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RESEARCH ARTICLE

THE COMBINATION OF SWIRL COMBUSTORS WITH FURNACES

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ABSTRACT

Swirl combustors are commonly used to produce high strength flames for industrial applications like the gas turbine. The swirl generates a central region of reverse flow to efficiently stabilize the flame. The high levels of turbulence and the associated mixture gives a rise to the flames which are stable over a wide range of operating conditions. This has led to the use of furnaces for the incineration of waste gases. The swirl burner is fired into a furnace which gives a high level of confinement. This assists the flame stabilization by the re-radiation of heat from the furnace walls. Quenching by the reducing the low temperature gasses. The swirl burner/furnace systems have been found to be capable of incinerating particulate loaded waste gases utilizing their inherent low calorific value. This paper work on the incineration of low calorific value gases has reviewed and discussed the mechanisms which happen within these systems. The potential of these systems lies not only in their ability to incinerate waste gases with reduced capital and running costs, but also as a high intensity combustion system for use with low ranking fuels. These systems may prove suitable as a direct replacement for conventional combustors in converting boilers, driers, etc., to fire on alternative fuels.

Key Words: Swirl, Combustor, Furnace.

INTRODUCTION

Waste gases of low calorific value are often produced as a by - product of industrial processes (e.g. the off gases from the manufacturing of carbon black and smokeless fuel). These are regarded as a nuisance and are frequently disposed of by incineration which often requires the addition of premium fuel to ensure stable combustion. However, these gases can be disposed of more cost effectively in a swirl burner/furnace system which utilizes their inherent potential as low grade fuel (Mkpadi *et al.,* 2002). Swirl combustors are widely used to produce high intensity flames for industrial applications such as gas turbines and utility boilers. Firing a swirl burner into narrow cylindrical furnaces produces a system which is well suited for the incineration of waste gases as shown in Fig.(1). A region of reverse flow is generated in the exit of the combustor by the swirling action of the flow. The flame stabilizes in the wake of this aerodynamic blockage. The high levels of turbulence where the forward flow stagnate causes intimate mixing of the fresh reactants with the hot active species. This coupled with the re-radiation of heat from the furnace walls gives rise to a highly stable intense flame. A small proportion of the flow is drawn into reverse flow and re-circulated. The majority of the flow passes from well stirred region into a less turbulent plug flow region where the reactions are completed. Particles tend to be retained in the furnace by the centrifugal action of the swirling flow until they are completely consumed. The system is therefore well suited for the incineration of tar and dust laden gases. Previous research into swirl burner/furnace interactions is briefly reviewed before discussing recent work which has led to a better understanding of the mechanisms involved and to improvements in the furnace design (Syred, 2006).

Swirl burner and Furnace Interactions

In most practical applications, the swirl combustor is fired into a furnace. The degree of confinement can be defined as the ratio of the cross sectional areas of the furnace (A_f) and the combustor exit (A_t).

Where A_f/A_t is large (e.g. > 100) then the furnace walls have a little effect on the flow and the flame behaves like free jet. Nevertheless, the flame is closely confined ($A_f/A_t \approx 10-30$), the entrainment of the jet creates a tangential recirculation zone between itself and the furnace walls (Wu and Fricker, 1976; Afrosimova, 1967). Afrosimova (Afrosimova, 1967) showed that at $A_f/A_t \approx 10$ as the swirl level was increased so the central reverse flow zone (C.R.F.Z.) increased at the expense of the tangential recirculation zone. This was also observed by Mathur and Maccullum (Mathur *et al.,* 1967) for an even more confined flame.

There was also proof of the disappearance of the recirculation zone for swirl number >1.6. This can be attributed to the rapid expansion of the swirling jet from the burner causing it to adhere to the furnace walls. The size of the C.R.F.Z. has been found to be dependent on the proportions of the furnace (Beltagui, 1974). Baker *et al.* 1975 have taken measurements of velocity by laser anemometry for a vane swirled gas flame (S=0.52) firing into a furnace with $A_f/A_t = 11$ and compared those with those with a flame with zero swirl. These clearly show the tangential recirculation zone and the formation of a C.R.F.Z. When the swirl is applied Fig. (2). Combustion caused the C.R.F.Z.to increase in the size and move downstream.

