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na temat

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Gdańsk, 24 - 27 września 1974 r.

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on

STEAM TURBINES OF GREAT OUTPUT

Gdańsk, September 24 - 27, 1974

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III НАУЧНАЯ КОНФЕРЕНЦИЯ

на тему

ПАРОВЫЕ ТУРБИНЫ БОЛЬШОЙ МОЩНОСТИ

Гданьск, 24 - 27 сентября 1974 г.

Mr. R. Dvořák

Limits of Transonic Flow Calculations Through Cascades

At present numerous methods for transonic flow calculations are available. Especially in the aeronautical field there exists a great number of very sophisticated and elaborate methods. Most of them, however, have never been used in turbomachinery, as for various reasons — they have not fully satisfied the designers.

On the other hand, with the effort invested into aerodynamics so far and with the background of sufficiently big computers ready to solve almost everything, we are really facing a problem who is to be blamed for this situation.

As a theoretical aerodynamist who has worked for many years in close cooperation with industry, I should look for the answer in the rudimentary and inadequate philosophy of transonic flow in cascades. The common approach is still that of an aircraft aerodynamist, neglecting thus the specific features of various phenomena, as, e.g., flow separation, shock wave and boundary layer interaction, etc.

As there is no time for giving detailed reasons for this opinion, I would just mention a few examples to initiate the discussion.

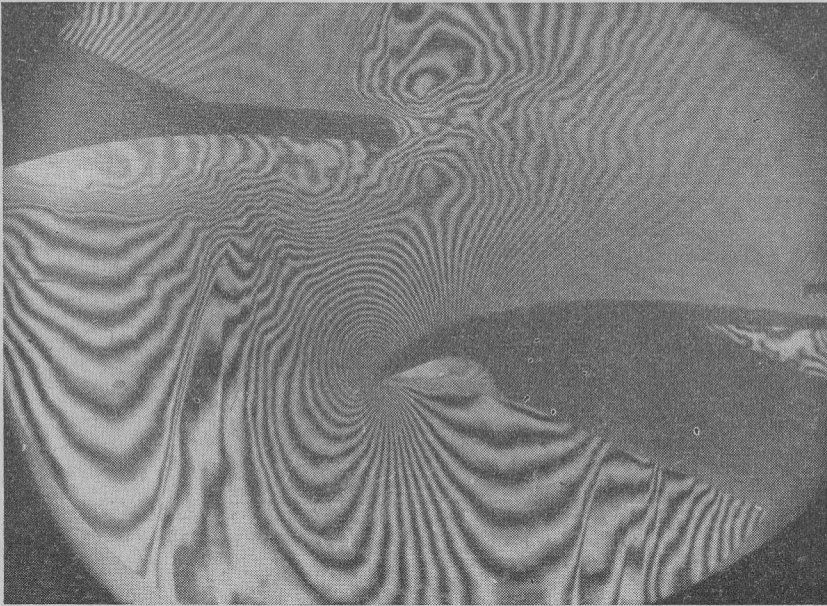


Fig. 1

Though we have now the 70th anniversary of boundary layer theory, most of it was directed towards single slightly curved and slender airfoils or bodies and we still badly need to revise the results from the turbomachinery point of view. This general experience becomes even more pronounced in the transonic field, where the boundary layer displacement effect not only quantitatively, but also qualitatively affects the whole flow field and is responsible for the most important limitations of all transonic flow calculation methods. Perhaps, the examples in the following few figures may support this opinion.

