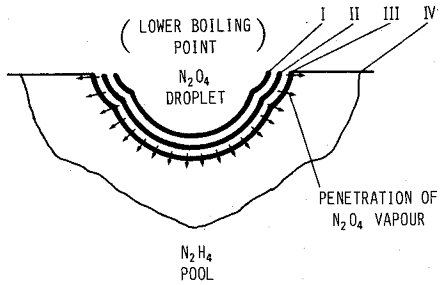

Fig. 4 Explanation of the explosion phenomenon observed in Fig. 3.

It is well known that, when nonreactive droplets interact with a pool surface, a splash appears around the droplet and that the main constituent of the splash is the pool liquid. In the present experiments, it was generally observed that in the N_2H_4(droplet)/N_2O_4(pool) system the splash hardly appeared, as can be seen in Fig. 1. One of the causes of this will be that the main constituent of the splash is N_2O_4, which has a high volatility.

Although there exists some difference between the fluid dynamical processes observed in the N_2H_4(droplet)/N_2O_4 (pool) and the reversed systems, it is seen that the probability of explosion and the strength of the explosion are nearly the same for the two systems.

Summarizing the results, it can be concluded that, for explosions induced by the contact of hypergolic liquids, more evidence has been obtained to support the presumption that the sudden gasification of the superheated surface layer of the more volatile liquid playes the role of a trigger.

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Simulation of Wake Passing in a Stationary Turbine Rotor Cascade

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Introduction

FLOW unsteadiness has been found to exert a considerable influence on the aerodynamic and heat-transfer performance of turbomachinery blades. The most significant contribution to this unsteadiness is caused by "wake passing," the term used here to describe the flow produced on a downstream blade row as it periodically chops through the wakes shed by the upstream blade row. The effect occurs both in the compressor and turbine blade passages, and has been studied by Evans,[1] Walker,[2] and others, for the case of compressors. Turbine studies of the unsteady boundary layer on the rotor blade of a single-stage low-speed axial flow turbine have been performed by Dring et al.[3] and Hodson.[4]

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In cooled gas turbine blades the aerodynamic fluctuations due to wake passing may greatly affect the heat-transfer rates to the blade surface. Dunn and Hause[5] have performed some heat-transfer measurements on a small turbine stage.

Although these experiments have indicated that the effects of wake passing on turbine blades may be substantial, the mechanical complexities involved in obtaining measurements from a high-speed high-temperature rotating turbine stage have as yet precluded detailed boundary-layer and heat-transfer studies at Reynolds and Mach number conditions appropriate to large modern aircraft engines. The fully rotating experiment is not convenient for such detailed investigations. This is partly due to the problems of adequate instrumentation, and obtaining satisfactory flow visualization in rotating turbine stages. In the turbine, it is also difficult to vary independently parameters such as wake characteristics, and the spacing between the wakes.

This Note describes a new experiment that has allowed wake-passing flow to be generated in a stationary cascade of turbine rotor blades mounted in a short-duration wind tunnel. Examples are given of the flow visualization and unsteady heat flux results, obtained using a typical modern turbine blade profile operating at full-scale Reynolds and Mach numbers. Flexibility in the experimental design has allowed effects of wake size, spacing, and combinations of wake passing and freestream turbulence to be assessed. In addition, by running the wake generator at subsonic and sonic flow-relative speeds, studies have been made of the effects of wake passing with and without associated shock waves. Schlieren flow visualization has been used to chart the progress of the wakes through the blade passages. This provides the time history of the wake in the external flow, and, coupled with the boundary-layer history provided by the unsteady heat-transfer and pressure measurements, has revealed the unsteady transition process responsible for the heat-transfer effects.

