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## CRANFIELD

# Experiments on an Induction Type High Speed Wind Tunnel Driven by Low Pressure Steam

-by-

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## SUMMARY

The performance of an induction type high speed wind tunnel driven by low pressure steam (up to 120 lb. per sq.in. absolute) has been investigated up to a Mach number of about 1.7. It was found that by suitable design a range of Mach numbers could be attained over a wide range of supply pressures and steam quantities. Comparison with previous experiments in which compressed air was used to drive the tunnel show that the required steam and air pressures and quantities are comparable. These results imply that in many cases existing boiler plants can readily be adapted to drive high speed tunnels of useful dimensions.

An approximate theoretical analysis of the performance of this type of tunnel is developed in the Appendix.

It is not anticipated that the method will have any large scale applications, but it is suggested that it may provide a simple and inexpensive method for installing small high speed tunnels in Engineering Colleges and similar establishments where a steam supply is already available.

This investigation was performed at the suggestion of Professor Cave-Browne-Cave of University College, Southampton in his laboratories.

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## 1. Symbols

| | |
|---|---|
| $a$ | velocity of sound ($a^2 \equiv \gamma p/\rho$) |
| $A$ | area of cross-section of mixing zone |
| $A_s$ | area of the high pressure slot |
| $A_w$ | area of the working section |
| $b$ and $c$ | constants in the Callendar equation of state for steam |
| $C$ | a function of $M_5$, the Mach number at the end of the mixing zone |
| $C_p$ | specific heat of dry air |
| $i$ | total heat |
| $J$ | mechanical equivalent of heat |
| $m_1$ | mass flow of dry air |
| $m_2$ | mass flow of steam |
| $M$ | Mach number |
| $n$ | ratio of specific heats in supersaturated steam |
| $p$ | pressure |
| $Q$ | mass flow of steam lb. per hour |
| $r$ | $\dfrac{\text{Area of working-section}}{\text{Area of mixing zone}}$ |
| $R$ | constant in equation of state |
| $T$ | absolute temperature |
| $U$ | velocity |
| $v$ | specific volume |
| $\gamma$ | ratio of specific heats in dry air |
| $\gamma_m$ | ratio of specific heats in air-water-vapour mixture. |
| $\eta_\sigma$ | diffuser efficiency |
| $\mu$ | $\dfrac{\text{mass flow of dry air}}{\text{mass flow of steam}}$ |
| $\rho$ | density |

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| | |
|---|---|
| r | refers to conditions in compressed air receiver |
| s | refers to conditions in steam pressure chamber |
| o | refers to conditions of dry air at intake to tunnel |
| m | refers to conditions of the air-water-vapour mixture downstream of the mixing zone |
| 1,2,3,5,6 | refers to conditions at the respective numbered section on Fig.2. |

2. Introduction..

## 2. Introduction

Considerable experience has been obtained at the National Physical Laboratory in the use of air injectiors to drive high speed wind tunnels, but the use of steam injectiors for this purpose appears to have received comparatively little attention.

The use of steam has been discussed by Poggi[3] and tunnels using steam at high pressures and superheat were built in Germany between 1940 and 1945. More recently Professor Cave-Browne-Cave suggested that the method would have certain advantages for driving small high speed wind tunnels at Engineering Colleges, since if the boilers were available the remainder of the plant could be very simple and cheap. It was at his request that the present experiments were performed in his laboratories.

The main experiments described below have been made on the N.P.L. 2 1/4 in. diameter tunnel using dry saturated and slightly superheated steam at pressures up to 120 lb. per sq.in. absolute. Some preliminary flow observations were however made with a 2 in. sq. glass-sided working section.

## 3. Apparatus

The flow of air through the working-section was induced by a flow of low pressure steam (up to 120 lb./sq.in. absolute) through an annular injector slot placed downstream of the working section. The common flow was then discharged into a conical diffuser.

The preliminary work using the N.P.L. 2 in. sq. tunnel[4] consisted of observations of the flow in the effuser and working section with a shadowgraph system and measurements of the steam supply.

Later experiments were performed on the N.P.L. 2 1/4 in. diameter tunnel[1,2]. A diagram of the experimental plant is given in Fig.1. Three different effusers and working sections I, II and III were used to give $M_1$ subsonic, $M_1 \approx 1.4$, $M_1 \approx 2.0$ respectively. The ratio of slot area to working section area was varied by fitting suitable nozzles inside the ejector box. The nozzles tested gave slot widths of 0.01, 0.02, 0.04, 0.06 and 0.08 ins. respectively.

The static pressure in the working section was measured by connecting a Bourdon-type vacuum gauge to a pressure tapping in the wall. Measurements were also made of the steam temperature and the total head of the steam in the pressure chamber.

The boiler, used in these experiments, had a diameter of 6ft., height 10ft. 6in. with a grate area of 12 sq.ft.

## 4. Preliminary Tests

The 2 in. sq. tunnel was tested with three different liners giving $M_1 \approx 1.2$, 1.5, 1.6 respectively. It was found that the tunnel shock could not be moved back to the end of the working section, but this was probably due to the transition piece, connecting the working section to the circular injector. It was know from experiments with air that the presence of the transition piece had an appreciable effect on the performance.

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## 5. Experimental Results

The 2 1/4 in. diameter tunnel was tested with five different slot widths over a range of subsonic and supersonic speeds. The results are tabulated in tables 1 to 8 and plotted in Figs. 3 to 6.

The values of the total heat of steam in the reservoir have been taken from Callendar's steam tables.

The relative humidity of the induced air was 61 per cent at a dry bulb temperature of 66°F. Condensation was observed visually in the working section and an attempt was made to correct the measured static pressures at supersonic Mach numbers[5,6] for humidity. It was found that the Mach numbers obtained in this way only differed slightly from those obtained assuming isentropic flow. It was therefore considered sufficiently accurate, in view of the preliminary nature of this experiment, to calculate the Mach number in the working section on the assumption of an isentropic expansion, thus,

$$M_1^2 = \left[\frac{2}{\gamma-1}\left(\frac{p_o}{p_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \qquad \ldots\ldots\ldots\ldots 5.1$$

The mass flow ratio $\mu$ was calculated from equation A 1.9 using $n = 1.3$ and $\gamma = 1.4$.

An energy ratio defined by equation A 3.2 was calculated with

$C_p$ = 0.24 C.H.U. per degree C

$\gamma$ = 1.4

$i_w$ = 15.0 C.H.U.

The mass flow of steam in lb. per hour was calculated from equation A 4.3.

## 6. Discussion of Results

A supersonic Mach number was obtained in working section III ($M_1 \approx 2.0$) only with an area ratio of $0.236_5$. If we refer to Fig. 3 we notice that for a given supersonic Mach number the pressure ratio rapidly increases with decrease of area ratio. It is apparent that the pressure ratios required by nozzle III at the small area ratio were excessive and unobtainable by the boiler plant.

The graphs (see Figs. 3 and 5) of results in the supersonic region have been plotted as follows. The experimental points for $M_1 \approx 1.32$ were plotted in Figs. 4 and 6 and extrapolated to an area ratio of 0.236. The latter value was then marked on Figs. 3 and 5 and a curve was drawn through the points at $M_1 \approx 1.32$ and $M_1 \approx 1.69$ for area ratio 0.236.
The curves for the smaller area ratios have been drawn parallel to the above. The exact shapes in the graphs near $M_1$ equal to unity are uncertain and need further investigation.

A comparison between the results obtained for steam and compressed air[1,2] is given in Figs. 7 and 8. The graphs show that

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at narrow slot widths the steam pressure is less and at large slot widths somewhat greater than the corresponding air pressure. The mass flow of steam is generally a little less than that of air. The observations are quantitatively in fair agreement with equation A 2.3.

The energy ratio is plotted against working section Mach number in Fig. 9. The curves in the supersonic region, which show a maximum near $M_1$ equal to unity have been plotted in a similar manner to that described above for Figs. 3 and 5. It should be noted that the energy ratio used here is not comparable with that used to express the efficiency of tunnels driven by electrical machinery; in order to compare the two it would be necessary to include losses in the boiler room, power station, transmission lines etc., in the case of the latter.

Figs. 10 and 11 show the advantage gained in running the tunnel at small area ratios. The boiler pressure must be increased but the quantity of steam required is considerably reduced. In general it is the latter factor that is the more important.

