Vortex Generators in Lean-Premix Combustion

A. Eroglu

K. Döbbeling

ABB Corporate Research Ltd.,
Baden-Dättwill, Switzerland

F. Joos

P. Brunner

ABB Power Generation Ltd.,
Baden, Switzerland

A novel fuel-air mixing technique on the basis of vortex generators has been developed and successfully implemented in the worlds first lean-premix reheat combustor of ABB's GT24/GT26 series industrial gas turbines. This technique uses a special arrangement of delta-wing type vortex generators to achieve rapid mixing through longitudinal vortices, which produce low pressure drop and no recirculation zones along the mixing section. In this paper, after a short introduction to the topic, the motivation for utilizing vortex generators and the main considerations in their design are explained. A detailed analysis of the flow field, pressure drop and the strength of the vortices generated by a single vortex generator are presented as one of the three main geometrical parameters is varied. The results obtained through water model tests indicate that an optimum vortex generator geometry exists, which produces the maximum circulation at a relatively low pressure drop price. Moreover, the axial velocity distribution along the mixing section stays uniform enough to assure flash-back free operation despite the elevated inlet temperatures encountered in a reheat combustor. After selecting this optimized geometry, the process of the arrangement of multiple vortex generators in an annular combustor segment is described. The optimum arrangement presented here is suitable both for gaseous and liquid fuel injection, since it requires only one injection location per combustor segment.
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Introduction

On the way to reach the ultra low emission targets of modern gas turbines, lean premixed combustion appears to be the most promising technique available today. This technique requires, on the one hand, passing the maximum amount of air through the combustor, and on the other, a complete mixing of the air and fuel injected into it. Only after complete and uniform mixing of air with fuel, locally lean conditions can be achieved within the combustion zone, which in turn guarantees low NO_X formation. The success of this technique depends primarily on the quality of mixing that can be achieved prior to combustion.

However, achieving sufficiently good mixing within limited space and residence time available in the mixing section of a gas turbine combustor is not a simple task. Difficulties arise due to conflicting requirements from different aspects of the combustor design, such as mixing, flashback safety, pressure drop, robustness and reliability of the design.

In order to obtain proper mixing of the fuel and the air streams both large-scale distribution and fine-scale mixing are necessary. However, given the fact that the mass flowrate of the fuel accounts only a few percent of the mass flowrate of the air, and the momentum of the fuel injection is limited with the available supply pressure, it is not possible to distribute the fuel uniformly within the air stream when a limited number of injection points are employed. Unfortunately, a potential multi-point injection solution runs into its limits too, when the size of injection orifices fall below an allowed limit. Additionally, suitability of such a solution for liquid fuel injection, which requires special atomizers, is questionable. Another problem which led to abandonment of this path in the past has been the combustion instabilities observed, especially under high pressure conditions.

A simple way of overcoming several problems associated with achieving proper mixing quality is utilizing the momentum of the air stream via vortex generators. By this way, large scale vortices can be created by the vortex generators which are employed first for bulk distribution of the fuel and subsequent fine scale mixing. A comprehensive research program has been undertaken at ABB Corporate Research Center to develop fast mixing techniques for low emission combustion, based on vortex generators. The requirements that no recirculation or low velocity zones can be tolerated and the pressure drop due to vortex generators has to be as low as possible led to vortex generators which generate exclusively streamwise vortices.

A design on the basis of these vortex generators have been developed and implemented in the second combustor (SEV) of GT24/GT26 as shown in Fig. 1. A more detailed view of the vortex generators, as pictured from the downstream end of the combustor, is presented in Fig. 2.

Previously, a detailed account of the development of the GT24/GT26 machines, EV burners and SEV combustors have been presented [1–5]. In this paper the fundamental findings acquired with various vortex generator geometries during the development of the SEV combustor are described. First, flow field measurements with laser Doppler anemometry (LDA) and mixing quality investigations with laser induced fluorescence (LIF) techniques from water model tests are presented. Then, conclusions are drawn on the optimum vortex generator geometry based on mixing speed, pressure drop and flashback danger. Additionally, the arrangement of multiple vortex generators with integrated fuel injection in a combustor segment and resulting vortex pattern and mixing quality are presented. Finally, main results and conclusions from these investigations are summarized.

Experimental Techniques

The mixing and aerodynamics investigations reported here have been carried out in a water channel with transparent models which have full optical access from all sides and from the downstream end for LIF and LDA measurements. Additionally, static pressure measurements have been conducted in these models with pressure tabs installed upstream and downstream of the mixing section model.

The water model has been operated in closed-cycle mode, with the exception of the LIF tests, during which it was switched to open-loop mode in order to prevent contamination of the main stream with injected dye. The mean axial velocity of the main flow in water model was 1 m/s, resulting in a Reynolds number on the basis of the hydraulic diameter of about 54,000. Upstream of

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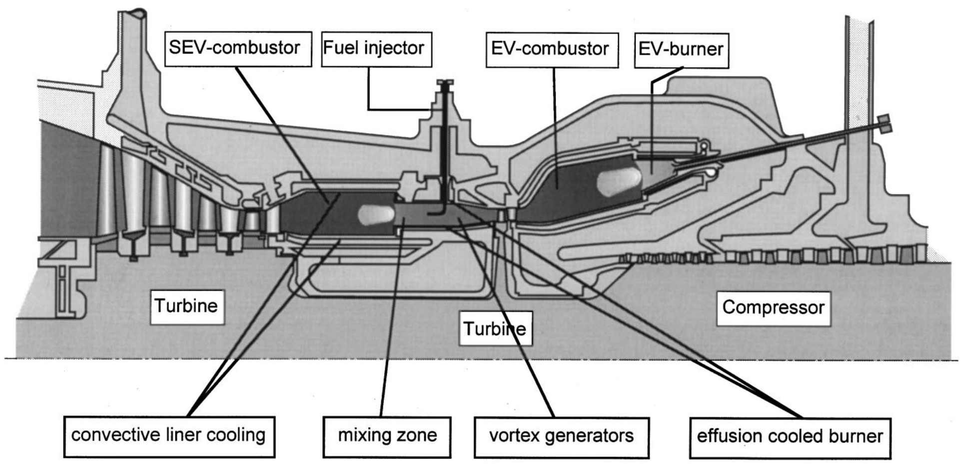

Fig. 1 Combustion system of GT24/GT26 gas turbines

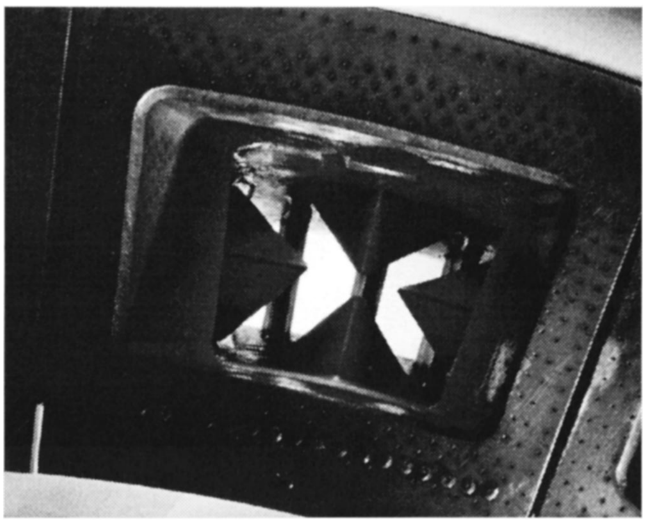

Fig. 2 SEV combustor as viewed from the downstream end

the test section, a settling chamber, equipped with honeycomb-screen type of flow straighteners, followed by a 9:1 area ratio matched-cubic contraction ensured nonuniformities in the mean axial velocity of less than 2 percent and a free-stream turbulence intensity of about 1.3 percent.

