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DEVELOPMENT OF RADIAL AERODYNAMIC SWIRLERS

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ABSTRACT

Experimental studies show that swirl has large-scale effects on flowfields: jet growth, entrainment and decay (for isothermal flows) and flame size, shape, stability and combustion intensity (for combustion flows) are affected by the degree of swirl imparted to the flow. This degree of swirl is usually characterised by the nondimensional number representing the ratio of axial flux of swirl momentum to the axial flux of axial momentum times the equivalent nozzle radius. This parameter, denoted by the symbol S, is called the swirl number and has been used extensively to designate the strength of the swirl. This paper is to review the aerodynamics of swirling flow in combustion system.

1.0 INTRODUCTION

There are several requirements that must be considered when designing a new combustor especially to meet the stringent regulations regarding emissions level from the exhaust. These requirements include: wide stability limits, high combustion efficiency, high intensities of heat release, high heat transfer rates from the flame, wide turndown ratio, low burner pressure drop and low emissions of pollutants. The design has to be based on compromise since some of these requirements are conflicting. Therefore, to achieve the best compromise maximum use of the knowledge of key processes must be utilised. One of the key processes is the mixing between the fuel and the air.

Good mixing of fuel and air can be achieved through premixing. However, premixing resulted in other major practical problems such as flame stability, autoignition and combustion efficiency [20]. Also premixed combustion systems are not favoured in industrial applications for reasons of safety. Therefore, attention must be directed towards mixing in non-premixed systems.

In non-premixed systems, the most obvious technique to mix fuel and air is to use the turbulence generated at the shear layer of the jet boundary. Usually there exists a high shear and high property gradients in the high turbulence zone at the interface between the jets of fuel and air. It is realised that high heat release rates can be achieved by having the regions of high shear stress. The mixing can be enhanced by increasing the velocity and species gradient in this zone. One way to achieve this is the use of swirling air flow that can be obtained by using swirl generators. Swirl flows has been widely employed in many engineering applications. In high-intensity combustion systems, the use of swirl has the following effects [22]:

1. To reduce combustion lengths by producing higher rates of entrainment of the ambient fluid and fast mixing near the exit nozzle and on the boundaries of recirculation zones.
2. To improve flame stability due to the formation of torroidal recirculation zones in strongly swirling zones.
3. As the blockage is aerodynamics, flame impingement on the burner can be minimized to ensure minimum maintenance and extended life for the unit.

Flow rotation or swirl can be generated by several methods. Generally, these methods can be divided into three principal categories [4]:

a) tangential entry of the fluid stream, or of a part of it, into a cylindrical duct;

b) the use of guide vanes in axial tube flow;

c) rotation of mechanical devices that impart swirling motion to the fluid passing through them. This includes rotating vanes or grids and rotating tubes.

Flow types in which fluid particles move on circular paths can be distinguished according to whether they are 'rotational' or 'irrotational' or also termed as 'forced vortex' or 'free vortex', respectively. The different between these two flows can be described by the following example. If a float is placed into a container filled with water in rotational flow, the float will rotate about its own axis while following the streamline in the flow. However, in irrotational flow, the float will follow a circular streamline without any rotation about its own axis.

The swirling flow differs from its simple counterpart by having a tangential velocity component. This tangential velocity distribution is a combination of the forced and free vortex distributions or sometimes known as Rankine vortex. In viscous fluid dynamics, rotating flows always possess a central core of solid body rotation (or forced vortex). Outside the central region, free vortex conditions may prevail. The tangential velocity component is zero on the axis of symmetry. The location of the maximum tangential velocity and its interaction with the axial velocity profile constitute critical elements in the flow field downstream of the burner. The central core of solid body rotation region exhibits flow field and turbulence characteristic which appear to be significantly different from those displayed by the surrounding free vortex flow field.

2.0 VORTEX BREAKDOWN PHENOMENON AND PRECESSING VORTEX CORE

The vortex breakdown phenomenon is a function of swirl strength and/or Reynolds number. In a swirling flow of constant swirl strength, as the Reynolds number is increased an instability develops. It is first manifest as a small closed bubble of circulating fluid on the axis of symmetry. This phenomenon can also be achieved by increasing the swirl strength at constant Reynolds number. Both operations have the same effect on the type and position of the vortex breakdown since both increase the axial vorticity, peak swirl and axial velocity overshoot in the upstream vortex core.

The flow then returns to a stable form for a small distance and then breaks down again, and when the Reynolds number is increased further, a large three-dimensional time dependent instability named the precessing vortex core develops after the second breakdown of flow. There appear to be three main forms of this second breakdown: the axisymmetric, spiral and double helix. Apart from the double helix breakdown, which occurs infrequently, the flow after the second breakdown is highly turbulent and appears to herald the onset of flow reversal and the formation of large torroidal recirculation zones.