It was noted throughout the experiment that the noise level of the tunnel was lower than that of the same tunnel driven by compressed air. No explanation has been put forward to account for this phenomenon.

The theoretical analysis developed in the Appendix gives satisfactory agreement with the experimental results when diffuser efficiencies between 0.80 and 0.83 are used. However since large variations in the performance are predicted by relatively small changes in $\eta_\sigma$ the theoretical results are inconclusive. The analysis may, however, provide useful preliminary design data.

## 7. Intermittent Operation

The results presented here refer to an installation in which the steam supply is sufficient to operate the tunnel continuously. If intermittent operation is acceptable it will be possible to use the boiler (and possibly also additional vessels) as a storage reservoir and run a tunnel of larger dimensions. The tunnel size and running time may in this case be calculated by the method outlined in ref.1.

## 8. Practical Considerations

In an induced-flow tunnel driven by an air injector it is often possible to obtain dry induced air by building a return circuit which after a short reliminary run becomes filled with the air injected through the injector slot. (This air will have been dried automatically in the compression-expansion cycle through which it is carried). This method cannot be used with steam as the inducing fluid and other methods for drying the induced air must be provided, unless the tunnel is to be used solely for demonstration purposes. Since an adequate source of heat is at hand the simplest method is probably to warm the induced air in some form of heat exchanger. The disadvantage of this system is, of course, that its working section and model will become unpleasantly hot.

The pressure chamber and the adjacent parts of the tunnel soon reach the temperature of the inducing steam and this should be borne in mind when selecting the materials from which the tunnel is made. The possible effects of differential expansion, in particular, should be remembered.

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## EXPERIMENTAL RESULTS

### TABLE 1

Psychrometric Data (Air in the Laboratory)

| | |
|---|---|
| Atmospheric pressure | 29.95 in. Hg. |
| Temperature dry bulb | 66.0° F |
| ditto wet bulb | 58.0° F |
| Relative humidity | 61.0 per cent |
| Specific humidity | 0.00836 |

The results quoted in the tables below have been evaluated using

$$\rho_o = 0.00233_5 \text{ slugs per cu.ft.}$$

### TABLE 2

Tunnel Dimensions

| | |
|---|---|
| Nozzle I (subsonic) | |
| Working section | 2.281 in. diameter |
| Nozzle II ($M_1 \approx 1.4$) | |
| Throat section | 2.098 in. diameter |
| Working section | 2.281 in. diameter |
| Nozzle III ($M_1 \approx 2.0$) | |
| Throat section | 1.418 in. diameter |
| Working section | 1.838 in. diameter |
| Mixing chamber | 2.58 in. diameter<br>2.0 in. long |
| Diffuser entry | 2.58 in. diameter |
| exit | 7.43 in. diameter |
| Angle of divergence (total) | 4° 12' |

/TABLE 3 ...

TABLE 3

$$\frac{\text{Area of slot}}{\text{Area of working section}} = 0.019_3$$

| Working section No. | Steam pressure lb./sq.in. absolute | Steam temp. $^oC$ | Steam total heat in pressure chamber C.H.U. | Static pressure in working section in.Hg. | Mach No. in working section | Mass flow ratio | Energy ratio | Mass flow of steam lb./hr. |
|---|---|---|---|---|---|---|---|---|
| I | 36.7 | 137.0 | 653.8 | 25.45 | 0.48 | 22.9 | 0.11 | 158.0 |
| I | 44.7 | 137.0 | 652.6 | 23.65 | 0.59 | 21.6 | 0.15 | 193.0 |
| I | 54.7 | 141.5 | 653.7 | 21.75 | 0.69 | $19.2_5$ | 0.18 | 236.0 |
| I | 62.7 | 146.5 | 655.3 | 19.75 | $0.79_5$ | 17.8 | 0.22 | 270.0 |
| I | 84.7 | 158.0 | 658.3 | 18.15 | $0.87_5$ | 13.7 | 0.20 | 360.0 |
| II | 114.7 | 170.0 | 661.5 | 10.55 | 1.32 | $8.7_5$ | 0.25 | 485.0 |

TABLE 4

$$\frac{\text{Area of slot}}{\text{Area of working section}} = 0.039_4$$

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| I | 26.7 | 131.0 | 652.3 | 25.95 | 0.46 | 14.9 | 0.07 | 235.0 |
| I | 31.7 | 133.0 | 652.4 | 23.95 | $0.57_5$ | $14.6_5$ | 0.10 | 280.0 |
| I | 35.7 | 134.5 | 653.8 | 22.55 | 0.65 | 13.95 | 0.12 | 315.0 |
| I | 44.7 | 135.5 | 652.1 | 19.75 | $0.79_5$ | $12.1_5$ | 0.14 | 395.0 |
| I | 45.7 | 137.0 | 652.6 | 18.15 | $0.87_5$ | 12.2 | 0.18 | 405.0 |
| II | 80.7 | 156.0 | 657.9 | 10.55 | 1.32 | $6.0_5$ | $0.16_5$ | 700.0 |

TABLE 5

$$\frac{\text{Area of slot}}{\text{Area of working section}} = 0.078_2$$

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| I | 21.7 | 132.0 | 653.4 | 26.35 | $0.43_5$ | $8.8_5$ | $0.03_5$ | 380.0 |
| I | 26.7 | 133.0 | 653.3 | 23.45 | 0.60 | 9.0 | $0.06_5$ | 470.0 |
| I | 29.7 | 134.5 | 653.2 | 21.75 | 0.69 | 8.7 | $0.08_5$ | 510.0 |
| I | 30.7 | 135.5 | 653.6 | 19.95 | $0.78_5$ | 8.85 | $0.10_5$ | 540.0 |
| I | 33.7 | 136.5 | 654.0 | 17.95 | $0.88_5$ | 8.4 | 0.13 | 580.0 |
| I | 34.7 | 136.5 | 653.8 | 16.95 | 0.94 | 8.2 | 0.13 | 610.0 |
| II | 56.7 | 143.0 | 654.2 | 10.35 | 1.32 | $4.2_5$ | 0.12 | 995.0 |

TABLE 6

$$\frac{\text{Area of slot}}{\text{Area of working section}} = 0.116_3$$

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| I | 19.7 | 128.0 | 651.4 | 26.15 | $0.44_5$ | $6.6_5$ | 0.03 | 515.0 |
| I | 22.7 | 129.0 | 651.4 | 23.75 | 0.59 | $7.0_5$ | 0.05 | 595.0 |
| I | 26.7 | 130.0 | 651.9 | 21.95 | $0.68_5$ | 6.5 | 0.06 | 700.0 |
| I | 27.7 | 131.0 | 651.8 | 19.85 | 0.79 | $6.6_5$ | 0.08 | 725.0 |
| I | 30.7 | 138.0 | 654.7 | 17.75 | 0.90 | $6.2_5$ | 0.10 | 790.0 |
| I | 31.7 | 139.0 | 655.3 | 17.15 | 0.93 | 6.1 | 0.10 | 815.0 |
| II | 47.7 | 139.5 | 653.7 | 10.75 | 1.32 | $3.4_5$ | $0.09_5$ | 1230.0 |

/TABLE 7 ...

## TABLE 7

$$\frac{\text{Area of slot}}{\text{Area of working section}} = 0.154$$

| Working section No. | Steam pressure lb./sq.in. absolute | Steam temp. $^{o}C$ | Steam total heat in pressure chamber C.H.U. | Static pressure in working section in.Hg. | Mach No. in working section | Mass flow ratio | Energy ratio | Mass flow of steam lb./hr. |
|---|---|---|---|---|---|---|---|---|
| I | 19.7 | 129.0 | 652.0 | 25.95 | 0.46 | $5.1_5$ | $0.02_5$ | 680.0 |
| I | 21.7 | 130.0 | 652.8 | 23.95 | $0.57_5$ | 5.5 | $0.03_5$ | 750.0 |
| I | 24.7 | 131.0 | 652.4 | 21.75 | 0.69 | $5.3_5$ | 0.05 | 855.0 |
| I | 26.7 | 133.0 | 653.2 | 19.75 | $0.79_5$ | $5.2_5$ | $0.06_5$ | 920.0 |
| I | 30.7 | 137.0 | 654.9 | 18.25 | 0.87 | $4.6_5$ | $0.06_5$ | 1060.0 |
| II | 40.7 | 133.0 | 651.6 | 10.55 | 1.32 | 3.0 | $0.08_5$ | 1410.0 |

## TABLE 8

$$\frac{\text{Area of slot}}{\text{Area of working section}} = 0.236_5$$

| Working section No. | Steam pressure lb./sq.in. absolute | Steam temp. $^{o}C$ | Steam total heat in pressure chamber C.H.U. | Static pressure in working section in.Hg. | Mach No. in working section | Mass flow ratio | Energy ratio | Mass flow of steam lb./hr. |
|---|---|---|---|---|---|---|---|---|
| III | 77.7 | 154.0 | 657.4 | 6.15 | 1.69 | $0.7_5$ | $0.02_5$ | 2600.0 |

/REFERENCES ...