The LIF tests have been conducted with the blue line (488 nm) of a 5 W Argon-Ion laser beam, transmitted to the test rig via fiber-optic cable and expanded to a sheet of about 0.6 mm thickness via a cylindrical lens. The injected fluid is a weak solution of disodium fluorescein, as the main stream is free of dye. The injectant concentrations visualized with this technique have been recorded with a monochrome CCD camera and digitized with the help of an 8 bit frame grabber board, which was installed on a computer. A commercial image processing software was used for evaluation of statistical values such as the mean injectant concentration and the standard deviation by averaging 10 successive pictures. The accuracy of this method is estimated to be better than 5 percent.

The velocity measurements have been carried out with a two-component LDA system, operated in backscatter mode. Two components of the velocity are measured simultaneously and the third one is measured separately by rotating the probe 90 deg with respect to first measurement. The measurement probe was traversed with a computer controlled three-axis traverse system.

Reference Case

As a starting point, the mixing characteristics of a fuel injector without any vortex generators are of interest. A number of different injection geometries, including transverse jets injected from inner and outer walls, in-stream tube injectors and central single point injection have been tested. Due to practical considerations (e.g., number of parts, cooling, suitability for liquid fuel injection, thermoacoustic instabilities) an injector geometry as depicted in Fig. 3 has been selected. This injector consists of a single tube which is inserted into the flow through outer liner and bent 90 deg in the flow direction. Four injection holes are located at the tip, pointing slightly away from the horizontal plane in order to achieve the best possible distribution over the channel cross sec-

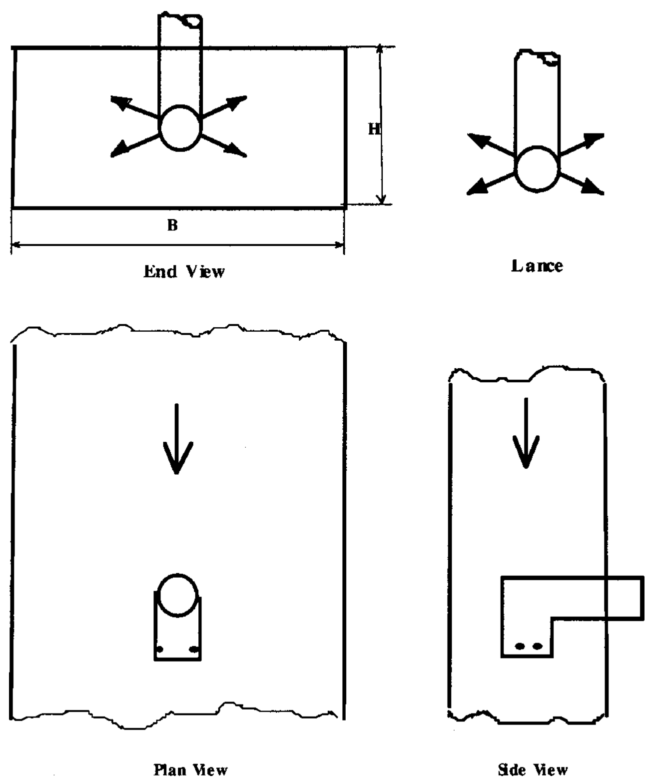

Fig. 3 Injection geometry for the reference case without vortex generators

tion without fuel engulfment in the wake of the injector and without impingement of the fuel jets on the liner walls.

The LIF pictures of injectant concentration over planes perpendicular to mainflow direction are given in Fig. 4, at streamwise distances of $z/H=0.1$, 1, 2, and 3. As can be clearly observed from these pictures, there exists zones with a wide variation in fuel concentration next to each other in addition to regions where no fuel exists, even at three channel-height streamwise distance from the injection. Additionally, with the light sheet positioned parallel to flow direction, radial and circumferential symmetry planes are given in Fig. 5. The flow direction is from right to left. The injector is partly visible at the right side of the picture. These concentration pictures indicate that the quality of both large and fine-scale mixing is far from being acceptable. Additional variants of the same injection geometry with increased injection momentum or other injection hole arrangements deliver similar results. Namely, only incremental modifications in the large-scale distribution pattern can be achieved when relied on the momentum of the injection alone. A major improvement in mixing requires utilizing the momentum of the main stream via vortex generators.

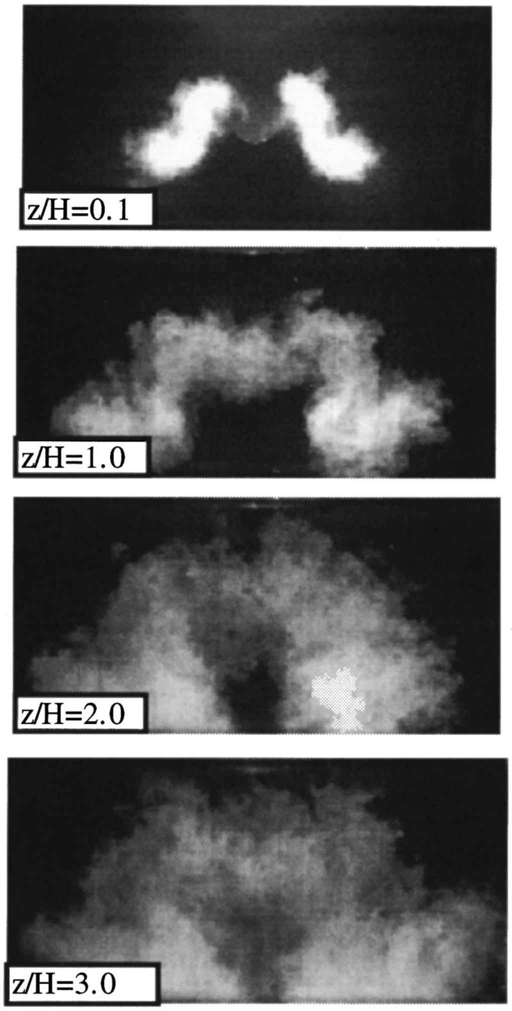

Fig. 4 The LIF pictures of fuel concentration at four successive stations downstream of a central lance without vortex generators

