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Review on Combustion Chamber Swirlers

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***Abstract*— Swirl flows offer an interesting field of study for aerospace and mechanical engineers in general and for combustion engineers in particular since it involves complex interaction of recirculation and turbulent mixing which aid flame stabilization in combustion systems. Swirling flow generates rotating flows, turbulence and free jet wakes at the downstream of swirler in combustion chamber. So there is complex interaction between pressure gradients and fluid flow. Swirling jets are used as a means of controlling flames in combustion chambers. Swirling flows in both reacting and non- reacting conditions occur in wide range of applications such as gas turbines, marine combustor burners, chemical processing plants, rotary kilns and spray dryers. Swirling jets are used as a means of controlling flames in combustion chambers. This flame stabilization can be achieved by various methods. The most common techniques used in a gas turbine combustor is to stabilize the flame in modern gas turbine combustors is swirl stabilization in which a swirl velocity is imparted to the inlet air using vane swirlers. Such flows have practical applications in many combustion systems, such as industrial furnaces and gas turbine combustors. Air swirlers are widely used in both tubular & annular combustors. Swirler flow has been commonly used for the stabilization of high-intensity combustion. Swirl can reduce combustion lengths by producing higher rates of entrainment of ambient fluid and fast mixing close to exit nozzle and on the boundaries of recirculation zones in strongly swirling zones.**

Keywords—swirler, downstream recirculation zone.

I. INTRODUCTION

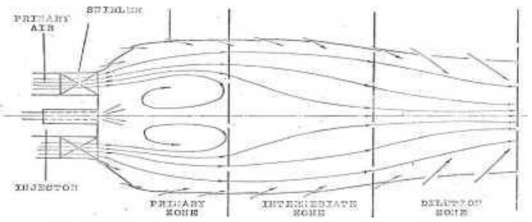
Swirling flow is a main flow produced by air swirler. Such flow is the combination of swirling and vortex breakdown. Swirling flows are widely employed in combustion systems for flame stabilization purpose. Swirl flows offer an interesting field of study for aerospace and mechanical engineering in general and for combustion engineers in particular since it involves complex interaction of recirculation and turbulent mixing which aid flame stabilization in combustion system. Swirling flows, which are highly complex, have the characteristic of both rotating motion and free turbulence phenomenon encountered as in jets and wake flows. The presence of swirl results in setting up of radial and axial pressure gradients, which in turn influence the flow fields. In case of strong swirl the adverse axial pressure gradient is sufficiently large to result in reverse flow along the axis and generating an internal circulation zone.

II. COMBUSTION PROCESS AND SWIRLING FLOWS

The combustion process is employed in thermodynamic cycles in order to increase the internal energy of the fluid. This process is performed in combustors or furnaces. Three main zones are primary, intermediate and dilution zones. Fuel is injected and ignited in the primary zone. Combustion is completed in the intermediate zone and hot gases are cooled to a low temperature in the dilution zone before expanding through the turbine.

The term combustion stability applies to the range of fuel-to-air ratio over which a stable flame can be maintained. An alternative definition for combustion stability considers maximum air velocity obtainable without flame extinction and is closely related to the flame speeds for the existing fuels. Combustion efficiency and stability are inversely proportional to the mean axial velocity in the combustor In fact; a combustor must be capable of running, without flame out or with very high reliability for relighting, over a wide range of air-to-fuel ratios. The only way of achieving this is by creating low velocity and good mixing regions (i.e. recirculation) in the combustor. The recirculation region provides a continuous hot source for a stable combustion since the hot combustion products flow in the upstream direction and give rise to the ignition of incoming fresh fuel-air mixtures. Creation of low velocities is also essential since the flame speeds for the most widely available fuels are much lower than the average velocities in combustion chambers.

A better way of flame stabilization at high mass flow can be attained by swirling the incoming flow to the combustor. Vortex breakdown is a well known phenomenon in swirling flows, causing a recirculation region to occur in the core region of the flow when the amount of rotation imparted to the flow is high. This type of recirculation provides better mixing due to the presence of swirl velocity components.