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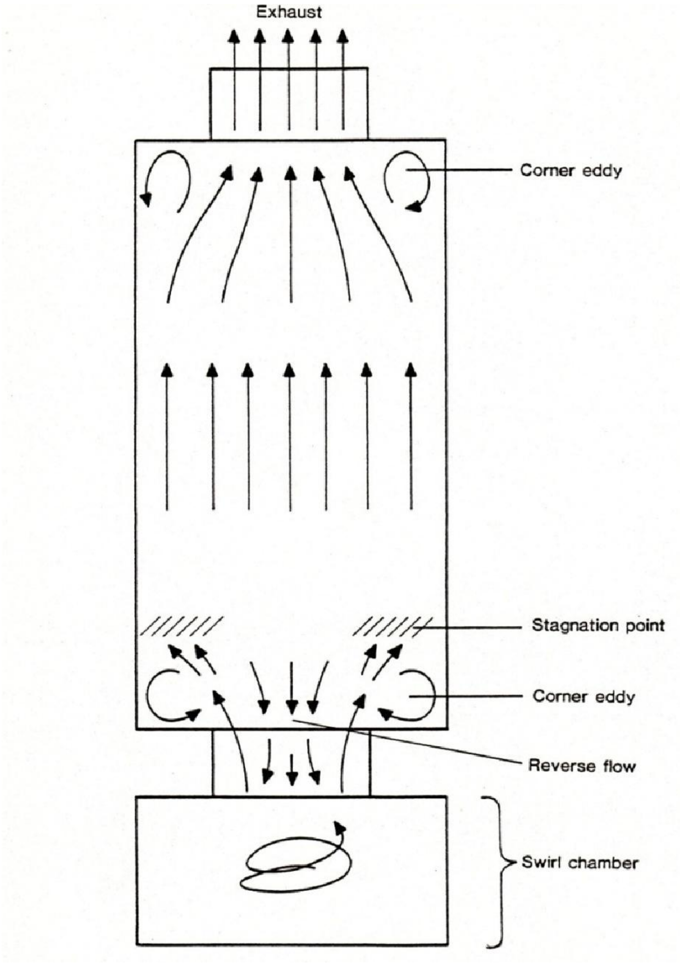


Fig.1. Schematic Diagram of Flow in Furnace

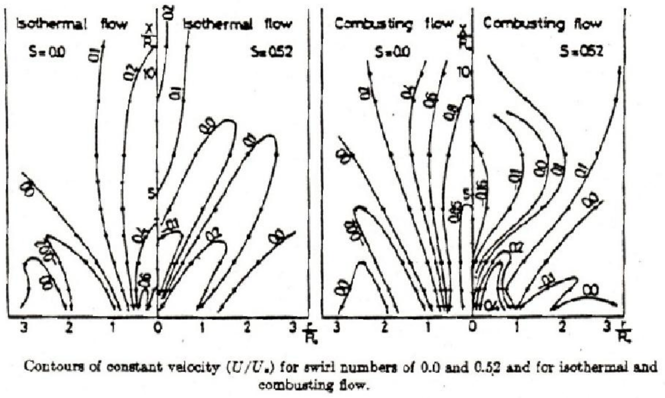


Fig. 2. Mean Axial Velocities by Baker *et al* [7]