Fig. 1 shows an interferogramme of one of the tip sections of the last stage turbine blading. The outlet Mach number is about 1.4 and the incidence about -20 degrees. The displacement effect of

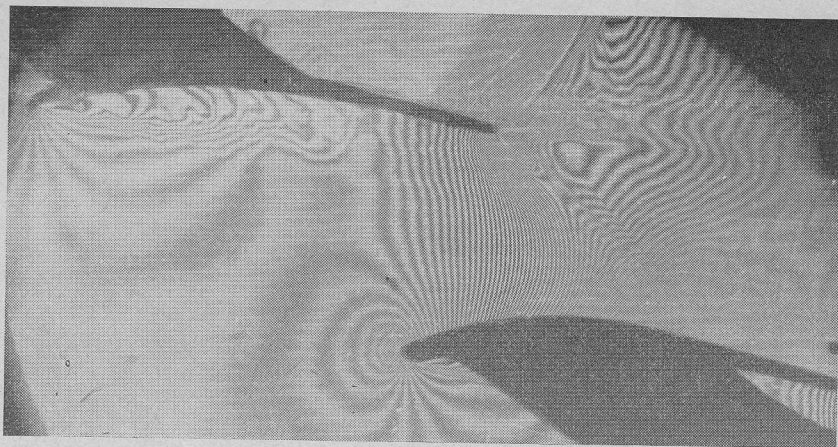


Fig. 2

the large leading edge separation bubble on the pressure side completely changed the flow pattern and resulted also in an inversion of the aerodynamic force on the profile. Due to this effect a concave surface turned into a convex one with a pronounced local supersonic region terminated by a shock wave — unfortunately a very unstable one — which became a front shock to the neighbouring profile. It is very difficult to account for this effect in a transonic region by the usual iterative approach recommended in current boundary layer calculations, as qualitative changes in the flow pattern follow each iterative step.

The next figure (Fig. 2) with the same cascade at a slightly lower Mach number, is instructive yet for another reason. The strong leading edge separation at negative incidences always develops in separation bubbles which become closed by the constructive effect of the sonic throat.

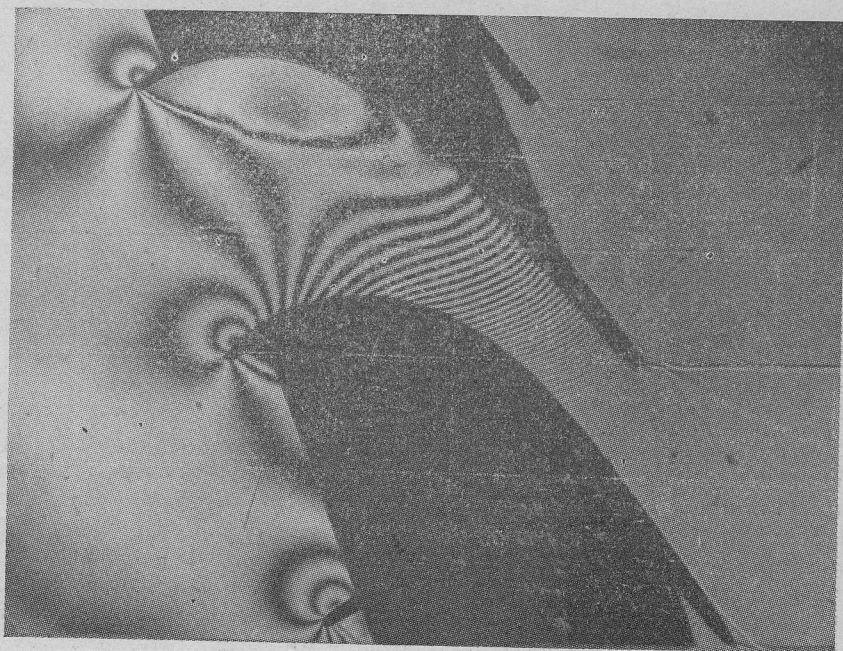


Fig. 3

In nozzle cascades the same holds true due to greater solidity also for positive incidences. This is quite a general experience that in transonic cascades the leading edge separation does not necessarily result in the same kind of unwanted phenomena to which it would lead with isolated airfoils. It also means that we need not be afraid of thin blades, or thin leading edges, if followed by strong positive pressure gradients. The next two figures (see Fig. 3 and 4) are interferogrammes of thin nozzle blades at $\pm 20^\circ$ incidence. The effect of both leading edge separation bubbles ceased down even before the sonic throat and it can hardly be traced in the wake, a result which is fully supported by measurements of the loss coefficients.