"Fig. 1" Air flow pattern in a conventional combustion chamber

III. METHODS OF OBTAINING SWIRL FLOWS

Methods of inducing rotation in a stream of fluid can be divided into three principal categories:-

1. Tangential entry of the fluid stream, or of a part it, into a cylindrical duct.
2. The use of guide vanes in axial tube flow.
3. Rotation of mechanical devices which impart swirling motion to the fluid passing through them. This includes rotating vanes or grids and rotating tubes.

The swirl intensity can be quantified, with good approximation, by an experimental parameter S, called swirl number. It is defined as the ratio between the axial flux of the angular momentum, and the axial flux of axial momentum multiplied by the exit radius of the burner nozzle. The degree of swirl in the flow is quantified by the dimensionless parameter, S known as the swirl number which is defined as the ratio of axial flux of angular momentum to flux of axial momentum.

(1) Weak swirl (S<0.3)

If swirl number is less than 0.3 it is classified as weak swirl. The pressure gradients are not large enough to generate recirculation zone in case of weak swirl. The basic characteristic of weak swirl is just to increase the width of free or confined jet flow but not to develop any axial recirculation.

(2) Medium swirl (0.3<S<0.6)

If swirl number is in between 0.3 and 0.6 it is called medium swirl. A light recirculation zone is generated due to larger axial pressure gradient in case of medium swirl.

(3) Strong swirl (S>0.6)

If swirl number is greater than 0.6 it is called strong swirl. A very large recirculation zone is generated due to the high pressure gradients developed in the core in case of strong swirl. It develops strong axial and radial pressure gradient, which aids to form central torroidal recirculation zone is due to imbalance between adverse pressure gradient along the jet axis and the kinetic energy of the fluid particles flowing in the axial direction.

In case of strong swirl, when the swirl intensity is increased in a jet, a point is reached when the adverse pressure gradient along the jet axis cannot be further overcome by the kinetic energy of the particles flowing in the axial direction and recirculating flow is set up in the central portion of the jet between two stagnation points. This recirculation zone, which has the form of torroidal vortex, plays an important role in the flame stabilization as it constitutes a well mixed zone of combustion products and acts as storage of heat and of chemically active species located in the centre of the jet near the burner exit.

Flame parameters such as stability and combustion intensity depend on the size and strength of the vortex.

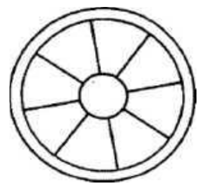
IV. SWIRLER

Swirlers are static mixing devices used to impart swirl to the flow. The goal of swirler design is to maximize the benefits of recirculation by imparting sufficient swirl to the flow while minimizing the incurred pressure losses. Modern combustors also use swirlers to promote mixing of the fuel and air in the premixer prior to combustion.

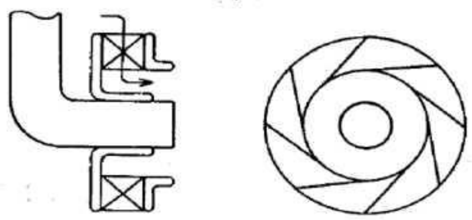
There are mainly two types of swirlers in practical cases and modifications are made in them to improve the performance of the swirler.

1. Axial swirler

2. Radial swirler

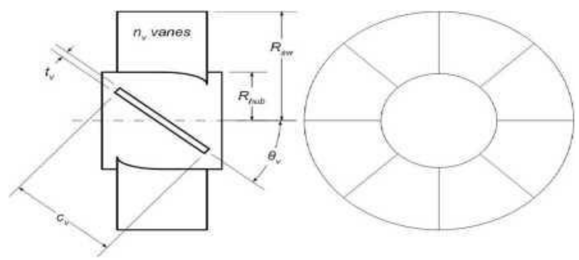


"Fig. 2 " Axial swirler



"Fig. 3" Radial swirler

Axial swirlers tend to have higher pressure losses than the radial type but are much simpler to manufacture. Parameters of interest to axial swirler designers are depicted by Fig.4. They include the vane angle vs, the inner hub radius Rhub, the outer swirler radius Rsw, the vane thickness tv, the vane length cv, and the number of vanes nv. Typical axial swirler designs have vane angle, vane thickness between 2mm, and 8 vanes. A useful parameter for design is the Swirl number, Sn.