Most of the work described has been for $A_f/A_t > 8$. However, if A_f/A_t can be reduced to 4, there can be considerable saving either in capital cost as a result of the smaller furnace required or in operating costs as a larger lightly loaded combustor could be used with reduced pressure losses. The latter is particularly important in the combustion of low C.V. gases which frequently involve handling large volumes of gas. Extensive measurements for this degree of confinement have been taken during the development of an incinerator for the low C.V. gases produced by carbon black works (Syred, 2006; Abdulsada *et al.,* 2012; Valera-Medina, 2009). The effects of varying a large number of parameters were investigated. These included the level of swirl, the swirl burner geometry and the furnace configuration as shown in (Fig. 3). In contrast to the above (Mathur, 1967), it was found even with swirl levels much higher than 1.6; the tangential recirculation zone was still present. However, it was shorter and restricted to the upstream corner (hence it formed the corner eddy). The attachment of the flow to the furnace wall enhanced the C.R.F.Z. and flame stabilization has also assisted by the re-radiation of heat from the refractory furnace walls. The use of a refractory quarl (the broken line in (Fig. 3)) eliminated the corner eddy and the C.R.F.Z. this reduced the flame stability. The C.R.F.Z. could be restored by the use of a large bluff body in the exit of the combustor. The optimum swirl number for the combustion of the low C.V. gas was found to be between 0.9 and 1.2.

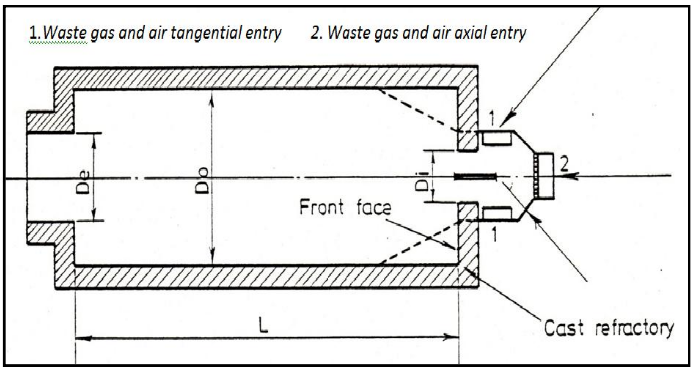
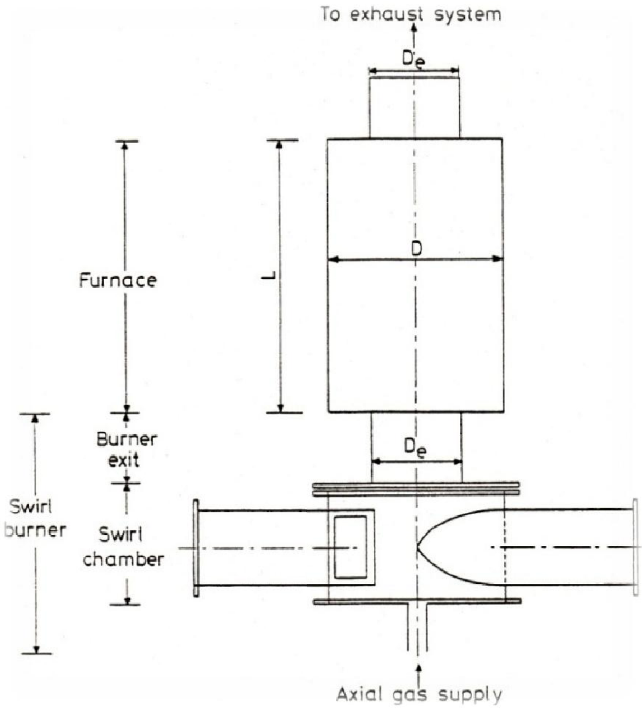


