A typical result of these experiments is as follows: With 1750 F gas a mean blade temperature of about 800 F can be attained with a water rate equal to 2.5 per cent of the gas flow. Data were taken for gas temperatures between 1150 and 2350 F. For the most useful range of spray rates at each gas temperature, the results of these tests can be summarized by the equations

$$T_G - T_{BU} = 0.15\ (T_G - 150) \text{ and } \left(\frac{T_{BU} - T_B}{r}\right) T_G = 438{,}000$$

Here T_{BU} is the uncooled blade temperature in deg F, T_B is the cooled blade temperature, T_G is the gas temperature, and r is the water-spray rate, as per cent of gas flow. Calculations indicated that in a turbine of several thousand horsepower, with larger blade chords and higher pressures, the percentage of water required should be only about one third of that given in the foregoing formula.

The optimum configuration consisted of two spray tubes (180 deg apart), each set into the middle of a turbine-nozzle passage. Each tube was equipped with one spray hole near the roots of the rotating blades, and so directed as to spray perpendicular to the gas stream. Varying the spray direction and the number of tubes had only a moderate effect on the cooling, but setting the tubes into the tails of nozzle guide vanes made the cooling much worse.

Theoretical studies of the effect of spray cooling on cycle efficiency led to the conclusion that, for the spray rates required in the tests, approximately one third of the increase in efficiency made possible by higher temperatures is lost as a result of cooling. If cooling of a practical turbine could be accomplished with only one third as much water, these losses would be reduced proportionately. The large increases in output made possible by higher gas temperatures are virtually unaffected by spray cooling.

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Discussion

J. C. Freche.[4] The paper represents a pioneering effort in a field which offers definite possibilities as an effective cooling method for gas-turbine blades. The experimental data obtained are rather extensive including operation over a range of speeds and inlet-gas temperatures and employing various water-injection configurations. The authors are to be congratulated upon a thorough approach and excellent presentation.

The results would be still more valuable if the experiments had been conducted on a larger blade. Rather serious limitations may be imposed on spray cooling if scale effects are a major consideration, a possibility which can only be determined with certainty by actual test. Because of the basic behavior of the spray-cooling process, similar blade temperatures should result for larger blades where wetting of the blade surface occurs. However, for an appreciable difference in blade size, uniform wetting of the blade surface may not be achieved with the same water-injection configuration. Unless satisfactory configurations are then achieved, the resulting large chordwise temperature differences between the wetted and unwetted blade portions would result in the introduction of shear stresses capable of sharply curtailing blade life.

As indicated by the authors, spray cooling also affords a method of achieving thrust increases in turbojet engines by reducing the blade temperature sufficiently so that the material will withstand the higher gas temperatures required. It should be emphasized, however, that water-spray cooling in flight applications is limited to brief intervals since there are definite limitations as to the quantity of coolant which may be provided. Nevertheless, thrust augmentation may be provided with a minimum-weight penalty for such conditions as take-off, passing into the supersonic regime, or for high-speed maneuver. Length of application of spray cooling is, of course, not a limitation in most stationary installations.

F. K. Fischer.[5] The authors in their paper describe a method of cooling gas turbines in which the blades can be held at a relatively low temperature while operating in an extremely hot gas stream. This is accomplished by direct injection of cooling water into the gas stream ahead of the blades. On first thought the writer believes we would all tend to reject this method as being impractical what with problems of moisture, erosion, corrosion, fouling, and the like. However, when considering a possible design of gas turbine using parts of ordinary

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steel while operating at gas temperatures of the order of 2500 F, spray cooling appeared to be the only method offering a possible solution if we were to use structures essentially as we know how to build them today.

The results which the authors describe were carried out on a supercharger modified and instrumented to permit water spray cooling to check the possibilities of this type of cooling on rotating apparatus. The results were gratifying.

In selecting a method of cooling where the blades are to be held appreciably below the gas-stream temperature, a difficult problem is to cool the trailing edge of the blade so that the temperature difference across the blade cross section is not too great. Theoretical studies indicated the difficulty of cooling the trailing edge effectively by internal cooling of the blade even with liquid as the coolant. Cascade studies on stationary blade packs indicated that direct water injection would cool the trailing edge satisfactorily. The supercharger tests indicated that spray cooling is effective on rotating apparatus. However, the supercharger blades are too small to permit accurate determination of temperature distribution across a blade cross section.

The tests which the authors describe indicate that direct injection of water will cool turbine blades effectively. As to the problem of moisture erosion, this should not be too serious based on steam-turbine experience where exhaust end blades operate in up to 14 per cent moisture at high tip speeds. The problem of fouling could be serious. The tests described were of relatively short duration and indicated some build-up of salts. It should be noted that there is plenty of exhaust heat to evaporate water if necessary, but this means added apparatus.

If appreciably higher temperatures than presently used in gas turbines are to be obtained, some method of effective cooling is necessary. Cooling permits the use of less-costly, less-difficult-to-fabricate materials thus reducing unit costs. This, combined with the other advantages of higher temperatures, such as increased efficiency and increased work per pound of air, resulting in smaller units, is so great that we will continue to see an increasing use of cooling of gas turbines. Water-spray cooling may well play an important part in this development of cooled gas turbines because of its extreme simplicity of application.

Authors' Closure

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