## REFERENCES

| | | |
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/APPENDIX ...

## APPENDIX

### 1. Derivation of equations for mass flow ratio and pressure ratio

A diagrammatic sketch of the induction tunnel is given in Fig.2. The suffices attached to the symbols below refer to the conditions of flow at the respective sections numbered in the above Fig.

The following assumptions have been made,-

(a) The expansion of dry air from sections 0-1 is isentropic.

(b) The expansion of steam from sections s-3 is supersaturated and isentropic.

(c) The steam reaches sonic velocity at section 3.

(d) The velocity, pressure and density of the air - water vapour mixture at section 5 are uniform across the section.

(e) The kinetic energies of the fluids at sections 0, s and 6 are negligible compared with that at section 1.

(f) The mixture between sections 5-6 consists of saturated air and water vapour.

(g) The friction or heat interchange between the mixture and its surroundings taking place between sections 3-5 is negligible.

(h) The heat interchange between the mixture and its surroundings between 5-6 is negligible.

(i) The area is constant from sections 1-2.

An extra assumption usually made in developing the theory of ejectors [2,7,8,9] and in the mixing of compressible flows[10], is that the pressure throughout the mixing region is constant. This would result in the pressures at sections 2, 3, 5 being equal in magnitude. This assumption is <u>not</u> used in the present report; all that is specified is that momentum and total energy is conserved between sections 1-2-5 and 3-5. In fact it is almost certain that the tunnel air will form a shock between sections 1-2 when the velocity is supersonic in the working section. This will however not invalidate the results given below which are true within the limitations of the theory, whether a shock is present or not.

The three fundamental equations based on one-dimensional analysis are-

Continuity

$$r\rho_1U_1 + (1-r)\rho_3U_3 = \rho_5U_5 \quad \text{A1.1}$$

Momentum

$$r(p_1+\rho_1U_1{}^2) + (1-r)(p_3+\rho_3U_3{}^2) = p_5 + \rho_5U_5{}^2 \quad \text{A1.2}$$

Energy

$$m_1i_o + m_2i_s = (m_1 + m_2)i_6 \quad \text{A1.3}$$

The 'Callendar' equation of state for dry superheated or supersaturated steam is

$$(v-b) = \frac{RT}{p} - \frac{c}{T^{10/3}} \qquad \text{.......A1.4}$$

The isentropic expansion of supersaturated steam is assumed to follow the law

$$p(v-b)^n = \text{const.} \qquad \text{.......A1.5}$$

For the range of steam pressures used in this experiment the magnitude of $b$ is negligible compared with that of $v$ and equation A1.5 therefore becomes

$$pv^n = \text{const.} \qquad \text{.......A1.5a}$$

The velocity of sound in steam has been calculated from

$$a = \sqrt{npv} \qquad \text{.......A1.6}$$

The compression of the mixture from section 5-6 is assumed to obey the law

$$\frac{p_6}{p_5} = \left[1 + \eta_\sigma\left(\frac{\gamma_m - 1}{2}\right) M_5^2\right]^{\frac{\gamma_m}{(\gamma_m - 1)}} \qquad \text{.......A1.7}$$

where $\eta_\sigma$, known as the diffuser efficiency, varies with $M_5$. It is further assumed that

$$p_5/\rho_5 T_5 = p_6/\rho_6 T_6 \qquad \text{.......A1.8}$$

If we define the mass flow ratio

$$\mu = \frac{\text{mass flow of air through the working section in unit time}}{\text{mass flow of steam through the ejector slot in unit time.}}$$

it can be shown that, on combining equations A1.1, A1.5a, A1.6, and rearranging,

$$\mu = \left(\frac{r}{1-r}\right)\sqrt{\frac{\gamma p_o \rho_o}{n p_s \rho_s}} \cdot \frac{M_1}{\left(1+\frac{\gamma-1}{2} M_1^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}} \cdot \left(\frac{n+1}{2}\right)^{\frac{n+1}{2(n-1)}} \qquad \text{....A1.9}$$

Similarly from equations A1.1, A1.5a, A1.6, A1.7, A1.8 we get

$$\left(\frac{\mu + 1}{\mu}\right)\sqrt{\left(\frac{\gamma p_o \rho_o}{\gamma_m p_6 \rho_6}\right)} \frac{M_1}{\left(1+ \frac{\gamma-1}{2} M_1^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}} = \frac{M_5\left(1+ \frac{\gamma_m-1}{2} M_5^2\right)^{\frac{1}{2}}}{r\left(1+\eta_\sigma\left(\frac{\gamma_m-1}{2}\right) M_5^2\right)^{\frac{\gamma_m}{(\gamma_m-1)}}}$$

....A1.10

/where ...

where $p_o = p_6$ by definition.

Equations A1.2, A1.5a, A1.6, A1.7 can be combined to give

$$\frac{\left(1 + \gamma M_1{}^2\right)}{\left(1 + \frac{\gamma-1}{2} M_1{}^2\right)^{\frac{\gamma}{\gamma-1}}} + \left(\frac{1-r}{r}\right) \frac{p_s}{p_o} (1+n) \left(\frac{2}{1+n}\right)^{\frac{n}{n-1}}$$

$$= \frac{\left(1 + \gamma_m M_5{}^2\right)}{r\left(1 + \frac{\gamma_m-1}{2} \eta_\sigma M_5{}^2\right)^{\frac{\gamma_m}{\gamma_m-1}}} \qquad \text{.......A1.11}$$

If we divide equation A1.11 by A1.10 and substitute the value of $\left(\frac{1-r}{r}\right) \mu$ obtained from equation A1.9 then,

$$C = \frac{\mu (1+\gamma M_1{}^2) + \sqrt{\frac{2\gamma(1+n)}{n} \cdot \frac{p_s\rho_o}{p_o\rho_s}} \cdot M_1 \left(1+ \frac{\gamma-1}{2} M_1{}^2\right)^{\frac{1}{2}}}{(\mu+1) \sqrt{\frac{\gamma\rho_o}{\gamma_m\rho_6}} M_1 \left(1+ \frac{\gamma-1}{2} M_1{}^2\right)^{\frac{1}{2}}}$$

$$\text{......A1.12}$$

where, $$C = \frac{1 + \gamma_m M_5{}^2}{M_5\left(1 + \frac{\gamma_m-1}{2} M_5{}^2\right)^{\frac{1}{2}}} \qquad \text{......................A1.13}$$

A knowledge of $\mu$ and $M_1$ together with approximate values for $p_s$ and $T_s$ will enable us to find $C$ from equation A1.12 and $M_5$ from A1.13. In general two values of $M_5$ will be obtained of which only the subsonic value has practical significance.

If $b$ is neglected from equation A1.4, then

$$\frac{p_s\rho_o}{p_o\rho_s} = \frac{R_sT_s}{R_oT_o} \left(1 - \frac{c\, p_s}{R_sT_s{}^{13/3}}\right) \qquad \text{................A1.14}$$

where, $p_o = \rho_oR_oT_o$.

We further assume that

$$\gamma_m = \frac{\mu \gamma + n}{\mu+1} \qquad \text{..............................A1.15}$$

and $$R_m = \frac{\mu R_o + R_s}{\mu+1} \qquad \text{..............................A1.16}$$

/where ...

where $p_6 = \rho_6 R_m T_6$.

The conditions at section 6 can be determined from equation A1.3 by successive approximation or by use of tables[11] giving the total heat of saturated air.