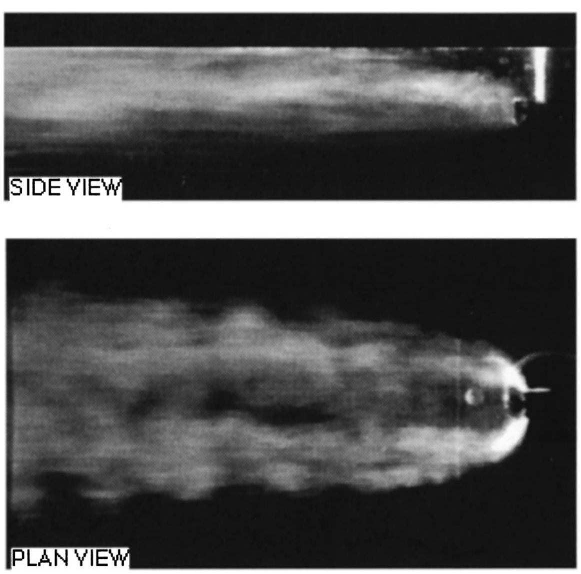

Fig. 5 The LIF pictures of fuel concentration in streamwise planes downstream of a central lance without vortex generators

Single Vortex Generator

Upon recognition of the fact that the mass and momentum flow rate of the injection are not high enough to achieve the mixing quality needed within an acceptable axial length, methods of utilizing the momentum of the main stream have been investigated. The main requirements from a successful technique are as follows:

1 no recirculation zones or regions of low velocity along the mixing section where self-ignition may occur or the flame can be attached
2 low pressure drop
3 applicable both for gaseous and liquid fuel injection
4 suitable geometry for cooling in case it is necessary
5 simple and robust design

The requirements of low pressure drop and high safety against flame in the mixing zone led exclusively to delta-wing type vortex generators which can generate streamwise vortices without any recirculation zones. In order to satisfy other practical considerations such as mechanical integrity and cooling, a tetrahedral geometry, which consists of two half delta-wing side surfaces and a full-delta-wing upper surface has been chosen. A sketch of this device is given in Fig. 6, labeled with the principal parameters which define the geometry.

A series of water model tests with this type of vortex generators have been carried out in order to optimize the strength of the vortices produced, the flow velocities downstream, and the pressure drop. These tests have been conducted in a rectangular plexiglas channel. The ratio of channel height to VG height H/h was above two in order to minimize the influence of channel walls on the flow field. The measurement planes are perpendicular to the flow direction and located at $z/H=0.1$, 0.5, 1.0, 2.0, and 3.0. The height to width ratio of the vortex generator was fixed as the length to width ratio of the vortex generator is varied in four

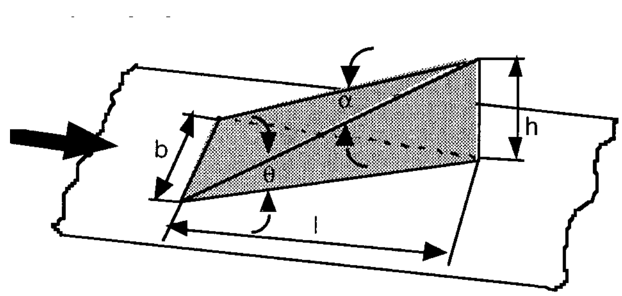

Fig. 6 The geometry of a single vortex generator element

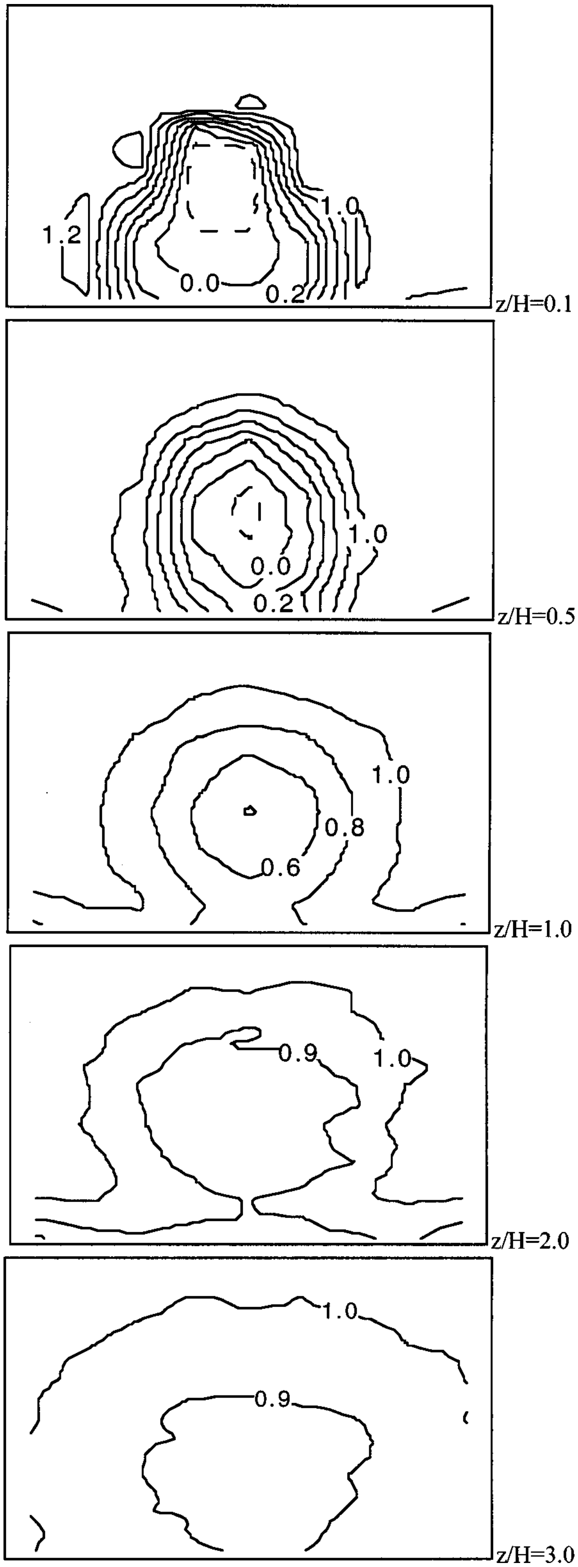

Fig. 7 Normalized axial velocity (U/U_∞) distributions at five successive planes downstream of vortex generator version A

