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Criteria for Condensation Free Flow in the R.A.E. No.18 (9 in. x 9 in.) Supersonic Tunnel

By

D. J. Raney and D. Beastall

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Criteria for Condensation Free Flow in the R.A.E. No.18 (9" × 9") Supersonic Tunnel

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SUMMARY

Tests have been made in the R.A.E. No.18 (9" × 9") supersonic tunnel to determine the dryness of the air circulating through the tunnel necessary to ensure condensation free flow through the working section. Results of the main investigation made without a model mounted in the working section are as follows:-

(1) To ensure condensation free flow at normal operating conditions of atmospheric stagnation pressure and 30°C stagnation temperature the humidity should be less than the critical values of 0.0014 and 0.0001 lb of water per lb of dry air at Mach numbers of 1.41 and 1.91 respectively.

(2) Condensation occurs when the free stream air temperature is from 38°C to 49°C below the saturation temperature over the range of Mach numbers from 1.41 to 1.91. Variation of supercooling with stagnation pressure and temperature is small.

A single test indicates that a strong shock wave has little effect in causing premature condensation but that local expansions around a model may substantially reduce the critical humidity.

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1 Introduction

It has previously been observed that variation of the moisture content of the air flowing through a supersonic tunnel can cause changes in the pressure and Mach number distributions. These changes are caused by condensation of some of the moisture in the air. The theory and mechanism of condensation in supersonic tunnels are discussed fully in Ref.1, and briefly described below.

When air is expanded adiabatically as in a supersonic tunnel, the fall of temperature results in a reduction of the saturation vapour pressure. This reduction is greater than that of the static pressure, and consequently a point is reached at which the air becomes saturated, and with any further expansion, supersaturated. This condition can be relieved by condensation of the excess vapour. For condensation to occur there must be nuclei present upon which the water droplets can form. As condensation on dust particles is negligible in a supersonic tunnel, it takes place on condensation germs consisting of a small number of water molecules. These germs continually form and break up once the air is saturated. The development of condensation depends upon their rate of formation, and this is primarily dependent on supercooling, the amount by which the local air temperature is below the saturation temperature.

When condensation occurs, it takes place suddenly causing a discontinuity in flow. This is referred to as a condensation shock. As disturbances originating from it are propagated downstream, it is obviously desirable that for tests where a uniform and steady flow is required, the condensation shock (if it exists at all) should either be downstream of the working section in which case it will not affect the flow there, or else be so weak that the disturbances caused by it are negligibly small. In this note results are presented of tests made during 1951 and 52 in the R.A.E. No.18 (9" × 9") supersonic tunnel, to determine the dryness of the air required to ensure condensation free flow through the working section (tunnel empty) to cover the normal range of operation of the tunnel. This data was required in the first place so that an accurate calibration of the tunnel liners could be made[2,3].

With a model mounted in the tunnel, there will usually be regions where locally the air is expanded above the free stream conditions, e.g. over the upper surface of a wing at incidence. These expansions may be strong enough to cause condensation in an airstream which would otherwise be free of condensation. A brief experiment is described in which a measurement of this effect was made.

No measurements have been made of the changes occurring across a condensation shock, other than the pitot pressure, but estimates have been made and are presented in this report.

Terms generally used in referring to the humidity of air, and other terms used in this note are defined in the Appendix with the aid of Fig.1.

2 Tunnel Design

The No.18 tunnel has a closed circuit and is capable of continuous operation up to a Mach number of 1.9 and over a range of stagnation pressure from about $^1/_5$ to $1\frac{1}{2}$ atmospheres. Liners are available for Mach numbers of 1.3, 1.4, 1.5, 1.6, 1.8 and 1.9. In each case the true Mach number is approximately 0.01 higher than the nominal value[3]. The simplified diagram of the tunnel layout shown in Fig.3 gives details of the design relevant to these tests. These are discussed individually below.

2.1 Driers

When the tunnel is in operation a proportion of the air circulating through the tunnel is bypassed from the working section and flows through two silica gel beds which absorb the moisture from the air. The quantity of air so bypassed, and therefore the humidity of the air in the tunnel circuit is controlled by valve No.1 (Fig.3). A water cooler ahead of the driers reduces the temperature of the air flowing through them, and thereby improves their performance. The driers are reactivated periodically by passing hot air through them, to remove the moisture absorbed during normal tunnel operation. Absolute humidities of less than 0.0001 lb of water per lb of dry air have been measured at atmospheric stagnation pressure. At lower stagnation pressures leaks into the tunnel limit the humidity which can be obtained to a substantially greater value.

2.2 Hygrometer

A frost point hygrometer[4] with carbon dioxide as coolant was used to measure the humidity of air bled from the maximum section. The tunnel trunking between the maximum and working sections is effectively free from leaks and so the humidity in the working section may be taken as that measured.

The hygrometer has not been calibrated against a standard instrument, but neglecting any basic instrument error readings of the frost point can be taken to within about $\pm 1\frac{1}{2}$°C. The corresponding error in humidity varies between ± 20% at a humidity of 0.0001 lb/lb, and ± 10% at 0.002 lb/lb. Error in the estimated values of supercooling from this source is about ± 2°C.

2.3 Stagnation Temperature and Pressure Control

Stagnation temperature is controlled by regulating the flow of water which circulates through the cooler in the maximum section to absorb the heat generated by the compressor. The normal range is small (between 20°C and 35°C). Higher temperatures are not recommended as warping of the wooden liners may result.

Most tests are made at atmospheric stagnation pressure, which can be maintained accurately constant by opening valve No.2 (Fig.3) leaving the maximum section open to the atmosphere, and by means of a speed control on the main compressor motor to minimise speed changes caused by fluctuations in the voltage.

To obtain stagnation pressures above or below atmospheric pressure, valve No.2 is closed and the pumps are used as compressors or exhausters respectively. When the required pressure has been obtained it is maintained constant by adjusting the setting of valve No.2 until the leak out of or in through it just balances the discharge of the pumps. Fluctuations in stagnation pressure are considerably greater than when operating at atmospheric pressure as the pumps have no speed control.

3 Details of Tests

A group of nine pitots covering a six inch square area was used for most tests to measure the pitot pressure in the working section.* The absolute pressure from the central pitot was measured with a mercury

*The tunnel choked with these pitots at a Mach number of 1.41. A second group of pitots, five inches square, was used at this Mach number, and for the tests described in section 3.2. No measurements could be made with the 1.3 Mach number liner fitted, because of tunnel choking.

barometer and compared with the stagnation pressure similarly measured to obtain the indicated Mach number. Differences in the pressures from each of the nine pitots were observed on a differential water manometer. By this method small changes in Mach number distribution could be accurately observed, as a pressure difference of one inch of water represents a change of Mach number of 0.01 and 0.005 at free stream values of 1.4 and 1.9 respectively at atmospheric stagnation pressure.

