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OBSERVATION ABOUT SECONDARY FLOW CONTROLLING MECHANISMS

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Abstract

To improve the performance of turbomachines, it may be beneficial to control the development of secondary flows. The present article reviews the status and outlook of secondary flow control mechanisms. Several techniques used over the past decades are considered and suggestions are made for further researches.

Introduction

A lot of efforts have been made to reduce turbine flow losses to improve the turbine performance. For high hub/tip ratio turbomachines such as gas turbines or the high pressure cylinder of steam turbines a large portion of the aerodynamic loss is known to arise from the effect of secondary flows. Such flow is a phenomenon in which a flow motion perpendicular to the primary flow direction is induced. This motion has long been known to occur in hub and casing wall regions of axial flow turbines, where the highly complicated three dimensional flows irreversibly produce what are called secondary losses of considerable magnitude.

The presence of secondary flows in turbines has two main effects. The first is to produce a variation of angle with radius at exit from a blade row. The second is to produce an increase in loss as discussed above. Hence, the majority of the investigations of secondary flows in turbine blading are conducted in order to understand the characteristics of such flows more clearly. The greater portion of these studies are experiments that have been performed with various blade shapes and flow conditions and with different measurement techniques. Today, it is commonly believed that the flow patterns

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associated with the secondary loss are adequately understood, but the variation of the losses with some important parameters is less so. From a practical point of view, the generation of secondary flow in a turbine passage has a very strong effect on the global aerodynamic properties, and a through, fundamental understanding of the phenomenon is obviously needed.

Horseshoe vortex

Numerous aerodynamic studies of the complicated nature of turbine passage secondary flows have been received a large amount of attention since the publication by Ainley in 1948. The parameters influencing the secondary loss such as the blade aspect ratio, blade loading and upstream boundary layer thickness were discussed by Dunham (1970). The effect of the inlet boundary layer was farther examined by Came (1973). Sieverding (1985) reviewed the results of experimental secondary flow researches in turbine blade passages, mainly for the the period 1974-1983. Some of the facts to emerge which are considered relevant to the discussion of losses are as follows.

There are two main features of a turbine cascade secondary flow, the passage vortex and the loss core associated with the inlet boundary layer. As discovered by Langston et al (1977), the vorticity of the inlet boundary rolls up and wraps itself around both sides of the blades forming the aptly named "horseshoe" vortex (Fig.1). This vortex gives rise to two separation lines, one sloping outward from the endwall on the blade suction surfaces and the other crossing the endwall to the surface of the adjacent blade. As discussed by Gregory-Smith and Graves (1983), this becomes associated with a counter rotating vortex in the corner formed by the endwall and the blade suction surface. These surface separation lines enable the losses caused by the fluid shear close to the suction surface to feed into the mainstream. It is the passage vortex which converts the loss core across the passage to the suction surface where it is then displaced outward to the separation line mentioned above. In 1977, Langston et al reported that there are two mechanisms which have a major influence on the generation of secondary flows in turbomachinary passages.

(i). Secondary flow due to rotation or curvature, which cause a flow with an initial distribution of normal vorticity to develop a streamwise component of vorticity.
(ii). Horseshoe vortex flow due to the interaction of end wall boundary layer flow with a blade leading edge.

Parameters influencing the generation of secondary losses

Basically, one might ascribe three possible contributions to an increase in secondary losses: boundary layer growth on the side wall; corner losses, and losses due to the interference of the end wall boundary layer with the suction side boundary layers. Earlier investigations (Schlichting and Das (1966); Salvage (1974)) showed that secondary losses must depend on blade inlet and outlet angles and profile shape, pitch chord ratio, incidence, axial velocity ratio, Mach number and Reynolds number. Two other quantities are also relevant: aspect ratio and the upstream wall boundary layer. In a real turbine there are a number of additional effects on the generation of secondary losses. The radial pressure gradients will cause migration of low energy fluid awing the suction surface of the blade, Gregory-Smith (1980). There will be effects due to blade clearance, discontinuous end walls, curved end walls, and the interference of one blade row on a following row. If there is a clearance (gap) between the tip of the blade and the side wall, the flow becomes even more complicated by the flow through the clearance.

All these types of secondary flow-clearance flow, corner flow, and circulatory flow resulting from deflection cause considerable energy losses, since their kinetic energy is lost and adds to the work losses. The secondary losses in many cases amount to about 50% of the total losses.

Objective

Secondary flow control based on a good understanding of the three dimensional nature of the flow may improve the turbine aerodynamic performance. In this paper, we want give detailed picture about secondary flow control mechanisms.