Thus all terms in equation A1.12 can be calculated.

The value of $r$ can be obtained from A1.10 and $p_s/p_o$ from A1.9 or A1.11.

## 2. Comparison between the mass flow ratio in an inducation tunnel driven (a) by steam and (b) by compressed air

The value of $\mu$ for a compressed air induction tunnel operated from compressed air at pressure $p_R$ and temperature $T_R$ is,

$$\mu_{air} = 1.728 \frac{p_o}{p_R} \sqrt{\frac{T_R}{T_o}} \left(\frac{r}{1-r}\right) \frac{M_1}{\left(1 + \frac{\gamma-1}{2} M_1^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}} \qquad \text{........A2.1}$$

If we drive a given tunnel, at a certain Mach number $M_1$, (a) by air and (b) by steam then, provided that $r$ is also maintained constant,

$$\frac{\mu_{steam}}{\mu_{air}} = \sqrt{\frac{\gamma}{n}} \cdot \left(\frac{n+1}{2}\right)^{\frac{n+1}{2(n-1)}} \cdot \frac{1}{1.728} \cdot \sqrt{\frac{p_R \rho_R}{p_s \rho_s}} \qquad \text{........A2.2}$$

In the present series of tests $T_s$ was approximately constant at 400°K. In the experiments[1] on a tunnel driven by compressed air $T_R = T_o$. If we now substitute these values into equation A2.2 we find

$$\frac{\mu_{steam}}{\mu_{air}} \hat{=} \frac{p_R/p_o}{p_s/p_o} \; 1.525 \qquad \text{..................A2.3}$$

## 3. To determine the energy ratio of the tunnel

$$\text{The energy ratio} = \frac{\text{rate of flow of kinetic energy at working section}}{\text{power input to tunnel}} \qquad \text{..A3.1}$$

The rate of flow of kinetic energy at the working section equals $\frac{1}{2} m_1 U_1^2$ while the power input

equals $m_2 (i_s - i_w) J$

where $i_s$ = total heat of steam in reservoir.

$i_w$ = total heat of feed water to boiler.

/Thus ...

Thus

$$\text{E.R.} = \frac{\frac{1}{2}\,\mu\,C_p\,T_o\,(\gamma-1)\,M_1^{\,2}}{1+\frac{\gamma-1}{2}M_1^{\,2}\,(i_s - i_w)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{A3.2}$$

4. <u>To determine the mass flow of steam</u>

The mass flow of steam Q in the lb./hr. is

$$Q = \frac{3600 \times 32.2 \times m_1}{\mu} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{A4.1}$$

but,

$$m_1 = \frac{\rho_o\,a_o\,A_w\,M_1}{\left(1+\frac{\gamma-1}{2}M_1^{\,2}\right)^{\frac{\gamma+1}{2(\gamma-1)}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{A4.2}$$

where $\rho_o, a_o$ are the density and velocity of sound of the air at rest, and where $A_w$ is the working section area.

Therefore

$$Q = \frac{3600 \times 32.2.\ \rho_o\,a_o\,A_w\,M_1}{\mu\left(1+\frac{\gamma-1}{2}M_1^{\,2}\right)^{\frac{\gamma+1}{2(\gamma-1)}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{A4.3}$$

----oOo----

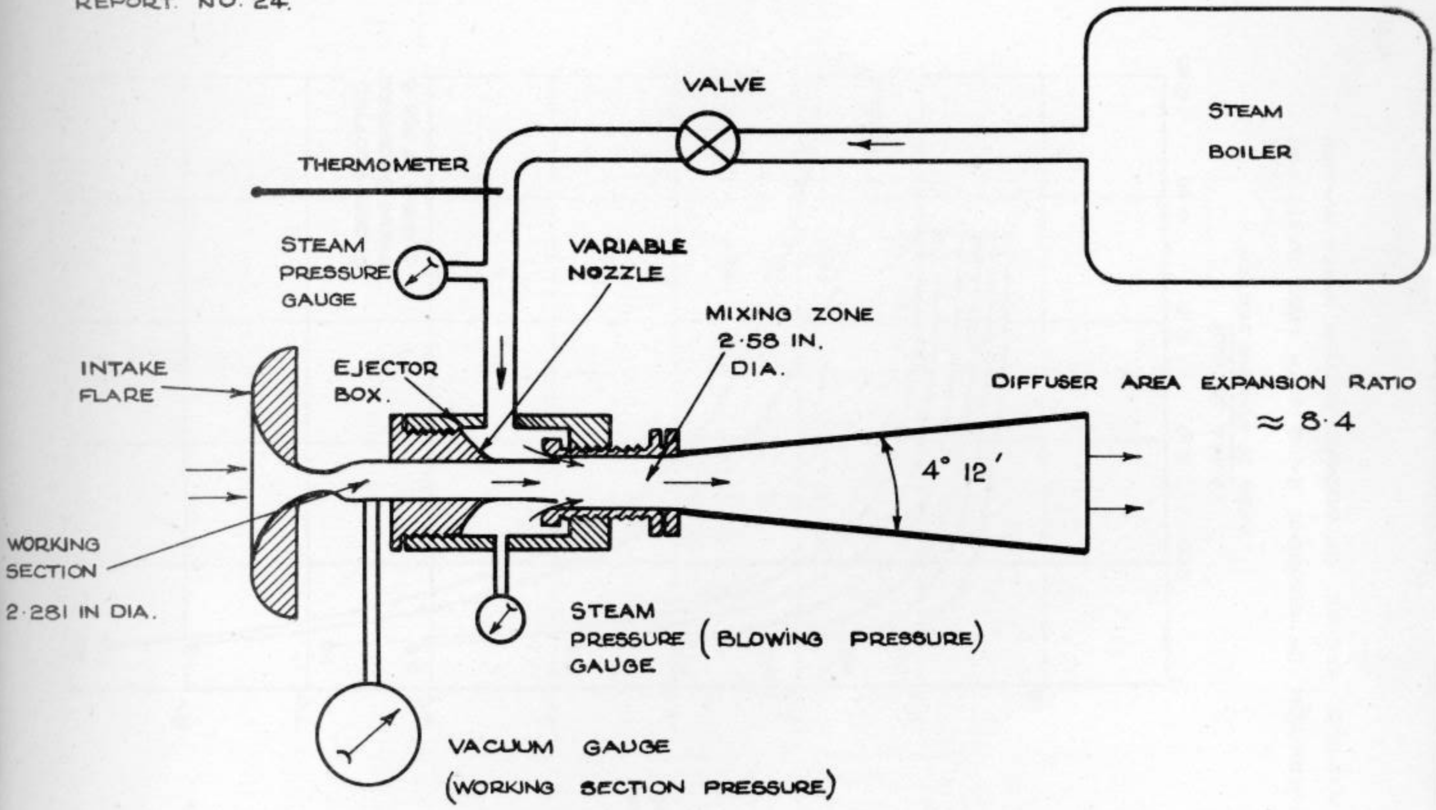
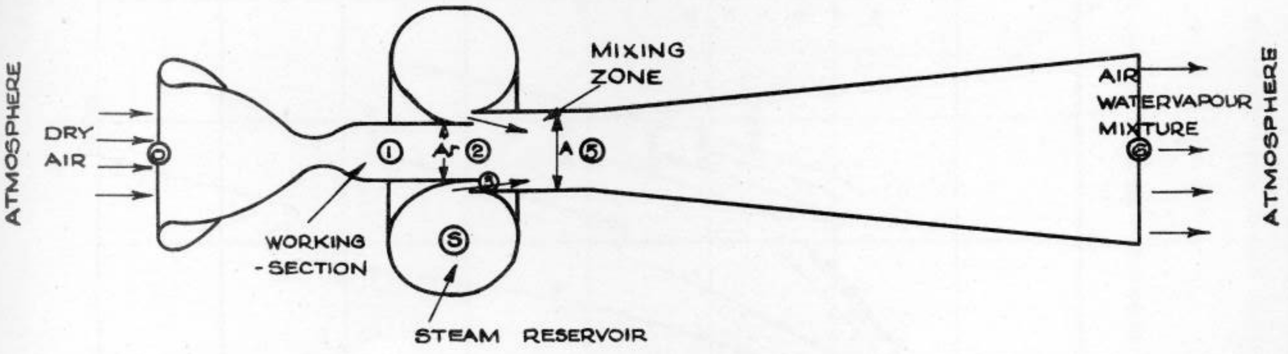