Test procedure was to keep stagnation pressure and temperature constant and measure the nine pitot pressures with the humidity increasing gradually from a value at which the condensation shock was estimated to be well downstream of the working section. In each test the pressures registered by the pitots were at first steady as the humidity was increased, but then changed suddenly and varied continually as the humidity was increased further. This disturbance indicated the passage of the condensation shock past the plane of the pitots. The conditions at which the first changes were observed are referred to as the critical conditions. As the critical humidity varies widely over the range of Mach number, stagnation pressure and stagnation temperature, it has been found more convenient to present the results in terms of critical supercooling, changes of which are found to be relatively small, and which is a more fundamental variable than humidity as explained in section 1. The critical supercooling is the amount of supercooling achieved before condensation occurs. It is determined from the difference between the saturation temperature estimated from the humidity and stagnation conditions, and the local air temperature at the condensation shock. This is equal to the free stream temperature in the working section, at the moment when the condensation shock passes over the pitots, and is estimated from the measured values of Mach number and stagnation temperature.

4 Results and Discussion

4.1 Tunnel Empty

In this section the results of the main series of tests are discussed, in which no model was mounted in the working section ahead of the pitots.

Two preliminary tests were made at atmospheric stagnation pressure and a Mach number of 1.51:-

(i) The first was to determine whether the condensation shock passed instantaneously through the whole length of the working section, or if the critical condition varied with distance back down the working section. No measurable difference was observed between two stations $10\frac{1}{2}$ inches apart.* All further tests were therefore made at a fixed position which was near the middle of the working section.

*In Ref.5 a similar investigation was made of the variation of critical conditions with distance down the working section. In a 4" × 10" tunnel tested at M = 2.0 a reduction in critical supercooling of $1\frac{1}{2}$°C per foot length of working section was measured and found to be approximately constant over the two foot long working section. Preliminary results in a tunnel five times larger are stated to agree with this. In a 3.4" square tunnel at M = 1.45, a result quite different has been obtained, but no explanation was put forward. A reduction in critical supercooling of 11°C was measured in the first six inches of the working section, with little further reduction through the rest of the working section.

(ii) Tests at stagnation temperatures of 22°C and 35°C showed that there was no measurable change in critical supercooling. Most tests were therefore made at high stagnation temperature (35°C) so that less drying was required to eliminate condensation effects and so that observation of the critical humidity was simplified as changes in pitot pressure were larger.

The following table summarises the main results. Those quoted for a Mach number of 1.51 at atmospheric stagnation conditions and 35°C stagnation temperature are average values obtained from eight sets of measurements taken at different times during the investigation. The critical supercooling varied within ± 2½°C of the average value giving an indication of the accuracy and repeatability of the measurements.

Mach number	Stagnation Pressure (atmospheres)	Stagnation Temperature °C	Critical Humidity lb/lb	Critical Supercooling °C	ΔM
1.41	1	35	0.0020	38	-
1.51	0.33	25	0.0024	42	-
	0.66	35	0.0020	41	-
	1	35	0.0010(5)	38½	0.002
	1.35	35	0.0006	36	-
1.61	1	35	0.0005(5)	40	0.003
1.81	1	35	0.0002	45	-0.002
1.91	1	35	0.0001(4)	49	0.003

ΔM is the change across the condensation shock of the average value of Mach number determined from the measurements of stagnation pressure and the nine pitot pressures.

Critical supercooling over the range of conditions investigated varies between 36°C and 49°C. This compares with 50°C quoted in Ref.1 as an average value to be expected for supersonic tunnels of this size; while 30° to 40°C is obtained from semi theoretical analysis[5] based on a limited number of experimental results within the range of the present investigation for tunnels 3.4" square and 4" × 10".

The variation of critical supercooling with Mach number is shown in Fig.4 and with stagnation pressure in Fig.5. Assuming that the effects of stagnation pressure and temperature measured at a Mach number of 1.51 are applicable over the whole range of Mach number, the variation of critical humidity over the normal range of conditions is plotted in Fig.6. This shows the advantage which can be gained by operating at a high stagnation temperature. It is worth noting that air at average atmospheric humidity, 0.005 lb/lb, would be sufficiently dry for condensation free flow up to a Mach number of about 2.0 at a stagnation temperature of 100°C. Isentropic expansions for different operating conditions are shown in a sketch of the temperature entropy diagram for water vapour (Fig.2), and discussed in the Appendix to illustrate qualitatively methods for eliminating condensation.

The last column of the table above gives values of the increase in the average value of indicated Mach number, ΔM, across the condensation shock at atmospheric stagnation pressure. At stagnation pressures other than atmospheric, accuracy is too low for these small increments to be measured. This change is in every case small and of the same order as the accuracy of measurement (± 0.005 and ± 0.003 at Mach numbers of 1.41 and 1.91 respectively). This may lead to the false impression that changes in the true Mach number are also negligible, and that consequently the attainment of condensation free flow is not necessary. This is disproved by estimates of the changes occurring across a condensation shock at atmospheric stagnation pressure and 35°C stagnation temperature - the conditions at which most tests were made. In making these estimates it has been assumed that condensation occurs as a normal shock and that all the excess moisture is condensed so that the air is just saturated after the shock. Although condensation is known to occur in an oblique shock rather than a normal one, these assumptions have previously led to estimates in good agreement with measured changes. The measured variation with Mach number of the critical humidity has been used as a basis for these calculations (see Fig.7a). The estimated increase of static pressure and decrease of stagnation pressure is shown in Fig.7b. This loss of total head will lead to false values of the change of Mach number if based on the stagnation pressure in the maximum section (Fig.7c). In these circumstances indicated changes are substantially less than the true changes particularly if obtained from the pitot and stagnation pressures as in the present tests.

At the stagnation conditions under consideration, and at an absolute humidity of 0.0002 lb/lb, the estimated reduction in Mach number across a condensation shock occurring at a Mach number of 1.81 is about $^1/_3$%.

4.2 The Effect of an Upstream Expansion on Critical Humidity

The measurements so far described were all made without a model in the tunnel. For most tests however, a model will be mounted in the working section and will produce:-

(i) A shock system through the working section.

(ii) Expansions, often producing local Mach numbers above the free stream value.

Either or both of these effects may contribute towards premature condensation, although conditions are such as would ensure condensation free flow if the tunnel were empty. A single test with a model producing a large region of increased Mach number showed this to be so.

