Differences between the results of this calculation and tests can be accounted for primarily by separation at the shock, and secondarily by wall friction.

The variation of flow through a convergent-divergent nozzle is reasonably consistent with the hypothesis of the preceding paragraph. Differences between calculation and test can be accounted for by separation at the shock, transmission of exhaust-pressure effect upstream through the boundary layer, and friction, in that order of importance.

### Acknowledgment

This paper would be incomplete without acknowledgment of the contributions to this project by Mr. Glenn B. Warren, Manager of Engineering of the Turbine Divisions of the General Electric Company. In his early days as a steam-turbine engineer, Mr. Warren conceived, designed, and constructed this testing machine. As engineer in charge of development, he continued in responsible charge of its operation, and the degree of success attained was largely due to his skill and judgment. In the early stages of its operation the machine was operated and its instrumentation was developed by Mr. Eugene E. Harris.

## Discussion

D. J. Bloomberg.[6] This particular nozzle-reaction-test apparatus was developed and used to obtain comparative performance data on different types of nozzle designs and constructions, including both nonexpanding and expanding nozzles. The main objective of the test was to obtain performance data over the efficient operating range of pressure ratios.

This nozzle-reaction-test apparatus has proved to be a very reliable tool for obtaining basic flow-path data, which even up to the present time are constantly being drawn upon for design information or to assist in analyzing results on nozzle and bucket flow-path test combinations.

In elastic-fluid flow-path design work, there is a decided advantage in obtaining basic data on the separate elements comprising the entire flow path. From these data a calculation system can be worked up which can be used to predict the performance of a flow path built up of various combinations of the separate elements. The performance tests on the combination of the separate elements should serve merely as a check on the calculation system and not as a source of basic data.

The author has analyzed the test data on the expanding nozzles in the low-pressure-drop region, which is usually neglected by the practical turbine designer who is mainly interested in the good-performance region. His demonstration of a calculation system which agrees even approximately with the performance data in the low-efficiency off-design region indicates knowledge of the flow action under those conditions and should be useful either in explaining performance results or in avoiding poor flow-path conditions in flow-path design.

The author makes reference to the application of the test data, obtained approximately 20 years ago, to present-day problems involved in gas-turbine design. At the time the test data were obtained, using steam with about 200 F superheat as the elastic fluid, their application to flow paths using other elastic fluids, such as hot gases or even higher-temperature steam, was not considered. The method of presenting the data in terms of velocity corresponding to isentropic-energy drop was at that time satisfactory.

The method of presenting the test performance of a flow-path element in terms of velocity coefficient, or in terms of efficiency based on isentropic velocities or energies, as used in this paper, and also in general use in the turbine field, may be satisfactory if the data are used for flow path operating with the same elastic fluid (steam) as used in the tests and with approximately the same conditions of supersaturation, Mach number, and Reynolds number.

If the test data obtained with steam, for example, are to be used accurately for the same flow path operating with hot gases or any other elastic fluid, then the data should be presented in the form of efficiency of the actual energy available in the test flow rather than that of the theoretical isentropic energy.

A separate energy correction factor or factors should be used to correct the isentropic energies for such availability factors as supersaturation, moisture, Reynolds number, and any other factor which will affect the availability of the conversion of energy to velocity. The use of the pressure ratio instead of velocity as abscissa will permit a more general use of the data.

The importance of this discussion stems from the difficulty of obtaining precise basic data of flow-path performance when hot gases are the flow medium. Steam is readily obtainable and its thermodynamics properties are probably better known than those of any other flow medium. With proper interpretation, the performance data obtained with steam can be applicable to the use of any other elastic fluid.

D. L. Mordell.[7] The author's results are a beautiful illustration of the statement that a given convergent divergent nozzle is efficient only at the particular outlet Mach number corresponding to the ratio of the throat area to the discharge area.

Referring to Fig. 1 of the paper, it is observed that the velocity coefficient remains high up to an isentropic velocity of approximately 2200 fps. The writer would like to inquire whether any check of the static pressure actually existing at the vane throat was made. Since the reaction is measured, there is no means of determining whether the velocity calculated was produced in the nozzle, as a result of a contraction prior to the geometrical throat, or whether it was produced by continued expansion in the exhaust chamber. The increase in flow coefficient just past unity Mach number favors this second possibility.

If purely convergent nozzles are employed in an annulus, the flow area downstream of the blades may be greater than the throat area if the gas deflects toward the axial direction, so that supersonic velocities may be produced by a type of Prandtl-Meyer expansion around the trailing edge of the blades—the type of flow which Stodola calls expansion in the wedge. The writer's experience appears to indicate that in actual machines, expansion to Mach numbers of the order 1.4 can be attained in this manner with purely convergent nozzles. In the author's test, the high flow coefficients at such Mach number are probably due to the available room for expansion in the exhaust chamber, but in the annulus this increase in flow area must be attained by a deflection. Does the author think it might be possible to make use of this to operate at Mach numbers up to, say, 2? If so it would simplify governing problems considerably.

W. R. New.[8] Nearly as long ago as the completion of the experimental program re-examined by the author, the writer's company constructed and operated reaction testers of several designs. On these machines tests were run over a range of subsonic and supersonic velocities on a number of convergent and convergent-divergent turbine nozzles of the types commonly employed in simple impulse and velocity compounded stages. Com-

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pressed air was the fluid used, and the nozzles discharged directly into the room. The range of geometrical proportions of vane and passage cross section investigated included designs somewhat similar to the smaller divergence ratios discussed by the author. One of the significant dimensions of the nozzles tested was the relatively small height, usually $^1/_2$ or $^3/_4$ in., as frequently specified in small and moderate power steam turbines operating on high pressure.

