INVESTIGATION ON PRESSURE LOSSES IN COMBUSTION CHAMBERS

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ABSTRACT

Swirl burners are now widely used. There is much current interest in those burners which are confined in combustion chambers and enclosures of different area ratio. Improved understanding can minimize capital and running costs by restricting the overall size of the combustion space (confinement ratio) and reducing the system's total pressure drop. The objective of this investigation was to obtain from the described combustor configuration, detailed isothermal and aerodynamics information, which could be correlated with parallel studies carried out in the burning state, so as to investigate the combustion chamber design parameters that affect the pressure losses in it. The experimental work was conducted on an instrumented horizontal water cooled furnace. Aerodynamic measurements comprise profile of axial, tangential and radial velocity and static pressure. The results describe an intensive series of aerodynamic tests carried out an area ratio ranging from 6.4 to 33.4, swirl intensity ranging from 0.32 to 0.75 and equivalence ratio ranging from 0.8 to 1.2 A comprehensive study on these parameters was made for both isothermal and flame models.

1. INTRODUCTION AND OBJECTIVE

In many industrial processes, swirl burners are constrained to fire into furnaces, boilers etc., of varying shape and size with the aim of good mixed and stable flame.

Mixing processes are of a paramount important in combustion and dilution zone of gas turbine combustor. In the primary zone good mixing is essential for high burning rates and to minimize soot and nitric oxide formation. Whereas the attainment of satisfactory temperature distribution in the exhaust gases is very dependent on the degree of mixing between air and combustion products in the dilution zone. Unfortunately, thorough mixing can be achieved only at the expense of length and pressure loss which is one of the most important factors that describe the flow field. Thus, a primary objective of combustor design is to achieve satisfactory mixing and stable flow pattern throughout the entire combustor, with no parasitic losses and with minimal length and pressure loss. Therefore among the combustor design requirements is the need to minimize the pressure drop across the combustor. Part of this pressure drop is incurred in simply pushing the air through the combustor. The remainder part is the fundamental loss arising from the addition of heat to high velocity stream.

Most of the work reported [1,2,3 and 4] has been carried out with values confinement ratio of $(A_f/A_b) > 8$ and shows that confinement and sometimes combustion can considerably affect the aerodynamics of the swirl burner. However for an application of large size, it has become clear that it is recommended to maintain burner confinement ratio, (A_f/A_b) around 4 for the following reasons [5]: First the overall diameter of the furnace can be made smaller, thus reducing either capital expenditure or operating costs. Alternatively, for a given size of furnace the swirl burner may be made some what larger and the combustor is highly loaded, this substantially reduces the system's total pressure drop and hence operating cost. The maximum loading of closely confined systems used for earlier work [6,7] was approximately 0.3 m^2 of furnace area per kg of total flow. However, an increase of 30% in linear dimensions, reduces the loading to 0.18 m^2/kg whereas the pressure drop falls from 150 mm w.g. to 50 mm w.g. This reduction in pressure loss is practically important in the combustion of poor quality gaseous fuel which frequently involves handling of large gas volumes.

Kilik [8] investigated the pressure loss characteristics of axial swirlers in a series of experiments that were designed to separate the effect of vane type (flat or curved) from those of vane angle. They show that curved vane swirlers create less pressure loss than flat-vane; the difference becomes more pronounced as the vane angle is increased. For both types of swirlers, increasing the space-chord ratio (i.e., decreasing the number of vanes) decreases the pressure loss coefficient. This is especially true for curved-vane swirlers and is due to the lower frictional loss associated with the reduction in vane surface area.

Against this background, the main purpose of the present work is to develop relationships between pressure loss, combustor size, equivalence ratio and swirl intensity, thus providing a rational basis for good aerodynamic design.