A 9° wedge of $2\frac{1}{2}$ inch chord and 7 inch span was mounted back to front in the tunnel two chords ahead of the pitot comb, and slightly above the tunnel centre line so that none of the pitots was in the wake. The incidence of the wedge was adjusted to give a local Mach number of 1.81 (estimated from the static pressure on the wedge) over the upper surface, compared with the free stream Mach number of 1.51. Observations of the critical humidity were made both with and without the wedge in position at atmospheric stagnation pressure and 35°C stagnation temperature. Changes with humidity of the pressure differences registered by individual pitots relative to the central one are shown in Fig.8 for two pitots and compared with results of tests without the wedge at free stream Mach numbers of 1.51 and 1.81. The curves shown for pitot No.6 are typical of all pitots below the wake. The critical humidity is slightly less than without the wedge at the same Mach number. Curves for pitot No.1 are typical of all pitots above the wake, and immediately behind the expansion over the upper surface of the wedge. For these pitots the critical humidity approximates to that measured without the wedge at a Mach number of 1.81 (equal to the local Mach number over the wedge). These results indicate that a strong shock wave has little effect on the critical humidity, but that local expansions around a model may reduce the critical humidity to that corresponding to a free stream Mach number equal to the maximum local value over the model. The following table which includes the values of supercooling quoted at a Mach number of 1.51 summarises the results.

Test Conditions etc.	Critical humidity lb/lb × 10^4	Supercooling °C at $M = 1.51$
(a) With Wedge; $M_o = 1.51$		
above the wake	3	24
below the wake	9	37
(b) Without wedge:-		
$M_o = 1.51$	2	20
$M_o = 1.81$	12	40

5 Conclusions

Tests have been made in the R.A.E. No.18, (9" × 9") supersonic tunnel to determine the dryness of the air circulating through the tunnel required to ensure condensation free flow through the working section with no model in the tunnel. Results are as follows:-

(i) To avoid condensation effects at normal operating conditions of atmospheric stagnation pressure and 30°C stagnation temperature, the absolute humidity should not be more than 0.0014 and 0.0001 lb of water per lb of dry air at free stream Mach numbers of 1.41 and 1.91 respectively. Critical humidities at other operating conditions are shown in Fig.4.

(ii) At atmospheric stagnation pressure, condensation occurs when the free stream air temperature is 38°C below the saturation temperature at a Mach number of 1.41, increasing to 49°C at a Mach number of 1.91.

(iii) The degree of supercooling attained before condensation occurs decreases slightly as stagnation pressure is increased. No measurable change in supercooling was observed for stagnation temperatures between 22°C and 35°C.

(iv) A single test with a model mounted in the tunnel working section indicates that a strong shock wave has little effect on critical humidity, but that local expansions around a model may reduce the critical humidity to that corresponding to a free stream Mach number equal to the maximum local value over the model.

(v) Changes in Mach number across a condensation shock determined from measurements of pitot pressure in the working section and stagnation pressure in the maximum section are small. Theoretical estimates show that the true changes are several times greater than the indicated values measured in this way. At a humidity of 0.0002 lb/lb the estimated change in Mach number is less than ½%.

APPENDIX

Isentropic Expansion of Water Vapour Mixtures

1 Definitions etc

Moisture content in a mixture of water vapour and dry air can be referred to by three terms:- absolute humidity, relative humidity and dew point.

Absolute humidity, Ω, directly defines the moisture content, and is equal to the mass of water vapour in the mixture per unit mass of dry air.

Relative humidity, ϕ, is the ratio of the vapour pressure to the saturation vapour pressure at the temperature of the mixture.

Dew point, T_{dew}, is the saturation temperature at the vapour pressure of the mixture.

Neither relative humidity nor dew point define the proportion of water vapour to dry air in the mixture, unless other properties of the mixture are also known. For this reason absolute humidity has been used throughout this report in referring to moisture content.

The relationship between these three terms was shown in Ref.1 with the aid of the temperature entropy diagram for water vapour. A sketch is reproduced in Fig.1, and includes the saturation line at one value of absolute humidity. Then considering point K:-

$$\text{Relative humidity, } \phi = p_1/p_2$$

$$\text{Dew point, } T_{dew} = T_R \text{ (Temperature at R)}$$

Two other definitions can be illustrated in Fig.1, by considering an isentropic expansion KLMN from an initial state defined by K. The vapour becomes saturated at L, where the expansion line cuts the appropriate saturation line corresponding to the absolute humidity. With further expansion the vapour is supersaturated and condensation occurs at N.

Supercooling at any instant between saturation and condensation is defined as the difference between the saturation and local temperatures. Thus, supercooling at M is $T_L - T_M$.

Critical supercooling is the value of supercooling attained just before condensation occurs. Thus the critical supercooling for this expansion is $T_L - T_N$.

2 Condensation Free Flow

A more detailed representation of the temperature entropy diagram for water vapour is shown in Fig.2. It includes condensation lines which define conditions at which condensation shocks occur in the supersonic expansion of humid air. They have been drawn assuming constant critical supercooling for all operating conditions. This is an approximation to the results of the present report. Lines are also shown in this figure representing isentropic expansion through a pressure ratio $p_1/p_3 = p_2/p_5$.

ABCDE represents an expansion from initial (stagnation) conditions of pressure p_1 and temperature T_A, to a pressure p_3. For an absolute humidity of Ω_1, the vapour becomes saturated at B and condenses at D before the end of the expansion at E. The discontinuity which would occur at D is not shown. The critical supercooling for this expansion is $T_B - T_D$.

If the humidity is decreased to Ω_2, saturation is delayed until C, and the complete expansion occurs without condensation. The expansion could continue to F corresponding to a pressure p_4 before condensation would occur.

It can also be seen from Fig.2 that expansion with a humidity of Ω_1 through the pressure ratio p_1/p_3 could be obtained without condensation by operating either at a higher stagnation temperature (expansion line A_1 B_1 E_1) or at a lower stagnation pressure (expansion line A_2 B_2 E_2).

It follows that if condensation occurs at any operating conditions of a supersonic tunnel, it can be eliminated by one or more of the following steps:-

(a) Reducing the absolute humidity.

(b) Increasing the stagnation temperature.

(c) Reducing the stagnation pressure

(d) Operating at a reduced pressure ratio, (i.e. at a lower Mach number).