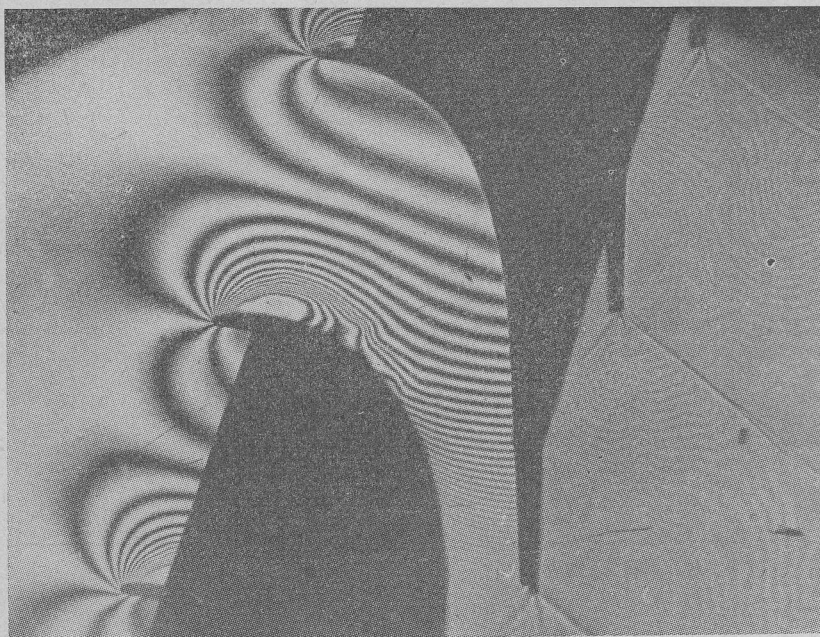


Fig. 4

My second example concerns calculation methods, which are the final result of our considerations. A detailed review of all these methods is given in [1] or may be obtained from papers collected in [2].

Judging the calculation methods, we have to distinguish between the direct and indirect problems.

At present there are very powerful, reliable and even quite handy numerical methods for solving the direct problem. They have to be, especially at off-design conditions, corrected by empirical data, mostly to take viscous effects into consideration. Combining the numerical or analytical approach with the empirical or semiempirical data, new profiles can be obtained for almost any transonic regimes. May I perhaps remind you of a similar procedure for isolated airfoils based mainly on the British NPL work. The same stage has not yet been reached in cascades. Works on the physical structure of the transonic flow in cascades are rare and their results have not been generalized so far to an extent applicable to blade designing.

One attempt for applying the semiempirical methods was reported a few years ago by Fottner [2, 3]. It has not fully accounted for the blade interference and for the actual structure of the transonic flow in a cascade (cf. papers presented by the present author and by Šafařík at Kamienny Potok in 1973 to the XIth Fluid Mechanics Symposium) and for $M_1 > M_{crit}$ it ended up with unacceptable differences (Fig. 14 in [3]).

On the other hand, if properly applied and based on an analysis of the transonic flow structure, they may be very useful. Fig. 5 is an interferogramme of another tip section of the last turbine stage. Without any detailed analysis it may be deduced from the picture that there are two unwanted pheno-