DIAGRAM OF THE EXPERIMENTAL PLANT

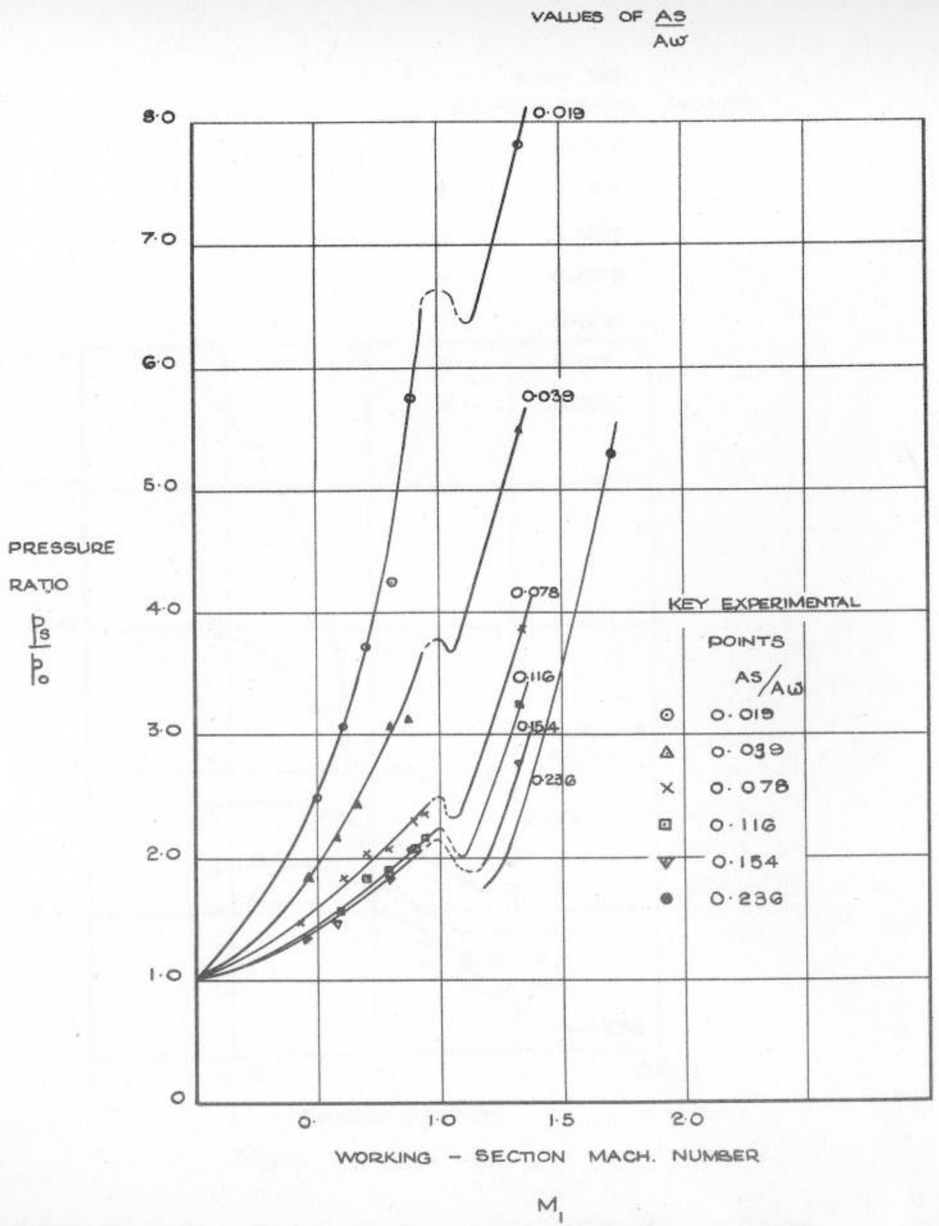
FIG. 1



SIMPLIFIED DIAGRAMMATIC LAYOUT OF THE INDUCTION TUNNEL DRIVEN BY STEAM

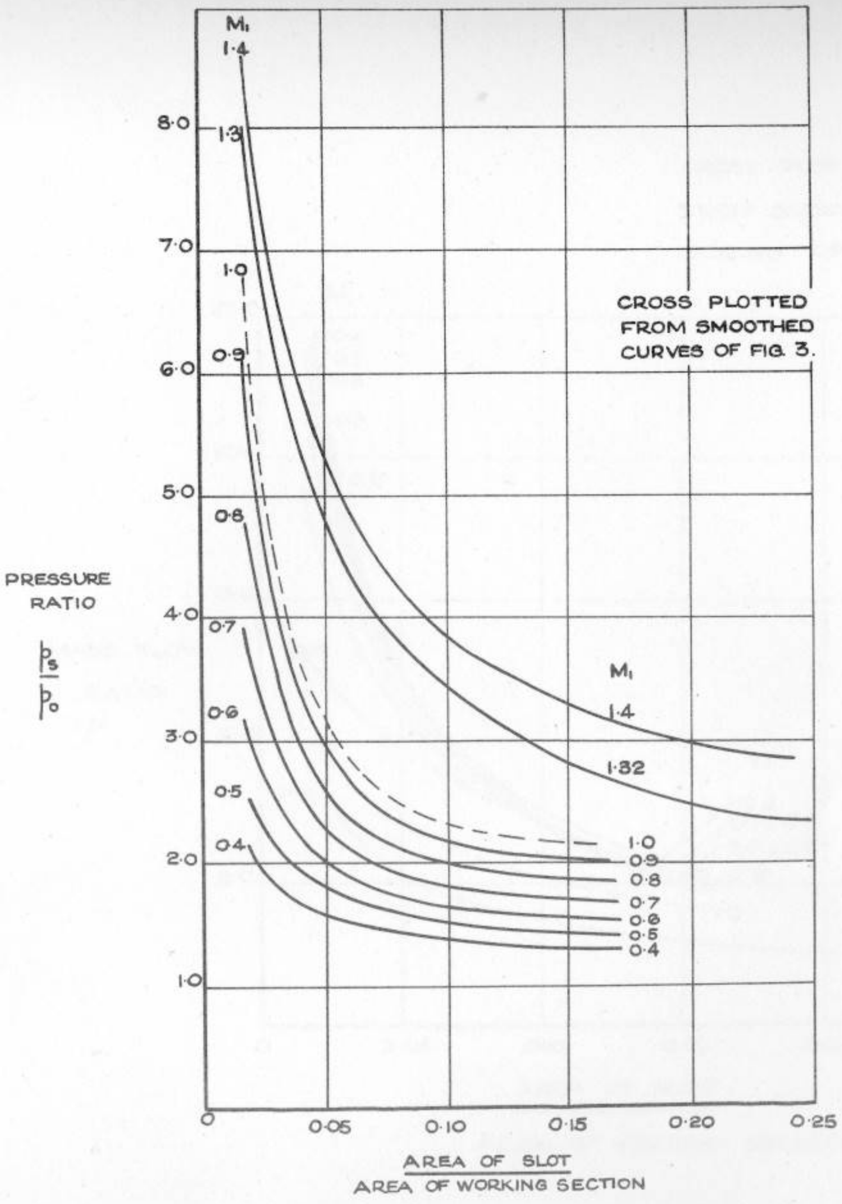
(NOTE:- IN THE EXPERIMENTAL TUNNEL THE AREA IS NOT CONSTANT FROM SECTION ① TO SECTION ②)

