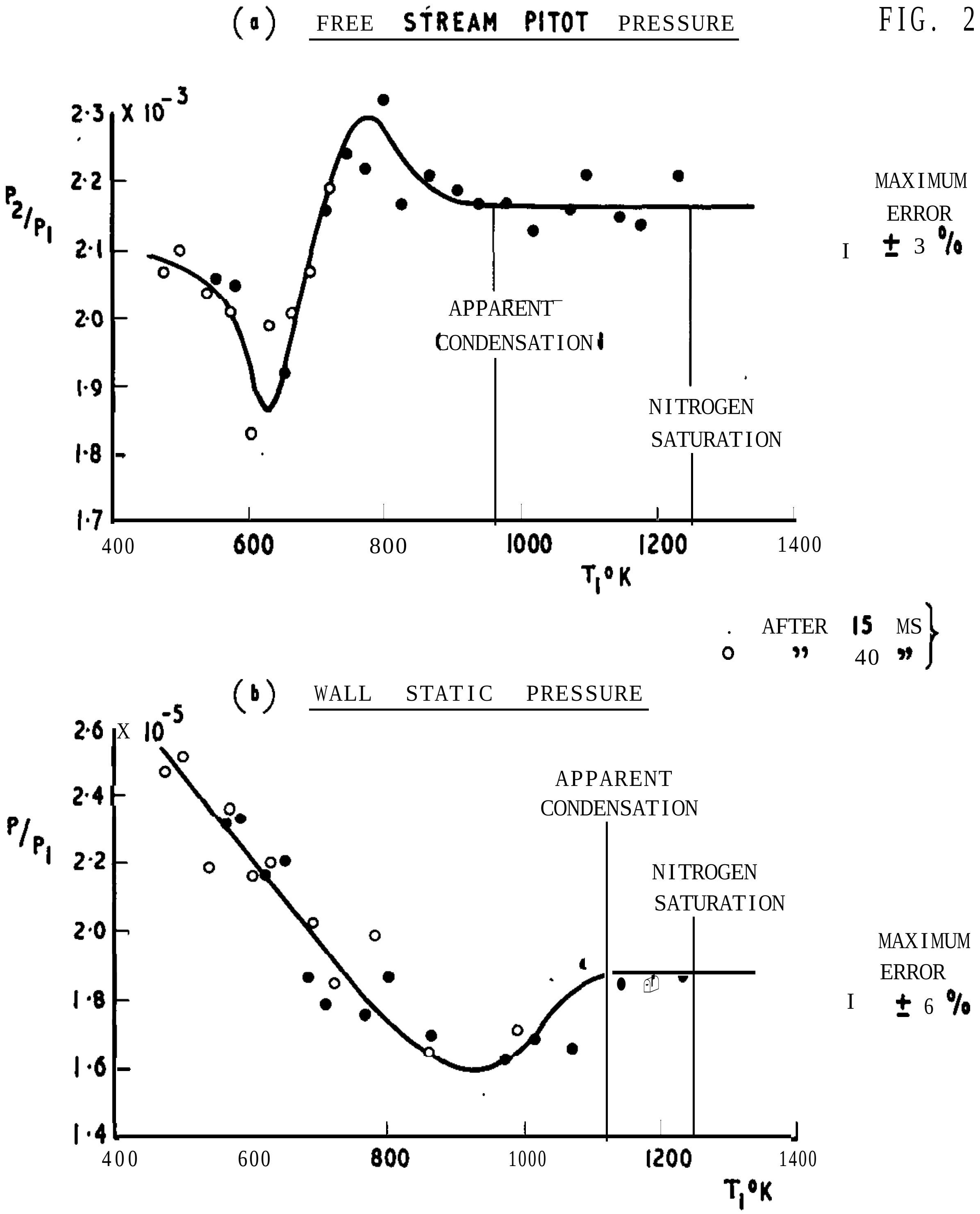

FIG 2 EFFECT OF CONDENSATION ON PITOT AND STATIC PRESSURES : M = 10·4

FIG. 3