Physical Nature of Secondary Flows

The flow pattern through a turbine cascade is very complex and detailed physical description of such flows was revealed by a long series of excellent flow visualization studies (Herzing et al 1954). Although the flow field has a strong dependence on the incidence angle, flow inlet angle, Reynolds number, characteristics of oncoming boundary layer flow, and the blade profile, the qualitative trends are quite general. The boundary layer flow in the two dimensional flow region, shown in Fig.2 is summarized from studies conducted by Hodson and Dominy (1987), Hoheisel et al (1987), and Nicholson (1981). On the suction side a laminar boundary layer grows from the stagnation line. Hodson and Dominy (1987) reported that the laminar boundary layer proceeds through separation, transition, and reattachment after which the flow becomes fully turbulent near the trailing edge. Vortices shed from the trailing edge are present in the wake region. The flow field, on the pressure surface, is also indicated in Fig.2. The laminar boundary layer develops from the stagnation line and a separation bubble forms near the leading edge. In the separation bubble, a transition occurs and develops into a fully turbulent boundary layer.

Based on earlier studies, the secondary flows in the three dimensional flow region within the blade passage are schematically presented in Fig.3 (Goldstein and Spores, 1988). When the boundary layer fluid approaches the blade leading edge, it is subjected to an adverse pressure gradient and starts to roll up to form a horseshoe vortex. Ahead of the leading edge of the blade, S_1-S_2 is the separation line of the horseshoe vortex and the two legs of the horseshoe vortex are, marked as vortices V_{sh} and V_{ph}. The leading edge corner vortex, driven by the horseshoe vortex, forms at the corner of the leading edge and rotates an opposite direction to the horseshoe vortex. Separating from the leading edge, the suction and pressure side leading edge vortices are marked as vortices V_{slc} and V_{plc} , respectively.

The strong pressure gradient in the blade passage is the main driving force of the complex secondary flows. It affects the path of low momentum flow, on the endwall as well as the secondary flows in the passage. It is also responsible for the overall downflow (toward the endwall) on the pressure surface and upflow on the suction surface. When both the suction side leading edge corner vortex and horseshoe vortex enter the blade passage, they experience a strong transverse pressure gradient and both vortices are kept close to the suction surface.

As the suction side horseshoe vortex travels along the suction surface toward the trailing edge, it moves away from the endwall toward the midspan and downstream to the separation bubble. When the suction side horseshoe vortex moves away from the endwall, its separation line is at S_1 , shown in Fig.3. Hodson and Dominy (1987) indicated that the direction of the rotation of the flow in the separation bubble is opposite to that of the suction side horseshoe vortex; as a result, the vorticity of this vortex decreases. As to the leading edge corner vortex, after it is forced toward the suction surface, its path is not easily traced nor do earlier studies have a clear view of it.

The pressure side horseshoe vortex leg, driven by the strong transverse pressure gradient, moves away from the pressure surface and toward the suction surface of the adjacent blade. During the transverse movement, it becomes a major component of the passage vortex (V_p) that entrains fluid from the end wall boundary layer, as wall as the mainstream.

After the passage vortex reaches the suction surface of the adjacent blade, it moves away from the endwall toward the midspan as it travels along the suction surface, toward the trailing edge. In Fig.3, S_2 is the extrapolation of the separation line of the passage vortex at the suction surface.

Due to the large energy losses associated with boundary layer separation, the feature of secondary flow in a turbine cascade is often controlled by the separation location. As defined by Flatt (1961), the term boundary layer control includes any mechanism or process through which the boundary layer is caused behaves differently than it normally would, were the flow developing naturally along a smooth straight surface.

Secondary Flow Controlling Mechanisms

Several techniques have been used to control the development of secondary flows in a turbine passage and hence, reducing losses. The earlier attempts in this field were made by Deish (1945) in the former Soviet Union and By Herzing and Hansen (1955) in the USA.

The techniques available can be classified in two distinct types as follows: The first dealing with structural measures (Fig.4) such as (a) baffles; (b) projections; (c) recesses and (d) cutoff plates. The second dealing with blowing and suction measures (Fig.5) such as (a) energy supply to end zone of secondary flow at the end surface, (b) supply of energy to zone of secondary flow at the pressure surface, (c) suction from the zone of secondary flow at the end surface, and (d) suction from the zone of secondary flow at the pressure surface.

In the following, some of the above mentioned techniques and another techniques appeared in the last ten years have been explained in details.

Fences

Prümper (1972) suggested that boundary layer fences installed on the hub and casing walls of an axial flow turbine might reduce losses. Unfortunately, neither the amount of loss reduction nor fence effects on such important secondary flow features as the vorticity and outlet flow angle distributions were submitted. Kawai et al (1990) followed the idea of Prümper and used two types of boundary layer fence . In the first case , fences of 0.5 mm thick were installed on the end wall, as shown in Fig.6a. The heights of the end wall fences were about 1/3 of the inlet boundary layer thickness. The fences had the same camber line as the blades and were located half a blade pitch away from the blades. Such a combination of height and location minimized the secondary loss, with 22 % reduction from the unfenced blade case. Also, this such method reduced the tangential force defect 60 % of unfenced blading value. In the second case, fences were attached to the blade suction surfaces, as shown in Fig.6b. These blade fences were as high as the suction surface boundary layer thickness measured at the midspan trailing edge. They were parallel to the end walls, and were located approximately one inlet end wall boundary layer thickness distance from the endwalls. Again such a distance minimized the secondary loss with a 32 % reduction. The main reason for this can be explained as follows: Through flow visualization, Kawai et al (1990) observed that the pressure side branch of the horseshoe vortex separation bubble is terminated at the fence, without reaching the suction surface of the neighboring blade. The end wall limiting streamlines between the fence and the blade suction surface are then directed more axially, so the endwall crossflow is weakened as compared with the unfenced (normal blading) case. Furthermore, the passage vortex three dimensional separation on the suction surface is reduced in size in comparison with the normal blading case.