FIG. 2



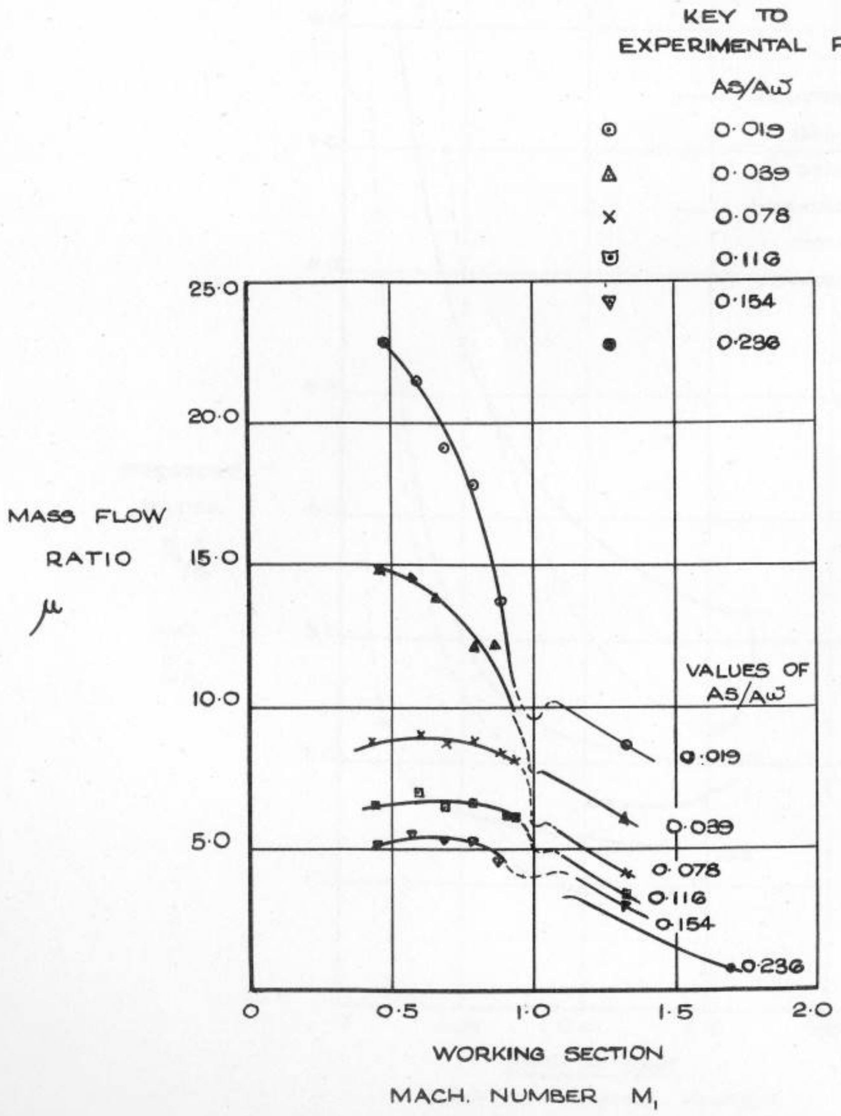
VARIATION OF PRESSURE RATIO WITH WORKING SECTION MACH. NUMBER FOR VARIOUS AREA RATIOS.

FIG. 3



VARIATION OF PRESSURE RATIO WITH AREA RATIO FOR VARIOUS VALUES OF WORKING SECTION MACH. NUMBER.

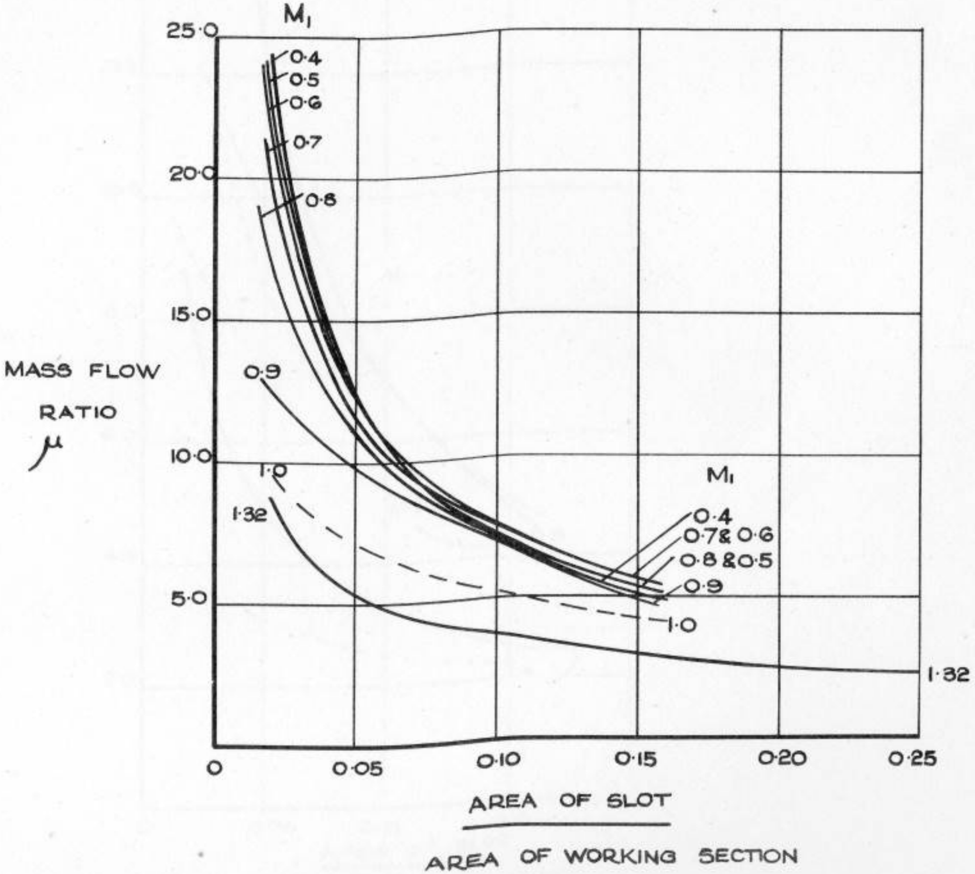
FIG. 4



VARIATION OF MASS FLOW RATIO WITH WORKING SECTION MACH. NUMBER FOR VARIOUS AREA RATIOS.

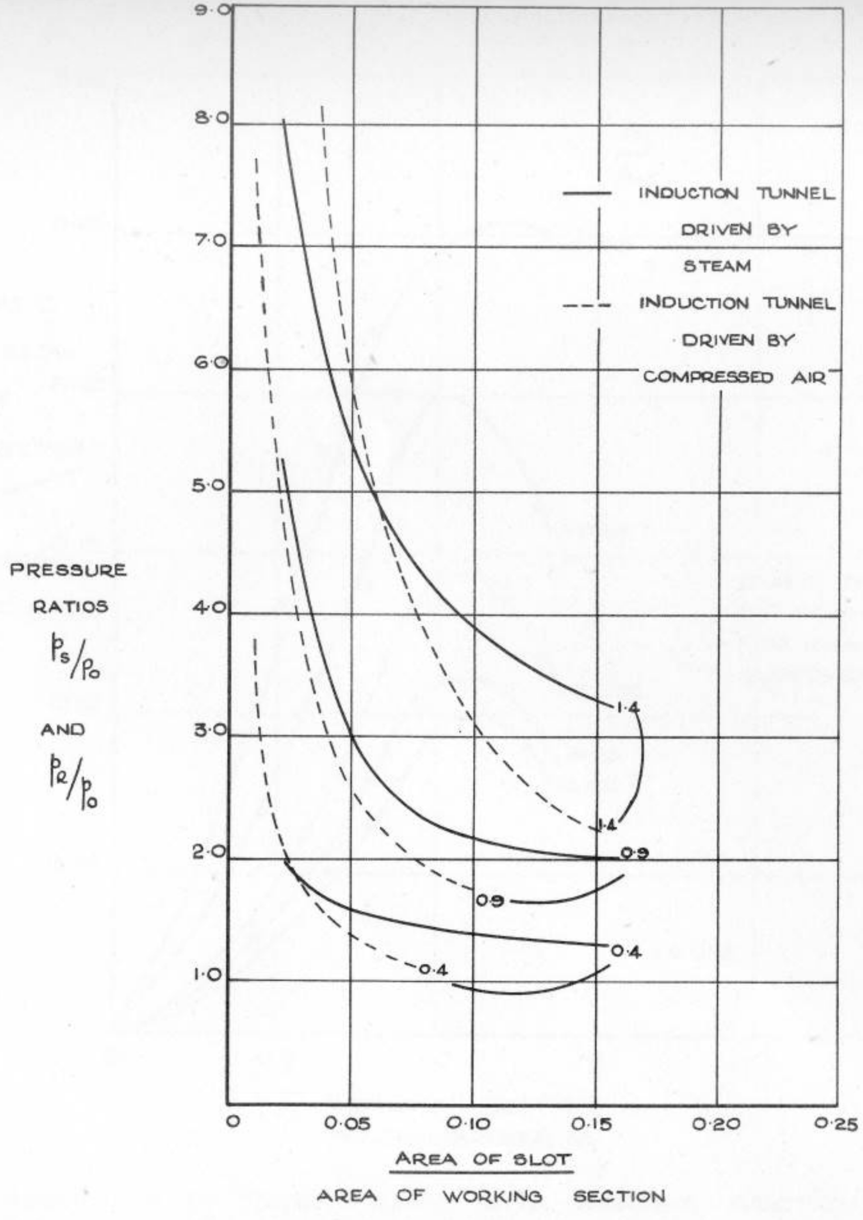
FIG. 5

CROSS PLOTTED
FROM SMOOTHED
CURVES OF FIG. 5.



