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Technical Evaluation Report on AGARD Technical Meeting

on

High Temperature Turbines

by

J.B. Esgar and R.A. Reynolds

NORTH ATLANTIC TREATY ORGANIZATION

DISTRIBUTION AND AVAILABILITY ON BACK COVER

TECHNICAL EVALUATION REPORT

on

AGARD TECHNICAL MEETING

on

"HIGH TEMPERATURE TURBINES"

by

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CONTENTS

The Proceedings of the Propulsion and Energetics Panel 36th Meeting, which was held at the Scuola di Guerra Aerea, Florence, Italy, from 21 to 25 September 1970, are published as AGARD Conference Proceedings No. 73.

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Published February 1971

621.438

Printed by Technical Editing and Reproduction Ltd
Harford House, 7-9 Charlotte St, London. W1P 1HD

I. INTRODUCTION

The 36th meeting of the Propulsion and Energetics Panel of the NATO Advisory Group for Aerospace Research and Development was held at the Scuola di Guerra Aerea in Florence, Italy from 21 to 25 September, 1970. The program, which was arranged by a committee under the Chairmanship of Ing. Principal M. Pianko, was devoted to the subject of high temperature turbines.

This topic was chosen by the P.E.P. and the timing of the meeting was most appropriate. Because of the continuing demand by the aircraft designer for engines that weigh less and, at the same time provide more thrust, the maximum cycle temperature at which aircraft gas turbines are designed to operate is increasing as rapidly as the technology of high temperature materials and blade cooling will allow. Practically all types of aircraft gas turbines are now designed for turbine inlet temperatures such that turbine blade cooling is an absolute requirement. In fact, in the higher temperature engines the heat fluxes are such that the simple convection cooling methods which have been used in the past are no longer adequate and they must be supplemented by more effective techniques such as film or possibly transpiration cooling. Another new development is the application of cooling in very small engines. Here the cooling problems become more formidable because of the difficult compromise which must be made in the selection of blade chords which are large enough to permit the provision of adequate cooling passages and yet which are not so large as to severely affect the aerodynamic performance of the blade row. Thus, since virtually all new aircraft gas turbine engine designs will incorporate blade cooling, this meeting provided useful and timely opportunities for the high temperature turbine specialists of the various NATO countries to exchange ideas and information.

The balance of the subject matter covered by the papers given at the meeting was reasonably good. Some observers felt that too much emphasis was put on the theory and fundamentals of blade cooling at the expense of more discussion of the application of theory to practice. However, it must be remembered that the meeting was unclassified and this, plus commercial considerations relating to proprietary information, would prohibit the inclusion of papers concerning the most advanced practical work which is underway.

The first paper of the meeting by Alesi* set the stage for those that followed by reviewing the improvements in cycle performance that can be obtained by going to higher turbine inlet temperatures. The remaining papers, which were organized in such a way as to provide a degree of variety, covered the following topics:-

- a review of the factors affecting the heat transfer processes involved in convection, film and transpiration cooling and an evaluation of the effectiveness of these cooling techniques
- the problems involved in cooling small turbines
- the practical problems involved in the application of turbine blade cooling to engines
- metallurgical problems to be considered in the selection of high temperature and cooled turbine materials
- heat transfer measurement techniques

It was quite fitting that a large proportion of the papers presented dealt with film and transpiration cooling since, though these cooling methods have not been extensively used in practice as yet, it is clear that they are going to become increasingly important in the future as turbine inlet temperatures continue to rise.

II. GENERAL REMARKS

There were thirty-two papers given at the meeting since three of the originally scheduled papers had been withdrawn. All but three of the papers which were presented can be divided into the five general categories mentioned in the Introduction and in this report the papers will be discussed under each of these categories. The three miscellaneous papers, which do not fit neatly into this grouping will be dealt with first.

As mentioned previously, the first paper of the conference by Alesi(1) presented a review of the improvements in cycle performance that can be obtained as design point compressor pressure ratios and turbine inlet temperatures are increased. This type of cycle analysis is, of course, not new to those involved in the design and use of gas turbine engines but the paper served as a useful introduction for the meeting as it focused attention on the importance of continuing the effort to achieve higher turbine operating temperatures.