Rotating Bar Wake Generator

The unsteady flow at the inlet to a first-stage turbine can be reproduced at the inlet of a stationary cascade of rotor blades

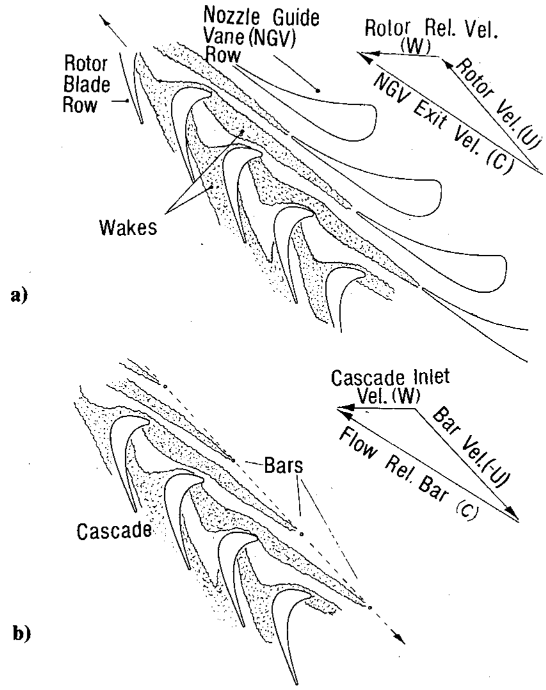

Fig. 1 a) The unsteady (wake-passing) flow in the blade passages of the first-stage turbine and b) the simulation of this flow in a stationary rotor cascade mounted in a wind tunnel by moving a row of wake-generating bars at the correct speed in front of the cascade.

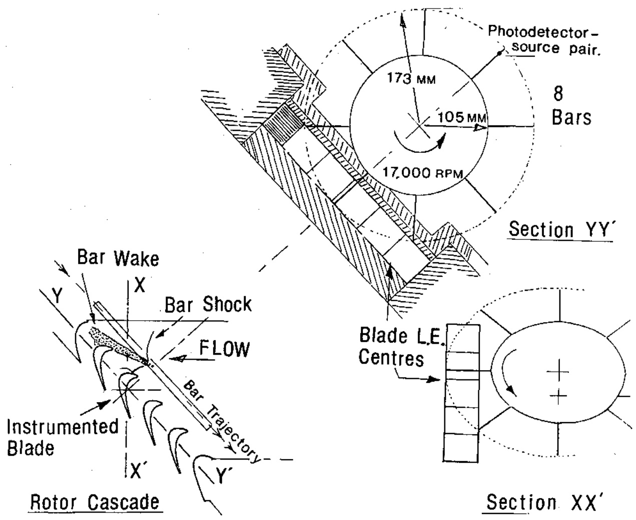

Fig. 2 Schematic of the rotating bar wake generator developed for the experiments.

as shown in Fig. 1. The relative flow velocity to the blades, W, is supplied by the wind tunnel, while the periodic chopping through the wakes from the upstream stage is reproduced by moving a row of wake-generating rods past the cascade at velocity U. Prior experiments showed that, at the rotor inlet position, the nozzle guide vane wakes were symmetrical and could be simulated by the wakes of small circular cylindrical bars and, by moving these bars across the cascade, the correct relative velocity vector diagram can be obtained (as shown in Fig. 1). For a two-dimensional rotor cascade, this could be achieved by passing a rectilinear ladder of bars past the blades, however, this is not mechanically feasible. The present experiments approximate this motion over one cascade blade passage by mounting the bars on the rim of a large-diameter rotating disk (Fig. 2). For structural reasons stranded wires are used, held out by the centrifugal force. This constrasts with the "squirrel cage" apparatus used by Pfeil et al.[6] and Bayley and Priddy.[7]

Test Conditions and Instrumentation

The transient cascade tunnel used for the test was the Isentropic Light Piston Tunnel (ILPT) at Oxford.[8,9] The computer and high-speed data acquisition are outlined by Oldfield et al.[10] and Doorly,[11] while the high-speed heat-transfer instrumentation is described by Oldfield et al.[12] For the heat-transfer measurements, the signals were recorded simultaneously at a 200-kHz sampling rate from seven surface film gages and an optical timing sensor. The flow Reynolds number (based on a model blade chord 67.8 mm and exit Mach number of 0.96) was 2.02×10^6, and for the heat-transfer studies the freestream total temperature was 430 K, corresponding to a realistic gas-to-wall temperature ratio for the blade surface (at ambient conditions) of 1.5. The stranded steel wires fitted to the wake generator measured either 0.9 or 1.7 mm in diameter. The larger diameter bars were used to represent a worst-case nozzle guide vane (NGV), whereas the smaller diameter bars model a more highly efficient NGV.

