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Improved Jet Coverage Through Vortex Cancellation

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I. Introduction

IN film cooling used in gas turbines, coolant from compressors is introduced to the hot gas stream of the turbine as crossflow jets. The jets form a film layer of cooler air that acts to insulate the turbine material from the hot combustion gases. Thus the ability of coolant jets to adhere to the surface is of crucial importance for the effectiveness of film cooling.

The interaction of the coolant jet and crossflow results in the formation of a pair of counter-rotating vortices, or kidney vortices. The sense of rotation of the kidney vortices is such that they exert two undesirable effects (Fig. 1): 1) hot air is forced down beneath the jet to the turbine wall, and 2) the vortices tend to lift the jet off the surface by the mutual induction between the vortex pair. Here we report the potential of promoting jet attachment by weakening the kidney vortices through cancellation. This is accomplished by introducing a vortex pair inside the jet passage that has a sense of rotation opposite to the kidney vortices (Fig. 2). (Even without the installation of vanes, the canceling vortex pair, or negative pair, can also be formed by proper contouring of the hole exit geometry.[1,2])

II. Experiments

A. Experimental Apparatus

The experiments were conducted in the University of Washington water tunnel facility.[1] The tunnel speed was 8 cm/s. At 26.4 cm from the leading edge of the test plate, a jet was injected from a 3.18-cm-diam (d) hole perpendicular to the oncoming crossflow. The displacement thickness of the crossflow boundary layer, which was laminar, was 0.3 cm. Within the jet passage, two vanes were installed at the sides of the hole, 5.3 cm from the exit ($z/d = -1.7$). By placing these vanes at an angle relative to the flow within the jet passage, a distinct counter-rotating vortex pair was generated as shown in Fig. 3.

The general liftoff behavior of the jet is governed by the blowing ratio, BR, which is the ratio of the mass flux of the jet to the mass flux of the crossflow. Since the densities of both the crossflow and jet are the same, the blowing ratio can be written as a ratio of velocities:

$$BR \equiv \rho U_j / \rho U_\infty = U_j / U_\infty \qquad (1)$$

The blowing ratio for the results presented is 1.6. At this ratio the jet with no vane deflection is completely detached from the surface. This selection thus enables the influence of the vanes to promote jet attachment to be more easily detected. Laser-induced fluorescence and particle image velocimetry were used to visualize the jet and to quantify the vorticity, respectively (for details, see Haven[1]).

B. Results

The kidney vortices can be traced to the vorticity originating within the jet passage boundary layer. This vorticity is initially aligned circumferentially; that is, there is no z component of vorticity w_z. As shown in Fig. 3b, deflection of the vanes generates a z component of vorticity. As a consequence, within the hole passage the jet boundary-layer vorticity and vane-generated vorticity do not interact with each other. Therefore, for this vane-generated vortex pair to have a canceling effect, the jet vorticity must first be turned.

As the jet exits the hole, the crossflow skews the velocity profile toward the downstream. The jet boundary layer along the sides of the hole is turned upward, which realigns the circumferential

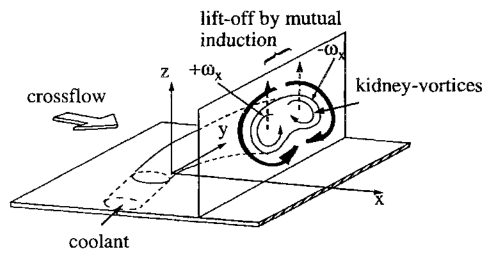

Fig. 1 Kidney vortices represented as $(\omega_x, -\omega_x)$.

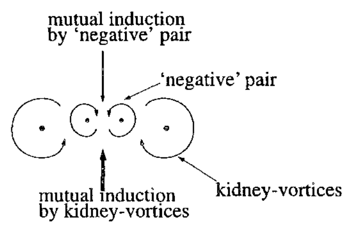

Fig. 2 Vorticity reduction through cancellation.

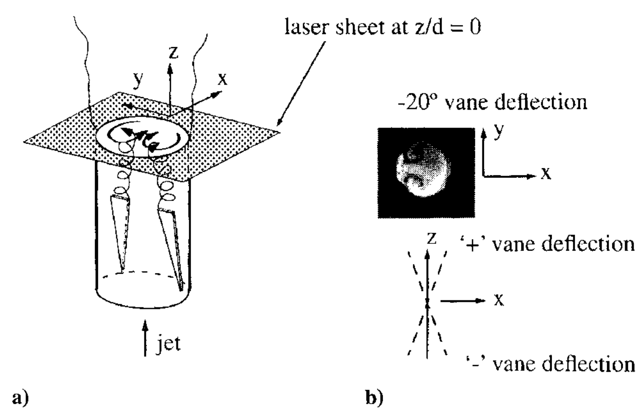

Fig. 3 a) Schematic of vortex pair generation using vanes placed at an angle of attack relative to the jet flow—no crossflow, and b) flow visualization using a laser sheet in the x–y plane located at the plate surface, $z/d = 0$. Vane deflection is -20 deg.