While the great majority of the papers presented at this conference were devoted to discussions of the currently applicable state-of-the-art of high temperature turbine technology, Esgar, in his paper(14), discussed both the limitations and the potential of the available air cooling methods as well as the problems involved in liquid cooling particularly if the engine fuel is used as a heat sink. It was pointed out that since very nearly the maximum possible gains have now been made using conventional convection cooling techniques, the next significant step in the achievement of higher turbine inlet temperatures will involve the use of full coverage film cooling or transpiration cooling. Esgar mentions, however, that further substantial gains could still be obtained with convection cooling if the temperature of the cooling air supply could be reduced and if improved materials, capable of operating at higher temperatures, become available.

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* Numbers in parentheses refer to the papers listed at the end of this report.

Richens (33) departed from the normal pattern in his paper in which he discussed the general philosophy of a development program involving an advanced engine. It is necessary to resolve the high risk areas and demonstrate the feasibility of advanced components as early as possible in the development cycle before the large sums which are involved in a full engineering development program are committed. This paper was useful as it gave the delegates an insight to the overall problems involved in an engine development program from the point of view of a contracting agency.

III. TURBINE BLADE HEAT TRANSFER DATA AND CALCULATIONS

One third of all the papers given at the five-day meeting concerned the acquisition of heat transfer data and the use of this data in carrying out meaningful calculations of gas turbine blade temperatures. All of the major cooling methods - convection, film and transpiration air cooling, liquid and liquid metal cooling - were discussed. The papers relating to convection cooling included (2), (3), (16) and (26). The first three of these papers dealt primarily with external heat transfer effects while the fourth discussed the internal heat transfer resulting from impingement convection cooling. The valuable paper of Dunham and Edwards (2) presented some interesting comparisons between external heat transfer coefficients calculated from measured test results with those predicted by theory. In general, the predicted heat transfer coefficients for both the pressure and suction surface of the trailing section of the blade were lower than the values obtained by experiment with the largest discrepancy occurring on the pressure surface. The theory indicated that the boundary layer should be laminar on the pressure surface but the values obtained for the experimentally determined heat transfer coefficients indicated the presence of some turbulence in the boundary layer. In spite of these discrepancies the prediction of surface temperature distribution for a turbine blade internally cooled by a large number of small holes agreed very well with measured values. The experimental results indicated that free stream turbulence level had a rather small affect on external heat transfer. However, these results do not agree with those obtained by Bayley of Sussex University and since, in addition, the turbulence levels used in the experiments described were low compared to those that would exist in an engine, some further clarification of the effect of turbulence on heat transfer is required.

The paper by Bassinot (26) on impingement cooling of stator vanes was also most timely since this method of cooling is finding application in an increasing number of engine designs. The paper provides a comparison between analysis and experiment and makes a number of recommendations, based on the author's experience, relating to the design of impingement cooled vanes.

Experimental heat transfer data for film cooling was presented in three papers. Eckert (17) presented the data he has developed for the effectiveness of film cooling downstream of rows of holes. Data, which were similar to that given in earlier publications, were presented for injection normal to the surface and with the hole inclined 35 degrees in the downstream direction. The author also reported on some new data which was obtained in order to shed light on the effect of a difference in density between the cooling air and the main stream. The data obtained tend to confirm the indications that the correlating flow parameter for film cooling should be the ratio of momentum flux (ρu^2) of the two flows rather than the ratio of the mass flux (ρu) which has been used in most previous correlations. The data presented in the paper by Liess (23) were open to some conjecture since it appears that there may have been heat losses from the adiabatic plate used. These data should therefore be considered as preliminary at this time.

Metzger (24) uses a different method of correlating film cooling heat transfer data than Eckert and Liess. His data are based on the average plate temperature, which includes the effects of conduction, downstream of the injection holes whereas the approach of Eckert and Liess uses the local temperatures. There are advantages to both approaches. That based on local temperatures is useful for studying the detailed temperature distribution and heat transfer processes downstream of individual injection holes while the average temperature approach is more useful for the case where full coverage film cooling, using multiple rows of holes, is considered.