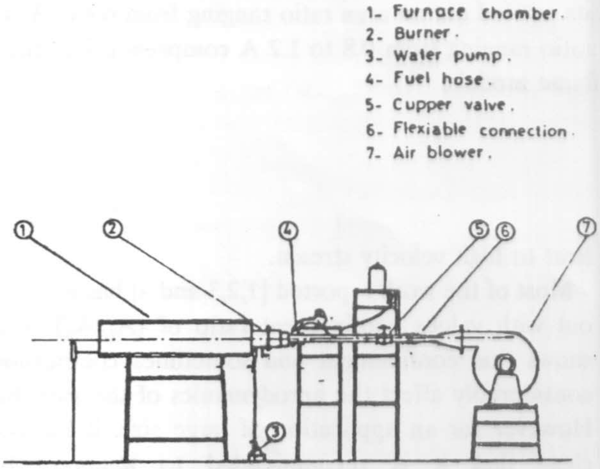

Figure 1. Test rig.

2. DESCRIPTION OF THE COMBUSTOR FACILITIES

2.1 Experimental Rig

The experimental work was conducted on an instrumented horizontal water cooled furnace. A schematic diagram of the test rig, which is situated at Faculty of Engineering Alexandria University, is shown in Figure (1). It consists mainly of a cylindrical furnace equipped with the necessary auxiliaries which facilitate its operation and control. The test-section is simply a horizontal straight seamless steel pipe 257 mm in diameter and 1430 mm long. Seven observation holes each of 10 mm diameter were drilled on one side of the furnace for aerodynamic measurements. Cooling was achieved using cooling coil of 27 mm pitch and 12 mm height. The cooling coil was welded around the furnace wall and fed with water by using water pump to produce efficient cooling. The outer surface of the coil was embedded and insulated by 11 mm thick layer of fire clay, cement and gypsum.

2.1.1 Swirlers

All the tests were conducted using axial vane swirlers according to the design of MATHUR and MACCALUM [1]. Construction details of the burner used are given in Figure (2).

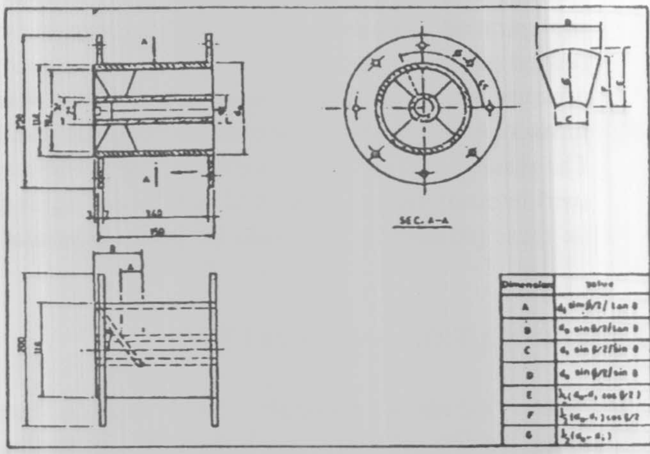

Figure 2. Details of swirl burner geometry.

2.1.2 Air Supply System

The required air was supplied from an air blower. Air flow rate was measured through a calibrated orifice meter. Pressure and discharge regulation equipment were fitted at suitable location as shown in Figure (1).

2.1.3 Fuel and Fuel Supply System

the trial was performed using commercial grade butane, which was composed of iso-and normal butane (C_4H_{10}) fuels with small amount of other gaseous hydrocarbons. The tests were carried out with a fuel input of 2.5 Kg/hr (22 KW firing) at approximately stoichiometric input conditions.

In the mixing section, butane fuel was introduced axially through 3 holes, down-stream, gas injectors, mounted to bluff plate. The function of this plate was to create a depression down-stream, which allowed the gaseous fuel to discharge into the high pressure air stream. The fuel rate was measured by a rotameter.

The flow parameters measured were the three components of the time-averaged velocity of the flue gases. The measurements were made by means of a water cooled three hole probe to the design of HIETT and POWELL [9]. The outside diameter of the probe tip was 6 mm. This probe was also calibrated for measurement of static pressure. The probe was connected to the terminals of the pressure transducer through two hoses. The pressure transducer was connected to the chart recorder through the amplifier.