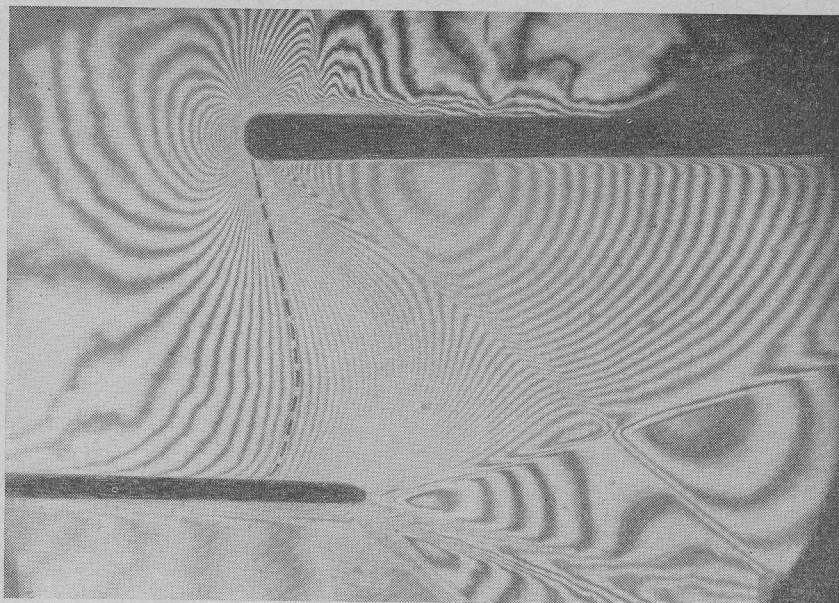


Fig. 5

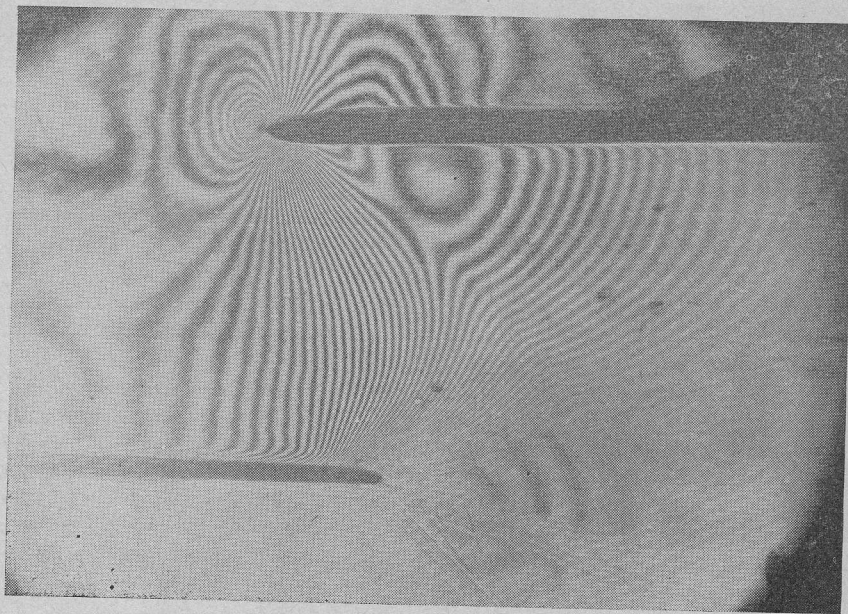


Fig. 6

mena — the small supersonic region with a terminal shock on the pressure side, and a kind of a lip shock on the suction side. The pressure side of the blade is not very much influenced by the neighbouring airfoil so that the results from the analysis of the transonic flow structure on isolated airfoils can be applied. Having done that, we were able to modify the leading edge (while observing at the same time all other technological and structural requirements) so that both shocks disappeared (see Fig. 6). This resulted

in a considerable improvement in cascade efficiency — the losses decreased to almost 50% of the original value.

The situation is not as optimistic in the indirect problem, nevertheless even here some progress has been made quite recently. In this case it is usual to start with a given (or properly chosen) distribution of pressure. The problem is to choose a suitable one. It was Dr. Růžička and Špaček [4] who first solved the variational problem of optimal pressure distribution, defined as that leading to minimum momentum thickness of the boundary layer on the suction surface. Beside these losses in transonic cascades, it is often necessary to take into account also those due to shock waves and their interaction with the boundary layer. To solve the optimal flow pattern in this complicated case, one has to use modern methods of the optimization theory. These methods, I believe, allow also for including all technological, structural, and geometrical constraints, which essentially means that they form a link between the theoretical solution and what can be described as the designer's skill and experience. Of course, there is still a lot to be done before these methods become currently available.