In fact, Kawai et al (1990) made the experiments on a blade of an aspect ratio of 1.4. But as we know, the secondary flow becomes more and more as the blade aspect ratio is decreased. In this case, the secondary flows mix with the mean flow. Therefore, our expection is the effect of these fences on the secondary flows will be exist, for the case of short blades also.

Endwall contouring

Single stage axial turbines operating at relatively high pressure ratio and inlet temperature have been used by many investigators for the sake of lightness, reliability, and high performance which are necessary for small aircraft engines. The first row design for such a turbine will have blades with high flow turning, low aspect ratio, high exit Mach numbers, and large trailing edge blockages to provide for effective cooling. These design features can combine to produce excessive secondary flows and losses which may seriously affect the performance of the subsequent high work rotor. Meridional endwall contouring is an effective tool to reduce exit flow profile distribution, as well as controlling secondary flow development. The benefits of the method were first reported by Deish et al (1960). According to these investigations, these benefits are due to the increase of the channel convergence, the decrease of the pitchwise pressure positive influence on the spanwise static pressure distribution at the blade trailing edge region. Kopper et al (1980) demonstrated a 17 % loss reduction due to endwall contouring in tests conducted on a linear nozzle cascade with an aspect ratio of 0.5 and an exit Mach number of 0.85. A major part of the measured improvement resulted from a reduction of secondary loss on the planar wall side of the cascade. The effect of contouring on stator and stage performance was reported by NASA researches (Haas, 1982; Haas and Boyle 1984) through experiments carried out on a highly loaded annular cascade (Zweifel coefficient 0.48) with near sonic exit conditions. These investigations showed that the improvement in stage efficiency due to contouring (about 0.5 to 0.8 %) stemmed largely from reduced stator profile and endwall friction losses. It was recommended that the merit of endwall contouring in reducing secondary losses be verified in a more heavily loaded design. Recently, Boletis (1985) described the effects of endwall contouring on the evolution of the three dimensional flow field in a low speed annular cascade. Contouring was found to decrease the overall losses by about 15 %. The observation of Boletis can be explained as follows: The transverse pressure gradient is significantly decreased at the front part, while the radial pressure gradient imposed by the blade design is counteracted by the creation of a low static pressure region at the tip endwall suction side corner. Certainly, this causes a reduction of inward migration of the low momentum material over the blade suction side surface. The effects of the contraction and the tip endwall curvature extend over the whole blade height. The exit flow field is characterized by a large reduction of the wake region. The overall losses decrease considerably compared to the cylindrical tip endwall case. However, the radial pressure gradients remain important and the radial flow angles in the wake region witness the spanwise migration of low momentum material from tip to hub through the wake.

Recognized that the overall performance would be influenced by changes in radial distribution of loss and exit flow angle. Thus, it is needed to know that the effect of the end wall contours on the stage performance with the rotor in place, allowing an assessment of rotor interaction effects on nozzle performance.

Cooling air injection into secondary flow zone

Turbines blades are cooled with secondary air (cooling air) so that they can withstand high temperature gas. The cooling air is thereafter, injected into the mainstream. Due to the interaction of the injected air with the mainstream, the turbine aerodynamic performance may be worsened, which may lessen the expected gain of the cycle efficiency.

The effect of cooling air injection on three dimensional flows within a linear cascade was investigated by Yamamoto et al (1991). The injection was made from a total of ten slits located around the blade surfaces, as shown in Fig.7. The cascade flows were surveyed with a five hole pitot tube at different measuring planes. The overall loss coefficient along the cascade passage with and without injection based on mass averaged cascade velocity at the exit was calculated. It was found that a small amount of injection from the leading edge in the direction of the mainstream leads to decrease the overall loss. The amount of loss reduction depends on the amount of the injection air and the location of the injection slits even on the suction side or on the pressure side. However, the injection air from the blade suction and pressure surfaces generally decreases the loss because of the additional momentum supplied by the injection air into the mainstream. Also, the injection air interacts strongly and mixes with the passage vortices that are weakened or strengthened by the injection.

In fact, this report studied only one loss coefficient. However, it is necessary to consider the merits and demerits of the injection from various aerodynamic and thermodynamic point of view on various sources of loss arising in cooled turbine.

