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Some Experiments on an Effusion Cooled Turbine Nozzle Blade

by

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Some experiments on an effusion cooled turbine nozzle blade

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SUMMARY

An experimental and theoretical investigation is carried out on effusion cooling of a turbine nozzle blade in a cascade tunnel. The permeable surface of the test blade is made of woven stainless steel wire cloth brazed to the spine in such a way that the effusion flow can be individually controlled over a number of regions on both convex and concave surfaces of the blade form. In this way, the chordwise effusion, flow distribution required to produce uniform surface temperature at mid-span, and the temperature distribution at mid-span produced by uniform effusion are determined and compared with the corresponding theoretical predictions.

In the laminar flow region of the blade boundary layer the effusion flow to achieve a required temperature is much higher than predicted and in the turbulent flow region the flow is lower than predicted. The two requirements combine to give an overall cooling effectiveness for the blade surface which is very little different from an internally cooled impermeable rotor blade also tested in a cascade. The large effusion flow required in the laminar region may be due to the practical limitation of the number of individually controllable effusion regions since the static pressure gradient over the leading edge part of the blade surface is very large and the variation in effusion cooling air supply pressures required must also, therefore, be very large.

The solution to this problem lies in the use of permeable materials of either variable permeability or variable thickness over a relatively wide range of permeability or thickness.

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1.0 Introduction

Of the various ways of cooling a turbine blade in a hot gas stream, there is one way which theoretically, under most circumstances, is very much more economical in cooling air than others. This method is effusion cooling, which means that the cooling air passes continuously from a cavity inside the blade, through a permeable surface into the external boundary layer. In doing so, the cooling air builds up a cool air film around the blade and reduces the rate at which heat is transferred to the blade. The extent to which this form of cooling is theoretically better than other forms, depends largely on the state of the boundary layer. If the boundary layer is completely laminar over the whole blade, then maximum economy can be achieved. If, however, there are large areas of turbulent flow on the blade surface, then theoretically, it is likely that the effusion cooling loses some of its considerable advantage and the loss is large or small depending on whether the Reynolds number is large or small.

Turning to the practical problem of turbine blade cooling it is necessary, of course, to check the theoretical result and to assess as far as possible the problems of introducing cooling air into the mainstream boundary layer in the quantities ideally required. A further unknown which could be of considerable importance is the effect of the effusion flow on the position of the transition point and the boundary layer conditions after the transition point.

To undertake an investigation of these effects it must be possible to determine the individual characteristics at the various chordwise positions over the blade surface. Figure 1 illustrates the turbine nozzle blade used for an investigation in a high temperature cascade tunnel. The eighteen individual passages taking the cooling air to the permeable surface give a considerable degree of freedom in application of cooling air and allow a fair comparison with theory to be made.

The two conditions most easily treated theoretically are first, the condition in which the blade surface temperature is maintained constant by chordwise variation of effusion flow rate on the blade and second, the condition in which the effusion flow rate is constant over the whole blade surface. This latter solution gives the chordwise temperature distribution over the blade and is true only for small blade temperature variations.

These two conditions have been thoroughly investigated experimentally over a wide range of Reynolds number, temperature and Mach number. A secondary aspect of the investigation is the reliability and structural difficulties associated with this form of cooling. These points are treated as secondary in the present investigation since the blade was designed primarily as a research instrument and not as a blade with necessarily direct engine application.

2.0 The test blade and high temperature tunnel

2.1 Blade design

The blade shown in Figure 1 is largely self-explanatory. The grooved blade spine made of mild steel produces eighteen separate and individually controllable cooling supply regions on the blade surface. A section of the blade is illustrated in Figure 2 and dimensions in tabular form are given in Appendix III.

The geometry of the blade is such that the permeable skin must be relatively thin and capable of being bent accurately to the blade form. The only available material to satisfactorily fulfil these and other necessary mechanical requirements at the time of manufacture of the blade, was woven stainless steel wire cloth, called Hollander cloth. The cloth is woven from 0.008 in. circular wire and is subsequently cold-rolled to produce within certain limits the required permeability. A micrograph of the cloth before and after testing is shown in Figure 2 and in this figure too, can be seen the direction of weave relative to the chordwise direction.

The cloth was brazed to the mild steel spine with 'Colmonoy' nickel-chrome brazing alloy at a temperature of about 1120°C. in a reducing atmosphere without a flux. This process requires a clearance of less than 0.002 in. between the wire cloth and that part of the blade spine to which it is brazed. The brazing caused no appreciable reduction in the permeability of the wire cloth and judging by subsequent tests, the joint between the cloth and the ribs of the blade spine was effective

Eighteen thermocouples were provided to measure the mid-span blade surface temperature for each separate effusion region and in addition two thermocouples to measure the spine temperature at mid-span.

2.2 Nature of the flow through the permeable surface

Ideally, the effusion flow through the blade surface should be uniform and normal to the surface over a small element of surface however small that element may be. The flow through the wire cloth is not of this nature owing to the finite number of wire strands per inch and the directional influence imposed on the effusion air by the weave of the cloth. As shown in Figure 2 that part of the weave of the cloth which appears on the surface runs in a chordwise direction and tests with water and smoke have indicated that the effusion flow through the wire cloth is of the type illustrated in Figure 2.

A further way in which the test blade departs from the ideal is due to the width of the slot constituting one of the eighteen injection areas. The external chordwise pressure gradient over one of these sections of the blade form periphery is such that the variation of pressure across the width can be many times greater than the pressure drop required to force the air through the permeable material (Figure 2). There is a tendency, therefore, for the mainstream gas to flow through the wire cloth into the cooling air slot in the high pressure region and flow out again mixed with cooling air in the low pressure region all within the width of one slot.

The only way of overcoming this effect is to have continuously varying thickness or permeability of the blade surface which, in the former instance, means having a very low permeability because the maximum thickness of material is limited by the geometry of the blade form. Some information on the permeability of wire cloth relative to other permeable materials is given in Appendix IV.

2.3 High temperature tunnel design

An illustration of the tunnel is shown in Figure 1 and indicates most of the features both of the tunnel and the cascade with the instruments.

The range of operation of the tunnel is between 200°C. and 1000°C. and blade exit Mach numbers of up to 1.0 with approximately atmospheric conditions at outlet. The temperature range from 200°C. to 450°C. is achieved by operation with one combustion chamber unlit. Effective mixing under these conditions is achieved by deflecting the air and gas streams at outlet from the combustion chambers so that the two streams meet in the centre of the mixing box. The success of this method is demonstrated by the temperature and velocity distributions shown in Figure 3. The cascade has eight blade pitches made up of eight water-cooled blades and the test blade, as indicated in Figure 1. The two-dimensional performance data for the impermeable cascade blade adjacent to the test blade is given in Figure 3.

2.4 Instrumentation

Apart from the blade instruments which have already been described, there is provision for motorised upstream and downstream traversing on the centre line of the cascade. Total pressure, temperature and angle measurements can be made at these positions and in addition there are fixed total pressure, static pressure and temperature instruments in the tunnel walls, upstream and downstream.

3.0 Test conditions

The tests of the effusion cooled blade are broadly divided into two parts. For the first part, the blade chordwise temperature distribution at mid-span is maintained uniform under a series of different mainstream test conditions. This is done by control of the cooling air flow rates in the eighteen effusion regions of the blade. For the second part of the series, the effusion is maintained equally divided between the eighteen regions for a similar set of mainstream conditions.

The results of the two parts are in terms of, first, the effusion flow rates required to achieve a uniform temperature distribution and second, the temperature distribution produced by uniform effusion.

The range of mainstream gas temperature is from atmospheric to 1000°C. and blade exit Mach number from 0.4 to 0.95. These combine to give a wide range of Reynolds number, not all of it however, completely free from Mach number effects. The cooling air temperature varies between 20°C. and 40°C. so the complete range of conditions is roughly:-

Re	$1.6 \rightarrow 10 \times 10^5$
T_G/T_C	$1.0 \rightarrow 4.2$
M	$0.4 \rightarrow 0.95$

4.0 Results of investigation

4.1 Theoretical

To provide information necessary for a theoretical analysis, the pressure distribution round one of the cascade blades was obtained at various Mach numbers by means of twenty static pressure tappings in the blade surface. From this distribution the incompressible velocity distribution was calculated and also the slope of the velocity gradients for a number of points on the blade surface. These results are tabulated in Appendix III. Using this information the chordwise temperature distribution for uniform effusion flow and the flow distribution required to achieve uniform surface temperature were calculated according to a method given in both References 1 and 2. Although the actual procedure of calculation is different in References 1 and 2, the two methods are the same in principle and yield very similar results. The principle on which the theory is based is that of approximating the flow over the turbine blade to the flow over a series of wedges, the angle of the wedges corresponding to the rate of change of the velocity at the particular point on the blade surface being considered.

Although the theoretical solution giving the variation in effusion flow required to give uniform blade temperature is generally applicable, the solution for the variation of blade surface temperature with constant effusion flow is true only for a small variation of surface temperature and is therefore, only an approximation in this instance. A further approximation which is made is to assume that the flow in the turbulent region is similar to that over a flat plate and that the Nusselt number in this region is unaffected by the effusion flow into the boundary layer and is therefore, the same as that for an impermeable surface without effusion. There is some evidence to show that the latter assumption is valid but the evidence is not conclusive.

The results of the theoretical work are shown in Figures 10 and 11 and will be discussed in conjunction with the experimental results.

4.2 The temperature distribution and cooling effectiveness of a blade with uniform surface effusion

Uniform effusion over the blade surface corresponds almost exactly to equal distribution of cooling flow to each of the eighteen slots in the spine of the experimental blade except at the leading edge and trailing edge. At these positions, the area of surface supplied individually with cooling air is about twice that at the other positions on the blade. This means, in effect, that if all the cooling air is divided equally between the eighteen effusion regions, the flow per unit blade surface area at the leading and trailing edges will be half that for the rest of the blade. The provision of equal flow for each slot was, however, accepted, because to set the leading and trailing edge flows in the correct ratio so that the flow per unit area of blade surface was uniform over the whole blade surface would have absorbed considerable testing time. Speed of testing was important because of the unknown life of the blade. The effusion flow was therefore uniform over all the blade surface except at the immediate leading and trailing edges where rate of effusion is about half what it should ideally have been.

The results obtained at a gas temperature of 250°C. and over a range of Mach number from 0.4 to 0.95 are shown in Figures 4 and 5. At each of these Mach numbers the variable is the cooling flow ratio, viz., the ratio of total cooling mass flow to the mainstream mass flow through one blade pitch. Against this parameter is plotted the gas outlet flow angle and loss coefficient at mid-span for the effusion blade and the adjacent solid cascade blade respectively. The mean mid-span blade relative temperature is also plotted against cooling flow ratio and is expressed in terms of the ratio of the surface mean blade temperature to the mainstream gas temperature taking the cooling air supply temperature as a zero.

The variation of the effusion cooled blade performance at the various Reynolds or Mach numbers is not great and in each instance the outlet gas flow angle seems to be unaffected by a change in effusion flow. The mid-span blade temperature of the effusion cooled blade is reduced to halfway between the gas and cooling air temperature for flow ratios of $1\frac{1}{2}$ per cent to 2 per cent.

The two-dimensional loss coefficient increases with increase in effusion flow at a rate such that the loss is about double that of the solid blade for between 3 per cent and 4 per cent cooling flow.

The loss coefficient corresponding to a particular effusion flow decreases a little as the temperature of the mainstream is raised from atmosphere to 250°C.

The surface temperature distributions at the mid-span of the blade for these conditions are shown in Figure 5. The general shape is similar throughout, the mean temperature level being a function of the flow ratio. The leading edge temperature is high corresponding to the region of high heat transfer. On the convex surface the temperature then falls and rises again at a position which could be the transition point. Surface marking on the solid water-cooled blades indicate that the transition point is at a position $x/c = 0.7$ measured from the stagnation point on the convex surface, with flow separation just upstream of the trailing edge. The test blade is not, however, so well cooled as the other cascade blades and the effusion flow is likely to cause transition much nearer the leading edge. Evidence suggesting therefore, that the transition point on the effusion blade is at a position $x/c = 0.35$ from the leading edge is not considered unreasonable. It is possible also that the flow separates from the surface before reaching the trailing edge. The surface markings on the concave surface of the solid blades indicate transition at an x/c of 0.7 from the leading edge and this corresponds to the position of a sudden rise in temperature on the concave surface of the permeable blade.

Figures 6 and 7 give similar information to that shown in Figures 4 and 5 but the variable is gas temperature instead of Mach number.