3. EXPERIMENTAL RESULTS, ANALYSIS AND DISCUSSION

In this work measurements of three velocity components and static pressure were carried out. These measurements in addition to some previous results are used in predicting the pressure drop inside the combustion chamber under different burner geometries and combustion intensity.

The radial distribution of the time-averaged three components of the flue gases velocity are presented in Figures (3,4 and 5). Also, a typical static pressure distribution is shown in Figures (6,7 and 8). The experimental results for both velocity and static pressure distribution illustrate some of the reasons for the very complex flow patterns which occur when swirl burners of different confinement ratio are used. To explain this static pressure distribution, it is necessary to reveal the reasons of reverse flow zones formation. Basically the flow processes occur:

i. at any given section, large gradient of static pressure occur (dp/dr) due to the centrifugal force. So, high subatmospheric pressure level is formed in the central region of the flow.

ii. Moving downstream, rapid decay of the tangential velocity usually occurs due to sudden expansion and mixing effect.

3.1 Velocity Distribution

A display sample of the measured time averaged three components velocity for different operating conditions are shown in Figures (3,4 and 5).

Axial velocity distribution for a selection of combinations of swirl intensity(S), equivalence ratio (ϕ) and confinement ratio (A_f/A_b) are given in Figure (3). The radial distribution of the axial velocity shows similarity for all investigated swirl numbers. It is noticed that the decay of axial velocity, especially at high swirl number (S = 0.75) is usually uneven across the enclosure, hence, strong annular zone of high axial pressure gradient may be created which, in turn, may set up several different regions of coaxial reversed flow. The decay of axial velocity tends nearly to the form predicted by theory [5] i.e $u/U \sim (x/D_f)^{-1}$. As a result of increasing swirl intensity (S), confinement ratio (A_f/A_b) and equivalence ratio (ϕ), the angle of spread of flame increases. Corresponding to this increase in the spread of the flame, the entrainment rate increases causing faster decay of axial velocity and pressure loss factor. This is illustrated by Figures (9,10 and 11) which represent the decay of the maximum axial velocity along the combustion chamber for various degree of swirl, confinement ratio and equivalence ratio.

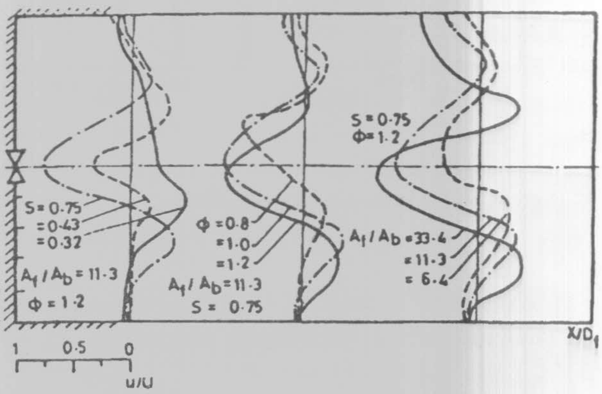

Figure 3. Axial velocity distribution at $\bar{x}$ = 0.058.

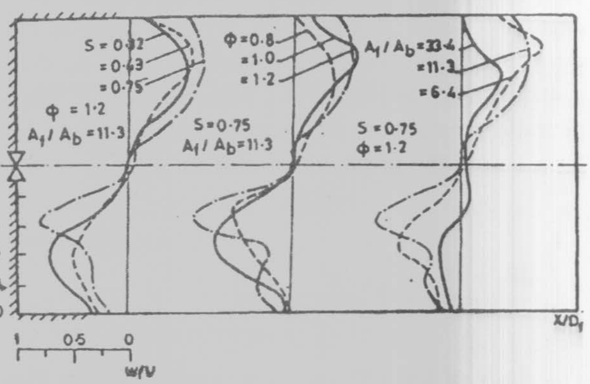

Figure 4. Tangential velocity distribution, at $\bar{x}$ = 0.058.