Two papers, (11) and (12), presented results of experiments using transpiration cooling. In their interesting paper (12) Bayley and Turner listed what they considered to be the nine steps leading to the development of the ultimate air cooling system - these started with simple convection cooling and ended with transpiration cooling using controlled porosity materials. It was also pointed out that, from a heat transfer point of view, there are really no greater uncertainties in the applicable gas side heat transfer coefficients with transpiration cooling than there are with convection cooling. They agree with Dunham and Edwards (2) however on the need for improved information on the nature and influence of the laminar/turbulent blade boundary layer transition. They also presented experimental data which indicated that drilled sheet was almost as effective a configuration as the more truly porous materials. Such results are most encouraging because of the advantages of drilled sheet over porous material with respect to structural integrity and oxidation resistance.

IV. COOLED TURBINE APPLICATION AND EXPERIENCE

Several excellent papers by representatives of engine companies were presented outlining their experience with the application of cooled blading to operating engines. In addition to reviewing the trend of turbine inlet temperature and blade cooling effectiveness versus time for a variety of British engines, Holland (4) outlined the details of the turbine cooling system employed in the Olympus 593 Concorde engine. The first stage turbine stator of the Olympus engine is impingement cooled at the leading edge by cooling air which is fed up through an insert within the vane. The thermal cracking of the stator vane that was discovered during the development of the vane was corrected by providing more accurate control of the positioning of the insert within the vane. These findings were described in order to emphasize the importance of a consideration of practical manufacturing tolerances in the design of cooled vanes and blades. It was pointed out that, at the high temperatures in which current turbines operate, an error of 15°C in metal blade temperature can change the creep life by a factor of two and therefore present methods for predicting blade metal temperatures are not adequate for absolute life prediction but are extremely useful for comparative purposes. Lombardo (13) reviewed the data obtained as a result of the practical application of transpiration cooling to a full scale engine. Although the engines used in this investigation were not modern high performance units the results obtained do lay to rest at least some of the fears that have been expressed regarding transpiration cooling. The tests that have been carried out have included some eleven hours at a turbine entry temperature of 2750°F (1510°C), one thousand hours of endurance time and one thousand rapid acceleration/deceleration cycles at a maximum temperature of 2500°F (1370°C). During these tests no problems were encountered with clogging of the porous blade surface material.

In a very comprehensive paper, Suciu (15) presented an overall view of the multiplicity of engineering considerations and decisions that go into the design and development of successful high temperature engines. His discussion touched on not only the cooling problems but among other topics on the importance of material selection and development, on manufacturing methods and on proving the design by life testing. The significant conclusion to be drawn from this paper is that the heat transfer calculations involved in the design of the blading is only one part of the balanced engineering approach that is required in building turbine blade cooling into a modern, high performance, aircraft gas turbine. Halls (25) reviewed the various methods of stator vane cooling that have been used on the various Rolls-Royce engines. He outlined the way in which vane cooling systems and manufacturing techniques have developed over the years and gave some indication as to the trends to be expected in the future. He was in agreement with other speakers in his conclusion that, in the future, additional use will have to be made of spent convection cooling air for surface film cooling or for transpiration cooling. In his paper, Bertrand (35) discussed SNECMA's experience with the manufacture of film cooled blades utilizing a large number of holes drilled by electron beam. The resulting blades had very good cooling performance and the drilling of multiple rows of holes appeared to have negligible affect on the material strength though the fatigue strength at one million cycles was lowered somewhat.

Two papers were devoted to the problems encountered in attempting to cool very small turbines. Okapuu and Calvert (10) suggested that the use of a radial type of turbine should be seriously considered in the design of small (of the order of 5 lb/sec flow), high performance gas turbines. Good efficiencies at high pressure ratios have been obtained on experimental radial units while cooled axial flow turbines suffer from the effect of low aspect ratio, thick trailing edges and large tip clearances. This paper dealt primarily with the mechanical design and stressing of the rotor and with the fabrication problems encountered in obtaining a satisfactory casting of such a complicated component. Since further casting development is necessary before an acceptable rotor is obtained and, since the results from the unit currently under test are not yet available, the potential advantage of this approach over the axial turbine remains to be demonstrated. Johnson (29) presented results that have been obtained on a small turbine which incorporated steam cooled rotor blades, the heat in the steam being rejected to the fuel used to raise the rig air supply temperature to 2300°F (1260°C). At this operating condition the fuel temperature rise was approximately 275 F° (150C°). The thermosyphon cooling system was found to work well as designed even though there was some loss of blade tip caps during the test. However, the results reported were from the early applied research phase and it is clear that much work would be required and many problems would have to be resolved before such a blade cooling system could be applied to a practical engine.