The effect of gas temperature on the relative temperature of the blade is small up to a temperature of 500°C. Above this temperature, the mean blade relative temperature at a particular flow ratio begins to increase. About 90 per cent of this increase can be attributed to the combined effect of radiation to the blade, from the surfaces at gas temperature upstream and downstream of the cascade and radiation from the test blade to the water-cooled blades in the cascade. The assumptions made to calculate the radiation are that the emissivity of all surfaces is 0.8 and that the blade receives heat from the tunnel surfaces (assumed to be at gas temperature) in the 'axial' direction and radiates to the cooler cascade blades in the 'circumferential' direction. The effective areas are taken to be the projected areas in each instance. This approximate correction to the relative temperature of the test blade is plotted in Figure 6 and indicates that the majority of the effect of increasing gas temperature is due to radiation from the surrounding surfaces.

The effect of high gas temperature, other than radiation, can be calculated by the method given in Reference 1. There is a tendency for the blade relative temperature to decrease with an increase of gas to cooling air temperature ratio but the effect is small.

As in Figure 5 the temperature distribution graphs on Figure 7 indicate that if there is boundary layer transition on the concave surface of the blade at $^x/_c$ = 0.7 the effect of it becomes more abrupt at the higher temperatures.

The temperature distribution curves show the position of a local failure of the brazed joint between the wire cloth and the blade spine at 770°C. The failure occurred towards the blade tip on the convex surface, so allowing the majority of the cooling air to pass chordwise and out at the trailing edge instead of passing through the permeable surface.

4.3 The effusion distribution and cooling effectiveness of a blade with uniform surface temperature

Figure 9 shows the flow distribution needed in the blade to achieve a uniform blade surface temperature at various Mach numbers. The temperatures are those measured by the thermocouples in the middle of each effusion flow area at centre span. The blade relative temperature, loss coefficient and outlet angle under these conditions of effusion flow are shown in Figure 8. Here again, the effect of Reynolds number and Mach number upon the cooling performance is not large. The effusion flow has little effect upon the gas outlet angle but produces an increase in loss coefficient to about the same extent as for the uniform effusion conditions shown in Figure 4. From Figure 9 it is clear that a large cooling flow is required at the leading edge of the blade. This curve of flow falls fairly rapidly away from the leading edge but increases again at distances 0.35 of the chord and 0.7 of the chord away from the leading edge on convex and concave surfaces respectively. The increase in effusion flow needed at these points is attributed to transition of the boundary layer from laminar to turbulent flow. In the turbulent region the flow requirement increases with an increase in Reynolds number as predicted theoretically and discussed further in Section 4.4

The large effusion flow required at the blade leading edge is probably greater than the ideal requirement for the following reason. The thermocouple which indicates the temperature of the leading edge effusion region is positioned near the stagnation point. This is the point of maximum heat transfer and maximum external pressure. The leading edge is supplied with cooling air at a constant pressure, so if the stagnation point is to be cooled to the required value, the other parts of the leading edge will be over-cooled, firstly because of the lower external pressure on the blade surface and secondly because of the lower heat transfer coefficients away from the stagnation point. The film-cooling properties of the excess of cooling air at the leading edge probably accounts for the fact that little or no cooling air is required for the effusion area directly downstream of the leading edge, on the convex surface of the blade.

4.4 Comparison with theory

For that part of the boundary layer flow which is laminar, References 1 and 2 give methods for finding theoretically the variation in effusion flow required to maintain constant surface temperature over the aerofoil. In Reference 2 an assumption is made which enables a solution to be obtained for the effusion requirement in the turbulent region. The assumptions are that the friction coefficients are the same as those for a flat plate with turbulent flow and that the Nusselt number is unchanged by effusion in this region and remains the same as that for an impermeable surface. The effusion requirements are, it is said, overestimated in this way by an unknown but probably small amount.

A solution is also given for the surface temperature variation produced by a uniform effusion flow over the surface but this is only a very approximate result unless the variations in surface temperature are very small compared with the difference between gas and cooling air temperature.

The theoretical results are presented in Figures 10 and 11. The upper graph shows the Nusselt number variation with and without effusion flow assuming transition at $x/c = 0.35$ from the leading edge on the convex surface and at $x/c = 0.7$ on the concave surface. It will be noted that sudden transition is assumed, whereas in practice transition probably takes place over a finite distance. The middle graph in Figure 10 shows the theoretical effusion flow quantities required to produce a uniform blade temperature which is halfway between gas and cooling air temperature at Reynolds number 1×10^5 and 5×10^5 respectively. This result is compared with the experimental distribution at a Reynolds number of 3.7×10^5. The effusion flow required is greater than predicted in the leading edge region and very much less than predicted in the turbulent region on the convex surface. These two inconsistencies combine to produce fair agreement between theory and experiment on the overall performance as shown in the lower graph. However, the assumptions made concerning the effusion flow requirement in the turbulent region and the assumption of immediate transition are both unrealistic by an unknown amount and it does not seem that a general agreement between theory and practice can be argued from this particular case.

The same can be said for the agreement between the theoretical and experimental temperature distributions and mean temperature for uniform effusion flow shown in Figure 11.

Considering the laminar flow regions only, it is this region in which theory and experimental results might be expected to agree reasonably well. The flow to produce a uniform temperature and the temperature for uniform effusion are both higher than predicted. There are two possible reasons for this. The first is that the effusion flow through the woven wire cloth is not the ideal homogeneous effusion flow normal to the surface assumed in the theoretical treatment and the effect of this non-homogeneity upon the conditions of growth and shape of the boundary layer represents an unknown factor. The second reason is associated with the limited number of independent cooling flow areas in the test blade. The pressure gradient over the blade surface is large compared with the pressure drop of the cooling flow in passing through the permeable surface. The effusion flow is not therefore uniform in the chordwise direction over the width of one of the cooling areas into which the test blade is divided. This is particularly true at the leading edge and as already described in the last paragraph of Section 4.3, it is at this position that the practical limitation results in the injection of excess of cooling air in order to cool the thermocouple at the stagnation point down to the required level

In the turbulent region the cooling air requirement is very much less than estimated theoretically. The theory is based on the assumption of Reynolds analogy and friction coefficients for flow over an impermeable flat plate. The effects of surface pressure gradient and effusion flow on the blade are not therefore considered. The validity otherwise of these assumptions, has yet to be investigated, but comparing the simplified theory with the experimental results, the mean Nusselt number in the turbulent region is only about half the predicted value.

4.5 The effect of local effusion on blade temperature

Figure 12 shows the chordwise temperature distribution over the blade achieved by effusion of a fixed quantity of air at individual cooling regions over the convex and concave surfaces of the blade. The test was intended to show the extent of the film cooling effect downstream of an injection position and also the most economical position at which to introduce cooling air on a film-cooled blade or blade in which the effusion is only local. The curves of Figure 12 show that the rate of increase in temperature downstream of an effusion region is generally fairly rapid. The gradient of this part of the curve tends to increase as the point of injection moves from the leading edge to the trailing edge. This would suggest that film-cooling is more persistent when the air is injected near the leading edge.

The mean blade temperatures under these conditions of local injection are shown in the lower graph on Figure 12. The two curves indicate that the most economical position for local injection is just downstream of the leading edge. An effusion flow of ½ per cent at this position reduces the mean blade relative temperature to 0.7. The effectiveness of local effusion is a function of both the persistence of film cooling effect downstream of the injection point and the Nusselt number at the point of injection itself. For most blade designs, therefore, there is probably an optimum point somewhere between the leading edge, where the heat transfer coefficient is high and the trailing edge, where film cooling can have no effect.

4.6 Blade spine temperatures

Figure 13 shows the blade spine temperatures measured at mid-span at the one third and two third chord positions indicated in the figure. The temperatures are plotted in the same non-dimensional terms as for the blade surface temperatures in Figures 4 and 6 and were in fact, obtained simultaneously with the results presented in these two figures.

At a gas temperature of 250°C., the spine temperatures are very much lower than the equivalent blade surface temperatures, but as the gas temperature increases, the spine relative temperature also increases, probably because of radiation from the wire cloth to the blade spine. If this is so, the effect should be diminished by an increase in Reynolds number because at the higher Reynolds numbers, the heat transferred to the spine by radiation will be a smaller proportion of the heat quantities being transferred by convection.

The fact that spine temperatures are much lower than the surface temperatures represents a considerable advantage which this type of blade has over those types in which the cooling process is distributed over the whole section of the blade. It means that the spine which would carry the bending and centrifugal loads on the blade is maintained cool and the permeable blade surface, which is at a higher temperature and has structurally a lower mechanical strength is carried by this cool spine.

4.7 Comparison with an internally air cooled blade

The cooling effectiveness of the effusion cooled blade is compared with that of a solid passage cooled blade in the upper half of Figure 14. The passage-cooled blade is that reported in Reference 4 and the mass mean temperature of this rotor blade in a cascade tunnel and in a turbine is compared with the surface temperature of the effusion cooled nozzle blade. The lower spine temperature of the effusion blade is not considered since its value probably depends on the detailed construction of the blade.

Considering the mean cooling of the effusion blade under conditions of uniform temperature and uniform effusion flow, the effectiveness is about equivalent to that of the passage cooled blade in the cascade and better than that for the passage cooled blade in a turbine. It is not known if a turbine rotor test of the effusion blade would reveal the same difference in performance as for the solid blade but it can be said that the figure reveals no outstanding advantage to be gained by effusion cooling in this particular way. Other points of comparison are considered in Section 6.0.

4.8 Effusion at constant pressure

The lower half of Figure 15 shows the big increase in blade loss coefficient and poor cooling achieved by effusion through a simple shell form of permeable material. The material was in this instance porous bronze 1/16 inch thick with a permeability of ($\alpha = 60 \times 10^{-10}$) and of the same shape as the cascade blades. The supply pressure was maintained at a level sufficient to pass the required total quantity of cooling flow but there was no control over the distribution of the effusion flow around the blade surface. Under these conditions the pressure drop through the permeable material was small compared with the pressure variation round the blade itself and mainstream gas flowed into the blade in the high pressure regions and flowed out into the mainstream mixed with cooling air in the low pressure regions. This probably accounts for the high loss coefficients and the poor cooling performance.

5.0 Mechanical strength and blockage of pores

The effusion cooled blade for the major part of the testing was constructed from a mild steel spine with stainless steel woven wire cloth brazed to it as shown in Figure 1. The brazing material was 'Colmonoy' and the process was carried out in an inert atmosphere at a temperature of 1120°C.

The blade failed at a temperature of 770°C. and the failure took the form of a separation of the wire cloth from the spine in the region of the brazed joint. It is possible that the failure was due to oxidation of the mild steel near the brazed joint and not failure of the brazed joint itself. The region of failure was, however, limited and a substantial part of the structure remained intact even after several hours running with a gas temperature of over 1000°C.

Measurements of the permeability of the wire cloth both before testing began and on completion of the whole test series revealed no evidence of blockage of the wire cloth by particles in the mainstream flow. The cooling air was dried with Silica Gel particles and filtered with a 'Porosint' porous bronze element with a pore size of about 0.0001 in. It is unlikely therefore, that particles of sufficient size to block the wire cloth were carried in cooling flow and no experience was gained on possible blockage using unfiltered atmospheric air.

6.0 Practical application of effusion cooling

The problems associated with effusion cooling which were expected from the theoretical analysis and emphasised by the test are, first, the importance of the pressure variation around the blade section and second the dependence of cooling effectiveness on the position of the transition region. As described in Section 4.3 the limitation of the number of independently controllable effusion regions probably accounts for the excess of cooling air over that theoretically predicted in the laminar flow region at the leading edge of the blade. The solution to this problem is either the use of variable permeability material or variable thickness material matched to the pressure distribution round the particular blade section being considered.

The permeability or thickness variation must also be matched to the effusion flow requirements in both laminar and turbulent flow regions on the blade surface. This is probably calculable in the laminar region but there is evidence to suggest that relative to the simplified theory, the heat transfer rates in the turbulent region are reduced by effusion and do not remain about the same as for an impermeable surface as suggested in Reference 5. Under these circumstances, the effusion flow required to achieve a particular cooling effect in the turbulent region would be less than those predicted, assuming the heat transfer coefficients of an impermeable surface.

If a design of permeable blade was contemplated in which the cooling air was supplied to a single cavity inside the blade, the pressure drop available for effusion flow would be a maximum near the trailing edge. The geometry of the blade imposes a limit on the thickness of material at this position, so the permeability to give the correct effusion flow would need to be very low. A permeability value (see Appendix IV) of the order of 5 x 10⁻ would be needed, which is only one sixth of the permeability of the woven wire cloth. The pore size under these conditions will be small and the blockage of the pores by particles carried in the cooling air will probably become a significant problem.

Supplying air to the blade at three or four different pressures by throttling would reduce the difficulties associated with the required variation in permeability or thickness but by no means remove them.

7.0 Conclusions

An investigation of the chordwise effusion flow required to maintain a turbine nozzle blade at a uniform temperature and the temperature distribution produced on the blade by uniform chordwise effusion has been made over a wide range of Reynolds number, temperature and Mach number. These experimental results are compared with theoretical predictions based on the most reasonable possible assumption in the light of past experience

The conclusions reached are that in the laminar flow region of the blade surface boundary layer the effusion cooling required is greater than that predicted theoretically and at least part of this effect is attributed to the limited number of individually controllable effusion regions.