Sieverding and Wilputte (1981) also studied the effect of the end wall cooling on secondary flow in a straight cascade. The cooling configuration as shown in Fig.8 consists of three inserts in the wall with double rows of holes positioned ; just ahead of the leading edge; inside the blade passage and in the throat. All holes are inclined at an angle of 30° with respect to the wall. The holes for each injection insert are parallel to each other. Fig.8 shows schematically the interference of the coolant flow with the end wall flow. The main results show that the influence of the end wall cooling on the secondary flows depends on the amount of coolant flow, its distribution across the blade passage and the injection flow geometry. The test data also clearly indicated a significant influence of end wall cooling air injection upon the losses and exit air angle distribution. The data suggest that the influence of cooling air should be considered in the selection of the optimum blading angle as well as in the prediction of turbine efficiency. Three cooling air parameters should considered as significant: the cooling to main stream total pressure ratio, the coolant mass flow ratio and the angle between coolant flow, main flow and end wall boundary layer.

Bump blades

Many investigators have studied the effect of blade shape on flow structure and losses in turbine cascades. The present authors (1993) made an attempt to control secondary losses using bump blades. The bump blade is a normal blade with bump on the suction and pressure sides or one of them, as shown in Fig.9. They found that the bump on the pressure side reduces in the secondary loss by about 4% compared to that of the normal blade. The secondary loss increased by 1 % when the bump was made on the suction side. When the bump was made on both the suction and pressure sides the profile loss became higher than that of the unbumped blade. It has to noted that work is needed to understand the effect of the bump on the flow field structure and to find out the optimum position of the bump. Therefore, we suggest that measurements and flow visualization are needed to understand the flow field within the bump blade passage.

Conclusions

Requirements for improved efficiency and flow performance in turbomachinery have led to secondary flow controlling mechanisms. These improvements have been achieved through the use of many types of such mechanisms together with the understanding of the nature of the secondary flow as discussed in this paper. More information is needed concerning the structure of channel flow and the mixing processes of the full turbine stage in the presence of secondary flow controlling mechanisms.

References

1. Ainley, D.G., The performance of axial flow turbines, Proc. Institution of Mechanical Engineering, vol. 159, 1948.

2. Boletis, E., Effects of tip endwall contouring on the three dimensional flow in a annular turbine nozzle guide vane: Part 1: Experimental investigation, ASME paper 85-GT-71.

3. Came , P.M., Secondary loss measurements in a cascade of turbine blades, Inst. Mechanical Engineering Conference Publication 3, 1973, p. 75.

4. Deish, M. E., The problem of end losses in the fixed blade channels of steam turbines, Sovetskoe Kotloturb Ostroenie, 1945.

5. Deish, M.E., Method of increasing the efficiency of turbine stages with short blades, Translation No. 2816, Associated Electrical Industries, Ltd. Manchester, England, 1960.

6. Dunham, J. A review of cascade data on secondary losses in turbines, Journal of Mechanical Engineering Science, vol. 12, 1970, p. 48.

7. Flatt, J., The history of boundary layer control research in the United States of America, Boundary layer and flow control, vol. 1, Pergman Press, Oxfored, England, 1961, pp. 122.

8. Goldstein, R. J., and Spores, R. A., Turbulent transport on the endwall in the region between adjacent turbines blades, ASME Journal of heat transfer, vol. 110, 1988, p. 862.

9. Graziani, R. A., Blain, M. F., Taylor, J. R., and Mayle, R.E., An experimental study of endwall and airfoil surface heat transfer in a large scale turbine blade cascade, Journal

of Engineering for Power, vol. 102, 1980, p. 257.

10. Gregory-Smith, D.G., Secondary flows and losses in axial flow turbines, ASME Journal of Engineering for Gas Turbine and Power, vol. 104, 1982, p. 819.

11. Gregory-Smith, D.G., and Graves, C. P., Secondary flows and losses in a turbine cascade, viscous effects in turbomachines, AGARD cp-351, 1983.

12. Haas, J.E., Analytical and experimental investigation of stator endwall contouring in a small axial flow turbine, (1) Stator performance, NASA Tp-2023, 1980.

13. Haas, J. E., and Boyle, R. J., Analytical and experimental investigation of stator endwall contouring in a small axial flow turbine, NASA Tp-2309, 1984.

14. Herzing, H.Z., and Hansen, A.G., Visualization study of secondary flow in cascades, Trans. American Society of Mechanical Engineering, 1955, p. 249.

15. Hodson, H. P., and Dominy, R.G., Three dimensional flow in a low pressure turbine cascade at its design condition, ASME Journal of Turbomachines, vol. 109, 1987, p. 201.

16. Hoheisel, H., Kiock, R., Lichtfuss, H., and Fottner, L., Influence of free stream turbulence and blade pressure gradient on boundary layer loss behavior of turbine cascade, ASME Journal of turbomachinery, vol. 109, 1987, p. 210.

17. Kopper, F.C., Milano, R., and Vanco, M., An experimental investigation of endwalls profiling in a turbine vane cascade, AIAA paper 80-1089, 1980.