After these few introductory remarks and examples, I think I have to return to our original question, and before starting the discussion I might, perhaps, summarize my own opinion:

1. With the existing possibilities and calculation methods already available I should not see absolute limits in the field of theoretical aerodynamics if the problems and requirements of turbine designers are reasonably and well posed. I would feel problems rather in the level of present understanding of the physical nature of the flow, and in the ability of both aerodynamists and turbine designers to apply the proper method.

2. However, the development of and materializing a new blading takes several years — perhaps a whole decade — and we face another limitation here whether the problem can be solved in due time by using a method comprising all up-to-date information (aerodynamical, structural, and technological), and cheap and rapid enough to be used even for all off-design regimes.

3. We can gain a lot of important and highly useful information from the purely analytical or numerical methods, however restricted they may seem to be by the simplifying assumptions — e.g., correlations between geometrical parameters of transonic cascades and their aerodynamic characteristics. Nevertheless, I consider the semiempirical methods to be the most prospective ones. Of course, they must be based on a detailed analysis of the transonic flow structure. There is another important fact which cannot be neglected. These methods are so far the only ones which can make full use of the huge amount of very often excellent experimental results and the designers' skill and experience.

4. In solving the indirect problem we shall most probably draw information from the theory of optimal control of distributed parameter systems.

References

- [1] R. Dvořák, *Současného problematika transonického proudění v lopatkových mřížích*. (The state-of-the-art in transonic cascade aerodynamics). In: Sborník č. 3 Čs. Společnosti pro mechaniku při ČSAV, Praha 1973.
- [2] Advanced Components for Turbojet Engines, part I, II. AGARD Conference Proceedings No 34, Sept. 1968.
- [3] L. Fottner, *Ein halbempirisches Verfahren zum Bestimmen der reibungsbehafteten transonischen Schaufelgitterströmung mit Einschluss von Überschallfeldern und Verdichtungsstößen*. Forsch. Ing. Wes., Bd. 36 No. 4, 1970.
- [4] L. Špaček, M. Růžička, *O jistém systému turbinových lopatkových mříží*. In: Základní problémy ve stavbě spalovacích turbin, Praha, NČSAV, 1962.

Discussion

Chairman: I would like to repeat the question: What are the limits of applicability of the theory of aerodynamics in turbine stage designing and what causes these limits and is there any chance to improve our present design methods?

Mr. E. Somm (to Mr. F. Lehthaus): What is the actual state of your tests with a cascade rotating blade which you are making in your Institute?

Mr. F. Lehthaus: For the last two years in our institute investigations of last stage tip section cascades were started in a test facility for rotating circular cascades. I am not personally involved in this job and, I am sorry, I cannot answer the question because I lack the materials.

Prof. R. Puzyrewski (to Dr. A. Roeder): Because of the limits in theoretical knowledge of what is going on in turbines is it possible to jump over the experimental investigation and construct a reliable, highly efficient and low price turbine?

Dr. A. Roeder: The comparison of the three-dimensional flow calculations and the measurements behind the last stage showed us that if we use the measured flow angle as input data for the calculation we could obtain the measured flow parameters like flow angles, pressure, etc. with good precision. From these measurements we learned that we could approve the design of the last stage moving blade. We used the knowledge from experiments for better designing of our last stage blades and for approving our methods to calculate the outlet angle of a moving blade cascade.

Prof. J. Jerie: The task of the panel was to show the role of theoretical aerodynamics and we hear from Dr. Roeder that it is the combination of theory and experiments which brings good results. The conclusion is that a close co-operation of theory and practice is absolutely necessary to get better results.

Dr. G. Gyarmathy: In turbines there are problems related to stationary phenomena and to non-stationary phenomena. Up to now non-stationary phenomena have not been mentioned. I would like to know what the applicability limits are when non-stationary phenomena are encountered?