The non-homogeneity of the effusion flow through the woven wire cloth is a possible cause of early transition on the blade convex surface and the position of the transition point could possibly be moved back towards the trailing edge if a homogeneous effusion could be produced.

When the cooling flow distribution is adjusted to give uniform surface temperature, the mean blade surface temperature is slightly lower than when the same total quantity of cooling air is effused at a uniform rate over the blade surface.

A decrease in cooling effectiveness at temperatures above 500°C. is attributed to radiation from the surfaces upstream and downstream of the cascade and at a gas temperature of 1000°C., the cooling effect is reduced by 20 per cent.

Compared with cascade tests on a passage cooled blade, the cooling of the effusion blade surface is very little better. On the other hand, the spine to which the permeable material is attached to form the nozzle blade has a much lower temperature, which, although presenting some differential expansion problems, may constitute a significant advantage for this type of construction.

The value of the blade loss coefficient at mid-span increases linearly with the cooling flow ratio, the loss coefficient being approximately twice the value for a similar impermeable blade when the cooling flow ratio is approximately 3 per cent.

From the foregoing conclusions, it seems that an improvement in overall effusion cooling performance might be obtained if (a) the effusion flow could be varied smoothly round the surface rather than in a few distinct chordwise steps, and (b) the porous skin had a greater number of smaller, more uniformly distributed pores so that the effusion flow would be more homogeneous and less likely to create early transition to turbulence in the boundary layer. Unless a blade meets these requirements, the present tests suggest that, if mean surface temperature is accepted as a criterion, then the effusion cooling shows little advantage in economy of cooling air over a good internally air cooled blade. Further tests are desirable to substantiate these views.

For a practical design of effusion cooled blade to meet the above requirements, the biggest foreseeable design problem arises from the large variation of external pressure round the blade section. To successfully introduce effusion cooling flow into the blade surface boundary layer against these pressures in the required quantities almost certainly involves the use of variable thickness permeable material or variable permeability with uniform thickness. The permeability under these circumstances will need to be very low, of the order of 5×10^{10}, and although this is an advantage from the point of view of mechanical strength, the blockage of the pores by particles carried in the cooling air may become a significant problem.

No blockage of the stainless steel wire cloth occurred during the whole test series and the failure of the brazed joint between the wire cloth and the blade spine was probably due to oxidation of the mild steel spine in the region of the brazed joint

REFERENCES

No.	Author(s)	Title
1	E. R. G. Eckert J. N. B. Livingood	Method for the calculation of heat transfer in the laminar region of air flow around cylinders of arbitrary cross section. NACA Tech. Note 2733. Lewis Flt. Prop. Laboratory, June, 1952.
2	R. Staniforth	A theoretical note on effusion cooled gas turbine blades. N.G.T.E. Memorandum No.M.158. C.P. No. 165. October, 1952,
3	T. W. F. Brown	The affect of the radiation correction on cooling loss in high temperature cooled gas turbines. Proceedings I. Mech. E. General discussion on heat transfer 1951.
4	D. G. Ainley	Research on the performance of a type of internally air cooled turbine blade Proceeding I. Mech. E. Vol.167, No.4, 1953.
5	P. Duwez H. L. Wheeler	Experimental study of cooling by infiltration of a fluid through a porous metal. Journal of Aeronautical Sciences, Vol.15, No.9, September, 1948.

APPENDIX I

List of Symbols

c	blade chord
x	distance along blade surface from stagnation point
α_1	gas inlet angle measured from the axial direction
α_2	gas outlet angle measured from the axial direction
$\overline{\omega}$	mean total pressure loss in passing through the cascade
V_1	inlet velocity to the cascade
V_2	outlet velocity from the cascade
m	cooling air mass flow
M	mainstream mass flow through one blade pitch
q	cooling mass flow per unit area per second
Q	mainstream mass flow per unit area per second
T_G	total gas temperature
T_B	blade surface temperature
$T_{\overline{B}}$	mean blade surface temperature
T_C	cooling air temperature
θ_{V_2}	temperature equivalent of outlet velocity
T_G'	effective gas temperature $(T_G - 0.14\ \theta_V)$
Mn	Mach number
Nu	Nusselt number
Re	Reynolds number $\rho \frac{V_2 C}{\mu}$
α	permeability defined in Appendix IV
P_t	total pressure
P_s	static pressure

APPENDIX II

Summary of experimental results

EQUAL PASSAGE EFFUSION FLOW

Mn	Re x 10^{-5}	Temp. °C.	n/Ms	Blade relative temperature: Concave surface	Blade relative temperature: Convex surface	Loss effusion cooled	Loss reference blade	α_2 effusion cooled	α_2 reference blade
0.42	5.21	28	1.66	-	-	0.069	0.038	-	-
0.43	5.45	30	1.02	-	-	0.066	0.037	-	-
0.43	5.32	28	0.80	-	-	0.059	0.036	-	-
0.41	5.00	26	0.83	-	-	0.061	0.039	-	-
0.41	5.12	25	0.81	-	-	0.063	0.036	63.3	63.9
0.41	5.14	27	0.41	-	-	0.059	0.035	63.5	63.6
0.42	5.17	26	1.04	-	-	0.064	0.037	63.3	63.4
0.42	5.20	26	1.60	-	-	0.074	0.038	64.0	64.1
0.42	5.39	21	2.72	-	-	0.088	0.039	63.1	63.9
0.43	5.45	22	2.15	-	-	0.080	0.038	63.2	64.0
0.43	2.64	252	3.23	0.336	0.533	0.078	0.029	63.4	64.3
0.44	2.69	252	1.60	0.339	0.531	0.060	0.031	63.4	64.5
0.44	2.70	248	2.46			0.070	0.048	63.2	64.2
0.43	2.66	248	2.57	0.404	0.400	0.072	0.046	63.0	64.2
0.44	2.72	243	1.07	0.639	0.635	0.055	0.046	63.0	64.2
0.44	2.77	242	0.54	0.807	0.803	0.049	0.046	63.6	64.2
0.60	7.45	27	0.90	-	-	0.069	0.042	63.1	63.9
0.60	7.47	27	0.70	-	-	0.065	0.040	63.2	63.9
0.61	7.49	29	0.35	-	-	0.063	0.042	63.3	64.0
0.61	7.49	28	1.60	-	-	0.076	0.040	63.2	64.0
0.61	7.50	29	2.10	-	-	0.081	0.041	63.3	64.1
0.61	7.44	30	2.80	-	-	0.090	0.042	63.2	64.0
0.62	3.75	253	3.40	0.313	0.298	0.082	0.046	63.1	64.0
0.62	3.79	253	2.41	0.412	0.389	0.071	0.046	62.9	64.0
0.63	3.81	253	1.68	0.522	0.483	0.064	0.046	62.8	63.9
0.61	3.72	253	1.35	0.573	0.529	0.059	0.043	62.9	64.0
0.61	3.73	248	0.78	0.708	0.697	0.053	0.043	63.1	64.1
0.74	8.35	26	1.71	-	-	0.080	0.036	63.6	64.9
0.75	8.37	27	1.19	-	-	0.075	0.038	63.6	64.8
0.74	5.90	118	2.30	-	-	0.084	0.040	63.8	65.0
0.72	5.76	121	0.52	-	-	0.065	0.038	63.8	65.0
0.75	4.25	251	2.76	0.363	0.392	0.087	0.037	63.8	65.0
0.75	6.00	253	1.45	0.582	0.552	0.064	0.042	63.4	64.4
0.75	5.99	257	1.02	0.683	0.671	0.062	0.041	63.4	64.5
0.73	6.02	256	0.52	0.802	0.822	0.056		63.6	
0.82	2.63	544	2.00	0.470	0.477	0.073	0.048	63.2	64.8
0.82	2.63	543	3.34	0.318	0.342	0.088	0.047	62.8	64.9
0.81	2.59	552	1.18	0.575	0.583	0.064	0.043	62.8	64.8
0.79	2.11	730	1.73	0.512	0.560	-	-	-	-
0.80	2.03	773	3.27	0.417	0.434	-	-	-	-
0.80	2.01	776	1.54	0.613	0.689	-	-	-	-
0.80	2.01	776	2.69	0.483	0.600	-	-	-	-
0.80	2.00	781	1.10	0.690	0.766	-	-	-	-
0.76	1.88	777	2.18	0.487	0.595	-	-	-	-
0.78	1.60	976	2.46	0.539	0.710	-	-	-	-
0.78	1.61	985	4.10	0.418	0.618	-	-	-	-
0.91	11.39	12	0.75	-	-	0.072	0.071	63.6	63.8
0.94	9.69	62		-	-	0.091	-	65.0	-
0.97	7.99	117	0.94	-	-	0.075	0.055	63.8	64.8
0.94	8.10	105	1.53	-	-	0.084	0.051	63.8	64.8
0.93	8.29	100	1.27	-	-	0.083	0.056	64.2	64.8
0.93	7.60	125	1.86	-	-	0.080	0.056	63.9	64.7
0.91	4.80	289	1.18	0.575	0.550	0.071	0.061	63.8	65.1
0.88	4.50	308	0.76	0.696	0.690	0.068	0.035	64.1	65.3
0.93	5.29	271	2.08	0.461	0.420	0.082	0.090	63.5	65.4
0.93	5.25	273	1.52	0.557	0.530	0.078	0.087	63.6	64.8

APPENDIX II

CONSTANT TEMPERATURE

Mn	Re x 10^{-5}	Temp. °C. Tc	m/M%	Blade relative temperature: Concave surface	Blade relative temperature: Convex surface	Loss effusion cooled	Loss reference blade	α_2 effusion cooled	α_2 reference blade
0.42	2.57	258	1.28	0.580	0.560	0.056	0.037	63.4	64.4
0.41	2.57	248	1.66	0.505	0.500	0.058	0.037	63.5	64.5
0.39	2.50	251	2.54	0.375	0.380	0.068	0.039	63.6	64.7
0.60	3.70	257	1.20	0.590	0.580	0.057	0.040	63.5	64.1
0.60	3.77	254	0.95	0.670	0.670	0.055	0.036	63.4	64.4
0.61	3.68	249	1.63	0.500	0.490	0.060	0.045	62.9	63.8
0.61	3.76	248	0.56	0.770	0.770	0.050	0.047	63.0	64.0
0.75	5.70	232	0.58	0.827	0.799	0.056	0.048	63.5	64.6
0.75	4.20	261	1.18	0.550	0.540	0.069	0.038	63.8	65.0
0.75	4.34	253	0.89	0.691	0.660	0.062	0.058	63.4	64.6
0.76	4.47	240	1.12	0.605	0.596	0.065	0.058	63.4	64.5
0.79	2.79	504	1.25	0.614	0.571	0.070	0.041	63.8	64.6
0.78	2.72	512	0.88	0.721	0.680	0.068	0.040	64.0	64.5
0.78	2.82	493	1.26	0.611	0.576	0.073	0.037	63.9	65.1
0.79	1.98	774	1.95	0.670	0.630	-	-	-	-
0.79	2.00	762	1.68	0.620	0.640	-	-	-	-
0.95	5.92	237	0.94	0.693	0.645	0.081	0.091	63.6	65.4

APPENDIX III

The static pressure distribution over the blade surface at Mn 0.24 and 0.58

Convex surface Mn 0.24

x/c	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
$\frac{P_{s_x}-P_{s_2}}{P_{t_2}-P_{s_2}}$	0.45	0.20	0.08	0.02	0	-0.03	-0.07	-0.14	-0.24	-0.31
x/c	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
$\frac{P_{s_x}-P_{s_2}}{P_{t_2}-P_{s_2}}$	-0.35	-0.36	-0.37	-0.35	-0.32	-0.28	-0.24	-0.22	-0.18	-0.14

Concave surface Mn 0.24

x/c	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45
$\frac{P_{s_x}-P_{s_2}}{P_{t_2}-P_{s_2}}$	0.87	0.85	0.84	0.83	0.81	0.77	0.68	0.60	0.59
x/c	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90
$\frac{P_{s_x}-P_{s_2}}{P_{t_2}-P_{s_2}}$	0.58	0.51	0.43	0.40	0.37	0.31	0.22	0.19	0.17

Convex surface Mn 0.58

x/c	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
$\frac{P_{s_x}-P_{s_2}}{P_{t_2}-P_{s_2}}$	0.51	0.34	0.22	0.16	0.12	0.09	0.03	-0.04	-0.015	-0.26
x/c	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
$\frac{P_{s_x}-P_{s_2}}{P_{t_2}-P_{s_2}}$	-0.32	-0.33	-0.35	-0.33	-0.30	-0.27	-0.23	-0.18	-0.15	-0.13

Concave surface Mn 0.58

x/c	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45
$\frac{P_{s_x}-P_{s_2}}{P_{t_2}-P_{s_2}}$	0.93	0.90	0.88	0.86	0.84	0.81	0.76	0.67	0.66
x/c	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90
$\frac{P_{s_x}-P_{s_2}}{P_{t_2}-P_{s_2}}$	0.65	0.59	0.50	0.46	0.43	0.37	0.27	0.24	0.21

APPENDIX III (cont'd.)