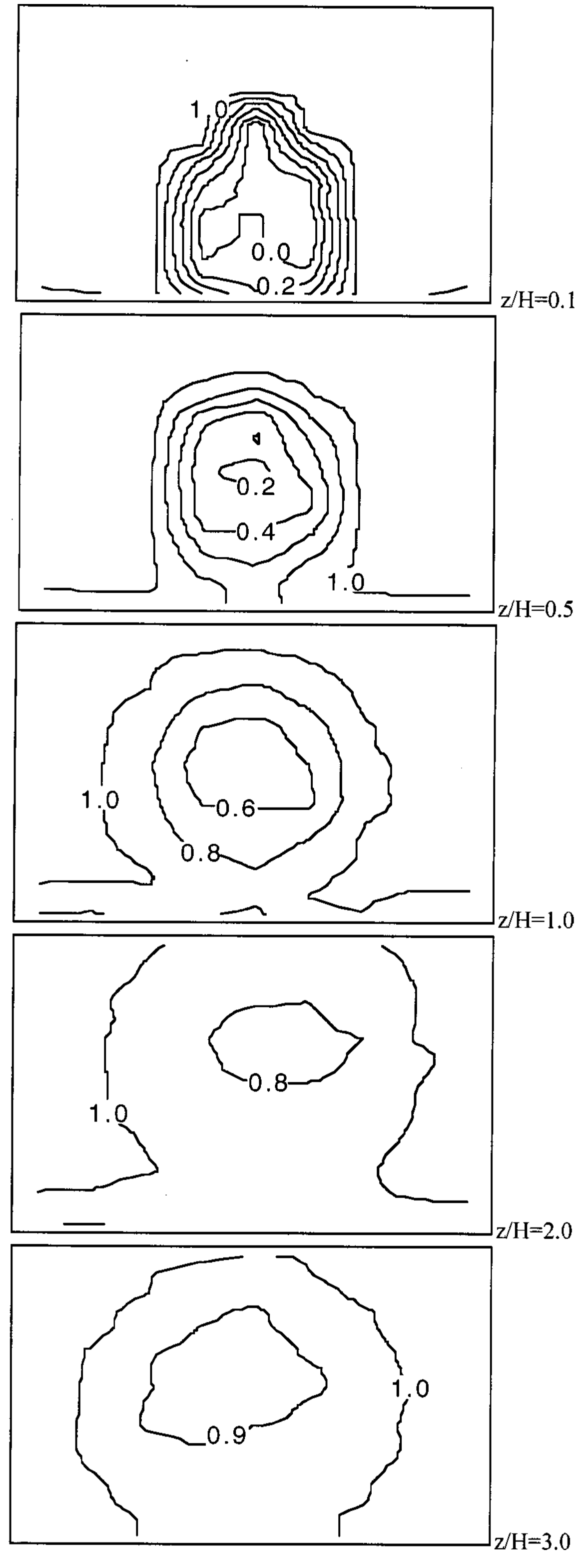

Fig. 8 Normalized axial velocity (U/U_∞) distributions at five successive planes downstream of vortex generator version B

discrete steps. These four steps are labeled as versions A: length less than width, B: length equal to width, C: length 50 percent greater than width, and D: length equal to twice the width.

Axial Velocity Distribution Along the Mixing Section. All three components of the flow velocity have been measured at successive stations downstream of a vortex generator for constant vortex generator height (h) and width (b), as the length of the vortex generator (l) has been varied. Among all velocity components, the mean axial velocity component is a good indicator of the potential flame stabilization danger in the mixing zone. In Figs. 7–10, a series of contour plots showing the distribution of

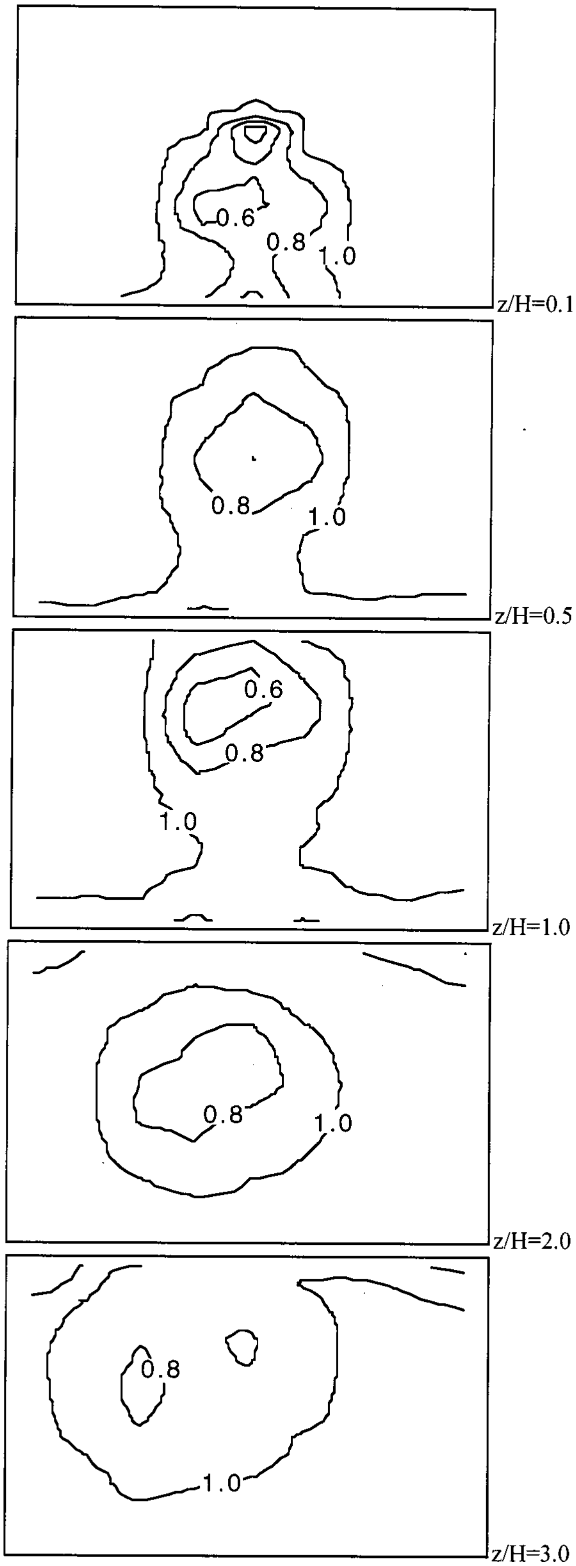

Fig. 9 Normalized axial velocity (U/U_∞) distributions at five successive planes downstream of vortex generator version C

the mean axial velocity over transverse planes downstream of the vortex generator are presented for all four geometries tested. The horizontal axis length of the plots correspond to the central 50 percent of the total channel width. The vertical axis of the plots covers the bottom 62.5 percent of the total channel height. The velocity values shown are nondimensional, normalized with the mean axial velocity.