18. Kawai, T., Shinok,i, S., and Adachi, T., Visualization study of three dimensional flows in a turbine cascade endwall region, JSME International Journal, vol. 33., 1990, p. 256.

19. Langston, L.S., Nice, M. L., and Hooper, R. M., Three dimensional flow within a turbine blade passage, ASME Journal of Engineering for gas turbine and power, vol. 99, 1977, p.21.

20. Mobarak, A., Khalafallah, M. G., Osman, A.M., and Heikal, H.A., Experimental investigation of secondary flow and mixing downstream of straight turbine cascade, ASME Journal of Turbomachines, vol. 110, 1988, p.497.

21. Nicholson, J.H., Experimental and theoretical studies of the aerodynamic and thermal performance modern gas turbine blades, Ph.D thesis, Univ. of Oxford, United Kigdom, 1981.

22. Prumper, H., Application of boundary layer fences in turbomachinery, AGARD ograph, No. 164, 1972, p. 311.

23. Sabry, T. I., Alam El-Din, A. M., and El-Hamied, A.A., The Flow Through Bump Cascade of Turbine Blades, International Conference of Mechanical Power Engineering, Alexandria, Egypt, 1993.

24. Salvage, J.W., A review of the current concept of cascade secondary flow effects, Van Karman Institute for Fluid Dynamics Technical Note 95, 1974.

25. Schlichting, H., and Das, A., Recent research on cascade flow problems, ASME Journal of Basic Engineering, 1966, p.221.

26. Sieverding, C.H., Recant progress in the understanding of basis aspects of secondary flows in turbine blade passages, ASME Journal of Engineering for gas turbine and power, vol. 107, 1985, p. 248.

27. Sieverding, C.H., and Wilputte, Ph., Influence of Mach number and end wall cooling on secondary flows in a straight nozzle cascade, ASME Journal of Engineering for gas turbine and power, vol. 103, 1981, p. 257.

28. Topunov, A.M., Tikhomirov, B.A., Chernysh, A.A., Chernousenko, A.G., and Lebedev, Y.I., Controlling secondary flows in the blade rows of axial turbines, Thermal Engineering, vol. 38, 1991. p. 293.

29. Yamamoto, A., Kondo, Y., and Murao, R., Cooling air injection into secondary flow and loss fields within a linear turbine cascade, ASME Journal of Turbomachinery, vol. 113, 1991, p. 375.

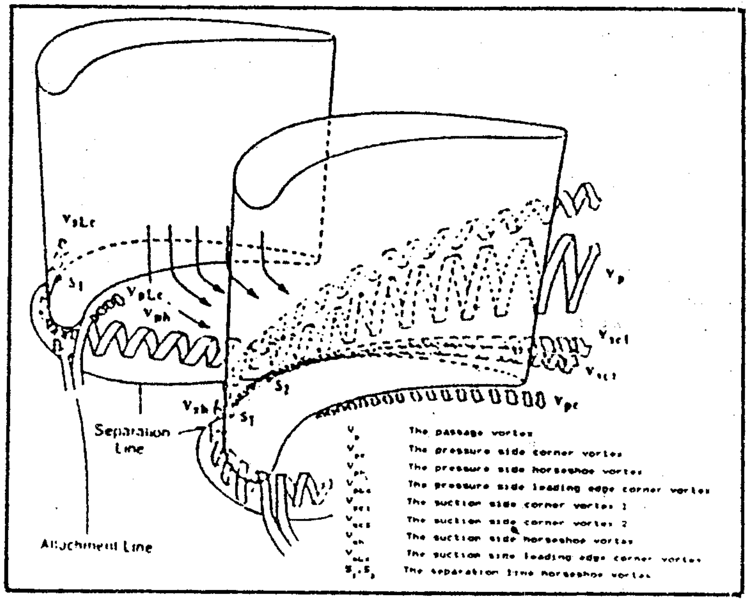

Fig.(3) Diagrams of turbine blade vortices, Chin and Goldstein, [1992].