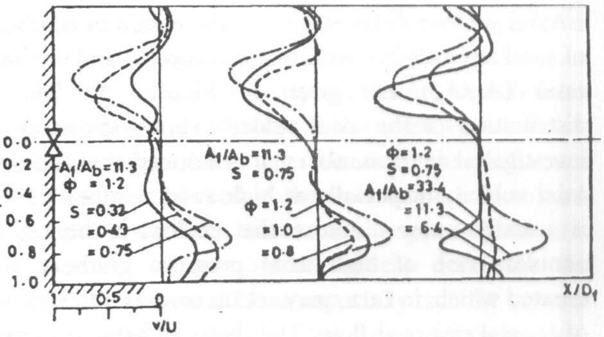

Figure 5. Radial velocity distribution, at $\bar{x}$ = 0.058.

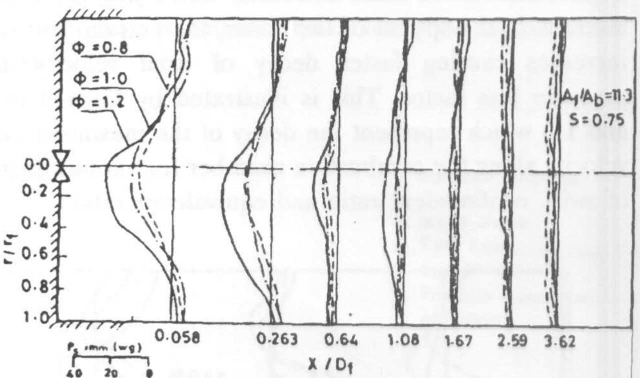

Figure 6. Static pressure distribution, effect of equivalence ratio.

Measurements of tangential velocity (w) for the selection of combinations of operating parameters (S, ϕ and A_f/A_b), are given in Figure (4).

It is well known that the tangential velocity has a promoted effect on the creation of central reverse flow zone and hence on the pressure loss inside the combustion chamber. Since at any given section, large gradients of static pressure occur (see Figures 6,7 and 8) due to the centrifugal force of swirling flow. The radial distribution of static pressure is obtained by integrating the following term across the given radial section

$$\int_0^{P} dP = \int_0^{T_R} \rho \frac{w^2}{I} dr$$

The study of the experimental results given in Figure (4) shows that the tangential velocity moves rapidly towards the furnace wall. Its value is extremely small (tends to zero) at the combustion chamber centre-line and maximum at a radius ($\bar{r}$), which increases with the increase in swirl number, Maximum tangential velocity of about (26 m/s) is found at $\bar{r}$ = 0.4. Rapid decay of tangential velocity is noticed when increasing (x/D_f). This decay can be attributed to the sudden expansion and mixing effect. Typically this decay of tangential velocity is proportional to $(x/D_f)^{-2}$. The effect of increased swirl number upon this configuration is shown in Figure (4). An increase of swirl numbers from 0.32 to 0.75 increases maximum tangential velocity from 16 to 26 m/s. The radial velocity distribution for different operating conditions (S, A_f/A_b and ϕ) are shown in Figure (5). The sign convention used is positive in the upper half corresponding to inward radial velocity components. In the lower half, the convention is reversed. Thus for perfectly symmetric flame the distribution are not symmetric. Frequently, the apparent distributions are not of this form. This is due to the buoyancy effect and experimental error in recording the radial velocity components.

The distribution shows that, close to the burner the radial components are of the same order as the axial components. Also the decay of radial components tends nearly to the form $(v/u) \sim (x/D_f)^{-1}$.

3.2 Static Pressure Distributions

The radial profiles of the static pressure distributions for different sections are shown in Figures (6,7 and 8). Measurements were carried out for flame and isothermal tests, for different confinement ratio, equivalence ratio and swirler vane angle. The figures illustrate the very complex flow patterns, which occur in case of combustion in a cylindrical furnace with different confinement ratios. The measured values of the static pressure throughout most of the flow are subatmospheric and raising near atmospheric or higher, close to the furnace walls at large dimensionless axial distances ($\bar{x}$). The effect of combustion is always to raise the static pressure in the vicinity of the centre-line closer to atmospheric pressure. For flow with (CRZ), confinement causes the pressure, near the centre line, to be depressed below atmospheric.