The incompressible velocity distribution over the blade surface and the slope of the velocity distribution curve.

Velocity distribution - Convex surface

x/c	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
V/V_2	0.630	0.843	0.909	0.945	0.966	0.985	1.012	1.045	1.094	1.15
$\frac{d(V/V_2)}{d(x/c)}$	5.1	2.2	1.0	0.52	0.38	0.46	0.58	0.78	1.2	0.74

x/c	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95
V/V_2	1.172	1.18	1.181	1.175	1.163	1.144	1.116	1.091	1.075
$\frac{d(V/V_2)}{d(x/c)}$	0.32	0.06	-0.04	-0.20	-0.32	-0.46	-0.54	-0.66	-0.26

Velocity distribution - Concave surface

x/c	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45
V/V_2	0.28	0.326	0.351	0.377	0.404	0.435	0.471	0.510	0.554
$\frac{d(V/V_2)}{d(x/c)}$	1.44	0.50	0.52	0.52	0.58	0.66	0.78	0.80	0.88

x/c	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85
V/V_2	0.601	0.652	0.710	0.752	0.783	0.816	0.855	0.877
$\frac{d(V/V_2)}{dx/c}$	1.0	1.1	1.06	0.70	0.64	0.70	0.64	0.36

APPENDIX III (cont'd.)

Distance of spine ribs from the stagnation point.

Convex surface

Rib number	1	2	3	4	5	6	7	8	9
Distance from stagnation point	0.284	0.532	0.76	0.98	1.19	1.404	1.628	1.822	2.02

Concave surface

Rib number	1	2	3	4	5	6	7	8	9
Distance from stagnation point	0.16	0.376	0.594	0.800	1.004	1.218	1.416	1.618	1.812

Width of ribs - 0.030 in.

APPENDIX IV

Permeability data for woven wire cloth and other permeable materials

$$\text{Permeability} = \frac{\text{Mass flow}}{\text{Surface area}} \frac{\mu}{\rho} \frac{t}{\Delta P}$$

where t is the thickness of the material and ΔP the pressure drop of the fluid passing through the material.

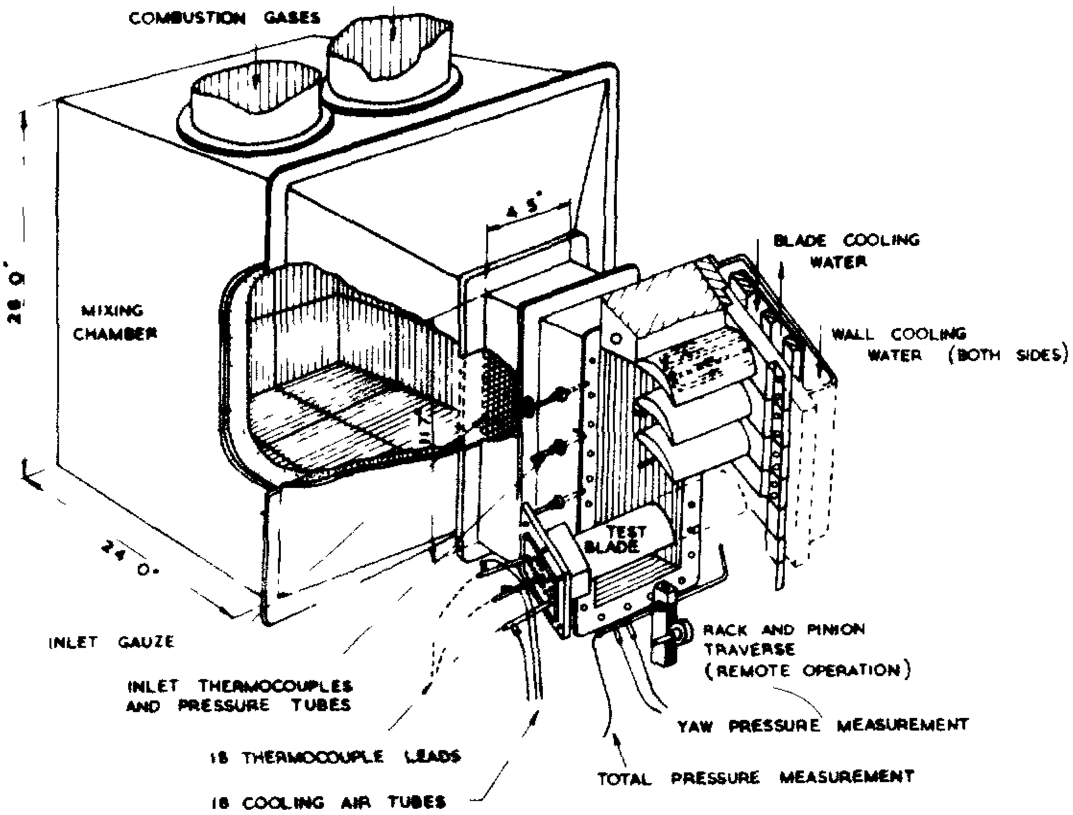
The following are the permeability values obtained by tests of the material atpressure drop of one pound per square inch and at atmospheric temperature.

Woven wire cloth (Hollander cloth)		30×10^{-10} sq.ft.
Sintered bronze (Porosint)	Grade A	20×10^{-10} sq.ft.
	Grade B	60×10^{-10} sq.ft.
	Grade C	210×10^{-10} sq.ft.

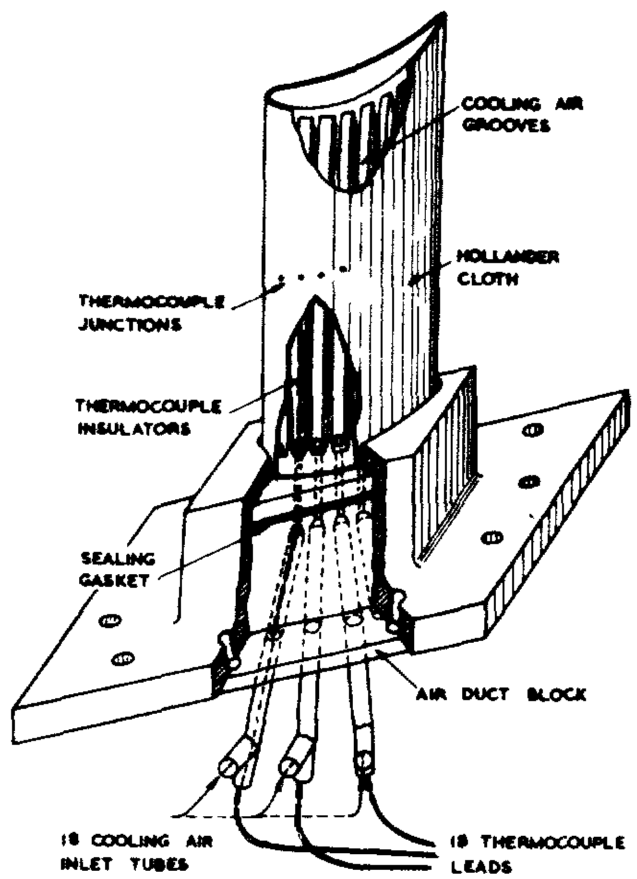
The permeability figures indicate the comparative qualities of the materials but since the nature of the effusion flow through the pores is affected both by their size and configuration the relation between pressure drop and flow at atmospheric temperature is:-

	Thickness	Pore size	Particle size	ΔP 1.0	10	100 in. H_2O
Porosint A	0.017 in.	0.0001 in.	0.0019 in.	0.010	0.10	0.94 lb./sec.sq.ft.
Porosint C	0.017 in.	0.0005 in.	0.0045 in.	0.11	0.76	1.54 lb./sec.sq.ft.
Hollander cloth	0.017 in.	-	0.0020 in.	0.020	0.118	0.67 lb./sec.sq.ft.

FIG. 1

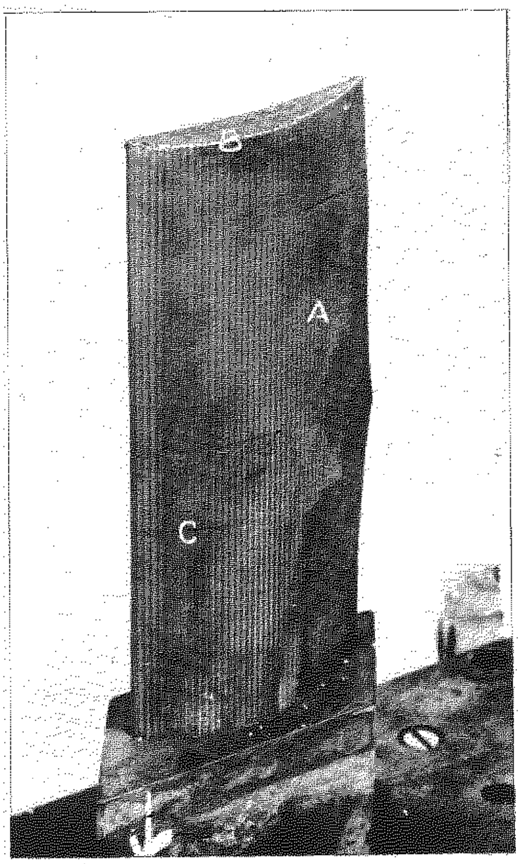


HIGH TEMPERATURE CASCADE TUNNEL



EFFUSION COOLING TEST BLADE

FIG. 2

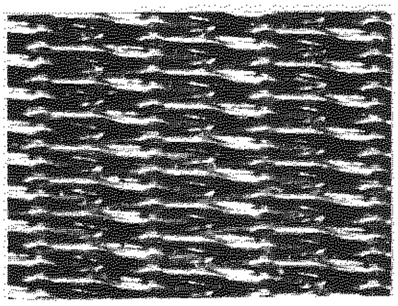


A AREA OF FAILURE OF BRAZED JOINT.

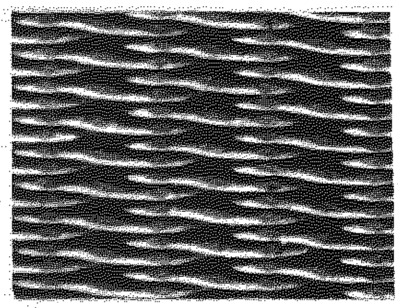
B FAILURE AT BLADE TIP.

C SEPARATION OF WIRE STRANDS.

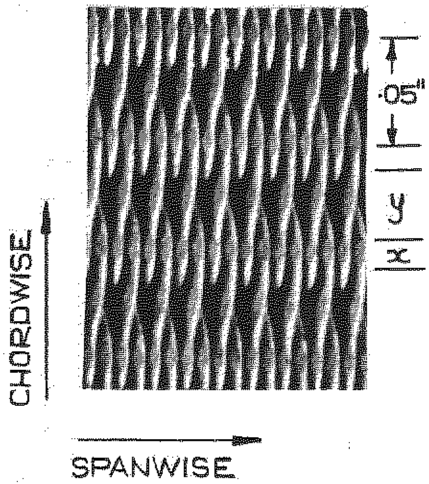
PERMEABLE BLADE ON COMPLETION OF TEST SHOWING POSITION OF JOINT FAILURES



WIRE CLOTH BEFORE TESTING (X 12)

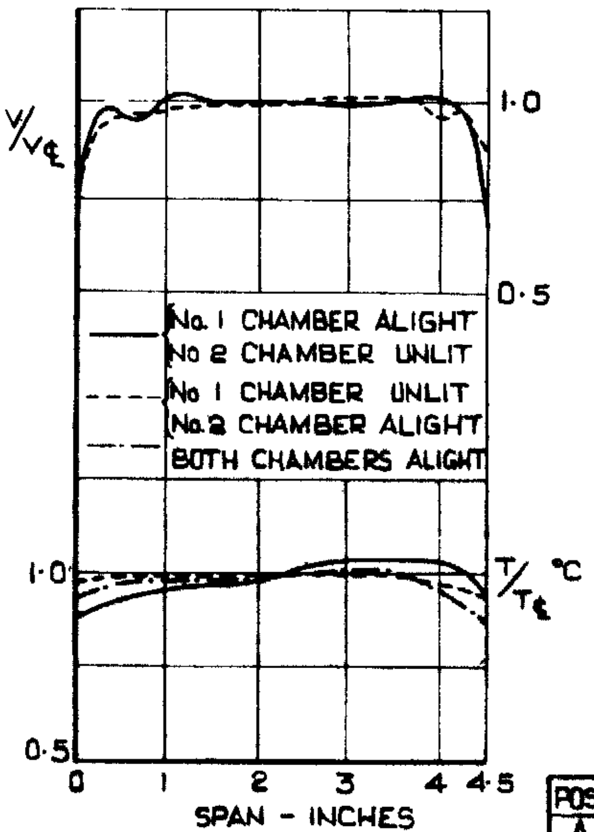


WIRE CLOTH AFTER TESTING (X 12)