In the occurrence of precessing vortex core phenomenon, the central core of solid-body rotation region of flow is displaced from the axis and starts to precess about the axis of symmetry. The precessing vortex core is usually situated in the immediate vicinity outside of the reverse flow central core region. On leaving the swirl burner the precessing vortex core is rapidly dissipated in any fully separated flow region. The precessing vortex core frequently occurs in isothermal swirling flows, especially inside long devices or burners (L/D > 1) or in the exit.

The precessing vortex core is responsible for high levels of pressure and temperature fluctuations and for the associated high levels of turbulence mixing within or near the recirculation zone [25]. Even though the precessing vortex core may be potentially beneficial in that it promotes mixing and aids in extending flame stability margin, it is usually not a desirable characteristics in industrial burners. This is due to the fact that large precessing vortex core may couple resonantly with fundamental modes of oscillation in the burner, hence creating violent flame pulsation and noise pollution at levels above the normal combustion roar [25].

In premixed combustion using swirling flow, the precessing vortex core is intensified to a great extent. However, in diffusion flame combustion this intensity is dampen. The enhanced precessing vortex core damping effect noted for the diffusion flames can be explained by the positive radial density gradient induced by the annular ring of air surrounding the flame (in the case of axial fuel injection). On the other hand, the excited instability of the premixed flames seems to be associated with small negative radial density or pressure gradients [22,23].

3.0 RECIRCULATION ZONES

In airflows with high swirl velocities, when the angular-to-linear-momentum ratio exceeds a critical value, a torroidal vortex-type recirculation zone is set up in the central region of the jet close to the nozzle [24]. This torroidal vortex system plays an important role in flame stabilisation since it constitutes a well-mixed zone of hot combustion products and acts as a storage of heat and chemically active species. Heat and mass is then transported effectively from combustion products to fresh combustible mixture by the high-intensity turbulence that prevails in the vortex region. The high temperature products serve as an energy source for preheating and ignition assistance for the incoming fresh combustible mixture. The process goes into a cycle and this keep the flame from extinguishing or having to ignite continuously. Between the forward flow and the reverse flow zone, there is a boundary of steep velocity gradients and high intensity turbulence that promotes high entrainment rates and rapid mixing between the fuel and air. Due to high entrainment and increased mixedness of the jets, swirl reduces the flame length and lengths of flame attachment while increasing the diameter of the flame. This results in a shorter combustor that is capable of complete combustion.

The recirculation zone length increases with increased in swirl intensity [5,14,23]. Khalil et. al. [13] demonstrated that the length of central recirculation zone is affected by the swirl intensity or swirl numbers (will be discussed in the following section). The higher the swirl number the longer the recirculation zone length. However, once the recirculation zone achieved a certain length, further increased in swirl number will not have much effect on the length of recirculation zone. At this point it is considered that the central recirculation zone has been well established. Once the central recirculation zone is well established, its maximum diameter is primarily a function of the burner diameter, and is only slightly altered by further increase in swirl, by combustion or by ratio of diameter of burner to diameter of swirler change.

Besides the influenced of swirl intensity on recirculation zones geometry, other parameters affecting the size and shape of the central recirculation zones are burner geometry, expansion ratio and the angle of divergence of the combustor walls, swirl generation methods and inlet swirl velocity profiles, swirl modes (either co- or counter-rotating), and also downstream restrictions (e.g. orifices, shrouds or outlet contractions).

Another type of recirculation zone, called the wall recirculation zone, is established by the geometry of the combustor as a result of a sudden 'dump' expansion. In this case, the recirculation zone occurs immediately downstream of the sudden increase in the cross section of the flow. The parameter affecting the geometry of this recirculation zone is the expansion ratio (i.e. ratio of the swirler outlet diameter to the diameter of the combustor). As mentioned in the above paragraph, as the swirl intensity is increased, the recirculation zone length and diameter is increased. However, at the same time the size of the wall recirculation zone is decreased [12].

Schadow and Gutmark [19] pointed out that at the early stage of the wall recirculation zone development, with the unburnt mixture on one side of the interface and the hot combustion products on the other side, intense mixing and burning are limited in this region. However, the combustion is still sustained by the interaction between the central recirculation zone and the fresh combustible mixture. As the wall recirculation zone develops further, a large interface between the fuel and air mixture and the hot products develops, leading to intense turbulence enhancement and sudden heat release. At this point, both the central recirculation and wall recirculation regions help in sustaining combustion.