Fig. 3. Swirl Burner / Furnace Combination

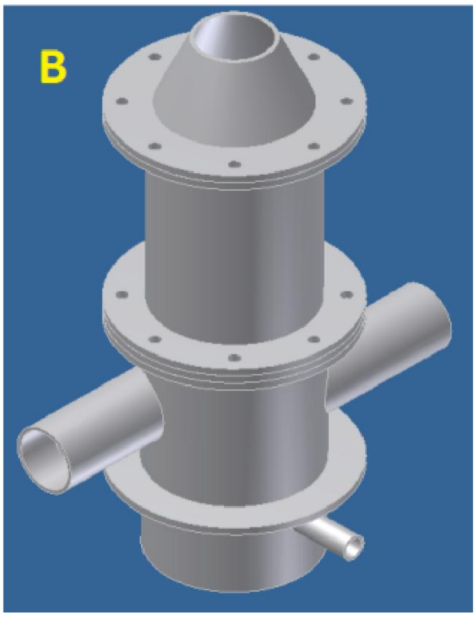
The use of the furnace with such a high level of confinement enabled lower C.V. gases to be burnt than with a free flame. This system has been installed on several carbon black plants for the incineration of the waste gas without the addition of support fuel. The heat generated is used in the process.

Experimental Setup

A swirl burner with simple inlet configuration had been developed as a result of earlier work on free flames (Valera-Medina, 2009) Fig. 4 and Fig.5.



(A)



(B)

Fig. 4. Swirl Burner/Furnace Combination (A and B)

This is well suited for the incineration of waste gases as the large inlets are not prone to becoming blocked by gas borne particles. In order to further develop systems for the combustion of low C.V. gases this burner was arranged to fire into a narrow cylindrical furnace ($A_f/A_t = 4$).

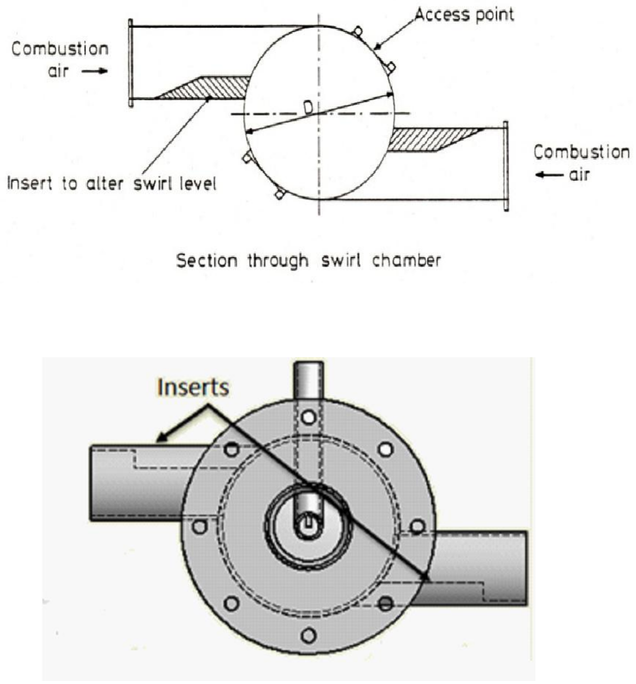


Fig. 5. Swirl Burner/Furnace Combination (section through the swirl chamber)

The level of swirl was characterized by the non-dimensional parameter of geometric swirl number (Syred *et al.,* 1984), which is based on the combustor geometry and the inlet flow conditions:

$$S_g = \frac{r_o.\pi.r_e}{A_t}\left[\frac{tangential\ flow\ rate}{total\ flow\ rate}\right]^2$$

Tests were carried out to examine the effect of furnace geometry on the flame and heat release within the furnace. These tests were carried out at a constant swirl level, Sg=1.08, which earlier work (Wu and Fricker, 1976; Afrosimova, 1967; Beltagui, 1974) had suggested was approximately the optimum value. Natural gas was supplied axially at a flow of I50 *l/min* while 10% excess combustion air was supplied tangentially. In ord.er to simulate a low C.V. gas, the airflow was increased to give 100% excess air, tangentially. Spatially resolved measurements of temperature were taken with miniature unshielded platinum 13% rhodium platinum thermocouples.