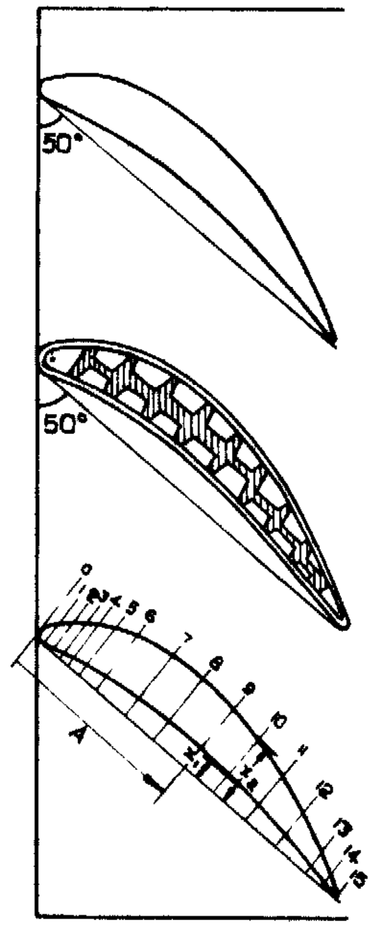


TESTS ON THE NATURE OF THE EFFUSION FLOW THROUGH THE WIRE CLOTH INDICATE THAT THERE IS NO FLOW IN THE REGIONS X AND FLOW APPROXIMATELY NORMAL TO THE SURFACE IN THE REGIONS y

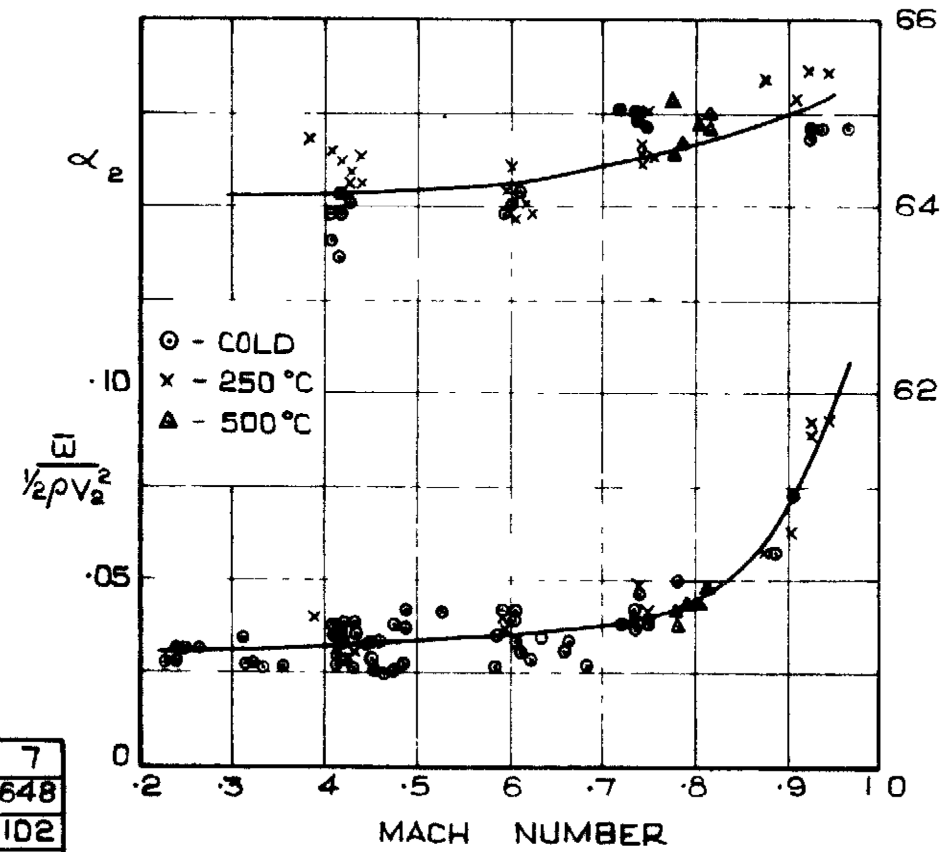
CASCADE DATA



SPANWISE VELOCITY AND TEMPERATURE PROFILE AT INLET TO THE CASCADE.



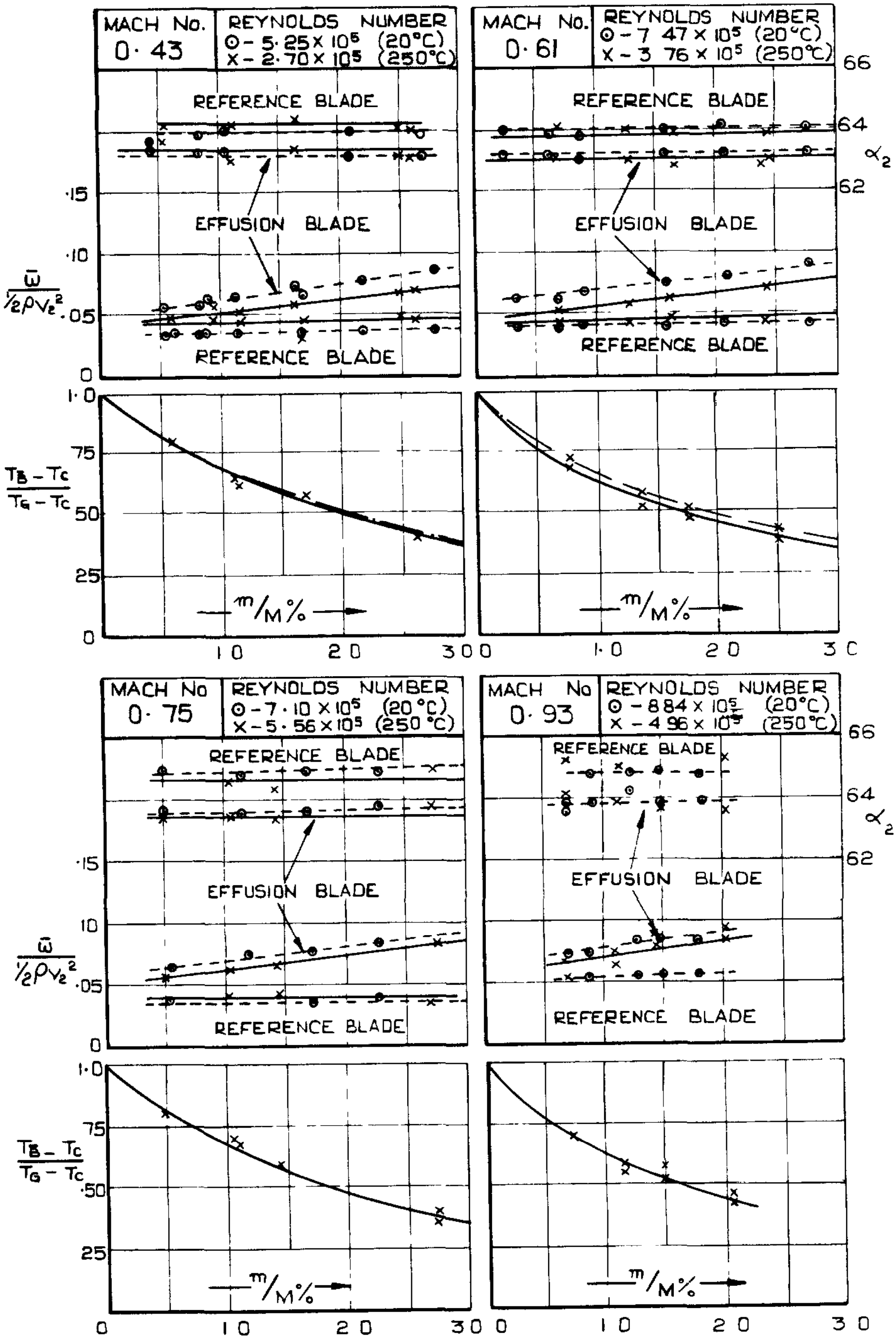
POSⁿ	0	1	2	3	4	5	6	7
A	0	·054	·108	·162	·216	·324	·432	·648
x_1	·030	·005	·012	·022	·032	·057	077	·102
x_2	·030	·130	·190	·234	·271	327	·370	·420
POSⁿ	8	9	10	11	12	13	14	15
A	·864	1·08	1·296	1·512	1·728	1·944	2·054	2 162
x_1	·113	·111	·102	·090	·070	·037	·020	0
x_2	·428	·412	·370	·303	·216	·115	·058	0



OUTLET ANGLES AND LOSS COEFFICIENTS FOR CASCADE BLADE.