4.0 SWIRL NUMBER

Experimental studies show that swirl has large-scale effects on flowfields: jet growth, entrainment and decay (for isothermal flows) and flame size, shape, stability and combustion intensity (for combustion flows) are affected by the degree of swirl imparted to the flow. This degree of swirl is usually characterised by the nondimensional number representing the ratio of axial flux of swirl momentum to the axial flux of axial momentum times the equivalent nozzle radius. This parameter, denoted by the symbol *S*, is called the swirl number and has been used extensively to designate the strength of the swirl. A mathematical representation of the definition of swirl number is given by Syred and Beer as:

$$S = \frac{G_\theta}{G_x R} \tag{1}$$

where

G_θ is the axial flux of swirl momentum, including the x-θ direction turbulent shear stress term

$$= \int_0^R (Wr)\,\rho U\, 2\pi\, r dr = \text{constant} \tag{2}$$

G_x is the axial flux of the axial momentum, including the x direction turbulent normal stress term and a pressure term (axial thrust)

$$= \int_0^R U \rho U\, 2\pi\, r dr + \int_0^R p\, 2\pi\, r dr = \text{constant} \tag{3}$$

R is the equivalent nozzle radius, and

u, v, w are the velocity components (x, r, θ) cylindrical polar co-ordinate directions.

Since the pressure term in Equation 3 is difficult to be determined due to the fact that pressure varies with position in the swirling jet, the above definition for swirl number can be further simplified by omitting this pressure term. Hence the swirl number can be redefined as:

$$S' = \frac{G_\theta}{G'_x\, R} \tag{4}$$

where

$$G'_x = \int_0^R U \rho U 2\pi r dr \tag{5}$$

The swirl number should, if possible, be determined from measured values of velocity and static pressure profiles. However, this is frequently not possible due to a lack of detailed experimental results. Therefore, it has been shown [4] that the swirl number may be satisfactorily calculated from the geometry of most swirl generators. According to Claypole and Syred [8], if a perfect mixing and conservation of momentum is assumed, then the swirl number can be defined in terms of the geometry of the combustor:

$$S_g = \frac{r_o \pi r_e}{A_t} \left[\frac{\text{Tangential Flow}}{\text{Total Flow}} \right]^2 \tag{6}$$

where

r_e is the radius of the swirler outlet,

r_o is the radius of tangential inlets from the centre of the combustor, and

A_t is the total area of tangential inlets.

Another form of geometric swirl number has been formulated by Al-Kabie, Andrews and Ahmad ([2] and is given as:

$$S_a = \frac{\sin\theta}{1+1/\tan\theta} \frac{A_3}{C_c A_2} \tag{7}$$

where

A_3 is the outlet area,

A_2 is the swirler minimum throat area, and

C_C is the swirler contraction coefficient.

Swirl numbers for typical burners are usually in the range from 0.6 to 2.5 [22]. Values of swirl number lower than 0.6 is considered as weak swirl and in this type of swirling systems, the axial pressure gradients are insufficiently large enough to cause internal recirculation. Only at swirl number greater than 0.6 that reverse flow commences. This effect of swirl number on the generation of reverse flow zone has been demonstrated by Chigier and Chervinsky [7].

5.0 EFFECT OF SWIRL LEVEL

Inlet flow swirl has an increasingly dramatic effects on the subsequent flowfield produced as the strength (intensity) of swirl increases. As the swirl increases, the angle of spread of jet increases, making the air meet the fuel at an angle and with a tangential velocity component. Corresponding to this increase the entrainment increases causing faster decay of the velocity and nozzle fluid concentration with distance from the orifice.

Swirl has several important effects on combustion system. The most important effect of swirl in combustion processes is that it improves flame stability [11] and extends flammability limits, even though some workers has disagreed on the latter. The flammability limits can be extended due to the increase in the turbulent burning velocity at the base of a lifted flame as a result of increase in swirl, thus ensuring blow off does not occur. Fricker and Leuckel [11] have observed that the use of swirl helps reduce the susceptibility to blow-off caused by spurious external changes (eg. small variations in fuel/air ratio during throughput alterations).

As mentioned in previous sections, increasing the swirl intensity increases the recirculation zone length and diameter. This happens only after a critical swirl number of about 0.6. After the recirculation zone has been well established, i.e. it has been fully developed, further increase in swirl number did not effect the recirculation zone size substantially. Beltagui and MacCallum [6] has shown that the maximum diameter of the central recirculation zone is uninfluenced by further increase in swirl once the central recirculation zone is well established. The maximum diameter is primarily controlled by the burner diameter. Khalil et. al. [13] also demonstrated the same effect and further obtained a linear relations between the swirl intensity and both the average and maximum recirculated mass flow.