From the figures it can be noticed that the centre-line static pressure decreases below atmospheric with increasing degree of swirl at large axial distances. Also, the minimum values of static pressure occurs at nondimensional radial distance ($\bar{r}$) which increases with increasing the swirl number (S) at the small axial distance. This can be attributed to the presence of (CRZ), which increases in dimensions with increasing degree of swirl and confinement ratio. This causes the pressure to be depressed below atmospheric pressure with the increase of radial distance. Since the points of low values of static pressure lie in the central recirculation zone, small scale recirculation is obtained with S = 0.33. The fairly intense mixing results in high volumetric heat release for stoichiometric mixtures. However, compared with systems employing large scale recirculation, the burning range is narrow and the low pressure performance is poor.

Experimental results for S = 0.32 showed that for isothermal test the minimum values of static pressure occurs at the central region as shown in Figure (7). However, for flame test the minimum values shift towards the wall, at nondimensional radial distances ($\bar{r}$) 0.3 and 0.4 at $\bar{x}$ = 0.058 and 0.263 respectively. This is due to the displacement of main flow area from the centre-line due to the combustion effect. On moving towards the jet boundary the values of static pressure raise progressively. With large values of nondimensional axial distance ($\bar{x}$), the distributions move towards uniformity, but with values near the wall approximately equal to atmospheric.

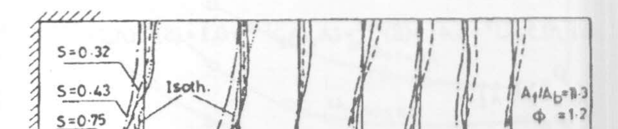

Figure 7. Static pressure distribution, effect of swirl intensity.

Generally speaking, from the experimental results on time average three velocity components and pressure losses inside combustion chamber it is clear that the following parameters have the dominant effect on the flow field.

3.2.1 Effect of Confinement Ratio

The effect of varying confinement ratio is complex due to the change in entrainment rate which strongly influences the system aerodynamics by reducing the rate of decay and altering the shape of three velocity components. It was postulated that alternations in the rate of decay and shape of the tangential velocity profiles might be made by increasing the confinement ratio. This can easily cause the flame to strike earlier and hence reducing the pressure recirculation zone. On the other hand, it can be noticed that the reduction in pressure recirculation zone has no effect on isothermal pressure drop (ΔP_c).

3.2.2 Effect of Equivalence Ratio

Increasing equivalence ratio tends to increase the magnitude of the three velocity components especially in the vicinity of burner exit (Figures 3,4 and 5) but has a little effect thereafter. Combustion and increasing equivalence ratio always bring the static pressure closer to atmosphere or higher at the combustion chamber walls, while increasing equivalence ratio would bring the static pressure to a higher negative value especially in early stages (primary and reaction zones).

3.2.3 Effect of Swirl Number

The angle of flame spread increases with the increase of swirl number (S). The spread of the flame up to the impinging point is mainly affected by swirl intensity. Equivalence ratio and confinement ratio have inconsiderable effect. This phenomena has a strong effect on the size of the peripheral recirculation zone and hence the isothermal pressure drop (Figures 6,7, and 8).

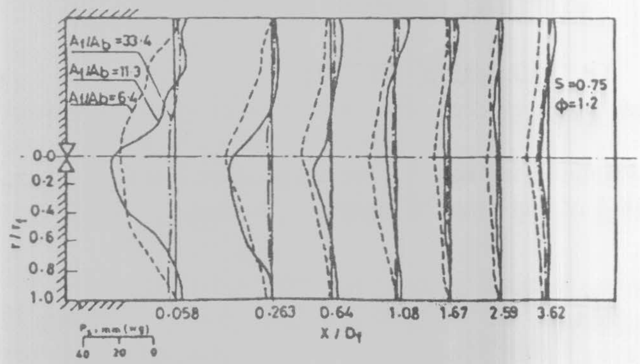

Figure 8. Static pressure distribution, effect of confinement ratio.