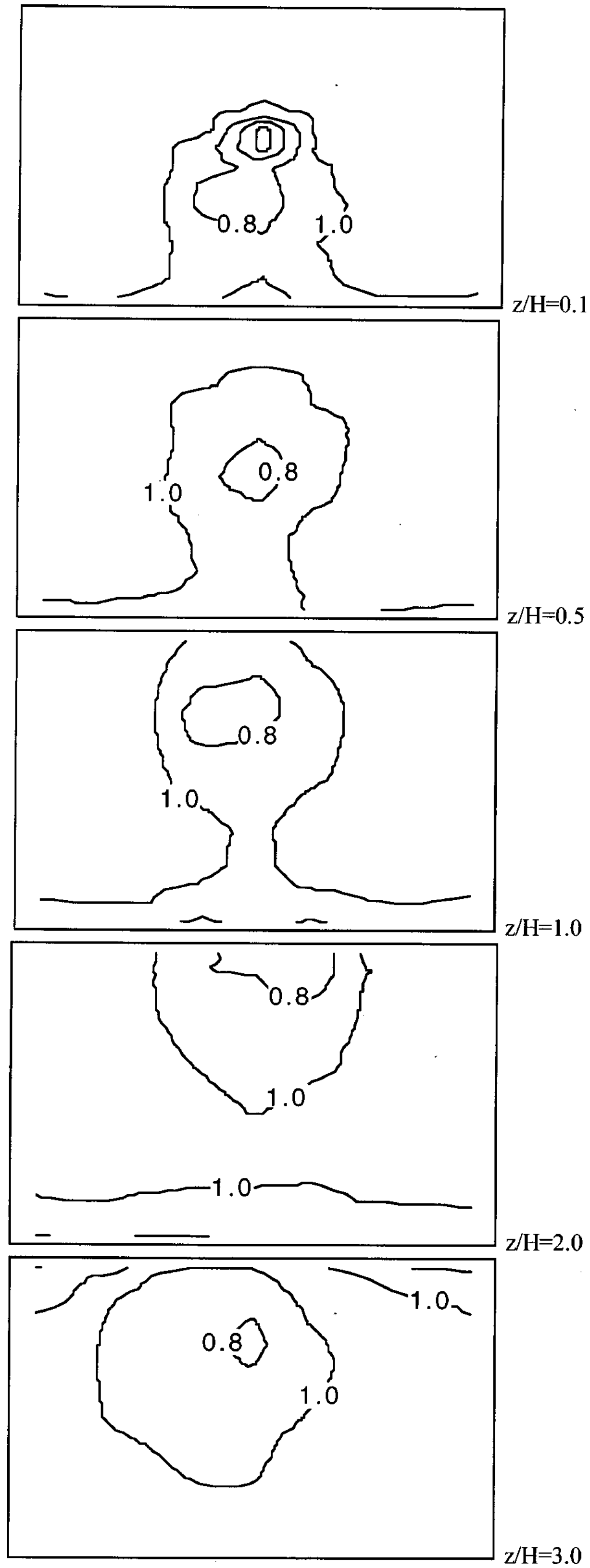

Fig. 10 Normalized axial velocity (U/U_∞) distributions at five successive planes downstream of vortex generator version D

The data from the first measurement plane at $z/H=0.1$ reveal that the first two geometries, namely A and B give rise to a recirculation zone at this plane immediately downstream of the vortex generator. The other two geometries, namely C and D do not exhibit any negative or zero velocity zones.

Further downstream at $z/H = 0.5$, the recirculation zone downstream of version B is already closed, as the negative velocities of version A are replaced by zero velocities. Evidently, all variants tested exhibit positive axial velocities starting from $z/H = 1.0$. The growth rate of the region which is influenced by the vortex generator is the largest for the version A. At $z/H = 3.0$, the influence of the vortex generator is visible over almost the entire channel cross-section for this shortest variant tested as the region influenced by the longest one is still relatively small at this station.

These results demonstrate that, for a given h/b ratio, a minimum l/b ratio is necessary in order to prevent the formation of a recirculation zone downstream of the vortex generator. The exact value of this critical parameter can be best determined after considering the remaining two aspects of the design. The first one is the circulation, which is a measure of the vortex strength or, indirectly, the quality of mixing that can be achieved by a vortex generator. The second one is the pressure drop caused by this device, which influences the efficiency and power output of the whole cycle.

Circulation Versus Pressure Drop. In addition to providing the basis for the assessment of the potential danger of flame stabilization in the mixing section, the velocity measurements mentioned above served to determine the strength of the vortices generated by each vortex generator. Based on the velocity distribution over transverse planes downstream of the vortex generator, it was possible to determine the vorticity distribution, which is defined as the curl of the velocity vector, namely

$$\vec{\omega} = \vec{\nabla} \times \vec{V} = \left(\frac{\delta}{\delta_x} \vec{e}_x + \frac{\delta}{\delta_y} \vec{e}_y + \frac{\delta}{\delta_z} \vec{e}_z \right) \times (U\vec{e}_x + V\vec{e}_y + W\vec{e}_z). \quad (1)$$

As far as the strength of the longitudinal vortices is concerned, the streamwise component of the vorticity vector is of main interest, which is defined as

$$\omega_z = \left(\frac{\partial V}{\partial x} - \frac{\partial U}{\partial y} \right). \quad (2)$$

The partial derivatives in Eq. (2) can be approximated by using a central differencing scheme

$$\frac{\partial V}{\partial x} = \frac{V_{i+1,j} - V_{i-1,j}}{2\Delta x} \quad (3)$$

and

$$\frac{\partial U}{\partial y} = \frac{U_{i,j+1} - U_{i,j-1}}{2\Delta y}. \quad (4)$$

Substituting (3) and (4) in (2) yields,

$$\omega_z = \left(\frac{V_{i+1,j} - V_{i-1,j}}{2\Delta x} - \frac{U_{i,j+1} - V_{i,j-1}}{2\Delta y} \right), \quad (6)$$

where i and j correspond to the coordinates of the grid point in x and y directions, respectively.