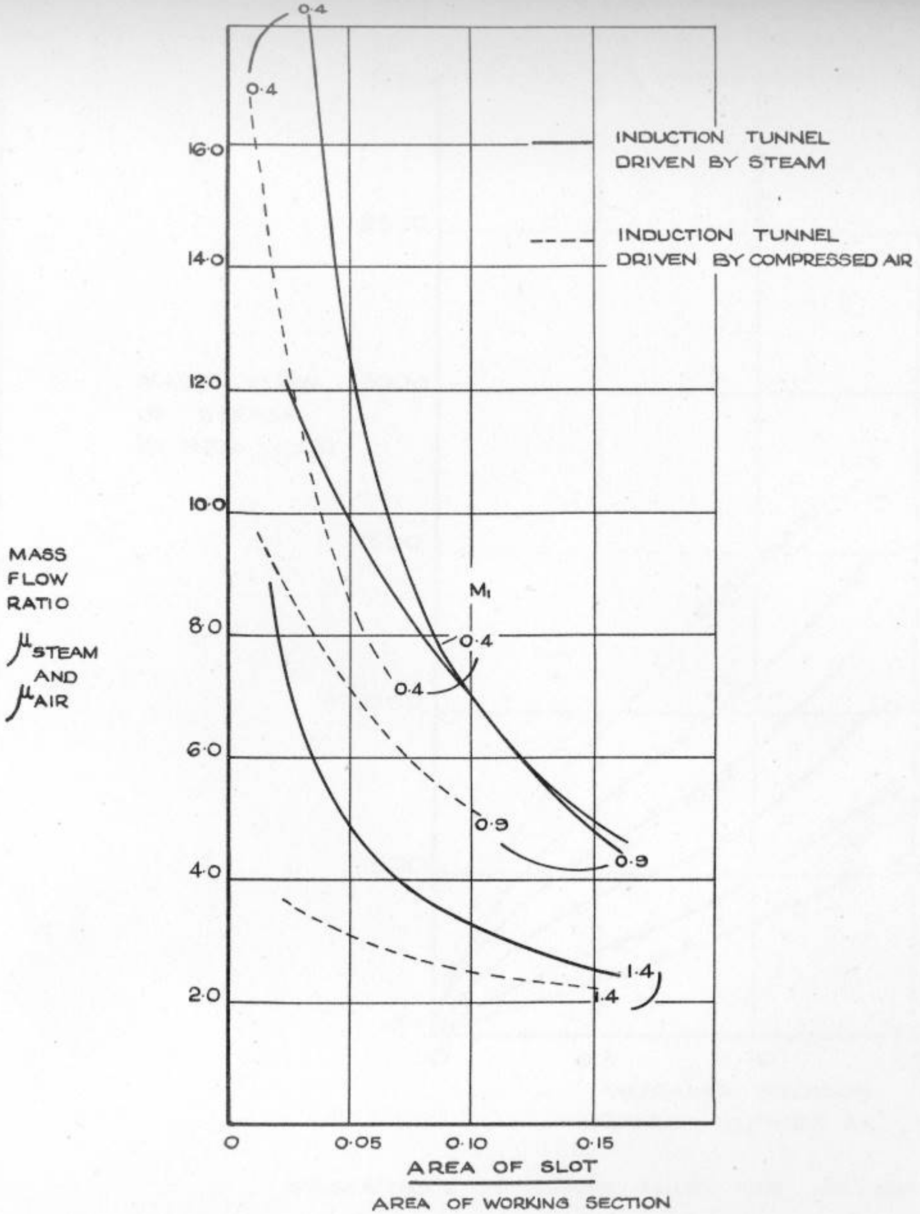
VARIATION OF MASS FLOW RATIO WITH AREA RATIO FOR VARIOUS VALUES OF WORKING SECTION MACH. NUMBER.

FIG. 6



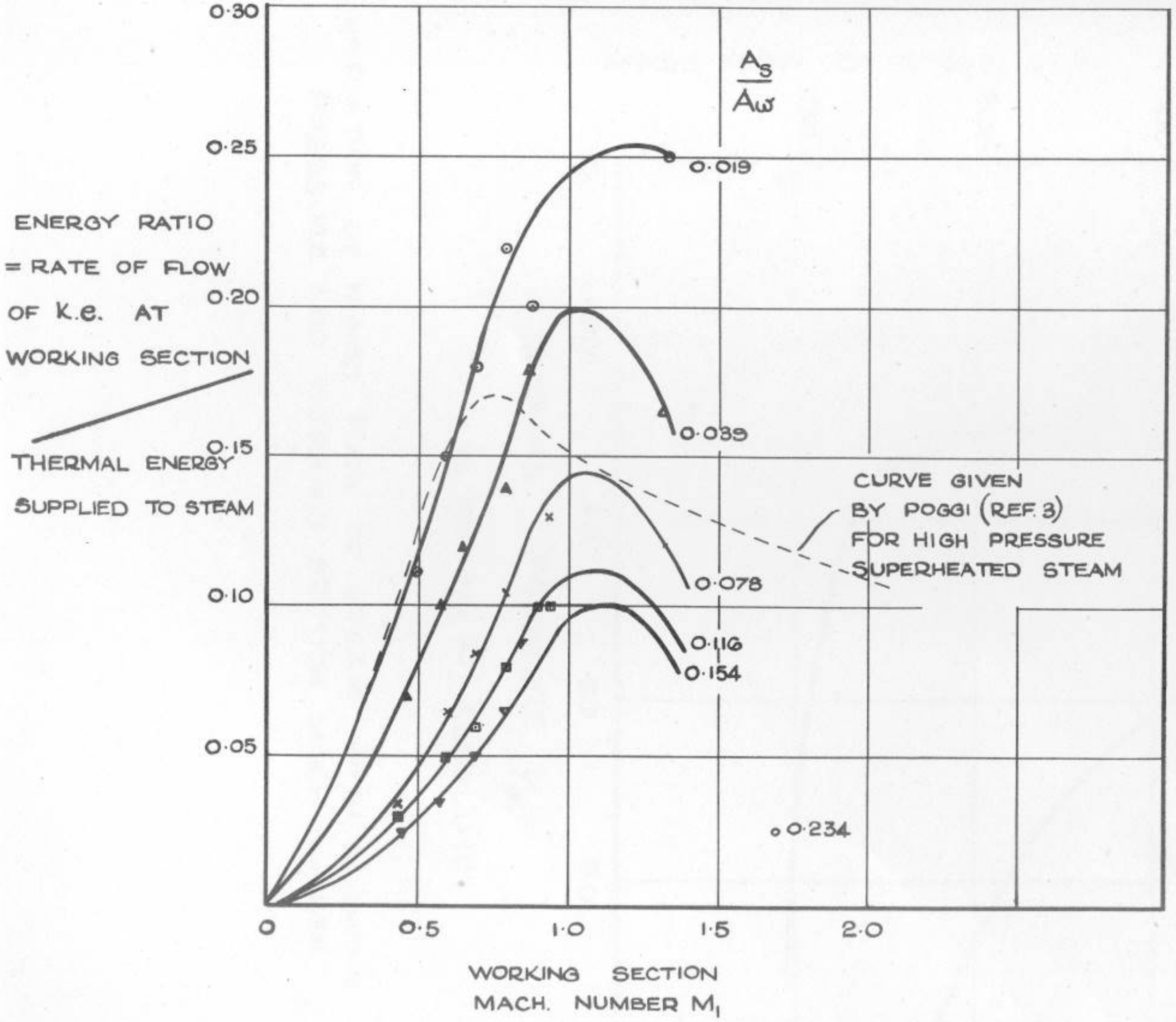
COMPARISON BETWEEN THE PERFORMANCE OF AN INDUCTION TYPE HIGH SPEED WIND TUNNEL DRIVEN (a) BY STEAM (b) BY COMPRESSED AIR