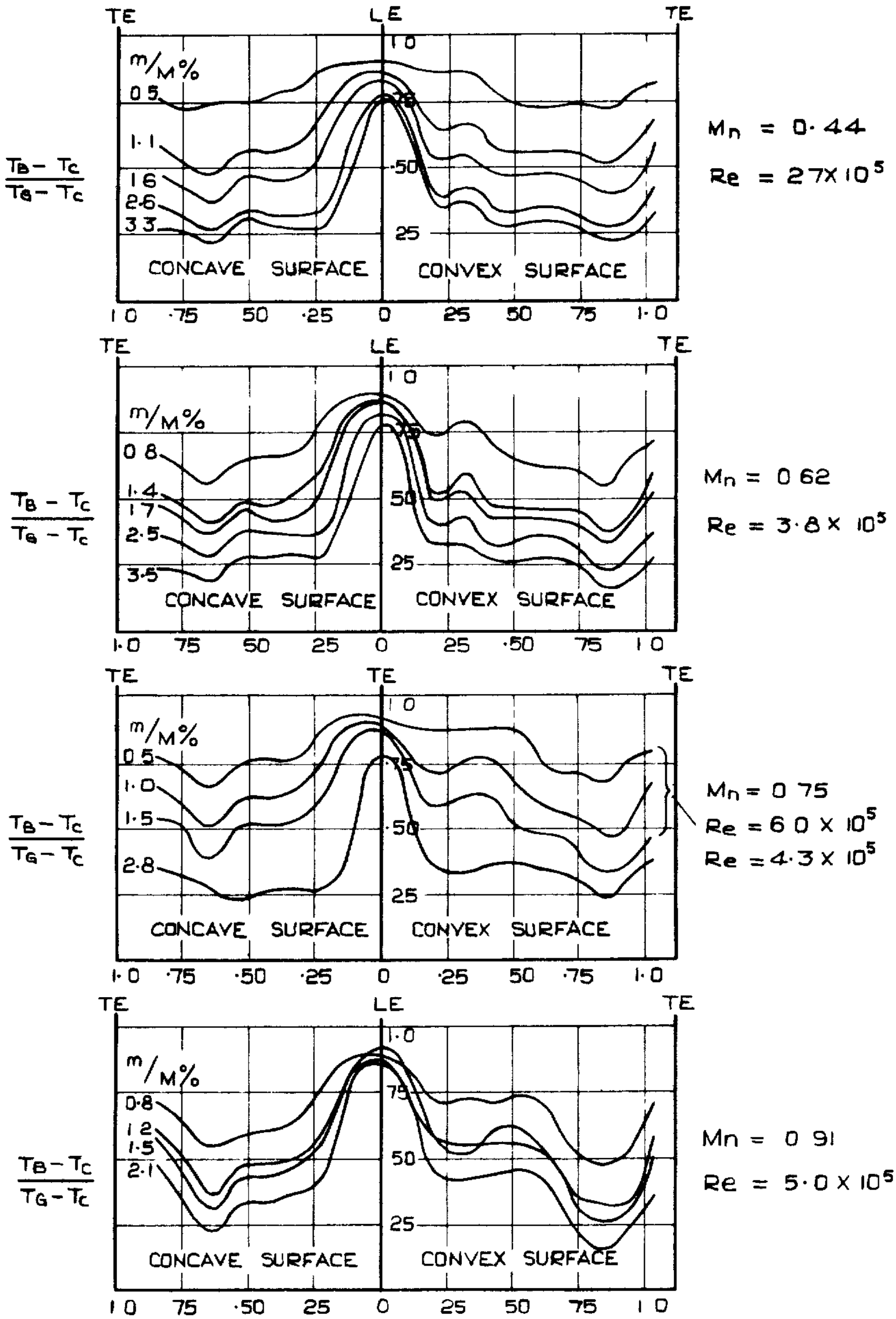
FIG. 3

FIG. 4



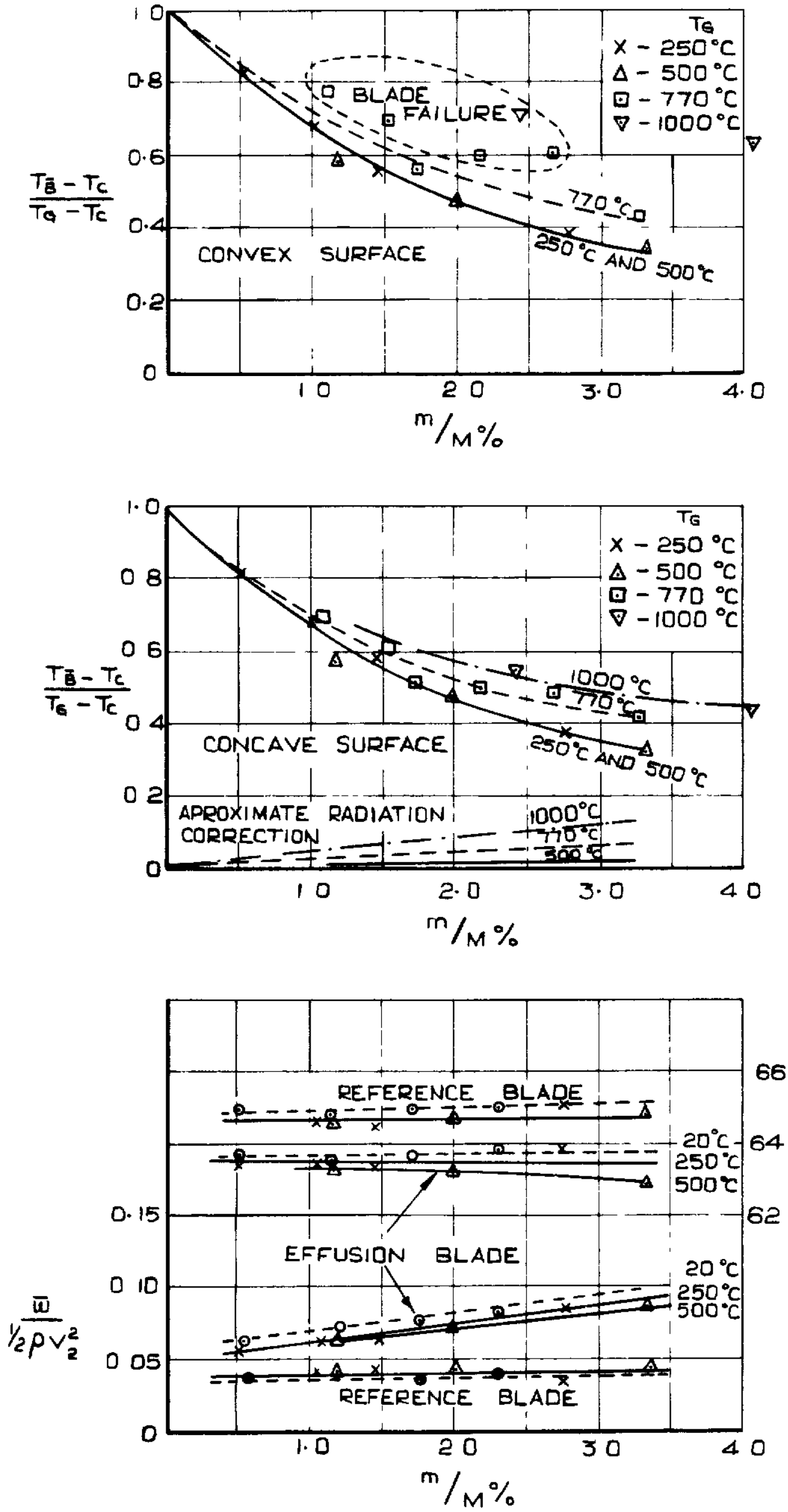
VARIATION OF TEMPERATURE RATIO, LOSS COEFFICIENT AND OUTLET ANGLE WITH EFFUSION FLOW (UNIFORM EFFUSION)

FIG. 5



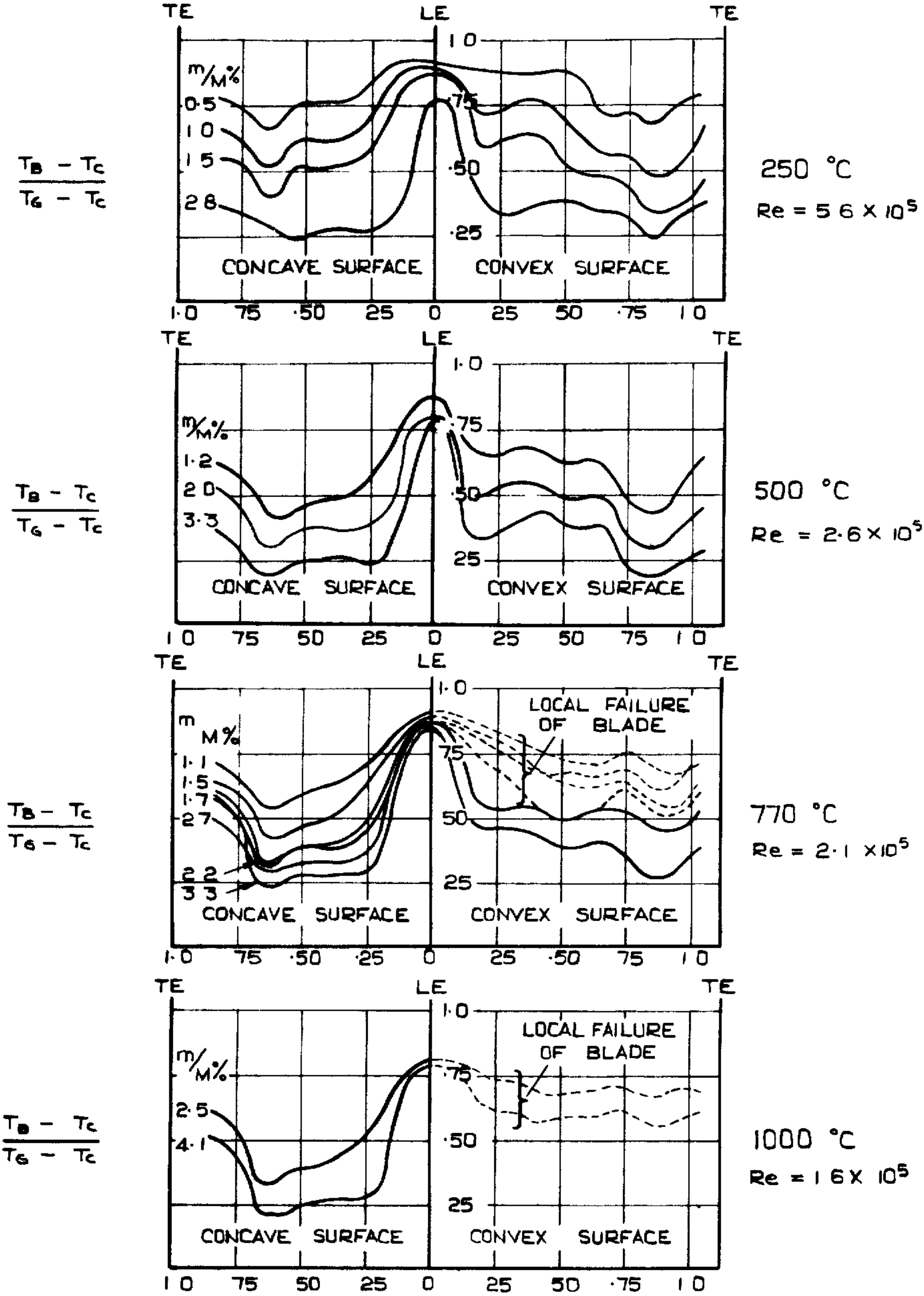
BLADE CHORDWISE TEMPERATURE DISTRIBUTION (UNIFORM EFFUSION)

FIG. 6



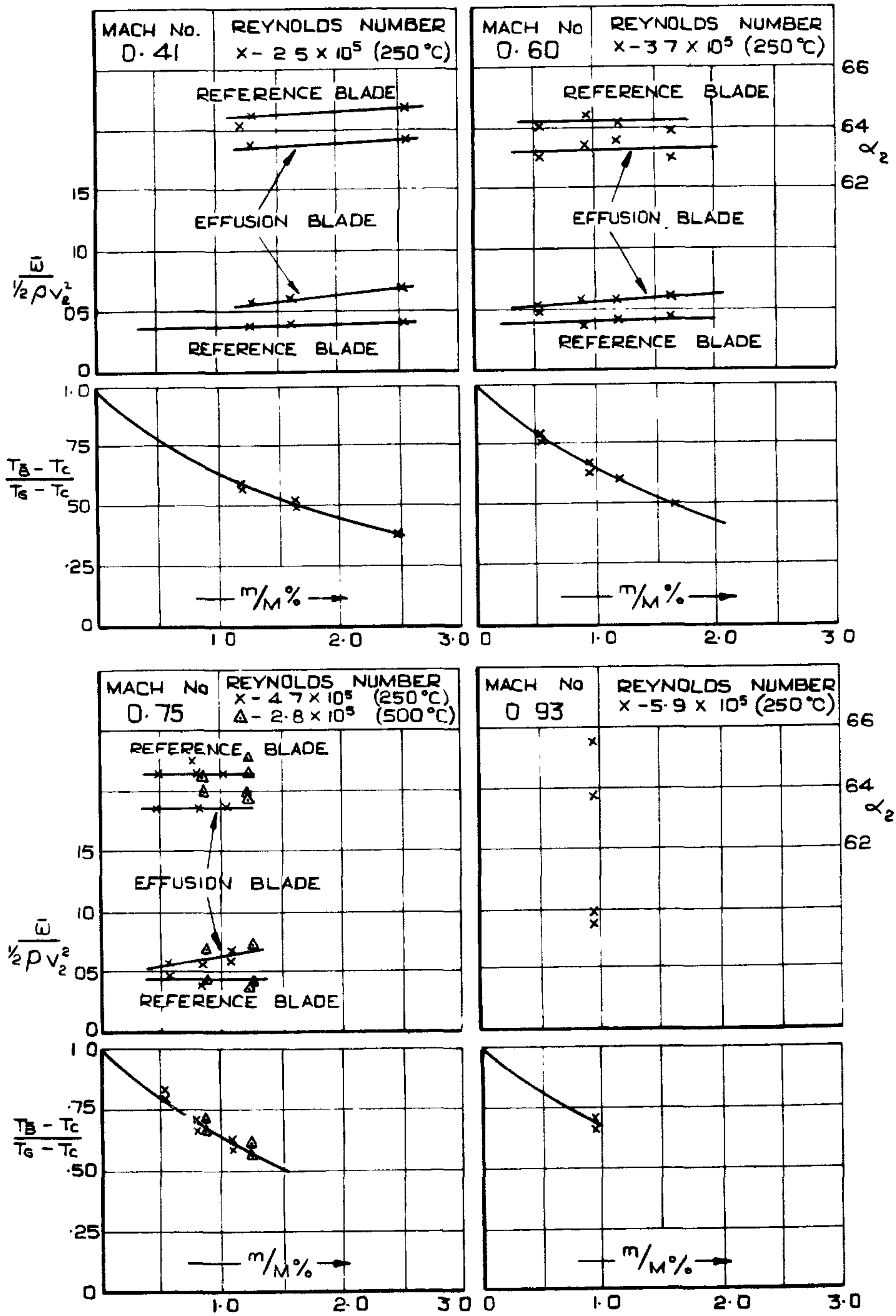
THE EFFECT OF TEMPERATURE ON BLADE TEMPERATURE RATIO, LOSS AND OUTLET ANGLE AT M_N=0·75 (UNIFORM EFFUSION)

FIG. 7.