4. ANALYSIS AND PREDICTION OF PRESSURE DROP IN COMBUSTION CHAMBER

The basic aerodynamic parameters which form the starting point of any combustion chamber design are:

mean velocity, residence time and pressure loss. These three parameters are interdependent and can be expressed in the form of pressure loss. Part of this pressure drop is incurred in simply pushing the air through combustor. This part is also manifested as turbulence, which is highly beneficial to both combustion and mixing. Aerodynamically, it may be regarded as equivalent, to "drag loss" and is called isothermal or cold pressure loss (ΔP_c). The remainder part is the fundamental pressure loss arising from the addition of heat to a high velocity stream and is called hot pressure loss (ΔP_h).

The losses arising from turbulence and friction that can be measured with reasonable accuracy from cold (isothermal) flow tests are given by:

$$\Delta P_c = (0.5U^2/C_d)(P/RT) \tag{1}$$

As the actual flow is not one-dimensional, due to use of swirler burner, the actual pressure drop will be a factor K_1 times (ΔP_c).

$$\Delta P_c = K_1(0.5U^2/C_d)(P/RT) \tag{2}$$

Under burning conditions these losses are augmented by the fundamental loss due to combustion. For uniform mixtures flowing at low Mach number through constant area duct, this may be derived from one dimensional flow momentum conservation as,

$$\Delta P_h = 0.5\rho U^2[(\frac{\rho_u}{\rho_b}) - 1] \tag{3}$$

Assuming, further, that the hot pressure loss P_h is a factor (K_2) of that given by equation (3), then

$$\Delta P_h = K_2(0.5\rho U^2)[(\frac{\rho_u}{\rho_b}) - 1] \tag{4}$$

The effect of confinement ratio (A_f/A_b) or variable area duct one ΔP_c and ΔP_h was introduced [10] and equations (2 and 4) become,

$$\Delta P_c = K_1(\frac{0.5U^2}{Cd^2})(P/RT)(\frac{A_b}{A_f})^2 \text{and} \ , \tag{5}$$

$$\Delta P_h = K_2(0.5\rho U^2)[\frac{\rho_u}{\rho_h}) - 1](\frac{A_b}{A_f})^2 \tag{6}$$

Therefore, the overall pressure loss in the burning case, in dimensionless form, is given by

$$\begin{aligned} \Delta\bar{P}_t &= (\Delta P_t/0.5\rho U^2) \\ &= \Delta\bar{P}_c + \Delta\bar{P}_h \end{aligned} \tag{7}$$

The term ($\Delta P_t/0.5\ \rho U^2$) is the so called "pressure-loss factor". It is of prime importance to the combustion engineer, since, it denotes the flow resistance introduced into the air-stream. By substitution, the pressure-loss factor is given by:

$$\Delta P_t/0.5\rho U^2 = (K_1/C_d^2)(A_b/A_f)^2 + K_2(A_b/A_f)^2[(\frac{\rho_u}{\rho_b}) - 1] \tag{8}$$

Extensive tests have shown that the factors K_1,K_2 and coefficient of discharge C_d form a complex function of burner geometry and combustion intensity. The actual values of these functions are determined experimentally and given by:

$$\Delta P_t/0.5\rho U^2 = 6.41 * (S)^{0.67} * (A_b/A_f)^{1.12} + 0.1 * (S)^{0.8}(A_b/A_f)^{2.07} * (\phi)^{2.8}$$
$$[(\frac{\rho_u}{\rho_b}) - 1] \tag{9}$$