The circulation, Γ, as the value of the net vorticity over a region of the flow, is defined by

$$\Gamma = -\oint \vec{V} \cdot d\vec{s}. \quad (7)$$

This line integral can be converted to a surface integral by employing the theorem of Stokes [6], namely

$$\Gamma = -\int_S \int (\vec{\nabla} \times \vec{V}) \cdot d\vec{S} \quad (8)$$

or

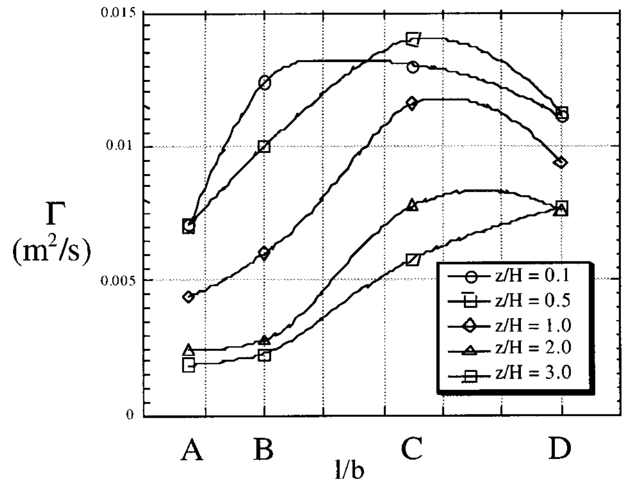

Fig. 11 Circulation values calculated from the velocity measurements at five successive planes as a function of length to width ratio of the vortex generator

$$\Gamma = -\int_S \int \vec{\omega} \cdot d\vec{S}. \quad (9)$$

This surface integral can now be calculated in discrete steps in order to calculate the circulation for each measurement plane as the sum of streamwise vorticity multiplied with the surface area of the element

$$\Gamma = -\sum_{j=1}^{M} \sum_{i=1}^{N} \omega_{i,j} \Delta x \Delta y. \quad (10)$$

This procedure has been repeated over all measurement planes for all four variants tested. The results are given in Fig. 11 for five successive planes, in the form of the circulation calculated with this method as a function of vortex generator length to width ratio.

Additionally, static pressure difference across the vortex generators, as measured between a plane located at one channel height upstream and a second plane located at eight channel height downstream of the vortex generator, are presented in Fig. 12. These measurements have been carried out both with a single element and four identical elements positioned side-by-side.

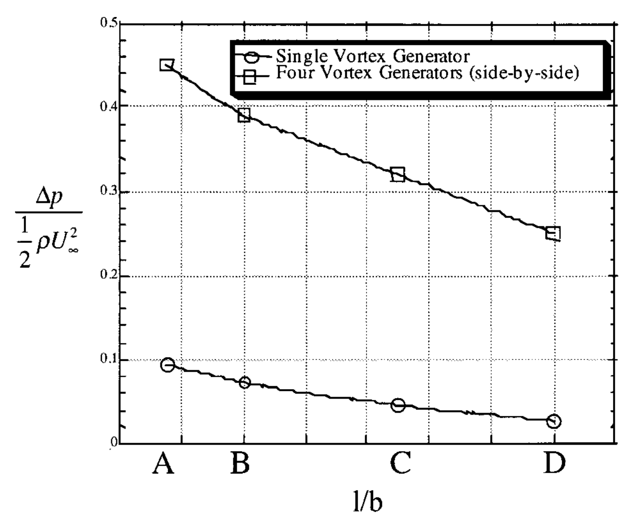

Fig. 12 The pressure drop coefficient of a single and four vortex generators as the length to width ratio is varied

The dependence of pressure drop coefficient on the vortex generator length is monotonic, as one would expect. In other words, the pressure drop caused by a vortex generator increases steadily with decreasing length. This can be attributed to the fact that with decreasing vortex generator length, the portion of the dynamic pressure which can be recovered downstream is reduced as the steeper angle of attack leads to higher transverse velocity components and eventually to a recirculation zone with zero and negative axial velocities.

On the other hand, the circulation distribution reaches a peak around version C as the vortex generator length is reduced. Further reduction in the length after this point causes the circulation to decrease. This also can be explained in the light of the velocity measurements which are in agreement with the previous studies on swirling flows and vortex breakdown. Studies on delta-wing type vortex generators have shown that for a fixed angle of sweep, increasing the angle of attack leads to breakdown position of the vortices to move upstream. In the extreme case of very high angle of attack, the breakdown position is located at the leading edge of the vortex generator. After breakdown, part of the streamwise vorticity is transformed into spanwise vorticity within the recirculation zone.

Based on this information, it can be concluded that for the tetrahedral vortex generator geometry selected, an optimum length exists which generates the strongest vortices for a given width and height. By selecting the geometry of the vortex generator at this optimum value, the most important requirement on the way to achieve the best mixing quality at the minimum pressure drop price is fulfilled.

Multiple Vortex Generators in a Duct Segment

Once the geometry of a single vortex generator element is defined for maximum vortex strength and for minimum pressure drop, the next step is the arrangement of these elements in a duct segment in a way which is compatible with the fuel injection. Ideally, the fuel is injected from a single location for each segment such that the same injection nozzle could be utilized for gaseous and liquid fuels.

The arrangement of the vortex generators has to be selected with this consideration in mind. Namely, the vortex pattern generated by a specific arrangement should be capable of distributing both gaseous and liquid fuel from a single injection location over the entire cross-section of the segment. A number of potential candidates for the arrangement have been considered and tested. A relatively quick and inexpensive method of determining whether a special arrangement is suitable for the large and fine-scale mixing purposes is the laser induced fluorescence (LIF) tests in water model. Here two example arrangements are presented.

A Pair of Opposing Vortex Generators with a Central Fuel Lance. In this arrangement, a pair of identical vortex generators are mounted on the opposing walls of the segment, as shown in Fig. 13. The fuel lance is located at the center, injecting through four holes which are pointing slightly away from the symmetry axis.