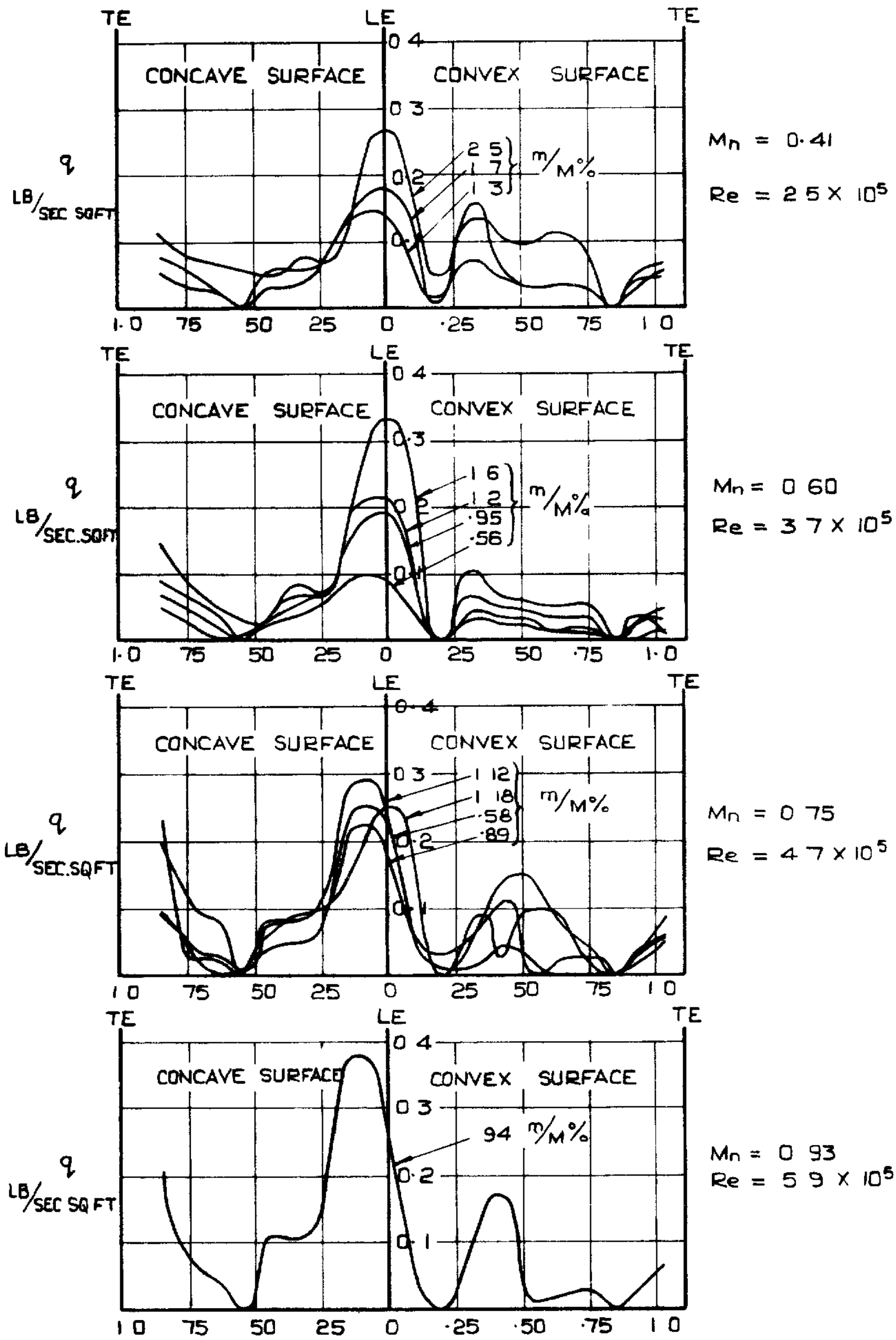
THE EFFECT OF TEMPERATURE ON BLADE CHORDWISE TEMPERATURE DISTRIBUTION. (UNIFORM EFFUSION)

FIG. 8



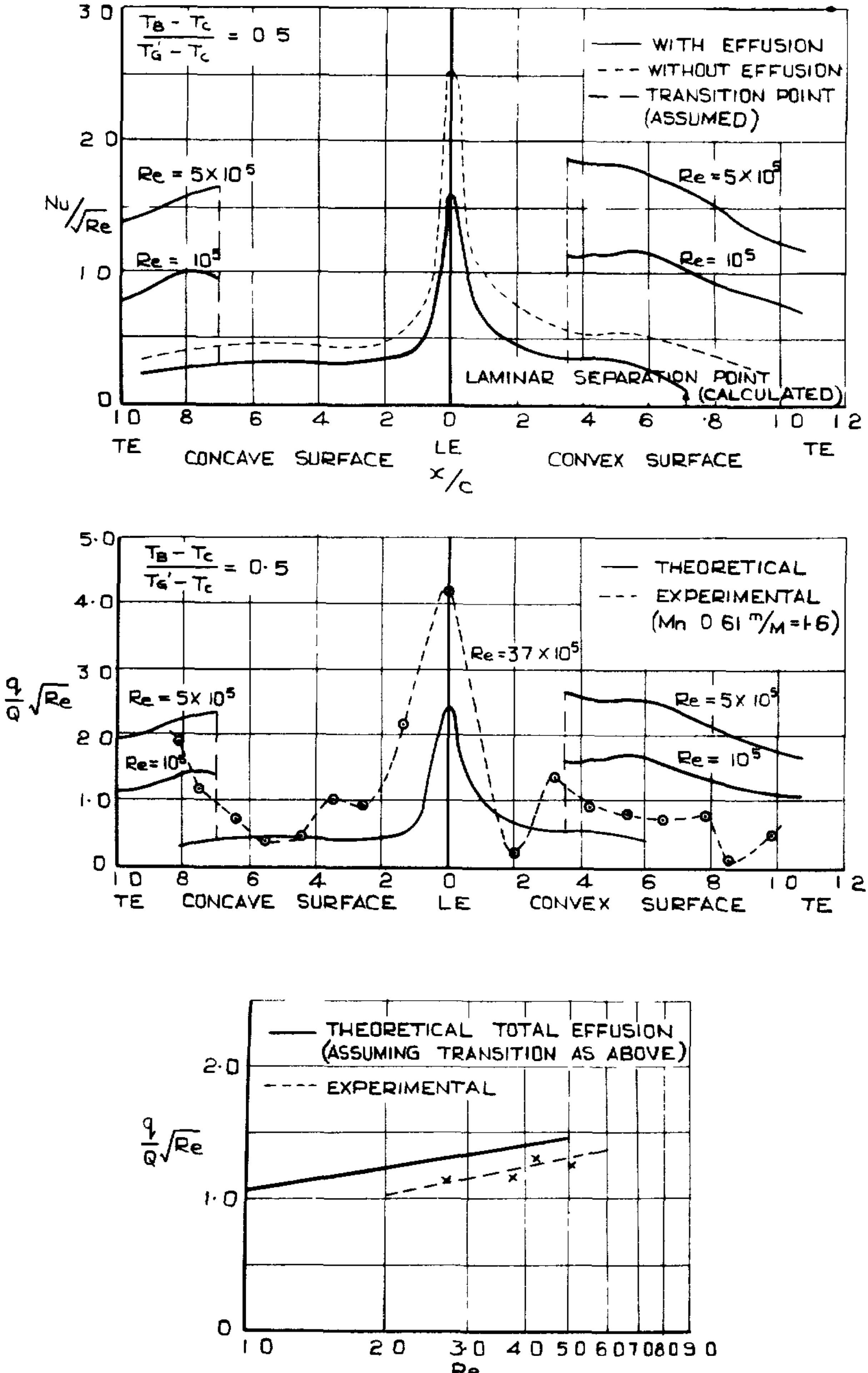
VARIATION OF TEMPERATURE RATIO, LOSS COEFFICIENT AND OUTLET ANGLE WITH EFFUSION FLOW (UNIFORM TEMPERATURE)

FIG. 9



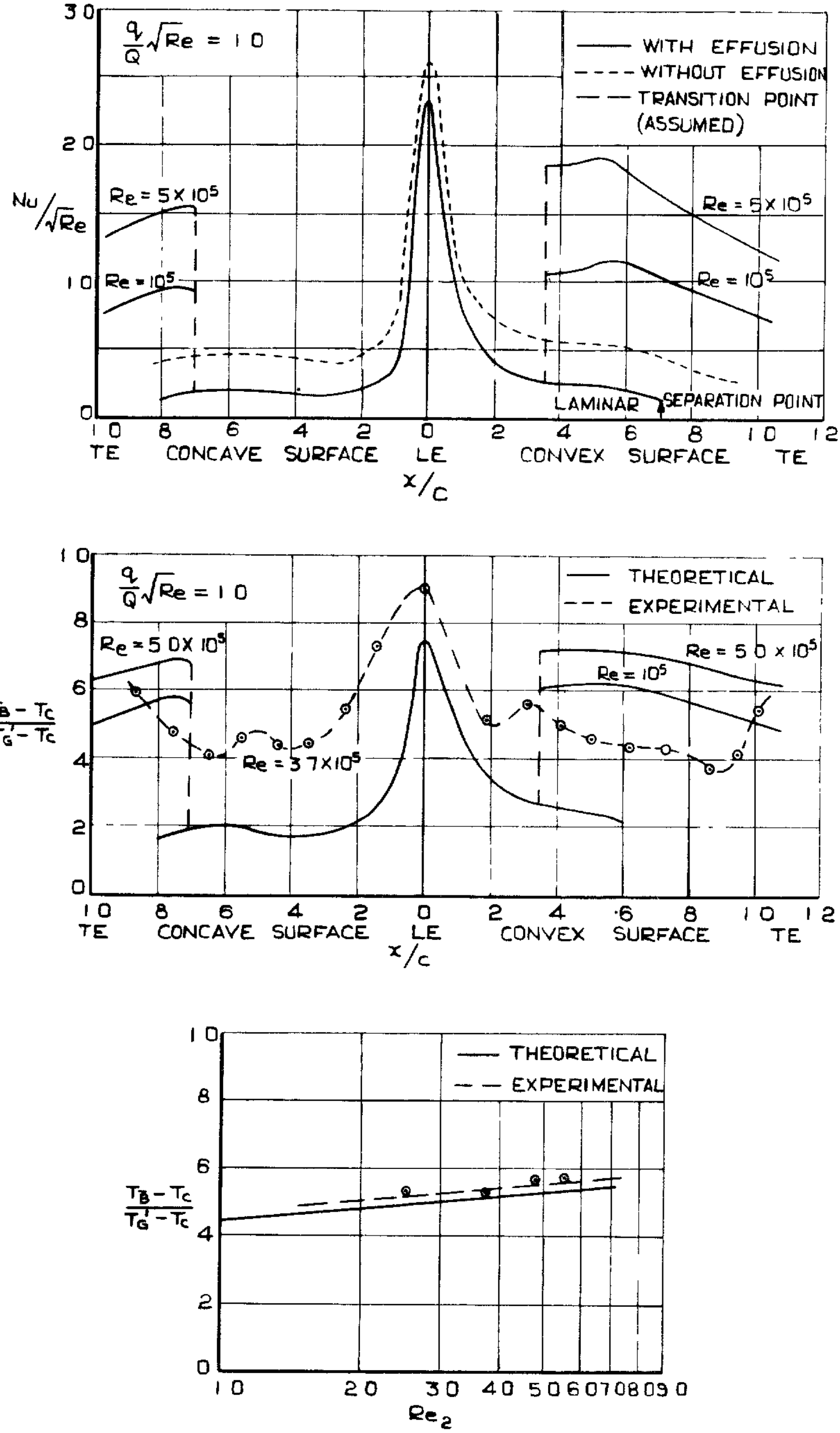
BLADE CHORDWISE FLOW DISTRIBUTION
(UNIFORM TEMPERATURE)

FIG. 10.



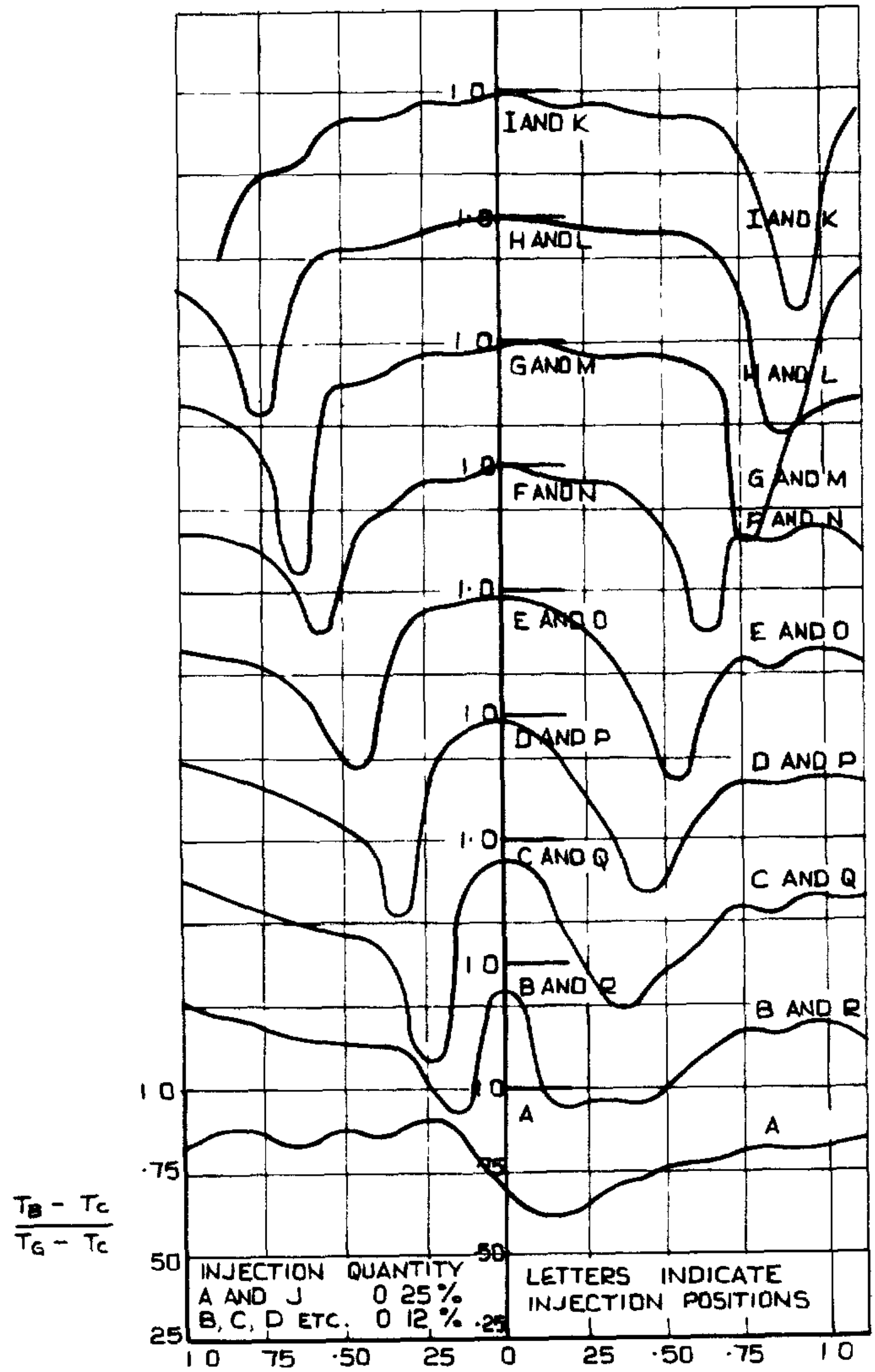
THEORETICAL AND EXPERIMENTAL EFFUSION FLOW REQUIRED TO GIVE A UNIFORM CHORDWISE BLADE TEMP $\frac{T_B - T_C}{T_G - T_C} = 0.5$