One way of increasing swirl number is by increasing the vane angle of the swirler. Several workers have demonstrated the effect of increasing vane angle and found the optimum vane angle where the recirculation zone reaches its maximum. Rao et. al. [17] investigated a range of vane angles of 0°, 15°, 30°, 45°, and 60°. They found that the 45° vane angle swirler gives the largest recirculation zone size. Further increase in vane angle to 60° however reduces the size of the recirculation zone. Rhode et. al. [18] also reached the same conclusion that the 45° vane angle is the optimum vane angle for recirculation zone size.

Fricker and Leuckel [11], however, had a different opinion. They believed that the increase in swirl intensity helps in promoting the mixing of fuel and air rather than increasing the reverse flow of hot burned gases back into the burner quarl. Claypole and Syred [9], on the other hand, believed that flame was not stabilized by the recirculation of hot active species in a large time-averaged recirculation zone, but was stabilized by the formation of well-stirred regions in which hot active species and isothermal fresh reactants become intimately mixed. However, the well-stirred regions were influenced by the degree of swirl.

Even though swirl is agreed to stabilize flame, Feikema et. al. [10] pointed out that excessive swirl can destabilize a lean flame, hence an optimum amount of swirl exists. This may be attributed to the fact that for higher degrees of swirl the recirculation vortex increases in size and entrains more cool incoming air that would be forced upstream to mix with the partially premixed reactants thus reducing the turbulent burning velocity.

In addition to flame stabilization, swirl also helps reduces the flame length. Milosavljevic et. al. [16]demonstrated this effect using nonpremixed flame. Beltagui and MacCallum [6] also demonstrated the same effect using peripheral fuel injection. This resulted in shorter combustor that is capable of complete combustion, hence very practical for aero-engine gas turbines.

Mestre [15] investigated a combustor with and without swirl. He demonstrated that swirl helps improve combustion efficiency by about 19 percent besides decreasing all pollutants levels by a great margin. This may be attributed to the increase in the flame temperature by about 200 K when compared to the non-swirl system. He also observed that flame with swirl was blue which indicated good mixing while the non-swirling system showed a yellow flame indicating that there are still some fuel (kerosene) left unvaporised. This also proved that swirl helps in atomising liquid fuel. The long yellow flame he observed indicated that the flame is not well mixed and may contribute more to pollutant formation as the residence times are much higher. Luminous flame is required in order to prevent radiation damage to the combustor walls by thermal cycling. However, Ahmad and Andrews [1] pointed out that for an enclosed flow, high swirl numbers may be detrimental to the achievement of a high combustion efficiency for premixed flames at lean equivalence ratios ($\varphi < 0.7$). On the other hand, they demonstrated that by keeping the swirl number at a constant value and increasing the pressure loss will improve combustion efficiency.

6.0 SWIRLER PRESSURE DROP AND DISCHARGE COEFFICIENT, C_D

In order to achieve rapid fuel and mixing downstream of a swirler, turbulence must be generated to promote mixing. Good mixing is important in that it reduces formation of pollutants. Turbulent energy is created from the pressure energy dissipated downstream of the flame stabiliser. In swirlers, turbulence can be generated by increasing the blockage or by increasing the pressure drop across the swirler. There are several ways in order to achieve this: eg. increasing the degree of swirl, decreasing the swirler outlet diameter by introducing shrouds or orifice plates, or by increasing the number of vanes. All of these methods also increase the size of the recirculation zone, and together with the turbulence generated in the shear layer region will increase fuel and air mixing significantly.

The discharge coefficients for radial swirlers were obtained by using the test rigs at cold flow condition. This was done by passing a metered air flow through the radial swirler and flame tube while monitoring the static pressure loss upstream of the swirler relative to the atmospheric pressure.

REFERENCES

1. Ahmad, N.T. and Andrews, G.E., Emissions from Enclosed Swirl Stabilised Premixed Flames, International Journal of Turbo and Jet Engines, Vol. 3, pp. 147-158, 1986.

2. Al-Kabie, H.S., Radial Swirlers for Low Emissions Gas Turbine Combustion, University of Leeds, Department of Fuel and Energy, PhD, 1989.

3. Al-Kabie, H.S., Andrews, G.E. and Ahmad, N.T., Lean Low NO_x Primary Zones Using Radial Swirlers, ASME Paper, 88-GT-245, 1988.

4. Beer, J.M and Chigier, N.A., Combustion Aerodynamics, Applied Science Publishers Ltd., 1972.

5. Beltagui, S.A. and MacCallum, N.R.L., Aerodynamics of Vane-Swirled Flames in Furnaces, Journal of the Institute of Fuel, Vol. 49, pp. 183-193, 1976.