RESULTS AND DISCUSSION

The main features of the flow can be seen from the mean temperature contours with 10% excess air for the long furnace ($L/D_f = 2.5$), (Fig.6). The fresh reactants enter the furnace in a forward flow which produces a low temperature region in the first section of the furnace ($0 < \frac{x}{r_e} < 1.5$). There is a C.R.F.Z. on the centerline in this region and a corner eddy between the forward flow and the wall. Both of these features re-circulate high temperature gases into the forward flow. The fresh reactants ignite at the stagnation point of the forward flow ($\frac{x}{r_e} \approx 1.1$). The majority of the chemical reactions occur immediately downstream, producing a rapid risen temperature. The temperature contours beyond this region ($\frac{x}{r_e} \approx 4$) tend to be parallel to the wall, indicating a balance between the heat released in the gas and the heat lost through the walls.

The flow separates from the wall at ($\frac{x}{r_e} \approx 8$) to pass through the exit. An eddy is formed in the corner which is bounded by the 1500K contour. The reaction continues down-stream of the exit, although it is subject to quenching by, the entrainment of air. Shortening the furnace ($\frac{L}{D_f} = 1.5$) does not affect the flame in the first section of the furnace (Fig. 7). The temperature contours are similar to those with the long furnace although slightly higher than maximum temperatures occur. However, the section of the flow where the temperature contours are parallel to the walls is considerably reduced. The flow in the exit region is similar to the previous furnace.

The use of a conical exit produces a smoother flow transition from the furnace to the exit (Fig. 8). The elimination of the corner eddy reduces the noise output of the burner. The high temperature region beyond the exit is longer and narrower than is found with the square exit. The peak mean temperatures are of the same order as was found for the long furnace. The flame pattern is similar with 100% excess air up to ($\frac{x}{r_e} \approx 3$) (Fig. 6), although the mean temperatures are slightly reduced by the action of the extra flow as a heat sink. The temperature beyond ($\frac{x}{r_e} \approx 3$) is decreasing indicating the heat lost via the walls to be less than the heat released. The reactions are completed within the furnace and there is no visible flame beyond the exit. The reduced heat loss with the smaller furnace produces a slightly more intense (higher temperature) reaction zone (Fig. 7). There is also the same general trend of the reaction being completed by ($\frac{x}{r_e} \approx 3$).The conical exit produces a smooth transition from the furnace to the exit flow (Fig. 8). The variation of outside wall temperature is independent of the furnace geometry (Fig. 9), which illustrates the similarity of the heat release patterns in the furnace. The wall temperature increases over the initial section of the furnace ($\frac{x}{r_e} > 4$) Where flame stabilization and the main chemical reactions occur. The wall temperature then remains reasonably steady. The heat absorbed by the additional flow with 100% excess air leads to lower wall temperatures.