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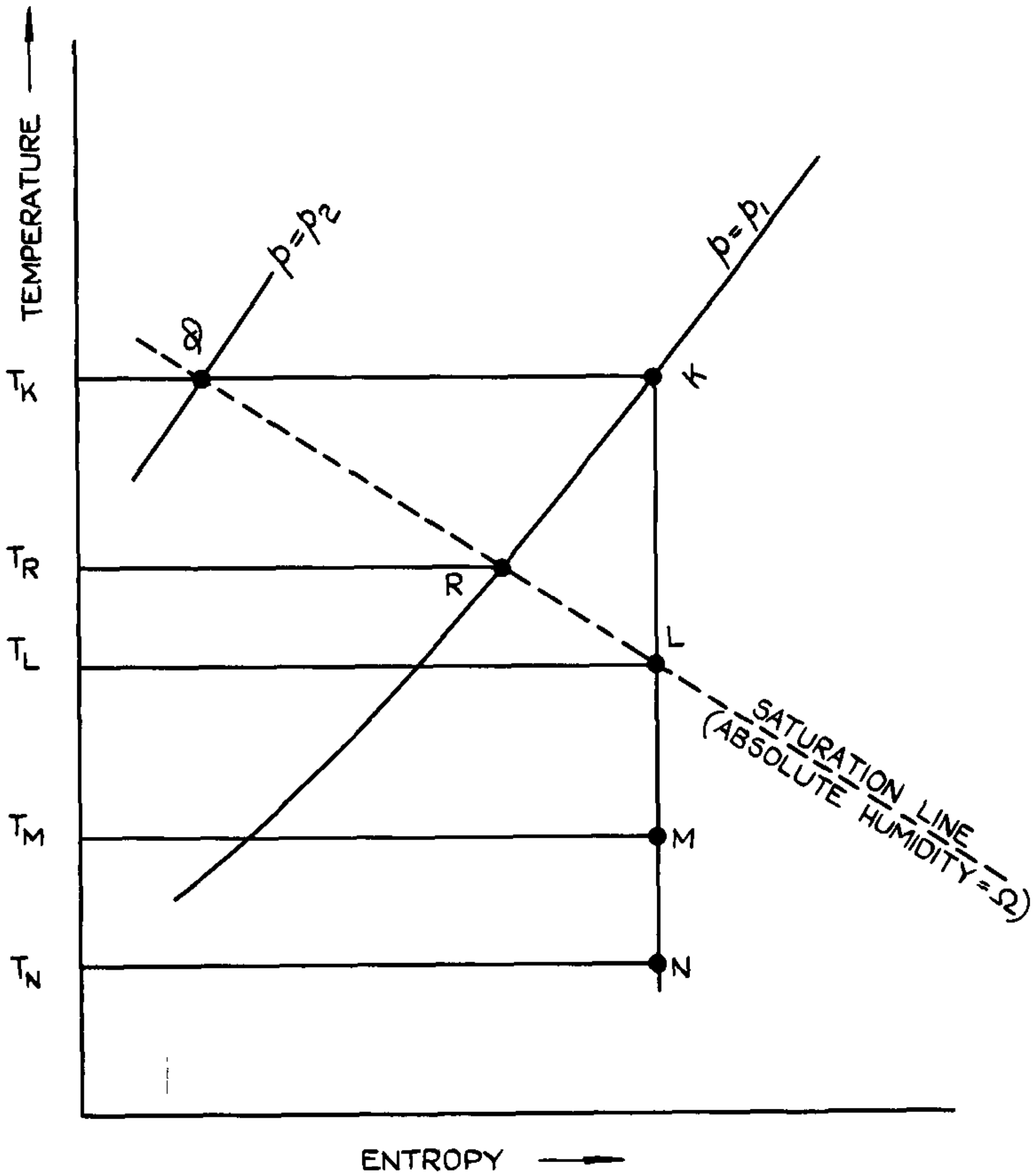


FIG.1. TEMPERATURE-ENTROPY DIAGRAM FOR WATER VAPOUR.

FIG.2.

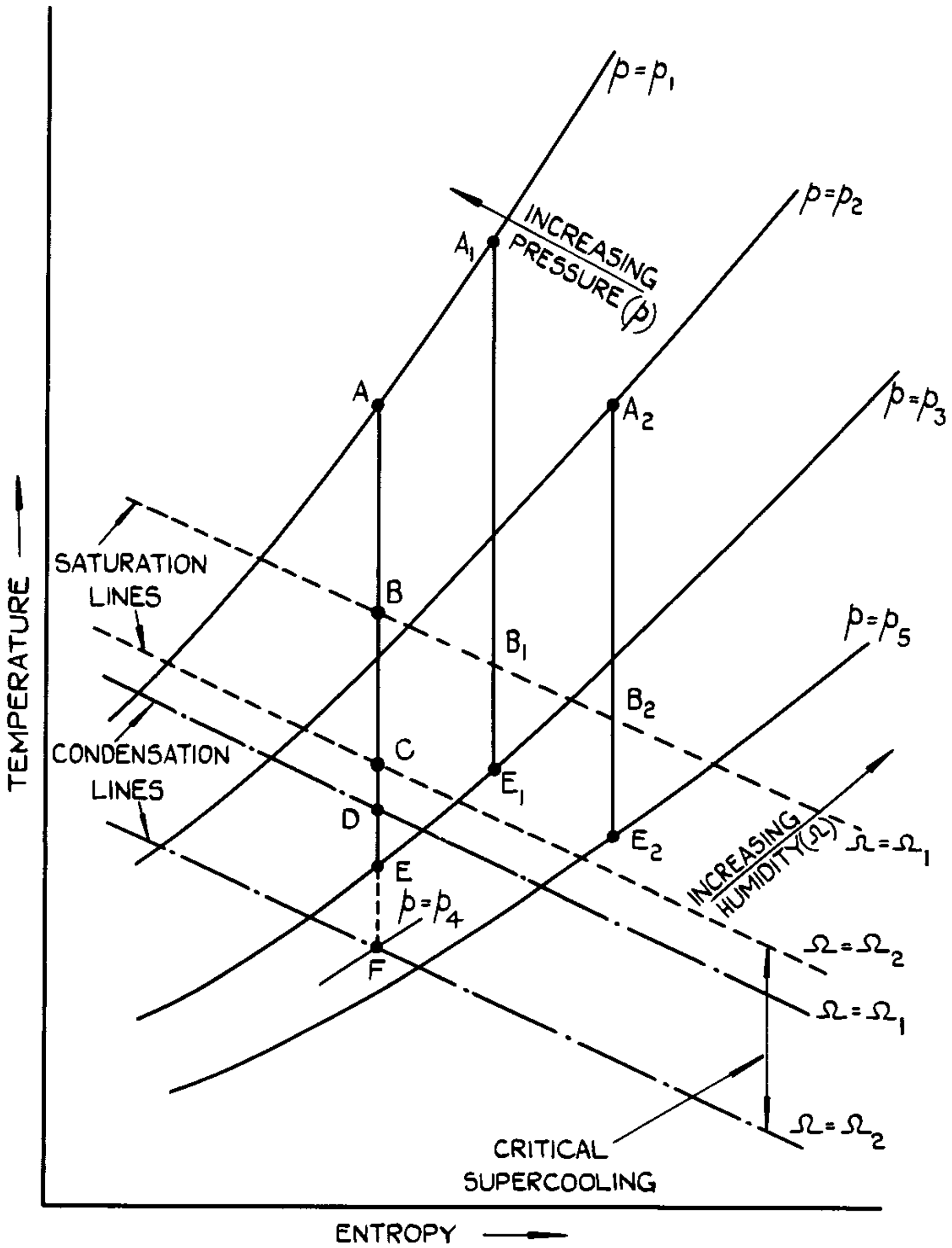


FIG.2. ISENTROPIC EXPANSION OF WATER VAPOUR ON THE TEMPERATURE - ENTROPY DIAGRAM.

