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Keynote Address

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Professor Lakshminarayana has asked me to provide the technical introduction to this conference, and it is a pleasure and an honor for me to do so.

The idea for this meeting on the fluid mechanics and design of turbomachinery was born at The Pennsylvania State University during the last year of Professor George Wislicenus' distinguished term of office as head of the aerospace engineering department and as director of the Garfield Thomas Water Tunnel. It was felt that there was a need in the United States for a wide-ranging discussion of turbomachinery aerodynamics and hydrodynamics and that it would be most appropriate to link this discussion with a tribute to Professor Wislicenus, in view of his own broad interests in the field. There have been two recent conferences on turbomachinery in Europe—the Royal Society Conference at Cambridge in 1967 (ref. 1) and the Brown Boveri Conference at Baden in 1969 (ref. 2), but I think it is true to say that they did not range as widely as this conference, which will cover basic fluid mechanics, propulsion aspects of the field, and design applications to turbomachines using gases and liquids.

The reason for the wide range of subjects at this conference is the breadth of Professor Wislicenus' interests. Each of us who has organized a session has been closely associated with him and benefited from his experience and wisdom; and each of us has tended to concentrate in a different specialist area. Yet Professor Wislicenus has made his mark in most of them—the design of one of the first supersonic compressors at Worthington; studies of the performance of the bypass engine (ref. 3); the work of Smith, Trangott, and Wislicenus (ref. 4) (perhaps the first essential statement of the streamline curvature calculation method); the mean streamline method for design of two-dimensional blading (ref. 5) (widely used in the turbomachinery designed here at Pennsylvania State and elsewhere); the contributions to design taking account of cavitation (refs. 6, 7, 8); basic thinking on marine propulsion (ref. 9); and a survey of noise generation (ref. 10). In passing, we may note that not the least of Wislicenus' achievements has been the establishment of his own "school" of research workers, many of whose names appear as joint authors of the publications I have quoted.

It is the hope of the organizing committee that this meeting will provide a unifying environment for workers in turbomachinery aerodynamics. Indeed, we have invited several people not directly in the field to contribute so that we may get a wider view of a difficult subject, for, if there is one area that has almost every difficulty and complication built in, it is turbomachinery fluid mechanics. It is unsteady; it may be incompressible but with cavitation; it may be compressible—mixed supersonic, transonic, and subsonic; it is certainly viscous—including laminar, transitional, and turbulent flows; it is highly three-dimensional and rotational; it may contain large separated regions; it is noisy; and it is closely linked with the thermodynamics of the working fluid. From this complicated fluid mechanics the designer must make his decision, taking into account overall cycle and/or propulsive efficiency. Professor Wislicenus' keen interest in the design aspects of turbomachinery is reflected in a special session we have devoted to this subject.

It is perhaps useful briefly to review some recent developments in the field of turbomachinery fluid mechanics to set the scene for this Conference. In referring to recent developments I would distinguish three phases.

First of all, in the era during and following World War II, the application of classical aerodynamics to turbomachinery design allowed the gas turbine to become a reality and steam turbines to be further developed. I have in mind developments such as the analysis of free vortex flows (which has been associated with the names of Whittle, Griffith, Tietjens, and von Kármán), which enables a rational design of long turbine blades to be undertaken; the analysis of potential flow in cascades by Howell (ref. 11), Kraft (ref. 12), Merchant and Collar (ref. 13), and others; and the application of aeronautical standards in experimental testing of turbomachines and their components. This led to the compressor cascade correlations of Howell (ref. 14) and Erwin *et al.* (ref. 15; see also ref. 16), which provided a sound base for the design of compressor blading. The careful analysis of experimental data from turbines and cascades similarly led to the blading design methods of Söderberg at Westinghouse (ref. 17), Ainley at N.G.T.E. (ref. 18), and Zweifel at Brown Boveri, for axial flow turbine blade sections (ref. 19; see also ref. 20).

Concentrated aerodynamic work continued for a substantial period with the actuator disc theory of Marble (ref. 21); the general equations of Wu (ref. 22); the secondary flow work of Mager (ref. 23), Hawthorne (ref. 24), Smith (ref. 25), Johnston (ref. 26), and Taylor (ref. 27). The diffuser work of Kline and his collaborators (ref. 28) and the work of Emmons (ref. 29) and others on rotating stall are some later examples. This period perhaps culminated in the outstanding review by NACA on axial flow compressor design (ref. 30).

The second major development over the last 10 years or so has been in the massive use of computers to analyze internal flows. Use of the computer has led to the rapid solution of the incompressible cascade flow (usually using the Martensen (ref. 31), Schlichting (ref. 32), and Stanitz (ref. 33) methods); of the three-dimensional meridional or axisymmetric flow (for example, Marsh's numerical solution (ref. 34) of Wu's general through flow equations; of flutter problems (for example, Whitehead (ref. 35)); of the flow past propellers or fans with widely spaced aerofoils (where we may not smear out the vorticity over the complete annulus); and of off-design performance. Perhaps in this stage we may not have continued sufficiently the careful aerodynamic experiments of the first stage, and we may have put too much emphasis on uncorroborated computer solutions. It is very often experimental work from the earlier era that we refer back to in making comparisons between theory and experiment.

I think perhaps we are now in a third era where we are absorbing new aerodynamic knowledge from other fields—the theory of boundary layers and acoustics—but at the same time making maximum use of the computer. This is particularly true in the general area of unsteady fluid mechanics, which is so obviously of vital importance in turbomachinery.[1] Here we see the application of established aerodynamic theory—the work of von Kármán and Sears before the war (ref. 37), for example, together with new questioning of established ideas (witness Giesing's work on the Kutta condition in unsteady flow (ref. 38), something of which you will see in a film to be shown during the symposium).

If there is a main challenge remaining—a fourth stage of development—it appears to me that it lies in the synthesis of all this developing fluid mechanics into the design process. For example, although we know the pressure distribution on the blades is unsteady, no designers are as yet calculating this pressure distribution together with the unsteady boundary layer development and optimizing design as a result. Although estimates of annulus wall boundary layer growth are made, predictions of angle variation through the boundary layer due to secondary flow are not included in the design—at least not to my knowledge. To include all these effects is a vast undertaking, principally in the education of designers and in the integration and management of design and research teams.

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[1] Professor Dean (ref. 36) pointed out some years ago that we would not get any change in stagnation enthalpy in reversible flow through a turbomachine unless the flow were basically unsteady.

So although great progress has been made in the understanding of the internal fluid mechanics of turbomachines, and in establishing this field as a recognized technological discipline, much remains to be done, particularly in the application of the results of research. It is to further this end that this conference has been initiated jointly by The National Aeronautics and Space Administration, The Pennsylvania State University and The Department of the Navy.

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