FIG 7



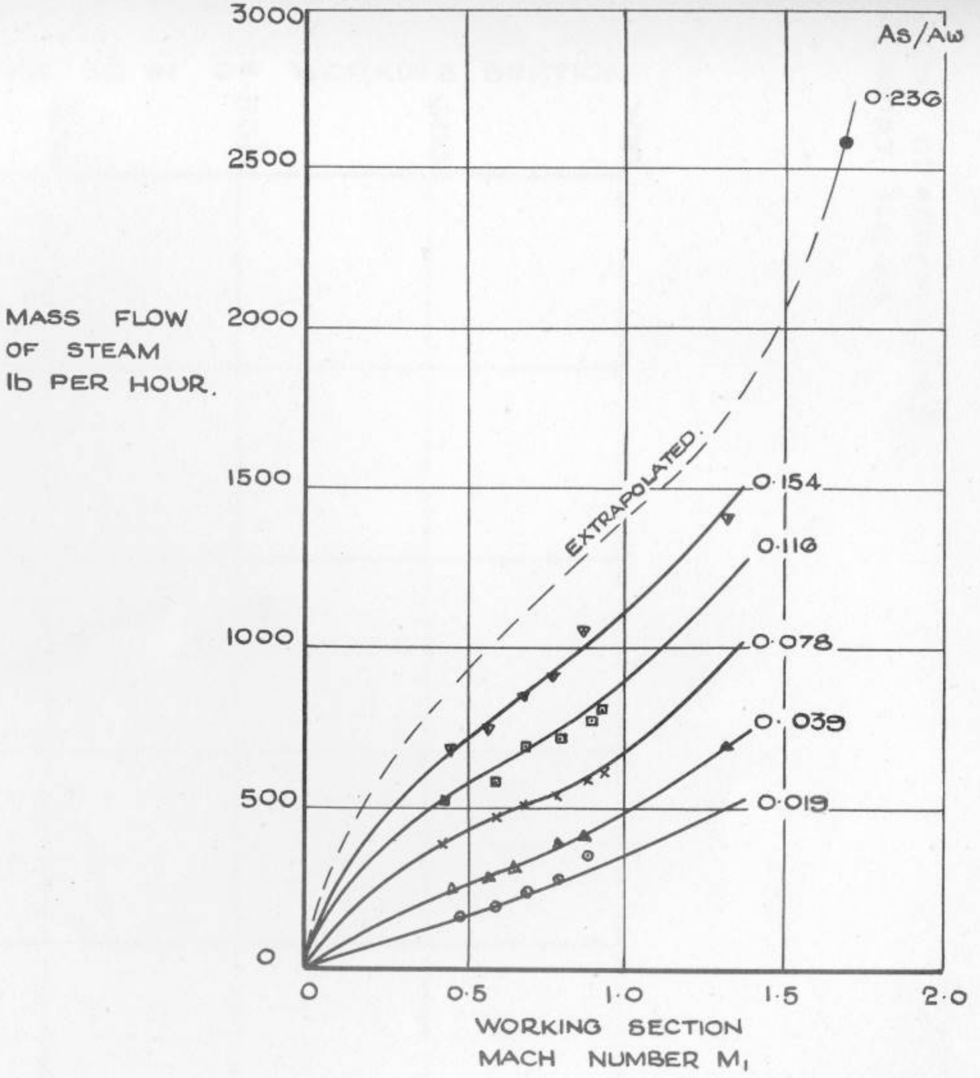
COMPARISON BETWEEN THE PERFORMANCE OF AN INDUCTION TYPE HIGH SPEED WIND TUNNEL DRIVEN (a) BY STEAM (b) BY COMPRESSED AIR.

FIG.8



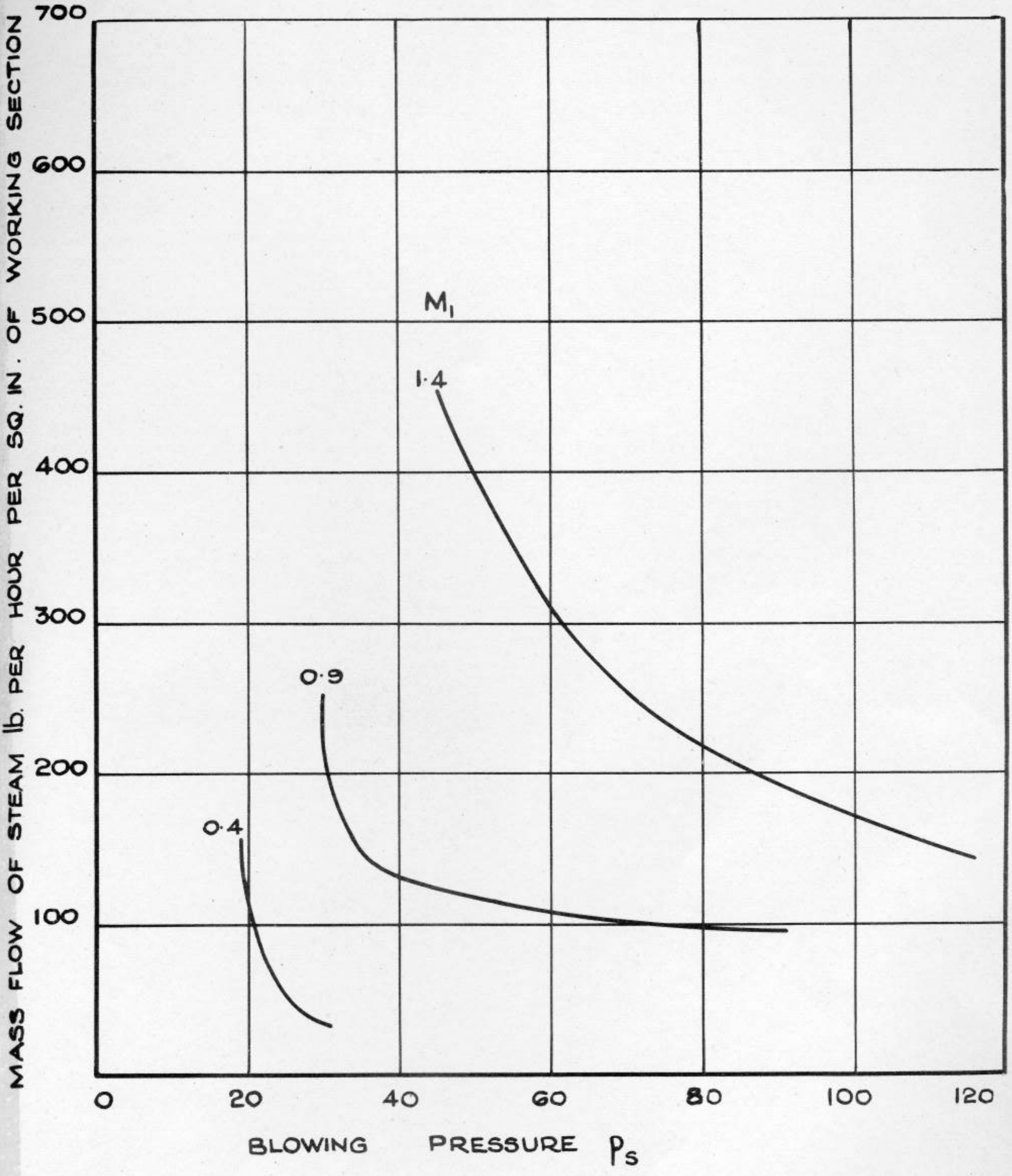
VARIATION OF ENERGY RATIO WITH WORKING-SECTION MACH. NUMBER.

FIG. 9



VARIATION OF MASS FLOW OF STEAM WITH WORKING SECTION MACH NUMBER.

FIG. 10



VARIATION OF MASS FLOW OF STEAM WITH BLOWING PRESSURE AND WORKING SECTION MACH NUMBER

FIG. 11