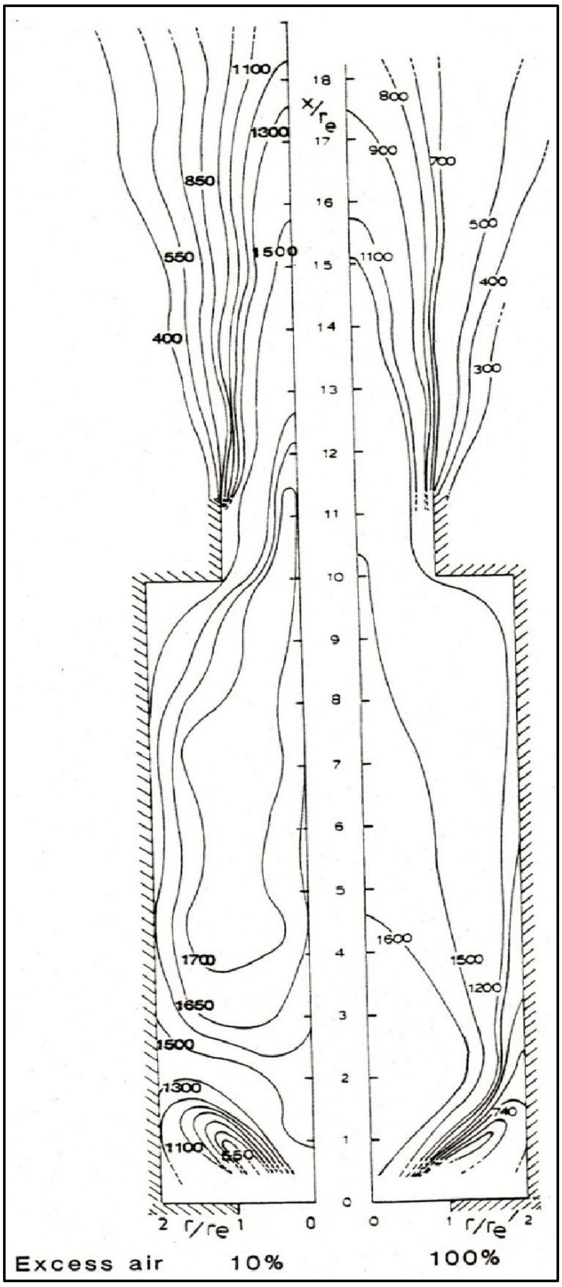


Fig.6. Mean Temperature Contours for Long Furnace

The flame stabilizes in the well stirred region which forms at the stagnation point of the forward swirling jet (This has also been observed in the free flames). The majority of the chemical reactions occur in this region ($1.5 < \frac{x}{r_e} < 3$) where the fresh reactants become intimately mixed with the hot products of combustion. The substantial heat release which occurs produces a rapid rise in mean temperature. High concentrations of CO and H_2 (which are the main intermediate products of the combustion reaction) have been forward in this region in free flames (Syred *et al.,* 2012).