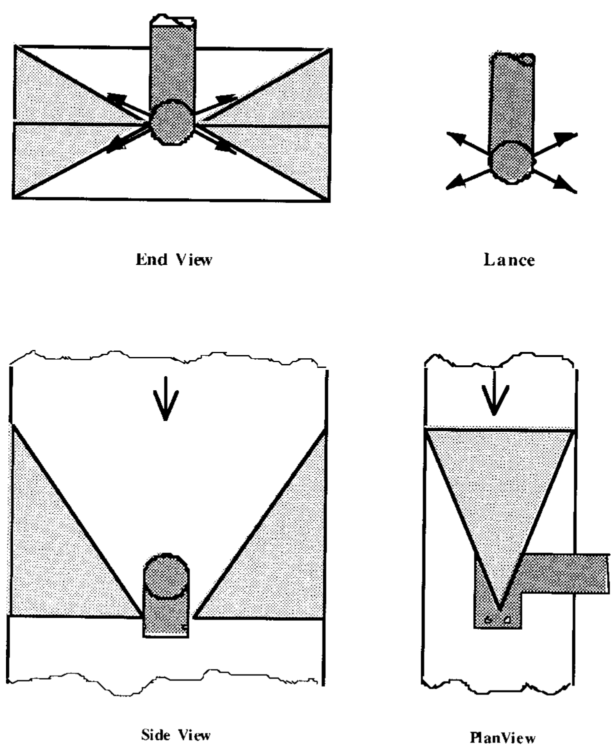

Fig. 13 The geometry of two opposing vortex generators with central injection

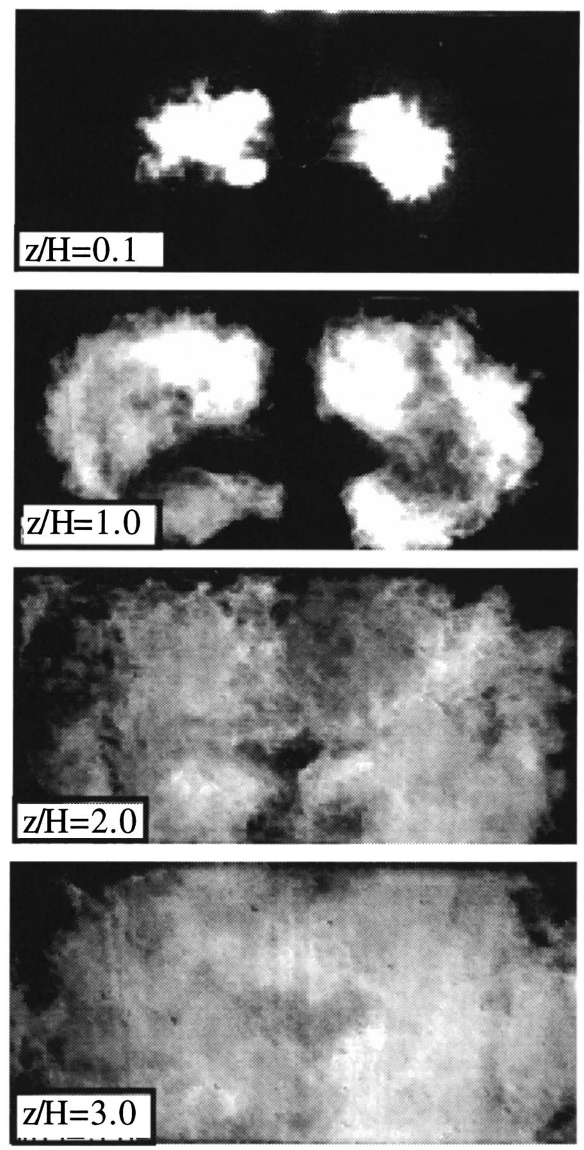

Fig. 14 The LIF pictures of fuel concentration over four successive planes downstream of a pair of opposing vortex generators with central injection

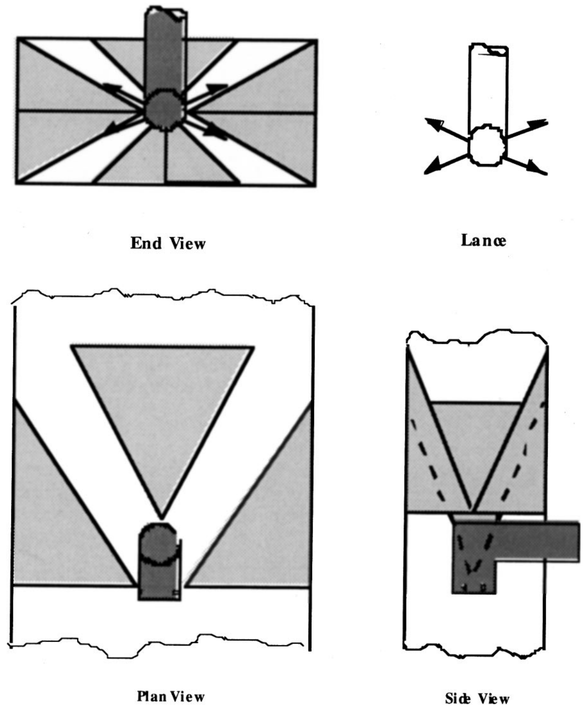

Fig. 15 The geometry of two pairs of opposing vortex generators with central injection

The LIF pictures associated with this case are presented in Fig. 14. It is evident from these pictures that the large scale distribution of the injected fuel is not complete even at three channel height downstream from the injection. Given the fact that the length of the mixing section in the machine is less than two channel heights, it is difficult to achieve the emission targets with this configuration. Additionally, due to almost completely fuel-free outer regions, insufficient flame stabilization is to be expected with such a configuration, since the recirculation zones after the sudden expansion into the combustor could not be efficiently used.

Further attempts in the direction of optimization of the mixing quality with this configuration, by modifying the injection angle and momentum of the fuel jets or the geometry of vortex generators, brought only marginal improvements at the cost of increased pressure drop and flashback danger.

Additional tests with the similar configuration, but with vortex generators mounted on the upper and lower walls have produced similar results, namely, a good portion of the channel cross-section not receiving enough fuel, resulting in large nonuniformities in mixing. As in the reference case mentioned earlier, when the momentum of the main stream is not used to the extent it is needed, problems with increased flashback danger arise due to overloading of the vortex generators by increasing the angles of attack and sweep in order to increase the mixing quality. This problem can be avoided only by increasing the number of the vortex generators, namely from a pair to two pairs as will be explained in the next section.

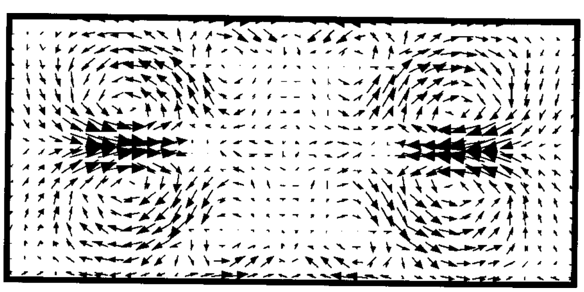

Fig. 16 The vortex pattern generated by two pairs of opposing vortex generators at the fuel injection plane