In our tests the most important characteristic of the velocity coefficient, when exhibited as a function of a Mach number, was that it reached a maximum at a Mach number greater than that corresponding to the nominal expansion ratio of the nozzle. Nominal expansion ratio was defined as the mouth area divided by the throat area of the passage. For example, in Fig. 4 of the paper we would have called $(0.188 \times 0.604) \div (0.162 \times 0.604) = 1.16$ nominal expansion ratio, whereas the author selected $(0.224 \times 0.604) \div (0.162 \times 0.604) = 1.38$ called nominal divergence ratio, to identify the nozzle. The ratio of isentropic enthalpy change at maximum velocity coefficient to that corresponding to the nominal expansion ratio of the passage ranged from about 2:1 in the case of convergent nozzles to a little over unity in the case of nozzles of large expansion ratio.

The second kind of anlytical approach employed by the author to rationalize the performance of expanding nozzles, delivering to a back pressure substantially higher than that corresponding to their expansion ratio, was found in fair agreement with the results of experiments on straight-line-axis nozzles of the type frequently used in ejectors. For turbine nozzles with a curved-line axis intersecting the plane of rotation at a very acute angle, the assumption of isentropic processes modified only by shock normal to the axis was considered to be an oversimplification.

With the focus of attention on improving the design of turbine stages rather than exploring nozzle characteristics, our use of the reaction testers for nozzle work was rather short-lived. The problems of step up, leakage, entrainment, and moisture effects on the nozzle, working in conjunction with a closely spaced bladed wheel, so dwarfed the information which could be gained by reaction tests on nozzles alone that we expanded these experimental efforts in the direction of single and multiple-stage turbine testing. Another successor to the nozzle reaction tester was the impact-traverse type of flow exploration. This we employed for many years in investigations of the effects of all features of geometry and Reynolds number in passages of larger aspect ratio, primarily those of interest in reaction-turbine stages. The exploratory traverse work was confined generally to the field of subsonic velocities.

**Benjamin Pinkel.**[9] The author is to be congratulated on presenting an interesting and informative paper on an important field in which there is very little information.

The following questions come to mind in reading this paper:

1 When an annular nozzle diaphragm is formed from any one of the nozzles tested as elements, what change in performance is anticipated when the flow attempts to establish radial equilibrium between the pressure and the centrifugal forces?

2 For an underexpanded nozzle, particularly in the case of the complete annular diaphragm, would one anticipate a change in direction of the flow in the free-expansion process?

## AUTHOR'S CLOSURE

Mr. Bloomberg points out that "with proper interpretation, the performance data obtained with steam can be applicable to the use of any other elastic fluid"—or, one might add, to the flow of steam under conditions differing from those of the tests. The effect of moisture,to which he refers, was discussed in the paper and was shown to be quite negligible in all but one of the nozzles tested.

He suggests the use of pressure ratio rather than isentropic velocity for the abscissa. Probably Mach number would be better than either. A Mach number of unity is indicated in the figures.

One can readily agree with Mr. Bloomberg that the turbine designer would like to know the effects of supersaturation, moisture, Reynolds number, and (though it was not mentioned by Mr. Bloomberg) specific-heat ratio.

In response to Mr. Mordell's question it may be said, in view of various parallel investigations on nozzles similar to that of Fig. 3, that no contraction exists prior to the geometrical throat.

It is doubtless true, as Mr. Mordell suggests, that for low exhaust pressures a Prandtl-Meyer expansion occurs around the exit edge first encountered by the stream and that this results in an outward deflection of the jet (for the nozzles of these tests as well as for an annulus of nozzles). Certainly nozzles can be designed for Prandtl-Meyer expansion, and indeed, all oblique-outlet nozzles for supersonic velocities should be so designed if the highest efficiency is the object. For a Mach number as high as 2 such a nozzle may prove to have some divergence by virtue of the curvature of the surface near the trailing edge of the partition. It is doubtful, however, that better efficiencies will be attained at low velocities by this method.

Several implications in Mr. New's last paragraph do not seem to be well founded. The reaction method of testing can provide information on the effects of step up and of moisture. Such information from the reaction test is of more general application than that from tests of turbine stages, because it is complicated to a lesser degree by other influences. The impact-traverse type of exploration is not simply an alternative to the reaction test. One might well arrange the impact-traverse, the reaction test, the turbine-stage test, and the multistage turbine test, in that order ranging from the most elementary to the most comprehensive test. It is obvious that each has its function. A rounded turbine development program might well include all these types simultaneously—as did the program of the General Electric Company at the time these tests were run.

The answer to Mr. Pinkel's first question probably depends upon many things not specified in the question. For instance, should the nozzle form be modified to make the passages "nest" together? Should the axis of the nozzle stream be directed tangent to the pitch circle of a nozzle or to that of the bucket? The problem is a complicated one to which these reaction tests yield no answer.

The answer to his second question seems to be that for a row or an annulus of nozzles if the exhaust pressure is lowered to less than that corresponding to the area ratio of the nozzle the stream will deflect outward away from the plane of the nozzle openings. In the extreme case, where the axial component of the velocity leaving the plane of the nozzle openings is everywhere supersonic, any decrease in exhaust pressure will serve to increase only the axial component of the final velocity, and will leave the tangential component unaffected.

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