Prior to the run, the tunnel working section was evacuated and the wake generator driven by a small turbine to a steady speed. The tunnel was then fired to give a 0.3-s steady flow, the cascade exit conditions being maintained by a downstream choked throat.

Schlieren

At 0.17 s into the run, schlieren pictures were taken at various times in the wake-passing cycle. For the schlieren studies, the cascade tunnel was operated at blade design Mach and Reynolds number conditions, but with the upstream total temperature reduced to 300 K. Sequences of photographs were obtained that show the progression of wakes from the large- and small-diameter bars through the cascade. Two photographs from one of these sequences are shown in Fig. 3. The schlieren results have been used both to determine the external flow history and to compare with simple numerical predictions of the wake trajectory through the blade passage.

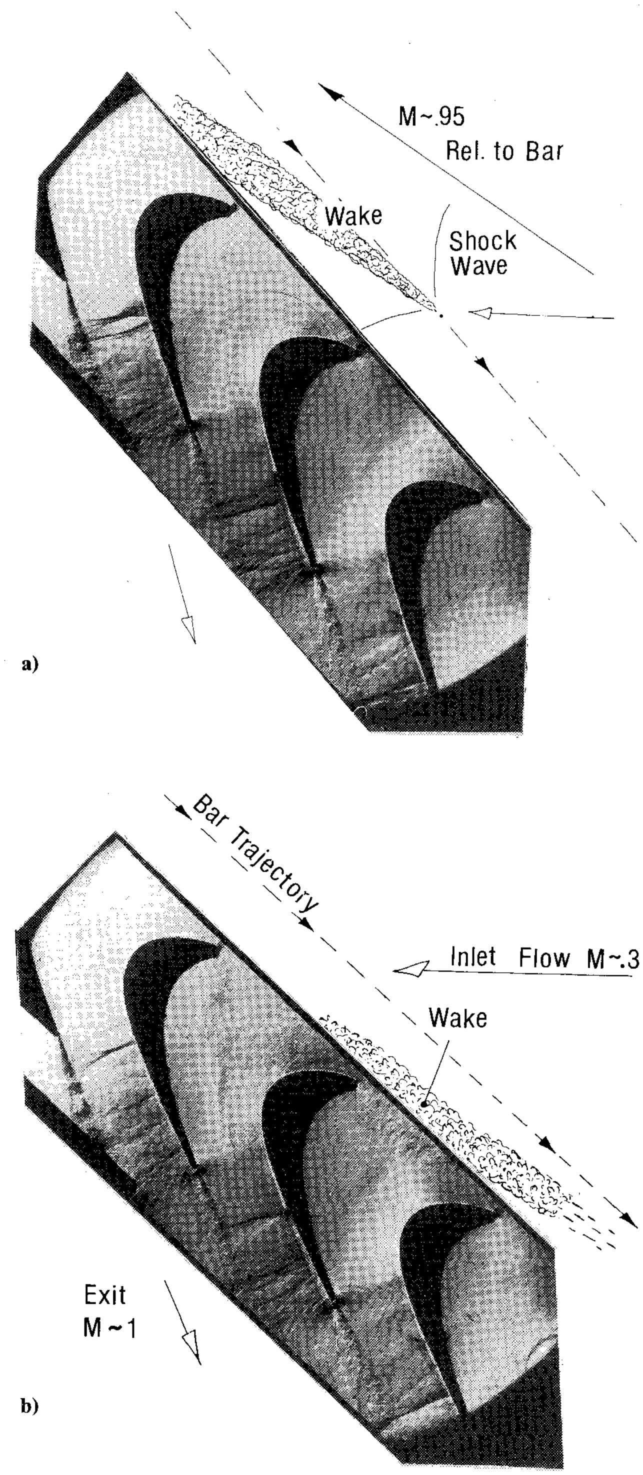

Fig. 3 Two extracts from one of the sequences of spark schlieren photographs obtained: a) At this instant, the recompression shock wave from the bar is shown impinging on the suction surface of the central blade in the photograph. b) Taken at a later time in the cycle, (after the bar shock wave has passed out of the field of views). The high-velocity gradients are observed to result in a gross distortion of the wake in the upper passage. [Exposure ~0.25 μs, shock and wake from large (1.7 mm diameter) bar.]