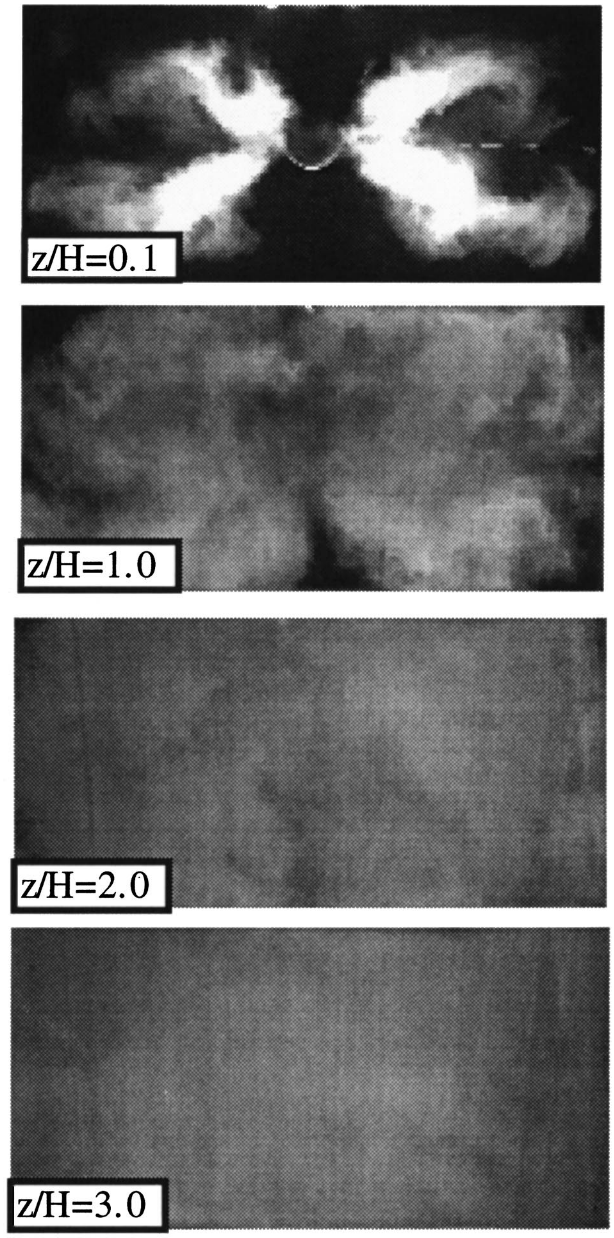

Fig. 17 The LIF pictures of fuel concentration over four successive planes downstream of two pairs of opposing vortex generators with central injection

Two Pairs of Opposing Vortex Generators with a Central Fuel Lance. This arrangement is similar to the previous one, with an additional pair of vortex generators mounted on the upper and lower walls, as shown in Fig. 15. The axial positions of the ends of the pairs are shifted with respect to each other, in order to provide the space needed for the central injector.

The vortex pattern generated by this arrangement is shown in Fig. 16, composed of velocity components perpendicular to the mean flow direction. This measurement has been carried out at the axial location of the tip of the fuel lance, in the absence of the lance itself. All four pairs of counter-rotating vortices are visible,

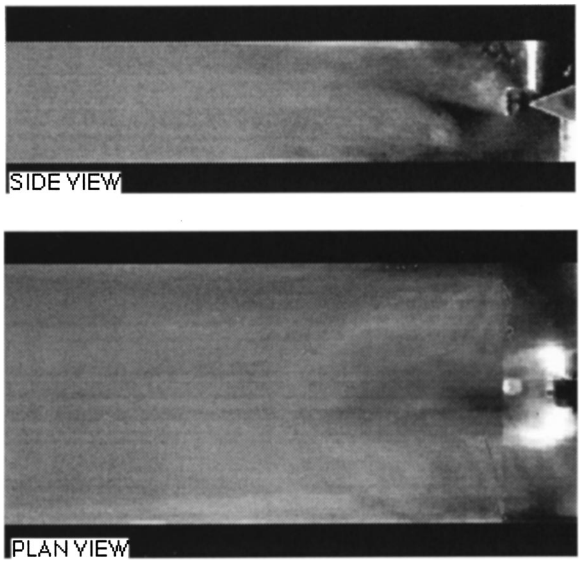

Fig. 18 The LIF pictures of fuel concentration over streamwise planes downstream of two pairs of opposing vortex generators with central injection

each generated by one of the vortex generators. The pairs from the side vortex generators are clearly larger, in order to provide better penetration and distribution of the fuel to both sides, which are distanced further from the lance with respect to upper and lower regions.

The LIF pictures of fuel concentration for this configuration over four transverse planes downstream of the injection are given in Fig. 17. A dramatic increase in the quality of the mixing is observed from these pictures, when compared to the case with a single pair of vortex generators. Already at one channel height downstream from the injection plane, the large-scale distribution of the fuel is practically completed. Further downstream the fine-scale mixing progresses, yielding locally more uniform concentration distribution.

The LIF pictures from the same configuration in streamwise planes as observed from the side and plan views are given in Fig. 18. As it is evident from these pictures, the injected fluid is rapidly transported away from the injector and entrained into the vortices shown in Fig. 16. Moreover, no significant impingement of injectant to the side or top and bottom walls is visible, indicating that, in the case of liquid fuel injection, the coke formation danger due to droplets contacting hot surfaces prior to evaporation is practically nonexistent. An additional advantage of this configuration is that the fuel is transported away from the injector initially, to come back in the middle of the channel after the recirculation zone in the wake of the lance is closed completely, thus, ensuring no flashback danger due to fuel entrainment in the lance wake.

The fuel concentration recordings from LIF pictures have been evaluated with digital image processing techniques in order to quantify the mixing quality. The data from all three cases reported are presented in Fig. 19, where the standard deviation in local fuel concentration, σ, normalized with the mean concentration is plotted as a function of the axial distance from injection. Apparently, in the absence of any vortical structures, other than those generated by the injection itself, the mixing progresses very slow. After the first channel height axial length, the reduction in the normalized standard deviation is very gradual, reaching to a value of only about 45 percent at $z/H=3$. A single pair of vortex generators brings an improvement of about 12 percent in mixing quality at $z/H=3.0$, when compared to the reference case. The case with a pair of vortex generators shows the best value of 15 percent variation coefficient at $z/H=3.0$.

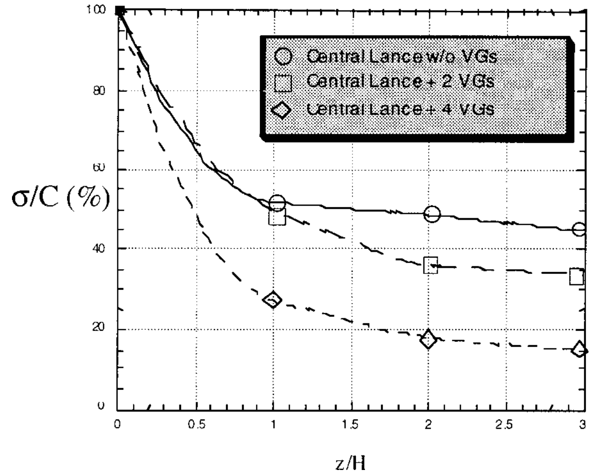

Fig. 19 Variation coefficient (standard deviation to mean concentration ratio) as a function of axial distance

Summary

A comprehensive investigation has been carried out with delta-wing type vortex generators with the aim of fuel-air mixing in a reheat combustor. This investigation produced an optimum vortex generator geometry, which provides the maximum vortex strength at the minimum pressure drop price. Owing to the longitudinal vortices generated by this geometry, no zones with reverse flow or unacceptably low velocities are encountered along the mixing section, thus ensuring reliable operation without flame attachment or flashback prior to complete mixing.

In addition to optimization of a single element, an arrangement of two opposing pairs of vortex generators in a rectangular combustor segment is presented. This arrangement allows rapid mixing with a single, central injector, both for gaseous and liquid fuels. The experience gained with this arrangement through a number of high pressure tests [5] verified the feasibility of the concept presented here. More recently, starting with the first GT24 machine in Gilbert, NJ, and the first GT26 machine in Birr, Switzerland, a number of gas turbines with this technology have been commissioned into service, confirming the findings from the development tests.

Acknowledgments

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