V. HIGH TEMPERATURE TURBINE MATERIALS

Five papers were presented relating to the properties and selection of materials for use in high temperature turbines. Coutsouradis (18) gave a survey of the properties and characteristics of conventional high temperature materials and reviewed the efforts being made by metallurgists to improve these properties. Brunetaud (21) pointed out some of the gains in thermal fatigue resistance and in creep strength that can be obtained by means of unidirectional solidification as well as the potential of isothermal forging and powder metallurgy.

The protection of super-alloys by means of coatings was discussed by Galmiche (20) and Stetson and Moore (22). The latter paper included a very detailed review of the results of tests that were carried out on six different coatings that were prepared by American suppliers. The discussion covered the metallurgical effects of the coatings on the base metal and the coating failure mechanisms when used on nickel base super alloys in a simulated turbine environment. In their paper on the application of fibre strengthening to nickel base alloys, Morris and Burwood-Smith (19) were not optimistic about the potential of this technique in high temperature applications, particularly in cooled blades which tend to be rather complicated mechanically. The authors rejected the use of whiskers and filaments in high temperature nickel base alloys because fabrication problems result in short lengths of reinforcing material and thus low strength. Refractory metal wires were indicated to have some potential for strength reinforcement but only in uncooled blades since cooled blade configurations are too complex.

VI. TURBINE LIFE

Methods of predicting the operating life of turbine blades and disks were reviewed in three presentations. Price (31) showed an interesting film on thermal fatigue but it gave a somewhat optimistic view of our current ability to predict the thermal fatigue life of turbine blades. The paper by Bullard and Baxendale (32), which was presented by Dr. Dunham, and that by Krempl gave a somewhat more realistic appraisal of difficulties which are still inherent in the current state-of-the-art methods of predicting blade life under thermal cycling conditions. (34).

VII. HEAT TRANSFER INSTRUMENTATION

Turner's paper (5) was given by Dr. Bayley who stressed the precautions that should be taken and the techniques that should be used in the measurement of gas and metal temperatures and of heat flux. This paper also contained an extensive and valuable bibliography of material on turbine temperature and heat transfer measurement and instrumentation. The sources of error in the use of thermocouples to measure temperature were also discussed by Stottman(8). The problem of catalytic effects on noble metal thermocouples was particularly stressed but the author had found that this could be controlled by the application of an unbroken coating of aluminum oxide on the surface of the thermocouple wires.

VIII. CONCLUSIONS

1) The papers presented at this 36th meeting sponsored by the Propulsion and Energetics Panel of AGARD provided a very good survey of the unclassified state-of-the-art of high temperature turbine technology. Considerations of security and the proprietary nature of company research prevented discussion of the most advanced and challenging developments in air cooled blading.

2) There was general agreement among the speakers and those who participated in the discussions that better utilization must be made of the available cooling air supply. Thus, after effective internal heat transfer (by convection and impingement) has been achieved the cooling air should be used externally to provide a film over the blade to reduce the heat transfer from the gas to the blade. There is some concern about the extent of the aerodynamic performance loss involved in this approach and more research is needed to determine the overall effect of film cooling on blade profile loss.

3) Though transpiration cooling is the most effective cooling technique that can be presently conceived it is doubtful that "true" transpiration cooling will be extensively used in the foreseeable future. Designers are reluctant to use this cooling method because of problems of oxidation, foreign object damage, pore clogging, blade profile control and rough surface finish. It seems more likely that drilled sheet structures which provide full coverage film cooling will be used more extensively than true transpiration cooled blades.