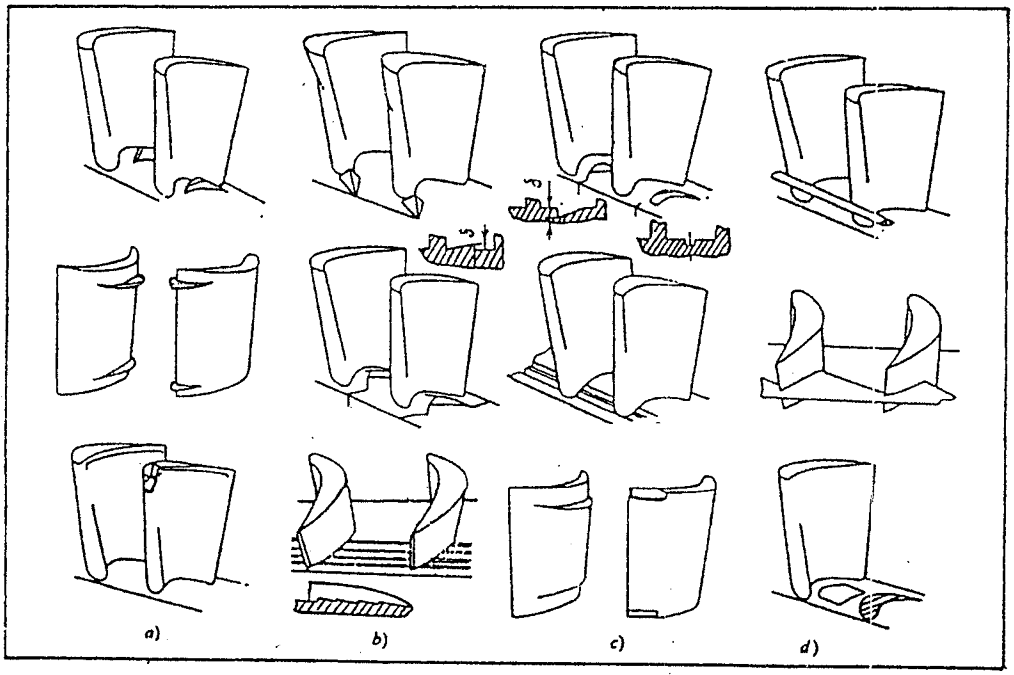

Fig.(4) Secondary flow controlling by changing channel structure, Topunov, [1991].

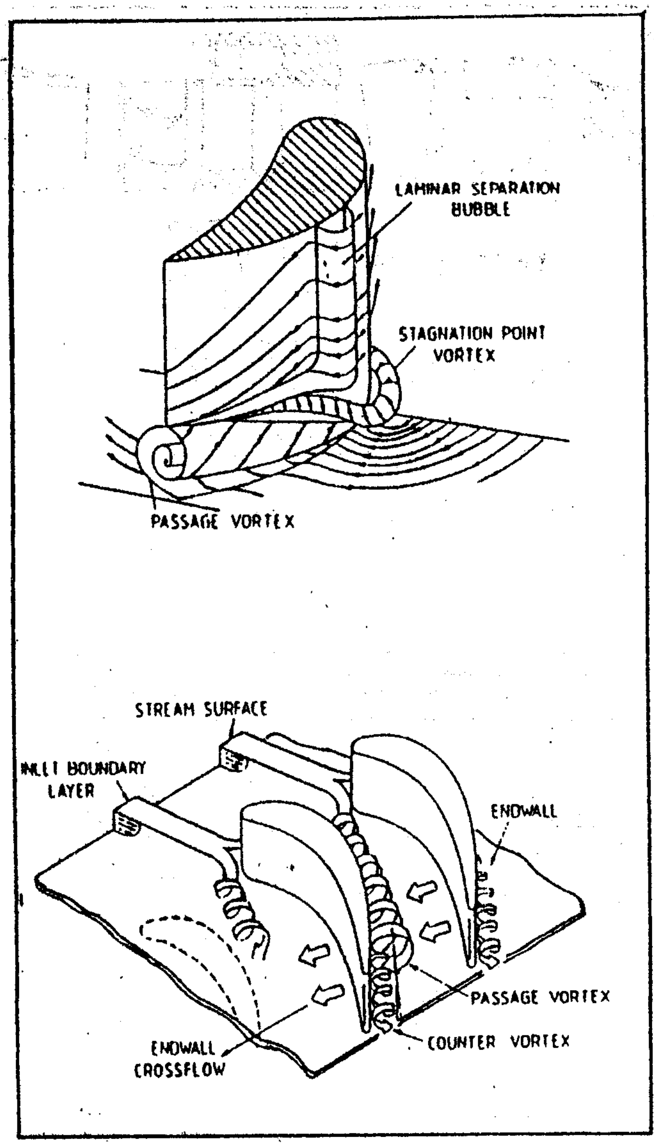

Fig.(1) Endwall flow of a turbine cascade, Langston, [1977].

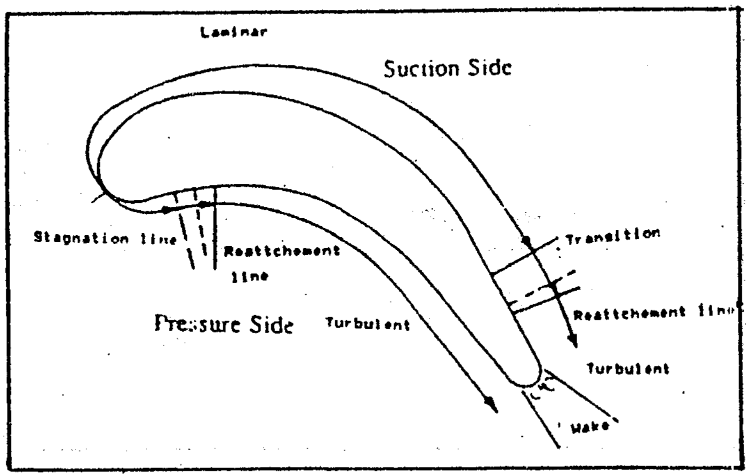

Fig.(2) Boundary layer over a turbine blade,
Chin and Goldstein, [1992].