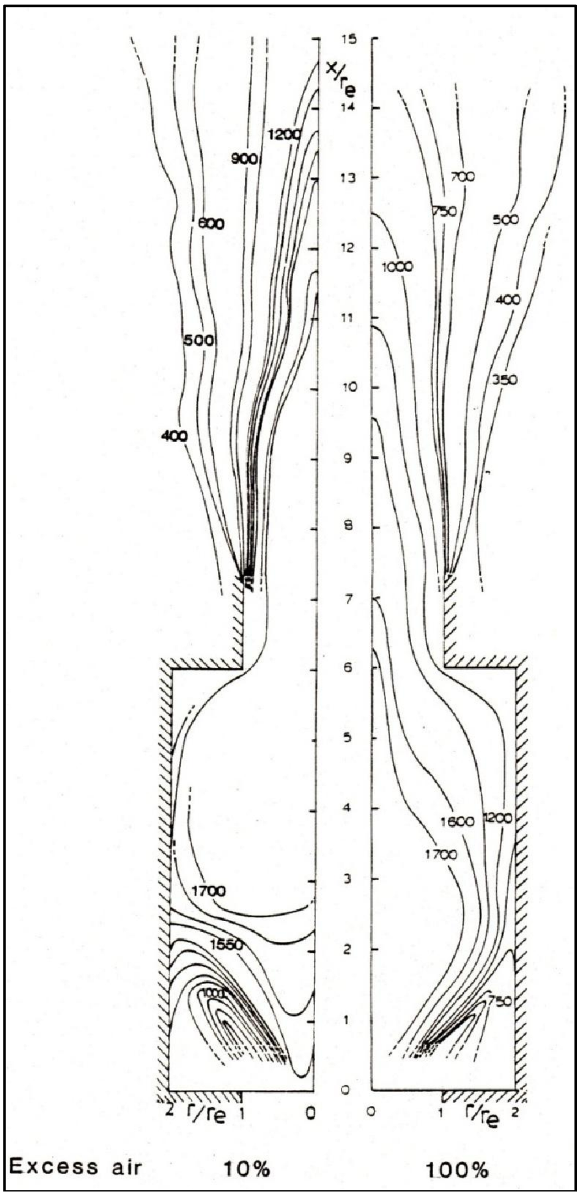


Fig.7. Mean Temperature Contours for Short Furnace

The centrifugal forces which arise from the swirling action of the flow cause the high temperature products of combustion to be centrifuged to the center of the flow, some of which are drawn into the C.R.F.Z. The entrainment of the forward swirling j*et al*so re-circulates hot products of combustion to the base of the furnace in the form of the corner eddy. However, since these are high temperature/low density flows, the re-circulated mass is quite small and does not substantially increase the temperature of the forward flow into the ignition region. Work on free flames (Valera-Medina, 2009) indicates the C.R.F.Z. contains less than 6% of the total mass flow. The centrifugal forces also cause particles, Such as coal dusts and tars, to be retained in the system until they are completely consumed. There is a plug flow region downstream of ($\frac{x}{r_e} \approx 3$) in which the heat released is equal to the heat lost via the walls. This produces parallel temperature contours. However, the heat lost via the walls represents at most only 5% of the total heat released in the combustor (Luo *et al.,* 2014). Shortening the furnace produces a more intense flame, probably a direct result of the proximity of the exit to the well stirred region where the flame stabilizes.

In view of the low level of reaction downstream of ($\frac{x}{r_e} \approx 3$), it is probably most beneficial to use a short furnace, thereby reducing the capital costs of a full scale installation. The use of a conical exit produces a smoother transition from the furnace flow to the exit flow, eliminating the down-stream corner eddy. This reduces the local turbulence and the associated noise.