Dr. R. Dvořák: It depends what kind of unstationary phenomena you mean. There are some unsteady effects in the transonic flow peculiar to the transonic flow and you simply cannot get rid of them. There is also a certain kind of instability which is due to the boundary layer and shock wave interaction beyond the critical Mach number. Further there are some unsteady effects which may be due to the inconvenient pressure distribution.

It is our experience that (e.g.) a flat pressure distribution like that on laminar airfoils is very sensitive to unsteady disturbances. The unsteady effects are very highly pronounced there and, therefore, this is not the best pressure distribution for a transonic cascade.

We have not discussed these phenomena because of the lack of time. A few results are already available that can be used in the design practice. I agree with you, however, that if there are real gaps in our aerodynamic knowledge it is mainly in these unsteady phenomena.

Mr. A. Smith: I would like to pose my first question to Dr. Roeder and the second to Dr. Dvořák.

What is your opinion, Dr. Roeder, on current methods of estimating losses in blading with extremely high tip to hub ratios, that is, in LP blading with steep cylinder wall gradients? Do you consider stream surface twist within the blade rows to be important, and if so, what use are two-dimensional test results in such a situation?

I envisage that three-dimensional influences extend throughout the blade length in these circumstances rather than be confined to the blade tip and roots because of differences in radial discharge angle between the suction and pressure surfaces along each blade. Have you any suggestions as to how this problem can be resolved?

There is another uncertainty, Dr. Dvořák, in the theoretical treatment of supersonic flows near LP blade tips and nozzle roots. Current methods of flow calculation are two-dimensional whereas in fact the problem is three-dimensional in a turbine. How are we going to estimate supersonic performance in these circumstances?

Dr. A. Roeder: Let me try to answer your first question. We compared theoretical values of the outlet angle with measured ones. We tried to find out why there was a big difference between them somewhere over the radius and we corrected our only two-dimensionally calculated outlet angles by a calculation which takes into account the influences of a conical stream line through a rotating blade. This correction is not due to losses coming from vorticities or from boundary layers on the side walls. We now apply an empirical correction to the theoretical values of the flow angles. I do not see any other way at the moment of introducing losses directly to the three-dimensional flow calculation. It comes to the same if we introduce losses or if we correct the flow angles. And it is easier to apply corrected flow angles instead of introducing losses.

Dr. R. Dvořák: You have asked me, in fact, two questions. The reason why I concentrate more on two-dimensional problems is, that, as an aerodynamicist I would like to learn more about the physical mechanism of the processes occurring in transonic or supersonic flows. I think it is much easier to study them in two-dimensional cases.

As far as the calculation methods for three-dimensional flow are concerned the only one I know was presented by Becker and Simon in a paper about the three-dimensional method of characteristics, published in *Z. Flugwiss.*, Bd 20 (1972), Hf. 1/2. I do not think you would be able to use this method in turbine calculations. It is more suitable for supersonic compressor cascades. Now, there are available up-to-date methods which can be used for calculating three-dimensional high speed flows, both transonic and supersonic. They are the so called time dependent methods, which, however, can be used only with big computers.

Mr. F. Lehthaus: I would also like to make a short remark on your point, Mr. Smith. Up to now we have restricted our investigations to two-dimensional cascades, using for experimental work a test facility for straight cascades and a new facility for rotating circular cascades. For the second facility our first step is to examine quasi-two-dimensional last stage tip section cascades, which in our opinion cannot be investigated in a straight cascade tunnel. The next step will go in the direction of three-dimensional flow, examining cascade flow on conical stream surfaces.

Dr. R. Dvořák: The problem is not so difficult as far as the rotor cascades are concerned. The three-dimensional effects are much higher in the stator (or in the nozzle blades), especially in the last stages.