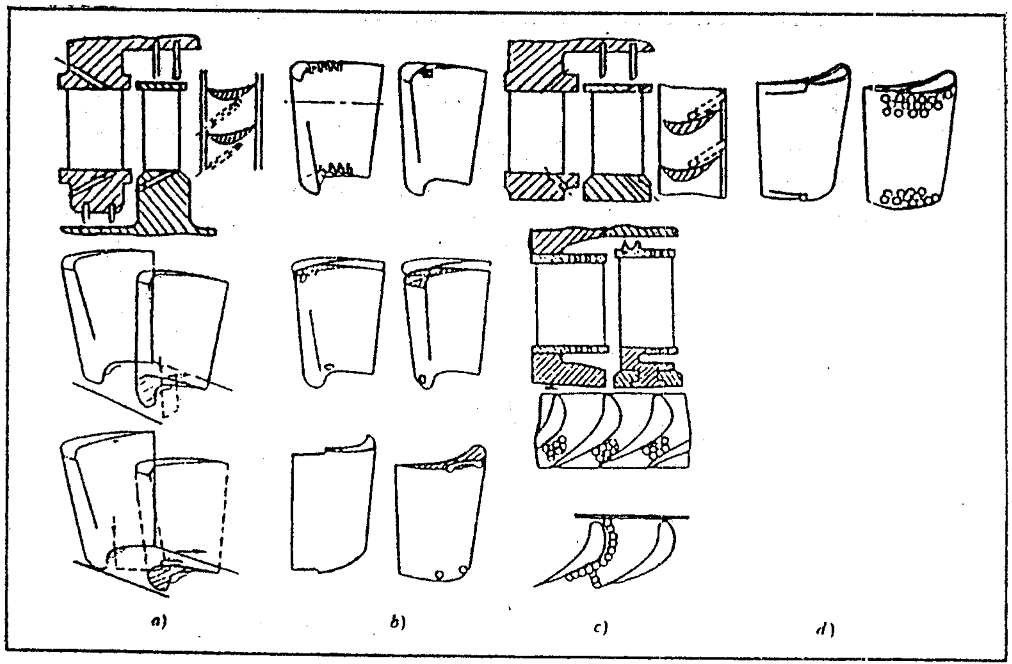

Fig.(5) Secondary flow controlling by using blowing and suction, Topunov, [1991].

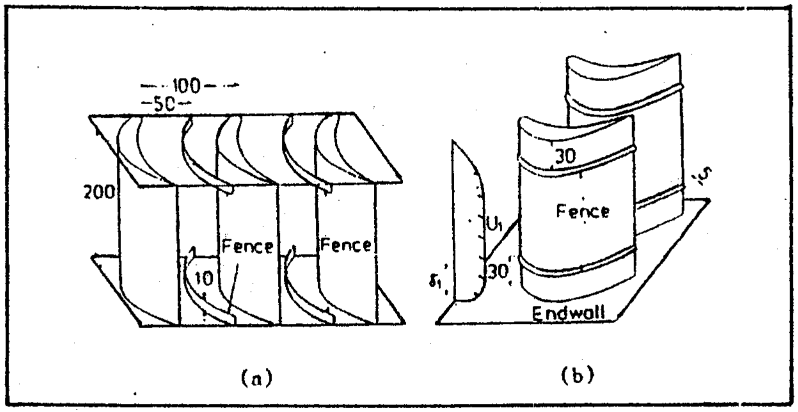

Fig.(6) Secondary flow controlling by using boundary layer fences, Kawai, [1990].

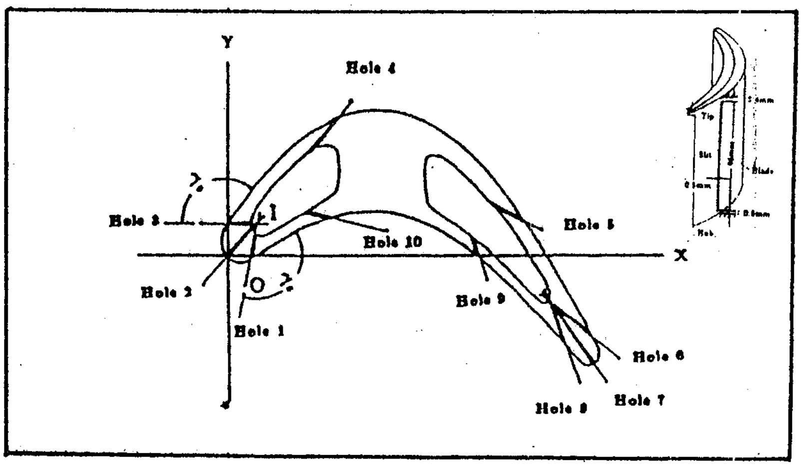

Fig.(7) Secondary flow controlling by using air injection, Yamamoto, [1991].