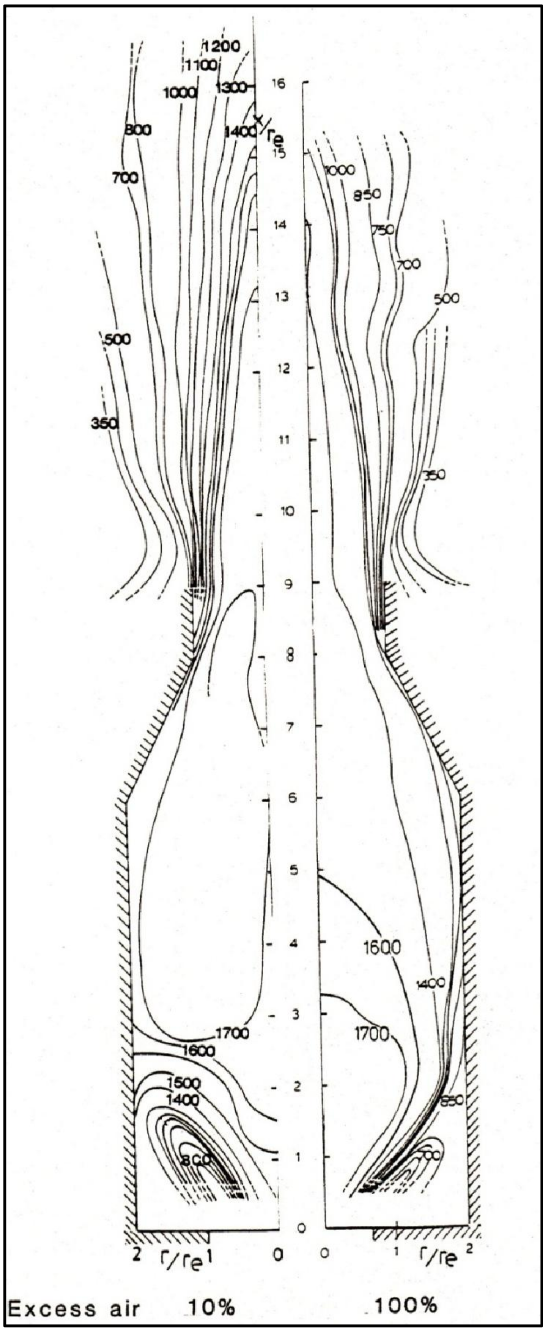


Fig. 8. Mean Temperature Contours for the Short Furnace with the Conical Exit

A generally accepted design criterion for the incineration of noxious gases is that it is necessary for the gases to have a minimum residence time which is a function of the incineration temperature. However the rate of chemical reaction is dependent on the level of turbulence (Solero and Coghe, 2000). The use of a swirl burner produces an intense turbulent flame with a high reaction rate. (Syred, 2006) found the reactions were completed within a furnace of 4 times the linear dimensions of the long furnace. However, since the mean axial velocities are of the same order in both systems then the mean residence time would be 4 times longer in the large scale system. This is still less than the residence time based on the mean temperatures. The increase in size would have greatly altered the scale of turbulence and there by increased the reaction rate.

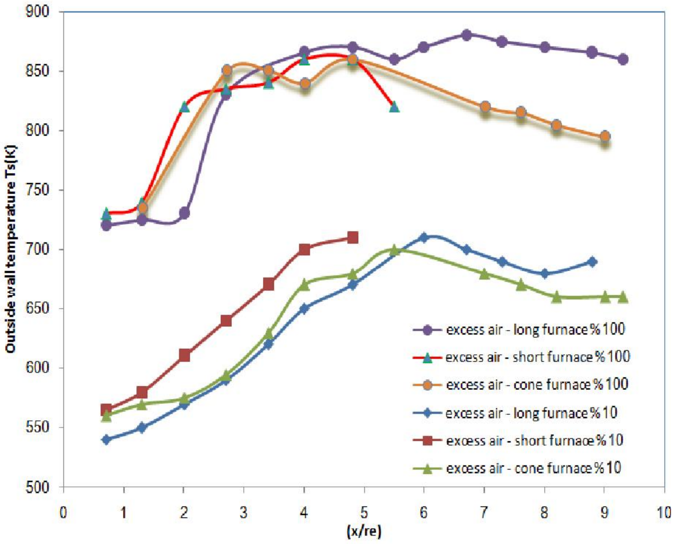


Fig. 9. Furnace wall Temperature K

Shortening the furnace approximately halved the distance from the point of ignition to the exit, thus approximately halving the residence time. If the residence time controlled the completeness of reaction then one would expect a significant difference in the composition of the gases leaving the furnace. This would have a significant effect on the flow downstream of the exit. However, the length of the furnace did not affect the flow issuing from the exit. The system is for the incineration of a variable C.V. gas laden with particulates and tars which is emitted when the carbonizing ovens are emptied. The system has proved very effective, completely incinerating the gas while retaining all the particulates until they are consumed. This not only produces a cleaner discharge gas than the existing flares tack system but also has considerably reduced the level of support fuel required. The furnace length has been reduced to be the same as in Fig.8 without any deterioration in performance. The resulting compact system shows a significant advantage over the large incineration systems based on mean residence time. There is not only the direct saving in capital cost, but also since the unit is comparatively light it can be mounted on top of the ovens, thus eliminating long runs of expensive irrigated pipe work. It is feasible for the furnace to be reduced still further in length (to$\frac{x}{r_e} = 3 - 4$) It is anticipated that such a short system may prove suitable as a direct replacement for conventional burners for the direct firing of driers, boilers etc., on waste gases or difficult fuels.

Conclusions

Flame stabilization occurs in the well stirred region of the furnace. Although the central reverse flow zone and the corner eddy are essential to the development of this region, they do not appear to play a direct role in flame stabilization. The majority of reactions occur in an intense combustion region between ($1.5 < \frac{x}{r_e} < 3$). The length of the furnace ca therefore be considerably reduced without impairing the performance of the system. This produces a compact system which is well suited to the incineration of dirty low C.V. gases, The system also has potential for the direct replacement of existing burners to enable lower grade fuels and waste gases to be used.

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