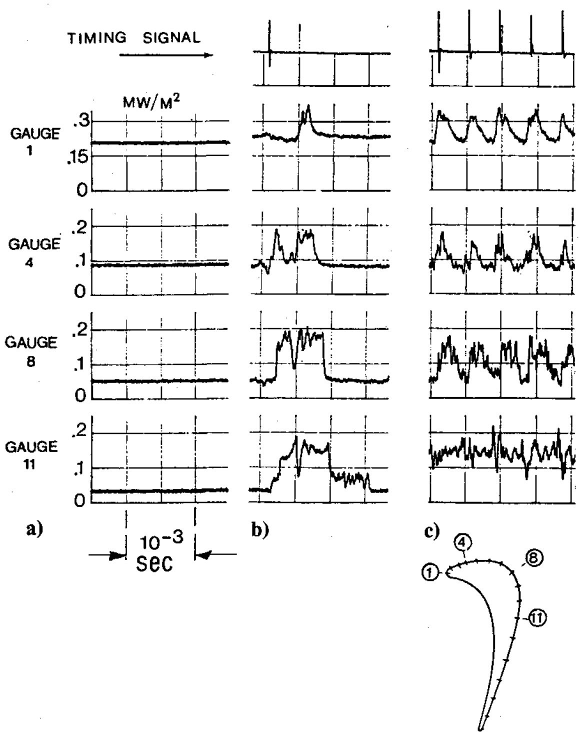

Fig. 4 Comparison of the fluctuating heat-transfer records obtained at four locations on the rotor suction surface for three different conditions, all with low freestream turbulence (<0.4%): a) No wake passing. Steady undisturbed laminar boundary layer at all gages with the mean heat-transfer rate decreasing with distance from the leading edge. b) Isolated wake passing (two bars on the wake generator). Wake from each passing bar produces momentary transition of the boundary layer, resulting in high transient heat transfer. The bar shock wave, which precedes the wake, also produces a turbulent boundary-layer patch; this is the reason for the double impulse seen on traces from gages 4-11. c) Full wake passing (eight bars on the wake generator). The turbulent patches produced by each wake passing have nearly merged by gage 11, to form a continuously turbulent boundary layer.

Unsteady Heat-Transfer Measurements

Heat-transfer data were recorded at a slow rate throughout the run, with a burst of 3000 high-speed data points per channel recorded 0.17 s into the run. Figure 4 shows extracts from the 200-kHz sampled heat-transfer traces at four gage positions on the suction surface, from the leading edge to about 50% surface length, for three different freestream conditions. The traces are all plotted to the same vertical scale and show that, in the absence of significant superimposed freestream turbulence, each passing wake results in a transient increase in the heat-transfer rate (of up to 500% of the undisturbed level).

Results and Conclusions

Analysis of the schlieren photographs and the heat-transfer and pressure measurements has shown that

1) The wakes undergo massive distortion due to the high-velocity gradients in the rotor blade passages.

2) Each passing wake produces a turbulent boundary-layer patch in the blade suction surface boundary layer, which is swept along the blade surface and is responsible for the dramatic transient increases in heat transfer.

3) When the bars were run at near sonic speed, the shock waves produced were also found to initiate turbulent boundary-layer patches. In each wake-passing cycle, the effects due to the shock immediately preceded those due to the wakes.

4) At conditions most representative of those found in the engine (i.e., with closely spaced wakes, and near sonic NGV exit flow velocities), both the wake and shock wave (from the preceding cycle) impinge simultaneously on the blade surface, and the turbulent patches produced in rapid succession during each cycle merge to form an unsteady, turbulent boundary layer by 50% surface distance on the suction surface. The resulting heat-transfer rate at this point approaches that associated with a "steady" turbulent boundary layer produced with the aid of a trip wire, or grid-induced turbulence.

The use of a rotating wake generator in front of a stationary turbine cascade has proved to be an extremely useful technique to study wake-passing phenomena in a turbine stage. High-quality schlieren photographs, combined with high-frequency heat-transfer rate measurements on a stationary blade, allow a comprehensive study of the phenomena involved without the expense and complication of experiments on a rotating turbine stage.

The heat-transfer fluctuations produced by wake passing are large and have a significant effect on the overall heat transfer to the turbine blade.

Forthcoming publications will analyze these wake-passing phenomena more fully than is possible herein, due to space limitations.

Acknowledgments

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