Mr. A. Smith: Rotational terms of the radial momentum equation would appear to induce stream surface twist in rotor blade rows, as can be seen in a recent paper by T. Araki given in the 1973 Warwick I. Mech. Conference on Heat and Fluid Flow in Steam and Gas Turbine Plant. Of course, streamline twist also occurs in stator blade rows with a conically shaped boundary because of sweep or the oblique approach of the flow to the nozzle leading edges.

Mr. E. Somm: Mr. Smith, may I refer to a paper of Roeder and Teufelberger which has been published in 1971 by the von Karman Institut at Brussels.

In this paper the influence of the conical shape of a transonic cascade on the efficiency and the flow angle at the outlet of the cascade has been demonstrated. The result was as follows: If we have a conical flow channel with the blade height b_3 at the throat and b_2 behind the cascade where the flow can be assumed to be homogeneous the ratio b_2/b_3 influences the cascade efficiency, so that e.g. for $b_2/b_3 = 1.1$ decreases 6% relative the case $b_2/b_3 = 1.0$. So I completely agree this is a very important thing. But I agree also with Mr. Lehthaus we have first to study the plain cascade and afterwards we have to handle this problem. Otherwise, we make a big mistake in the calculation of the efficiency.

Prof. J. Jerie: I think, there is a strong influence of turbulence in these experiments. Up to now most experiments with cascades were made in tunnels with turbulence of 1 or 1.5 per cent. But in fact we find very high turbulence intensity in very complicated flow patterns. It is a field which is not homogeneous from the turbulence point of view and which is anisotropic. There are very few studies of boundary layers in such profiles. There are studies of developed thermodynamics in Prague which bear the boundary layer studied in a flow of about 10 per cent turbulence intensity. If we try to integrate the Navier-Stokes equations in the space, and in two-dimensional space, it is necessary to take into account that the flow is turbulent although it is difficult to say what turbulence is. Statistical pressure loss in theoretical studies is quite different in a turbine. Besides in the Navier-Stokes equations there is a viscosity factor which is the physical viscosity of the fluid. The equations are correct, I suppose, but by calculating and integrating the physical properties of molecular viscosity into these equations we do not have the turbulent flow, we do not get the boundary layer. We must calculate them with something which from the mathematical point of view is not correct and it is the turbulent viscosity and we do not know in advance what the repartition of this turbulent viscosity across the profile is. We have no theoretical means at hand to find it.

I believe that the only way to find the real repartition of turbulent viscosity is to try to divide the turbulent viscosity across the field and the result of our integration would be similar to the experimental one. If we have our experiments we do not need calculations.

Prof. D. J. Ryley: I have shown commendable restraint until now and I would like the opportunity to make a short comment at the end of this Session!

If one constructs a curve showing results of almost any human activity against the effort needed to attain those results the curve has the form shown. Here we may think of results as aerodynamic progress made in blade design and effort in terms of the long period of time such research in blade design has been in progress. Since time is money, we could use Polish zlotys as the unit for the base.

Recently Mr. Allen Smith told me that some of his modern profiles designed by the most recent methods were very similar in shape to those designed nearly a hundred years ago by Sir Charles Parsons. I am wondering whether the aerodynamicists are now justifying their existence! It seems to me that they are working near the top of the curve, spending a lot of money and producing fine mathematics but failing to make much progress.

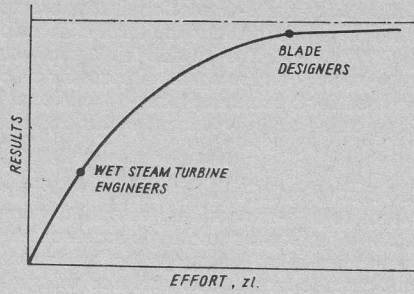


Fig. A

By contrast the engineers working on wet steam are still low on the curve and they have a much better future!

Prof. J. Jerie: We agree that there are limits of applicability of the theoretical aerodynamics to turbine stage design and we must know them to decide whether it is worthwhile to proceed further than the limits allow.

The text of the Panel Discussion contributions has been prepared for the publication by Mrs. Barbara Markiewicz and Mr. Mariusz Adelt.