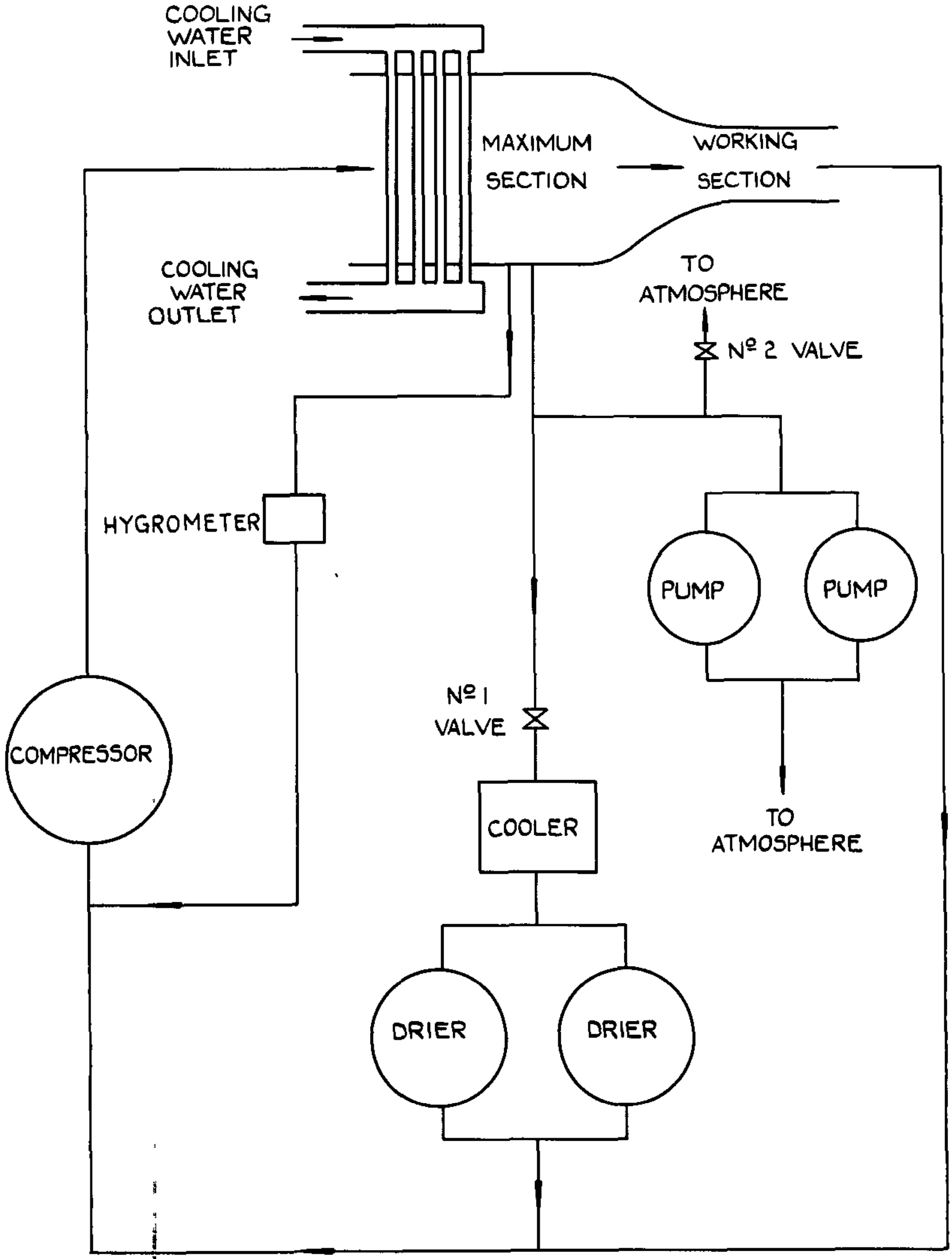


FIG.3. SIMPLIFIED LAYOUT DIAGRAM OF Nº18 (9" x 9") SUPERSONIC TUNNEL.