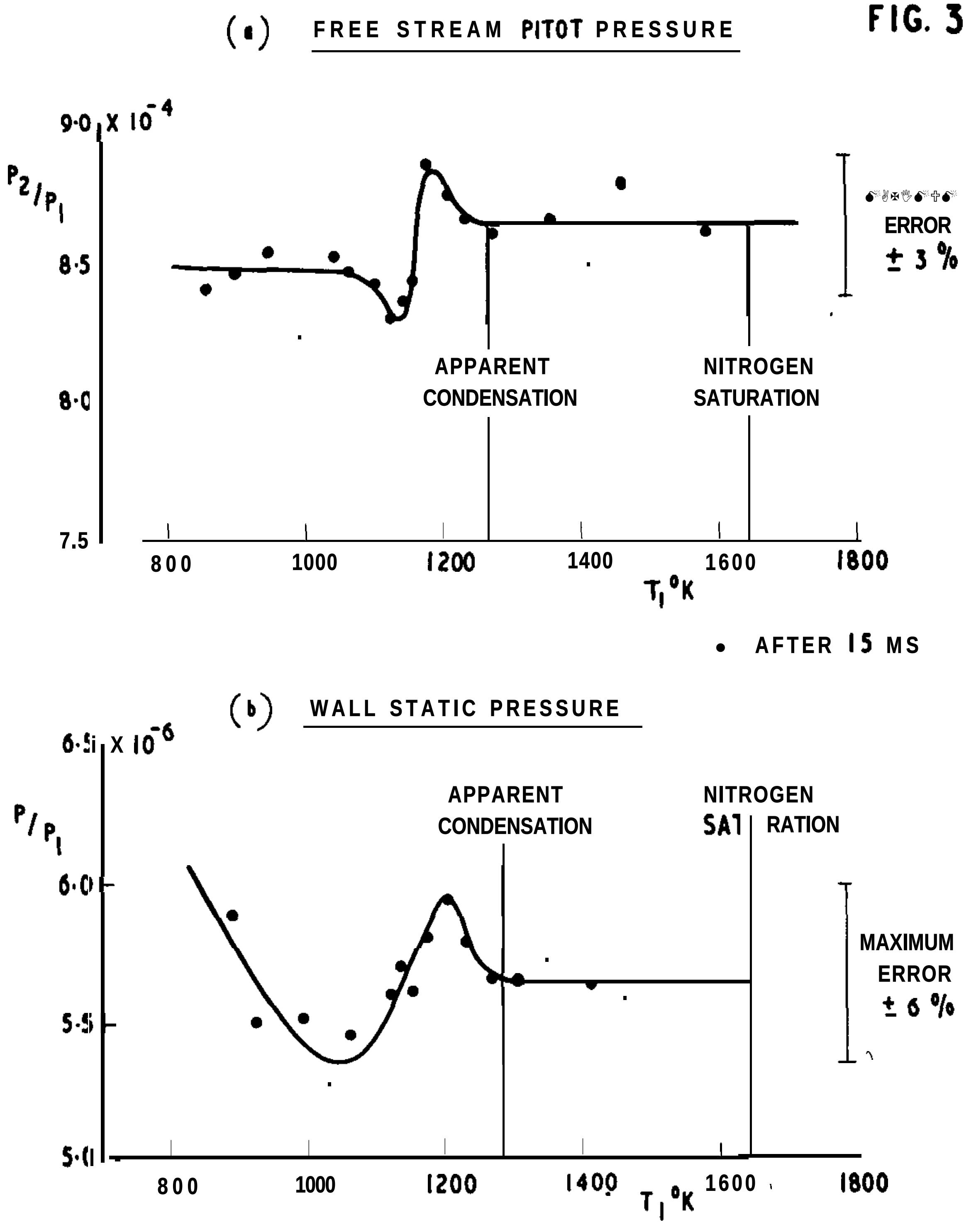

FIG. 3 EFFECT OF CONDENSATION ON PITOT AND STATIC PRESSURES: M=12·9

FIG.4

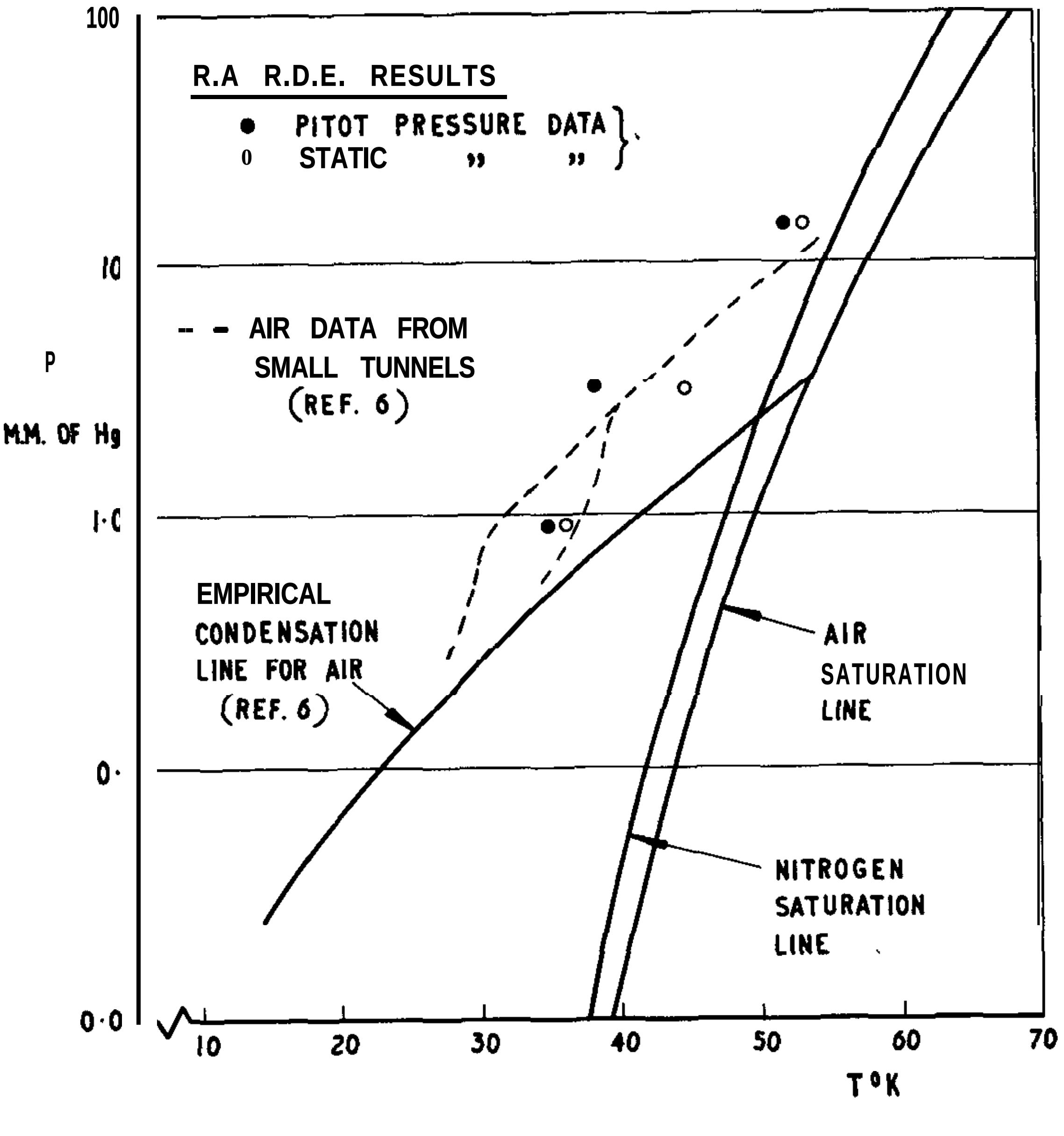

FIG 4 ONSET OF NITROGEN CONDENSATION IN R.A R.D.E. HYPERSONIC GUN TUNNEL

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