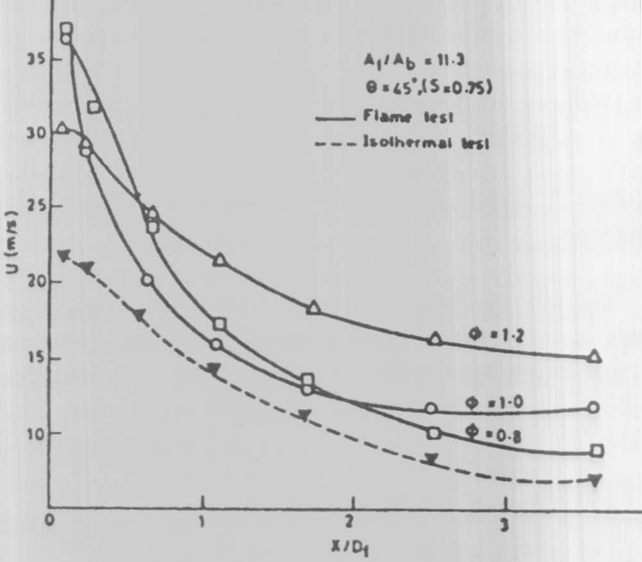

Figure 9. Decay of maximum axial velocity along the furnace, effect of equivalence ratio.

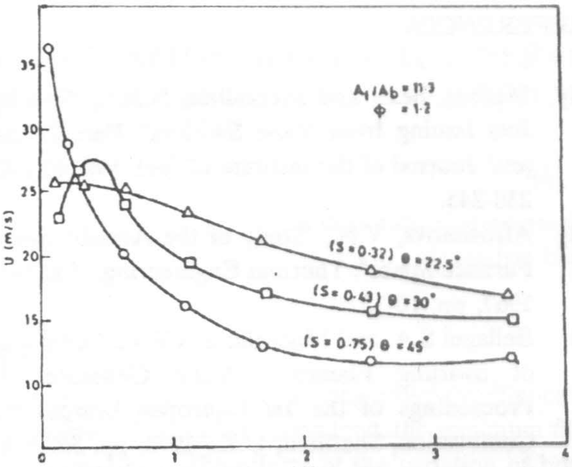

Figure 10. Decay of maximum axil velocity along the furnace, effect of swirl number.

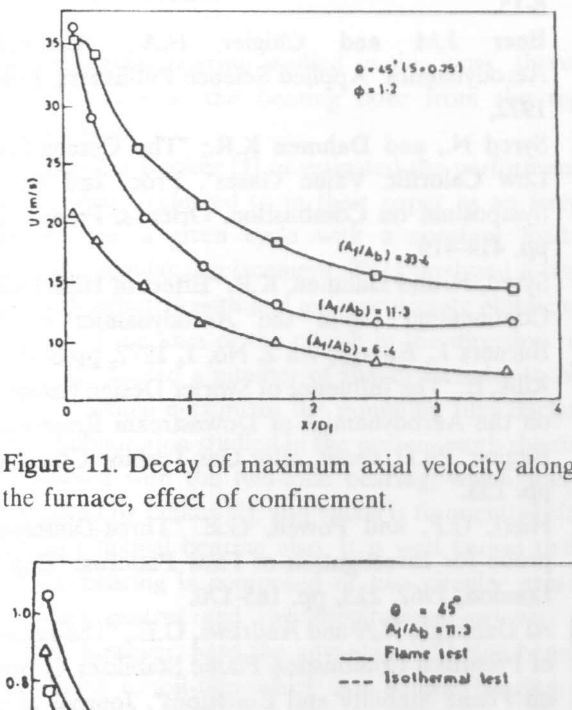

Figure 11. Decay of maximum axial velocity along the furnace, effect of confinement.

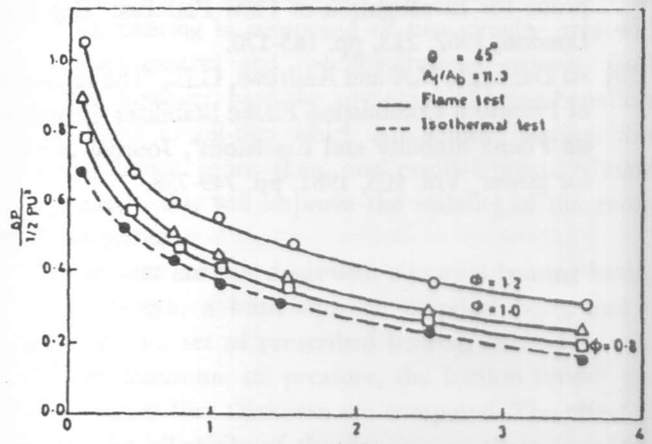

Figure 12. variation of pressure loss factor along the furnace, effect of equivalence ratio.