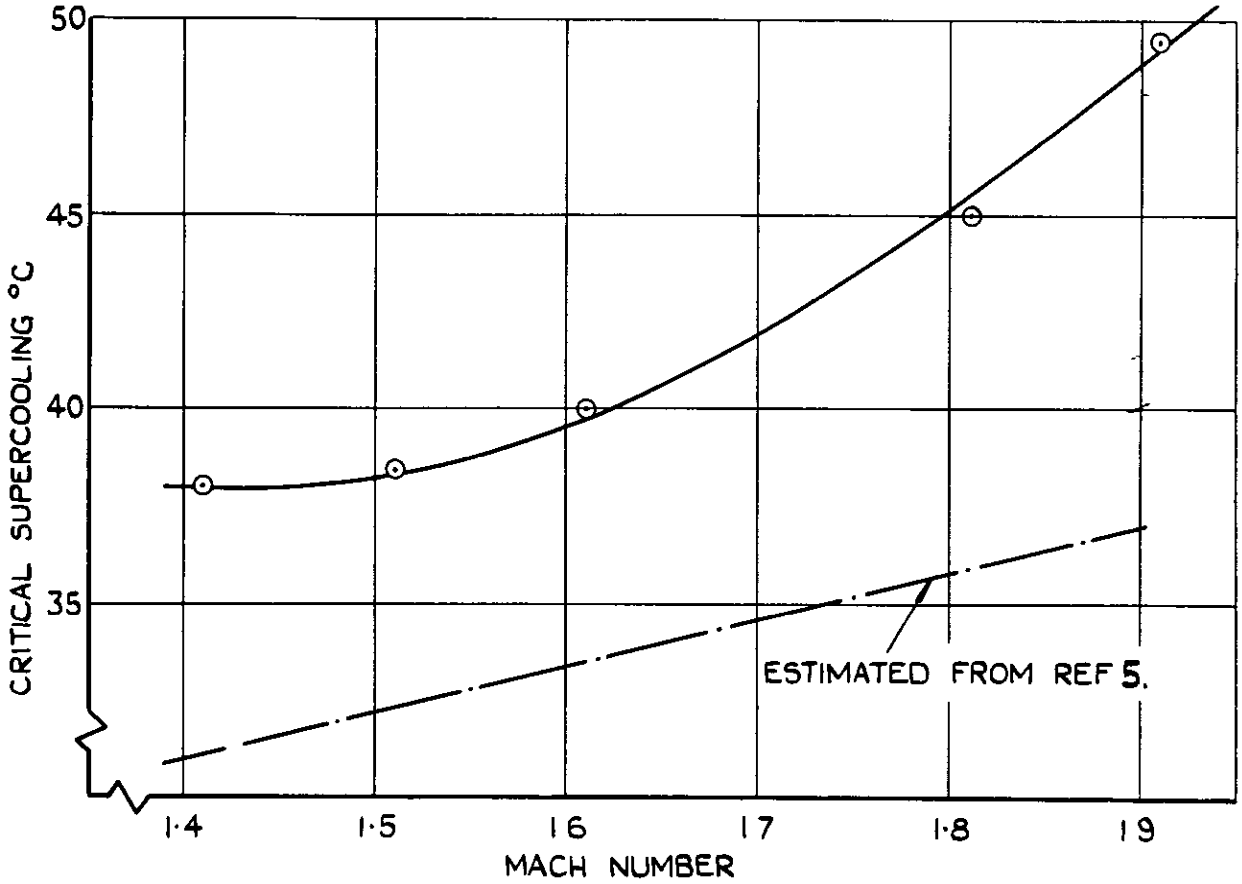


FIG. 4. CRITICAL SUPERCOOLING AGAINST MACH NUMBER.

p_0 = 1·0 ATMOSPHERES, T_0 = 35°C.

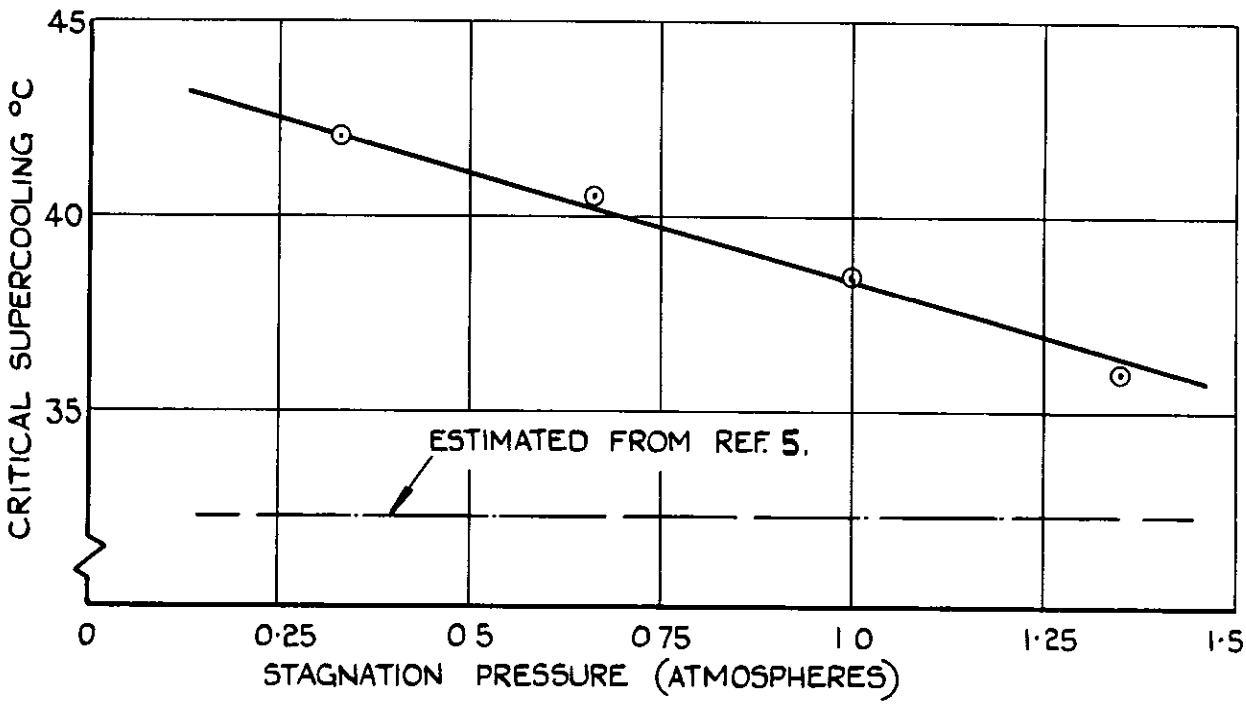


FIG. 5. CRITICAL SUPERCOOLING AGAINST STAGNATION PRESSURE.

M_0 = 1·51 T_0 = 25 – 35°C.