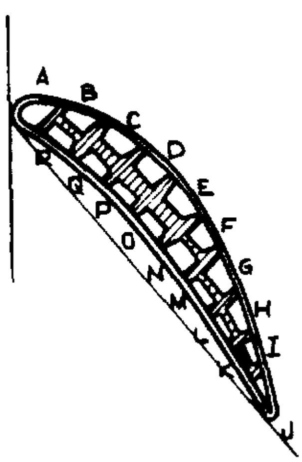
FIG. 11

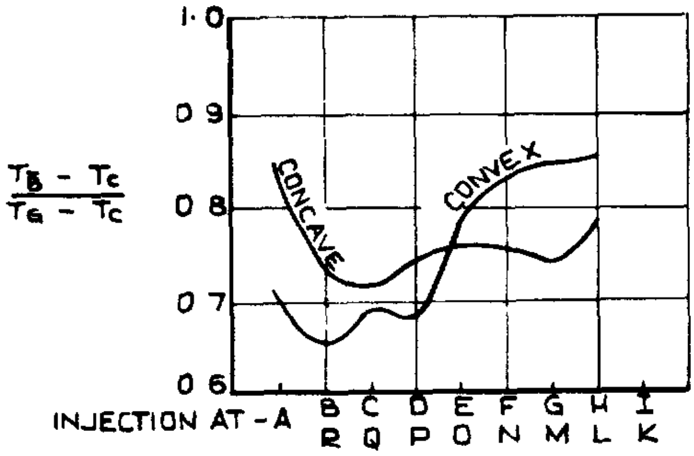


THEORETICAL AND EXPERIMENTAL TEMPERATURE DISTRIBUTION PRODUCED BY UNIFORM SURFACE EFFUSION ($\frac{q}{Q}\sqrt{Re}=1$)

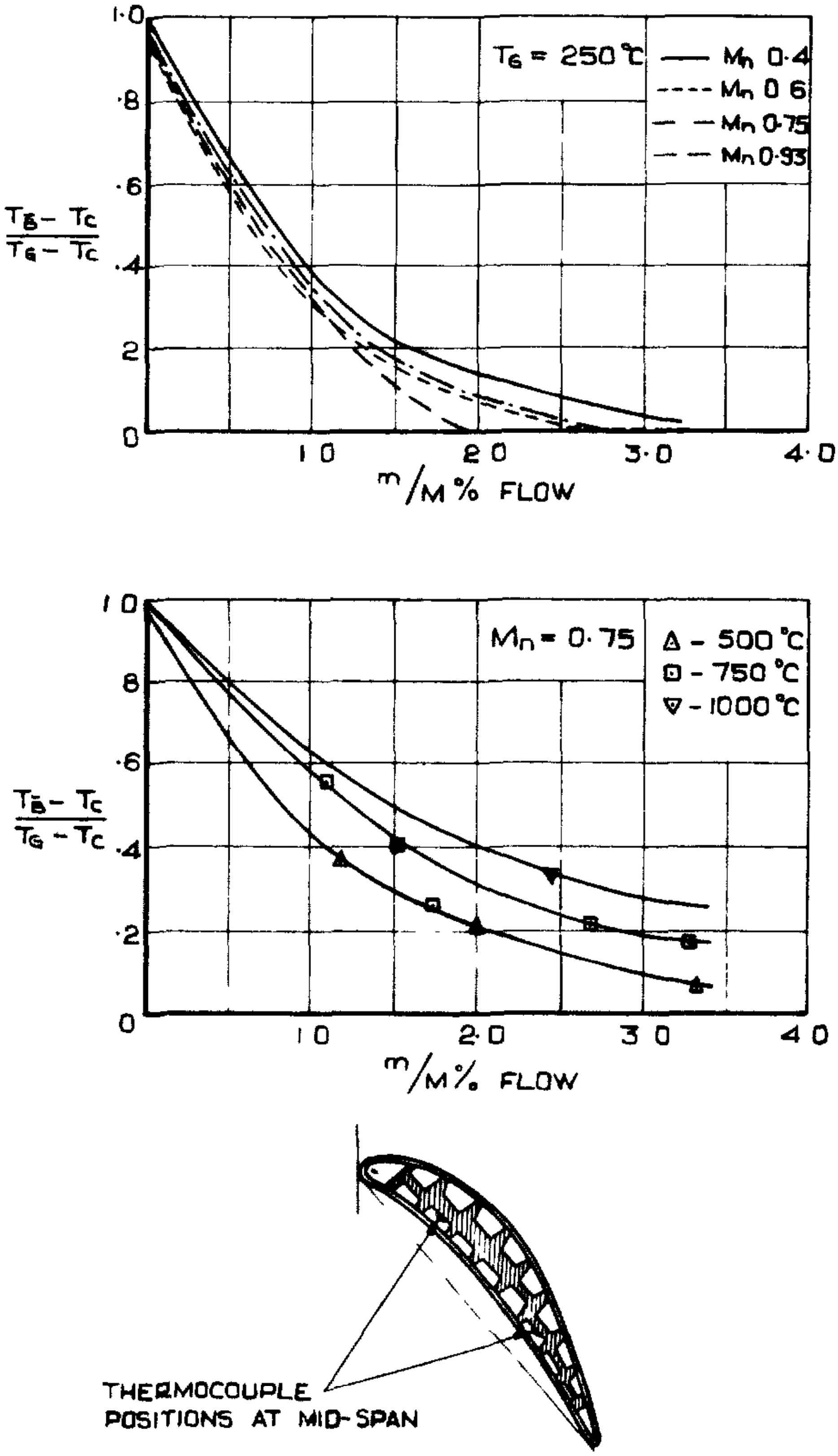
FIG. 12.





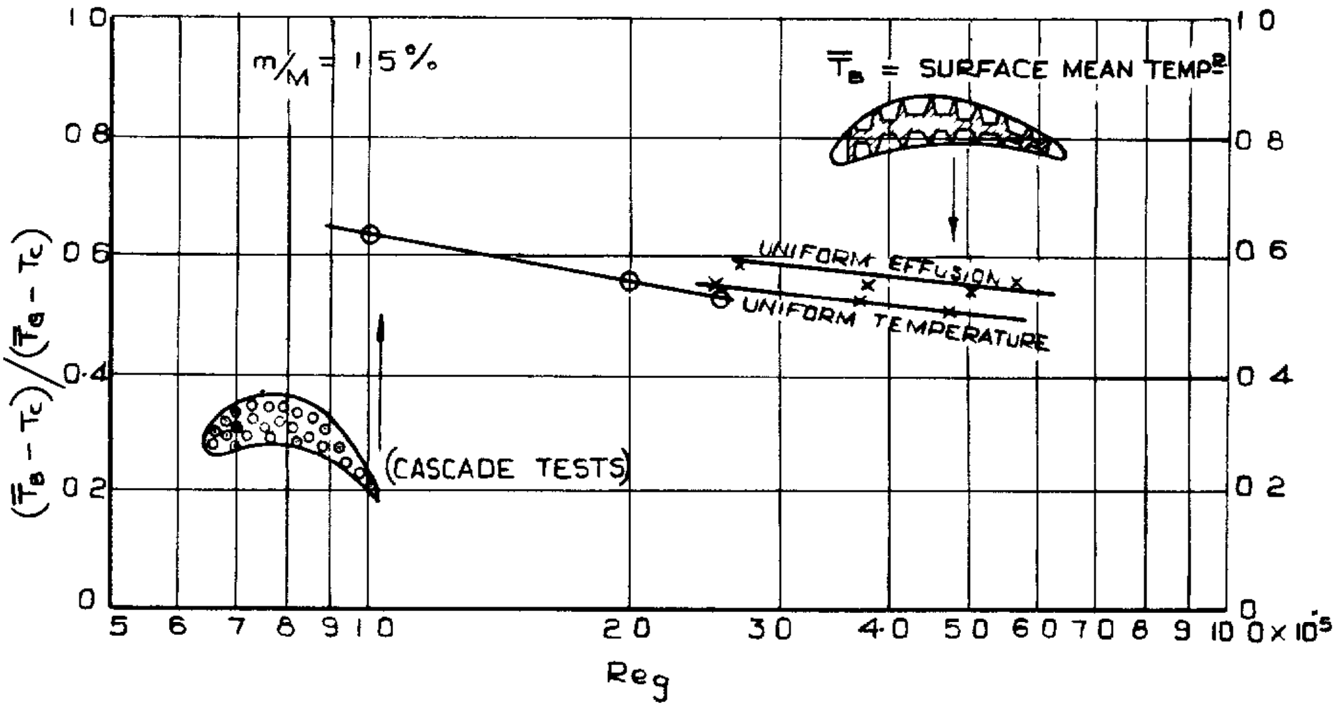


THE EFFECT OF LOCAL INJECTION ON LOCAL AND MEAN BLADE TEMPERATURE.

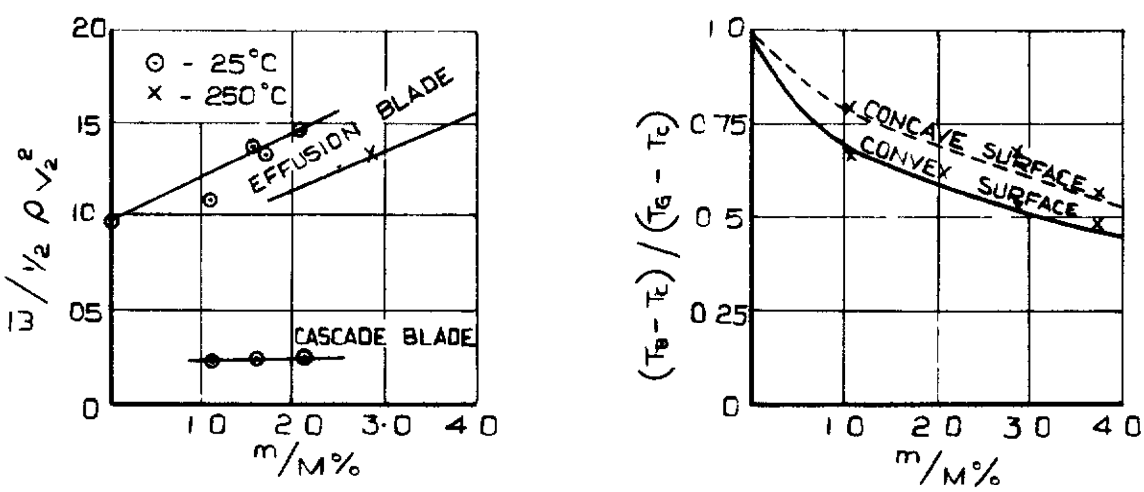


BLADE SPINE TEMPERATURES
UNIFORM EFFUSION

FIG. 14



COMPARISON OF EFFUSION AND PASSAGE COOLING EFFECTIVENESS.



BLADE SURFACE, PERMEABLE BRONZE

NO EFFECTIVE SEAL BETWEEN BLADE SPINE AND PERMEABLE SURFACE

ARROWS INDICATE PROBABLE MAINSTREAM GAS FLOW

THE EFFECT OF EFFUSION THROUGH A SIMPLE PERMEABLE SHELL.

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