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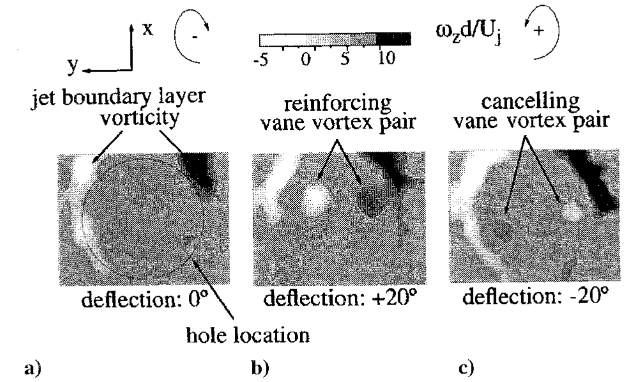

Fig. 4 Time-averaged PIV vorticity plots in x–y plane for $BR = 1.6$ and $z/d = 0.13$. Black and white regions indicate positive and negative vorticity, respectively. The gray regions indicate vorticity that is near zero.

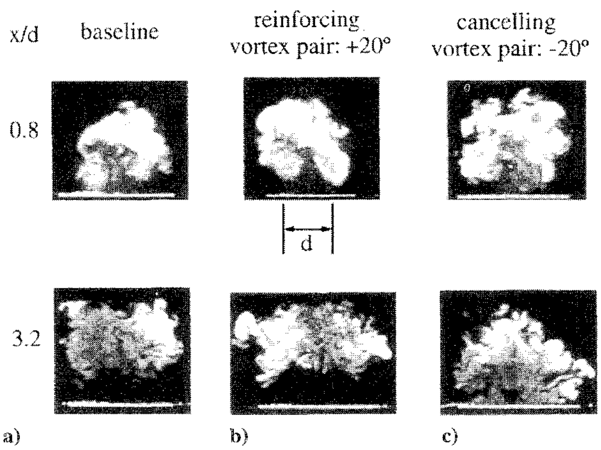

Fig. 5 Jet cross sections in the y–z plane ($BR = 1.6$) for vane deflections of 0, +20, and −20 deg. The hole trailing edge is located at $x/d = 0$.

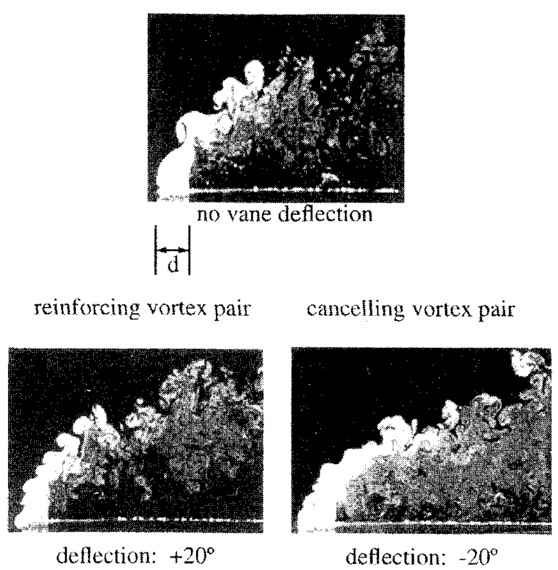

Fig. 6 Jet trajectory along centerline in x–z plane for vane deflections of 0, +20, and −20 deg and $BR = 1.6$.

vorticity and induces a z component of vorticity at the exit plane.[1] By placing a laser sheet at the jet exit in the x–y plane, this z component of vorticity becomes evident along the sides of the hole (see Figs. 4a–4c).

Figures 4b and 4c show that near the center of the hole a counter-rotating vortex pair is generated by the vanes. The rotational sense of this pair, determined by the direction of the vane deflection, is reversed between Figs. 4b and 4c.

Now that both kinds of vorticity are partially aligned at the hole exit plane, they can begin to reinforce or to cancel each other. Further downstream of the hole, the jet vorticity is convected by the jet and turned toward the x direction and becomes the conventional kidney vortices $(w_x, -w_x)$ in the y–z plane of Fig. 1. The vane vortices are likewise transported along the jet trajectory and show up in the y–z plane as either a canceling $(-w_x, w_x)$ or reinforcing $(w_x, -w_x)$ vortex pair. This is the very place where the interaction of the two kinds of vortices becomes visible.

This appears to be the reason why the jet cross sections of Fig. 5c show better attachment further downstream of the hole for the canceling vortex pair, as compared with the reinforcing vortex pair of Fig. 5b. This trend is also seen in the jet trajectory views of Fig. 6.

III. Conclusions

The kidney-shaped vortices formed by a jet in a crossflow, which promote jet liftoff, can be weakened by introducing a canceling vortex pair into the jet prior to the hole exit. Even for a jet that is completely detached from the surface, the cancellation of the kidney vortices causes the jet to reside closer to the plate surface.

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Multiple-Source Schlieren Noise Reduction Measurements

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Introduction

THE image produced by a schlieren system highlights gradients in air density which occur between the source slit and the knife edge, including inside the test section. The practice of verifying system alignment by observing the warm convective flow from one's hand is an example of the sensitivity to density gradients outside of the test section. Expansion of a flow to hypersonic Mach numbers leads to a lower static density than does expansion to supersonic Mach number. This low density, in conjunction with how the shock angles on relevant aerodynamic bodies at hypersonic speeds approach the Mach angle, leads to small density changes in the flow. Thus, density gradients outside of the test section (e.g., thermal currents from cooling of equipment) may be comparable in magnitude, yet are considered to be noise in the desired image. Minimizing these spurious density gradients is one step to alleviating image noise problems, with locating the schlieren system in an evacuated tank as the extreme case. Multiple-source schlieren modifications to existing systems has been shown be another, albeit unquantified, solution.[1] The present research quantifies system performance, supporting the previous theory. In addition, new nonaerodynamic

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