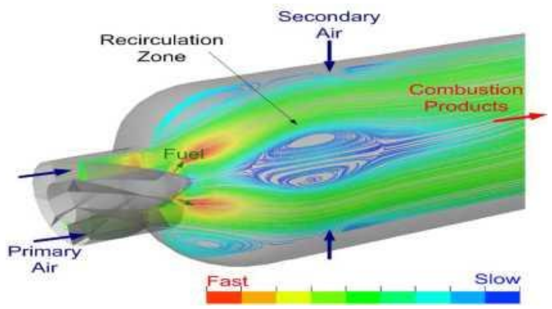


"Fig. 4" Design parameters of axial swirler

V. CENTRAL RECIRCULATION

Anchored flames cannot be established in flows with velocities significantly above the laminar flame speed. Fuel and air must move slowly enough for the flame to propagate upstream and ignite fresh mixture. The point at which the flame can no longer propagate back through the flow is the stabilization point or anchor. Zones of flow reversal help stabilize the flame by creating localized regions of low velocity flow called flame holders. Large scale central recirculation zones, as shown in Fig.6, serve many other purposes as well. Hot combustion products become trapped in the recirculating mass and are returned to the combustor dome inlet. This hot gas helps stabilize the flame by providing a continual source of ignition to the incoming fuel. It also serves as a zone of intense mixing within the combustor by promoting turbulence through high levels of shear between the forward and reverse flows. Lastly, CO, unburned fuel, and other intermediate species are able to reside within the combustor longer and react to completion. Fig.6 illustrates the process of recirculation in a gas turbine combustor using streamlines. These streamlines indicate the path which a fluid particle would follow.

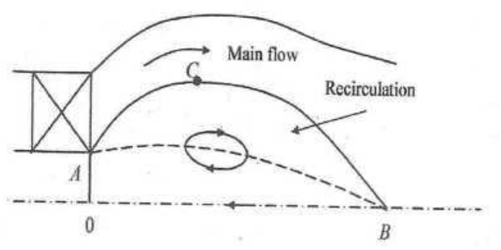
Flame stability, combustion intensity, and performance are directly associated with the size and shape of this recirculation vortex or bubble. It forms at the onset of flow reversal when an adverse axial pressure gradient exceeds the kinetic energy of the incoming flow [Beer & Chigier, 1972]. Adverse pressure gradients may be introduced by creating high degrees of swirl or angular momentum at the inlet of the combustor and large sudden expansions in areas such as dumps or bluff bodies.



"Fig. 5" Combustion streamlines

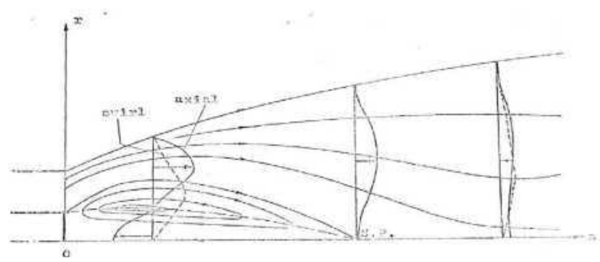
VI. SIZE OF RECIRCULATION ZONE

The recirculation region in a free swirling flow is shown in figure. Because the flow is assumed to be Ax symmetric, only half of the flow pattern is considered. The recirculation region is contained within the curve ACB. The point B is called the stagnation point. The flow outside ACB is the main flow which derives the recirculation along the solid curve AB. Conditions of zero axial velocity are represented by the dashed curve AB as shown in fig.6.



"Fig. 6" Recirculation region in swirling flow field

Typical axial and swirl velocity profiles are shown in figure. All the velocity components decay in the downstream direction. After the stagnation point the reversal axial velocities disappear, and further downstream the peak of the axial velocity profile shift towards the factors governing the size of the recirculation zone have been studied by several workers. The Kilik [4] examined the separate effects on recirculation zone size of variations in vane type [flat or curved], vane angle, vane aspect ratio and space to chord ratio.