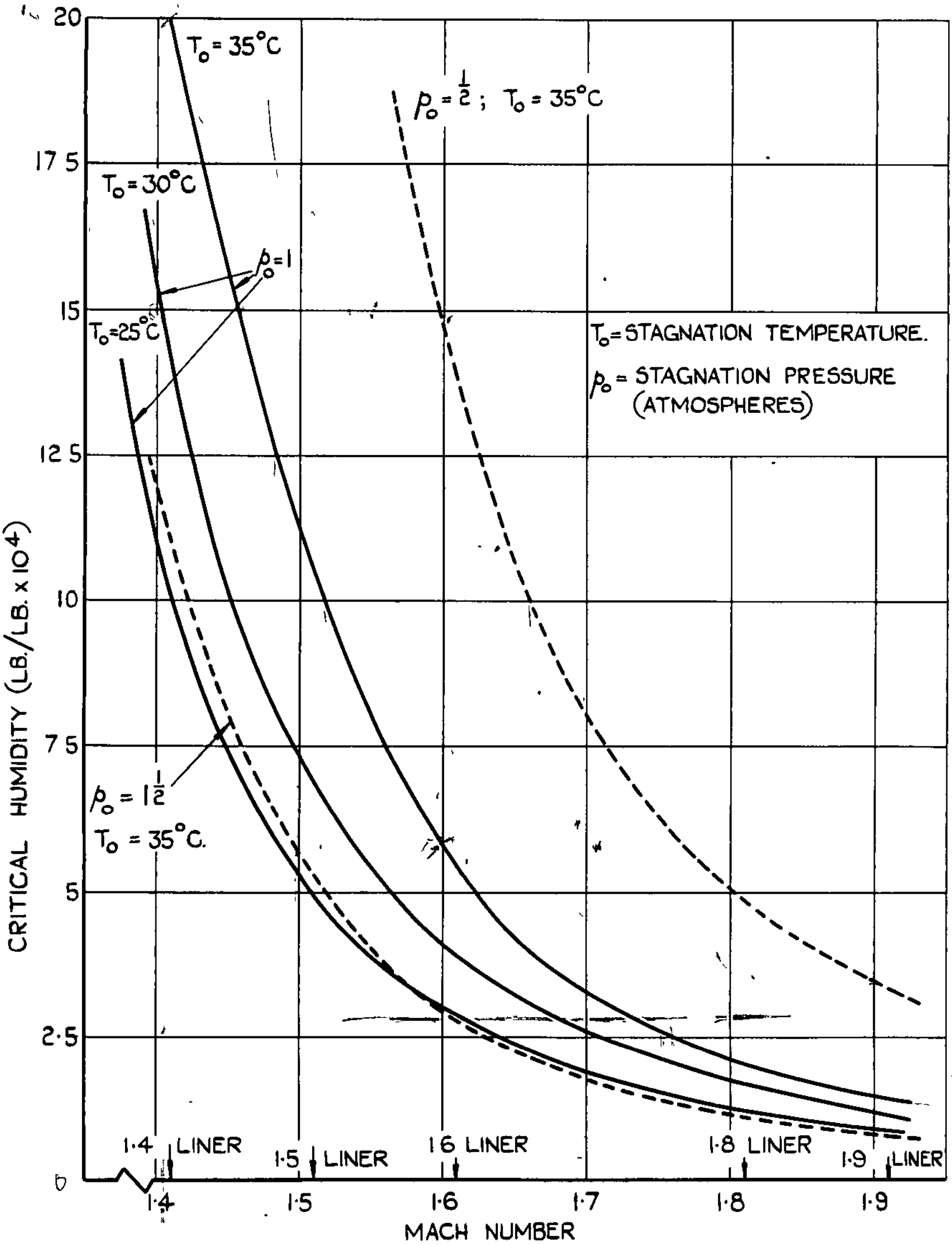
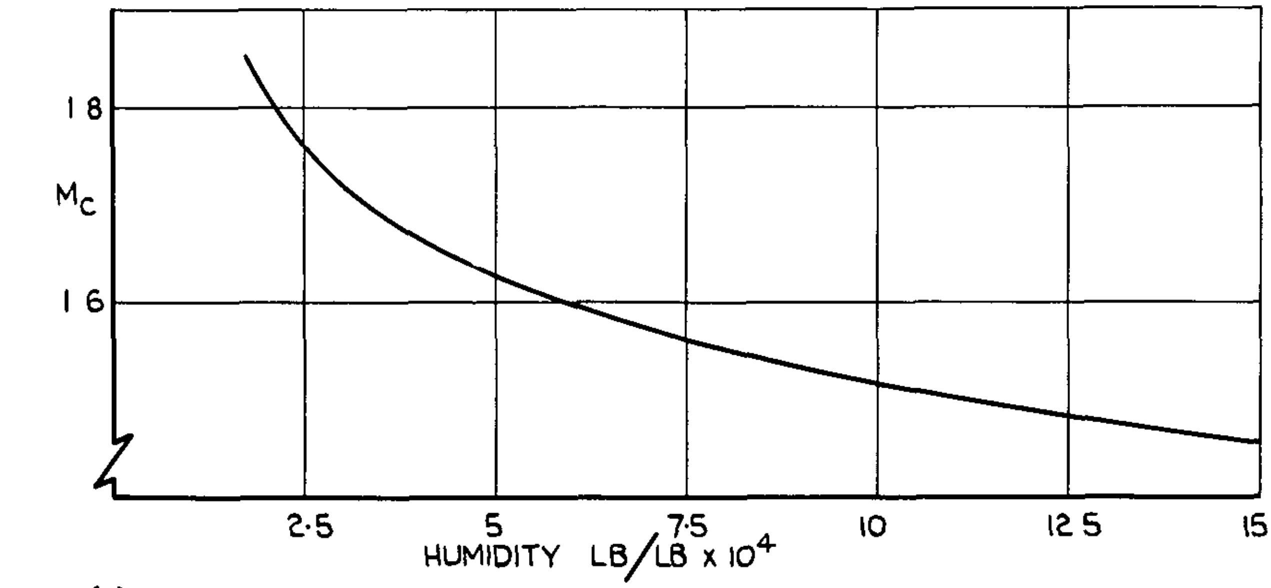
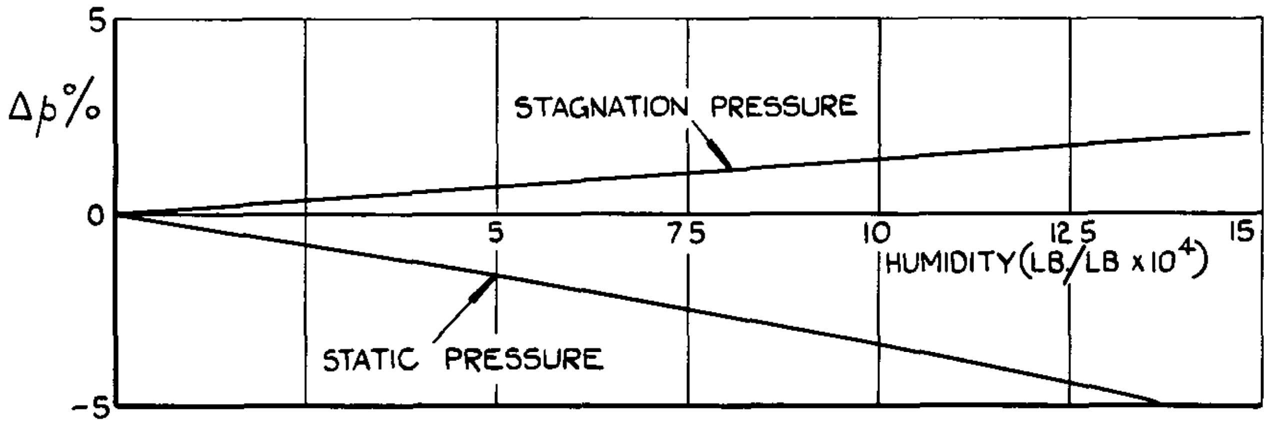


FIG.6. VARIATION OF CRITICAL HUMIDITY WITH MACH NUMBER FOR DIFFERENT STAGNATION CONDITIONS.