6. Beltagui, S.A. and MacCallum, N.R.L., Characteristics of Enclosed Swirl Flames with Peripheral Fuel Injection, Journal of the Institute of Energy, Vol. 61, pp. 3-16, 1988.

7. Chigier, N.A. and Chervinsky, A., Transaction of ASME Journal Applied Mechanics, E34, 443, 1967.

8. Claypole, T.C. and Syred, N., The Effect of Swirl Burner Aerodynamic on NO_x Formation, Eighteenth Symposium (International) on Combustion, pp. 81-89, The Combustion Institute, 1981.

9. Claypole, T.C. and Syred, N., The Stabilization of Flames in Swirl Combustors, Journal of the Institute of Energy, Vol. 55, pp. 14-19, 1982.

10. Feikema, D., Chen, R. and Driscoll, J.F., Enhancement of Flame Blowout Limits by the Use of Swirl, Combustion and Flames, Vol. 80, pp. 183-195, 1990.

11. Fricker, N. and Leuckel, W., The Characteristics of Swirl-Stabilized Natural Gas Flames. Part 3: The Effect of Swirl and Burner Mouth Geometry on Flame Stability, Journal of the Institute of Energy, Vol. 49, pp. 152-158, 1976.

12. Gupta, A.K., Lilley, D.G. and Syred, N., Swirl Flows, Energy and Engineering Sciences Series, 1984.

13. Khalil, K.H., El-Mahallawy, F.M. and Moneib, H.A., Effect of Combustion Air Swirl on the Flow Pattern in a Cylindrical Oil Fired Furnace, Sixteenth Symposium (International) on Combustion, pp. 135-143, The Combustion Institute, 1977.

14. Mathur, M.L. and MacCallum, N.R.L., Swirling Air Jets Issuing from Vane Swirlers. Part 1: Free Jets, Journal of the Institute of Fuel, Vol. 40, pp. 214-225, 1967.

15. Mestre, A. Efficiency and Pollutant Formation Studies in a Swirling Flow Combustor, Fluid Mechanics of Combustion, Edited by Dussord et. al., The American Society of Mechanical Engineers, New York, 1974.

16. Milosavljevic, V.D., Taylor, A.M.K.P. and Whitelaw, J.H., The Influence of Burner Geometry and Flow Rates on the Stability and Symmetry of Swirl-Stabilized Nonpremixed Flames, Combustion and Flames, Vol. 80, pp. 196-208, 1990.

17. Rao, A.N., Ganesan, V., Gopalakrishnan, K.V. and Natarajan, R., Experimental and Theoretical Investigations of Vane-Generated Swirling Flows in a Circular Chamber, Journal of the Institute of Energy, Vol. 56, pp. 137-144, 1983.

18. Rhode, D.L., Lilley, D.G. and McLaughlin, D.K., Mean Flowfields in Axisymmetric Combustor Geometries with Swirl, AIAA Journal, Vol. 21, No. 4, pp. 593-600, 1983.

19. Schadow, K.C. and Gutmark, E., Combustion Instability Related to Vortex Shedding in Dump Combustors and Their Passive Control, Progress Energy Combustion Science, Vol. 18, pp. 117-132, 1992.

20. Sotheran, A., Pearce, D.E. and Overton, D.L., Some Practical Aspects of Staged Premixed Low Emissions Combustion, ASME Paper 84-GT-88, 1984.

21. Syred, N. and Beer, J.M., Effect of Combustion Upon Precessing Vortex Core Generated by Swirl Combustors, Fourteenth Symposium (International) on Combustion, pp. 537-550, The Combustion Institute, 1973.

22. Syred, N. and Beer, M., Combustion in Swirling Flows: A Review, Combustion and Flame, Vol. 23, pp. 143-201, 1974.

23. Syred, N. and Dahman, K.R., Effect of High Levels of Confinement Upon the Aerodynamics of Swirl Burners, Journal of Energy, Vol. 2, pp. 340-346, 1978.

24. Syred, N., Chigier, N.A. and Beer, J.M., Flame Stabilization in Recirculation Zones of Jets with Swirl, Thirteenth Symposium (International) on Combustion, pp. 617-624, The Combustion Institute, 1971.

25. Syred, N., Gupta, A.K. and Beer, J.M., Temperature and Density Gradient Changes Arising with the Precessing Vortex Core and Vortex Breakdown in Swirl Burner, Fifteenth Symposium (International) on Combustion, pp. 587-597, The Combustion Institute, 1975.