4) Fruitful areas for additional research into the operation of cooled blades that were brought out during the meeting include:-

   (a) the need for improved knowledge concerning the gas to blade heat transfer coefficients for film and transpiration cooling under engine operating conditions. Associated with this is a need for improved knowledge concerning the nature of the laminar/turbulent boundary layer transition on the suction surface of blades.

   (b) evaluation of the effect of turbulence intensity and scale, at levels corresponding to engine operating conditions, on gas to blade heat transfer coefficients for convection cooling.

   (c) an assessment of the true aerodynamic penalties associated with the various methods of discharging cooling air through blade surfaces.

   (d) improved analytical techniques for predicting the life of high temperature turbine components.

5) Some important considerations relating to the design of high temperature turbines were not touched on in the formal presentations given at the meeting. Such factors as turbine casing cooling, which becomes more and more important as operating temperatures are raised above their present levels, and coolant flow distribution and pressure loss inside complex cooled blade configuration for example, are deserving of consideration.

IX. RECOMMENDATIONS

This meeting provided a very worthwhile opportunity for interested workers to exchange information on the technology of high temperature turbines incorporating blade cooling. This was particularly true for those who do not spend their full time in this field. For the experts in the field little that was technically new emerged from the formal presentations but this type of meeting provides ample opportunity for an informal sharing of experience and knowledge. It was also interesting to find, among those NATO countries engaged in the development of high performance gas turbines, a rather common approach to the design and development work involved in achieving the next increase in allowable turbine operating temperatures.

It is recommended that another AGARD meeting on high temperature turbines be held in 4-5 years. It appears that another significant step in the technology is about to occur which will allow turbine inlet temperatures to be increased to levels appreciably above the melting point of any of the super alloys now being used in engines. After this step has been successfully taken another meeting would be most useful.

Other meetings of this nature could be made more informative and productive for delegates by some minor changes in procedure, such as:

1) Utilization of uniform units by all authors. It might be possible to use dual scales on graphs for different units.

2) The labeling of slides and figures in both French and English to assist those not fluent in both languages.

3) Since all papers are not of equal importance the time allotted papers should be related to their value.

4) Session chairman should be prepared to initiate discussions on papers when questions are slow to come from the floor and related to this is the desirability of having preprints mailed to the invited delegates prior to the meeting so that more meaningful discussion can take place.

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3.	G. Chiron	Détermination des Températures dans les Aubes de Turbine Refroidies par Convection
4.	M. J. Holland	Olympus 593 Turbine Cooling
5.	A. B. Turner	Heat Transfer Instrumentation
6.		PAPER WITHDRAWN
7.	J. Michard	Mesures de Flux de Chaleur sur Aubes Fixes de Turbines
8.	P. Stottman	Temperature Measurements with Thermocouples Including Errors Caused by Catalytic Effects
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11.	N. Scholtz, H. Prechter, and A. Schönbeck	Effusion Cooling of Turbine Blades
12.	F. J. Bayley and A. B. Turner	Transpiration Cooled Turbines
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14.	J. B. Esgar	Turbine Cooling - Its Limitations and Its Future
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16.	W. Kühl	Experimental Investigation on a Single-Stage Air Cooled Gas Turbine
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20.	P. Galmiche	Protection des Superalliages Réfractaires pour Turbines à Gaz Aéronautiques par Voie Thermo-Chimique
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25.	G. A. Halls	Nozzle Guide Vane Cooling - The State-Of-The-Art
26.	E. Bassinot	Refroidissement des Aubes de Distributeur de Turbine par Effet d'Impact
27.	E. Le Grives and J. Genot	Refroidissement des Aubes de Turbine par Métaux Liquides
28.		PAPER WITHDRAWN
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30.		PAPER WITHDRAWN
31.	R. H. Price	Thermal Fatigue (Film)

No.	Author	Title, etc.
32.	J. B. Bullard and B. B. Baxendale	Some Mechanical Design Problems of Turbine Blades and Discs
33.	J. Richens	Air Cooled Turbine Design Criteria
34.	E. Krempl	Stress Analysis for Elevated Temperature Low-Cycle Fatigue With Hold-Time
35.	J. M. Bertrand	Les Aspects Technologiques du Refroidissement des Aubes de Turbine par Film d'Air

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