"Fig. 7" Typical profiles of axial and swirl velocity components in a strongly swirling flow

The size of the recirculation zone is increased by

1. An increase in vane angle.
2. An increase in the number of vanes.
3. A decrease in vane aspect ratio.
4. Changing from flat to curved vanes.

VII. SWIRLER WITH FLAT OR CURVED VANES

A vane swirler performs the task of turning the incoming flow to the combustor from a rather low absolute axial velocity to a higher absolute velocity having swirl and radial components. Due to this acceleration a pressure drop occurs through the swirler. Additionally profile and secondary losses occur within the swirler die to the vanes.

In the case of flat vanes the turning through the swirler is incomplete for high value of the space to chord ratio, because the air outlet angle becomes much smaller than the geometrical vane outlet angle. Ineffective turning of air through the swirler results in lower swirl and in consequence, lower radial velocity components. In other words, less angular momentum is imparted to the incoming axial flow. A smaller recirculation region and less turbulence intensities are, therefore induced. Inherently, the amount of recirculating mass flow drops.

The ineffective turning can be partly obviated by reducing the space to chord ratio. To obtain a tight swirl a space to chord ratio of 7 is used together with vane outlet angles 65° to 85° for flat vanes. This, however increase both the profile and secondary losses excessively. Additionally it may introduce blockage problems. All these resulting excessive losses eventually manifest themselves in the form of an excessive pressure drop through the swirler and the whole process of turning becomes quite inefficient.

Curved vanes are more efficient aerodynamically than flat vanes. This is because they allow the incoming axial flow to gradually turn, which inhibits flow separation on the suction side of the vanes. Thus, more complete turning and higher swirl and radial velocity components are generated at the swirler exit, which results in a larger recirculation zone and higher reverse flow rate. However these arguments in favor of curved vanes should not exclude the use of flat vanes in certain applications, one advantage of flat vanes is that they are cheap and easy to manufacture. Moreover, the flow separation associated with flat vane swirlers, which are created by the stalled regions attached to each vane, tend to promote a more stable flame and reduce combustion noise. Another asset of the flat vane axial swirler is that its exit velocity profile is less peaked and is less biased radially outward than that of the corresponding curved vane swirler. In consequence, it provides aeration of the main soot-forming zone, which is normally located just downstream of the fuel injector. For these reasons, flat vane swirlers are still preferred in some combustor configurations. However, when air swirlers are incorporated into air blast atomizers, curved vanes should always be used because the wakes produced downstream of flat vanes could adversely affect the quality of atomization.

VIII. PRESSURE LOSS FACTOR

Total pressure loss factor (PLF) is a dimension less number and is defined as,

Pressure loss factor (PLF) = $(P_{02} - P_{01}) / (0.5\rho U_0^2)$

Where the inlet stagnation pressure (PO1) is measured in the inlet pipe upstream of the swirler and exit stagnation pressure (PO2) is obtained at the exit of the expansion chamber and leaving to the atmosphere, p is density of the fluid in kg/m^3 and UO is mean bulk inlet velocity to swirler (m/s). With increase in vane angle pressure loss factor also increases. For efficient design of combustion chamber the pressure loss factor should be as minimum as possible but at the same time it should have more recirculation mass in the recirculation zone. So a compromise is needed between the recirculation zone formed and the total pressure loss across the swirler. It was found that the total pressure loss factor across 60^o swirler is nearly 3 times higher than that for 45^o swirler as well the recirculation zone size of both the 45^o and 60^o are almost the same. Pressure loss should be minimum for better fuel consumption in combustion system.

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CONCLUSION

The importance of the above discussion related to combustion chamber swirlers is to focus on the effective yielding of the central recirculation zone for the efficient combustion by doing comparison of different aspects and parameters affecting the recirculation zone.

The review helps to design a combustion chamber swirler which can burn a fuel efficiently by creating optimum central recirculation zone.

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