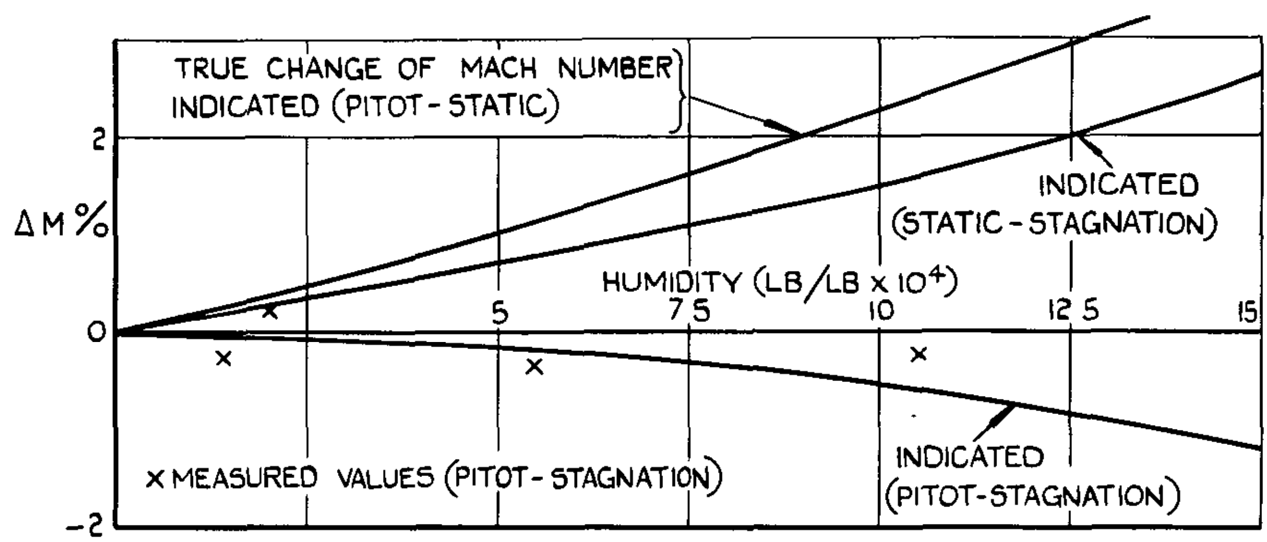
FIG. 7(a-c)



(a) MACH NUMBER, M_c, AT CONDENSATION SHOCK. (FROM FIGURE 4.)



(b) DROP IN STATIC & STAGNATION PRESSURE, Δp %



(c) DROP IN MACH NUMBER, ΔM%

FIG.7(a-c) ESTIMATED CHANGES THROUGH CONDENSATION SHOCK.

ATMOSPHERIC STAGNATION PRESSURE;
35°C STAGNATION TEMPERATURE.

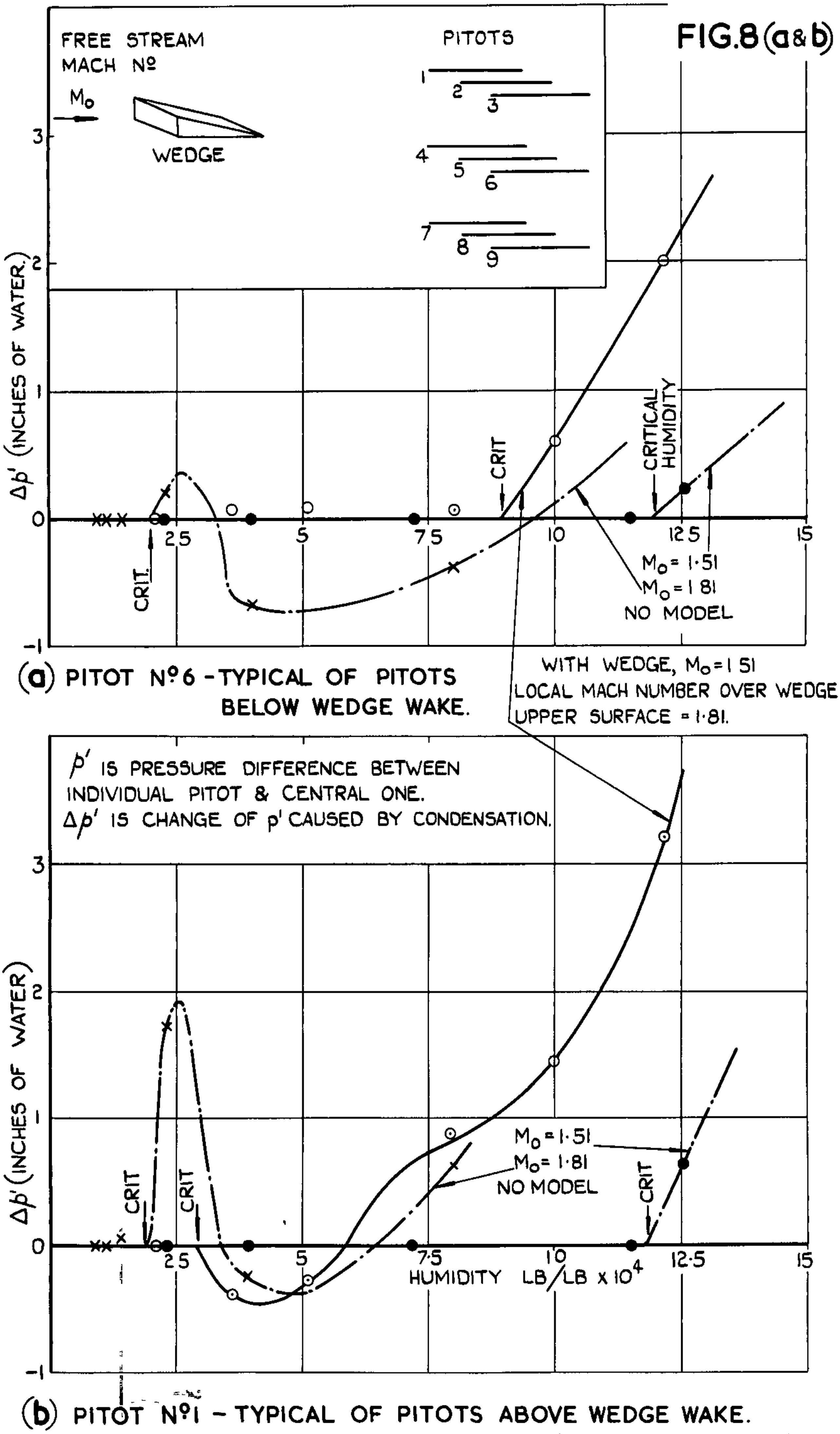


FIG.8 (a & b) VARIATION OF PITOT PRESSURE WITH HUMIDITY WITH & WITHOUT MODEL.

p_o = 1·0 ATMOSPHERES; T_o = 35°C

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