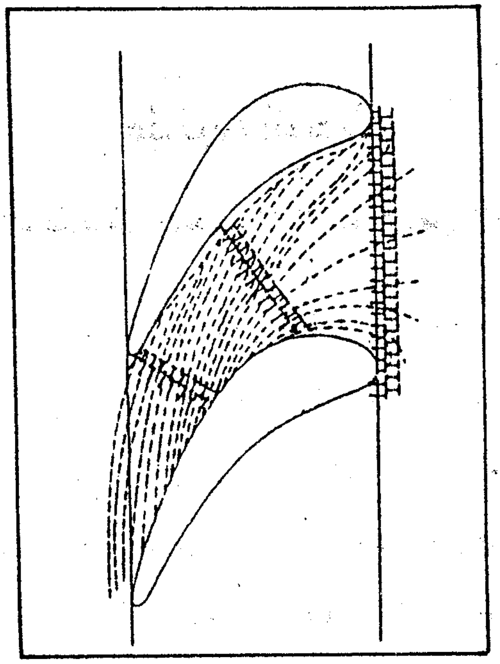

Fig.(8) Secondary flow controlling by using coolent air, Sieverding, [1981].

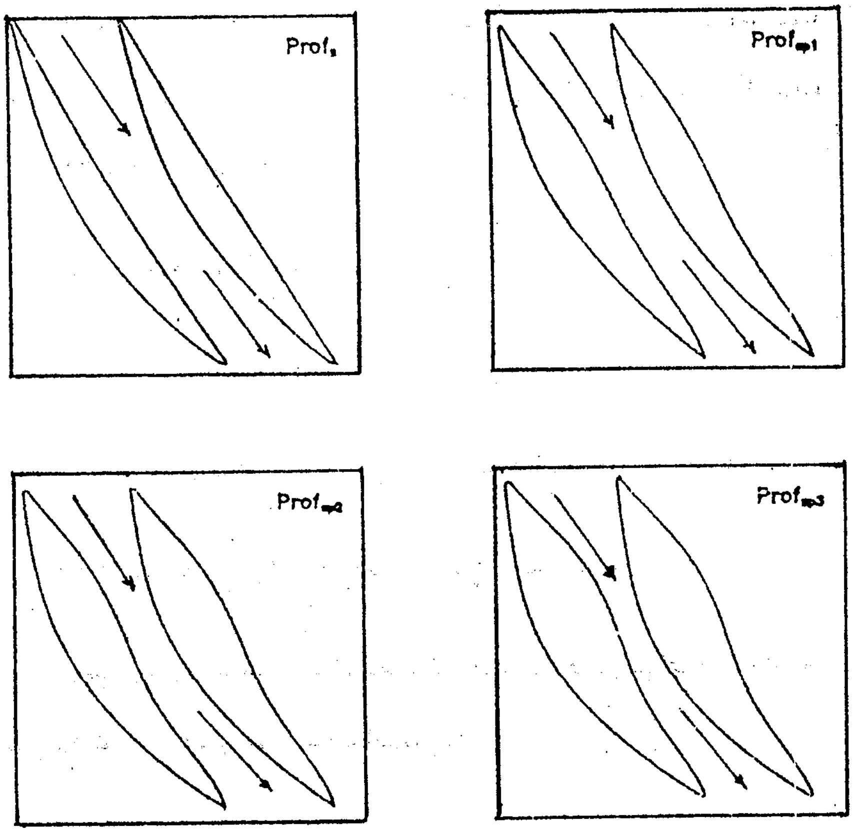

fig.(9) Secondary flow controlling by using bump blades, Sabry, [1993].

ملخص البحث

وسائل التحكم فى المفاقيد الثانويه لريش التربينات

تناول البحث شرح وتحليل كامل لظاهره تولد المفاقيد الثانويه خلال ريش التربينات ومن المعلوم ان وجود هذه المفاقيد تؤثر على كفاءه التربينات وحيث انه من الضروري العمل على رفع كفائه التربينات فذلك يستلزم دراسه وسائل التحكم فى تولد هذه المفاقيد وعلى ذلك تناول هذا البحث مراجعه شامله للوسائل المعمليه والنظريه المستخدمه حتى اليوم فى تقليل هذه المفاقيد .

ايضا اقترح فى هذا البحث عدة نقاط من الواجب دراستها وذلك للوصول الى أفضل طرق للتحكم فى توليد هذه المفاقيد ومن الوسائل التى تم مناقشتها فى هذا البحث هى :-

١ - استخدام طريقة الزعانف

٢ - تحدب نهاية طرف الريش

٣ - حقن الهواء البارد فى منطقة تولد المفاقيد الثانويه .

٤ - استخدام ريش ذات نتوء على جانبى الريشه .

وفى نهاية البحث تم استعراض النتائج التى تم الوصول اليها خلال الدراسات السابقه والتوصيات المقترحه .