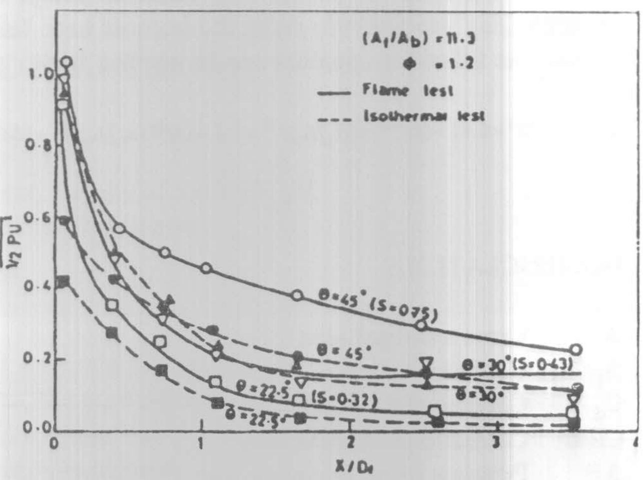

Figure 13. Variation of pressure loss factor along the furnace, effect of swirl intensity.

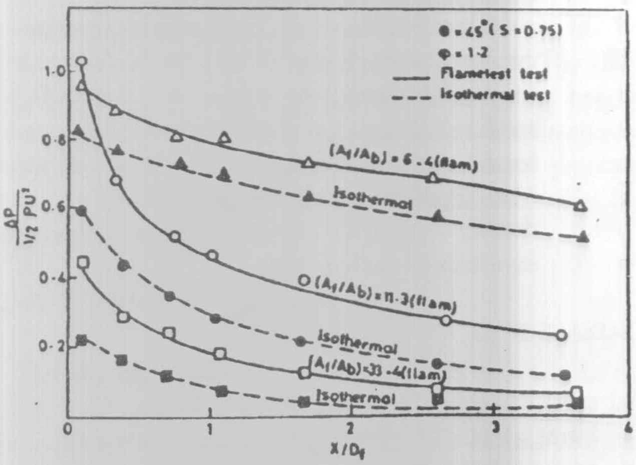

Figure 14. Decay of maximum axial velocity along the furnace, effect of confinement ratio.

CONCLUSIONS

Experimental studies were carried out with the objective of gaining a better understanding of the operating conditions that affect the total pressure drop across combustion chamber. Conclusions obtained are as follows:

1. When it is desirable to use swirl burner, with the aim of improving the overall performance of combustion system, care must be taken in selecting an appropriate burner geometry (S and Af/A_b) if the pressure losses are to be minimized. For example the combination of small swirl number and large confinement ratio substantially reduces the system's total pressure drop and hence operating costs.

2. For the purpose of combustion chamber design and estimating the pressure drop, the authors have found that the following equation can be applied fairly.

$$\Delta P_t/0.5\rho U^2 = 6.41 * (S)^{0.67} * (A_b/A_f)^{1.12} + 0.1 * (S)^{0.8}(A_b/A_f)^{2.07} * (\phi)^{2.8} \left[\left(\frac{\rho_1}{\rho_b}\right) - 1\right] \quad (9)$$

NOMENCLATURE

A	Cross-sectional area
A_f/A_b	Confinement ratio
C_d	Coefficient of discharge
CRZ	Central reverse flow zone
ΔP	Pressure drop, assuming one dimensional flow
P	pressure
$\bar{r}$	dimensionless radial distance
S	swirl number-based on burner configuration
U	average axial velocity
u	local axial velocity
v	local radial velocity
w	local tangential velocity
$\bar{x}$	dimensionless axial distance
ρ	density
ϕ	equivalence fuel-air ratio

SUBSCRIPTS

b_r swirl burner
b burnt gases
c cold or isothermal
h hot
f furnaee
t total
s static
n unburnt gases
u local axial velocity

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