R & D NOTES

Characteristics of Initial Region of a Double Concentric Jet

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As a jet issues from a nozzle into a stationary medium it entrains air from the surroundings. This important property of a jet has several practical applications. For example, the entertainment of hot furnace gases is responsible for a jet increasing in temperature and thereby igniting. The ignition process is generally well advanced within a few diameters from the nozzle, and knowledge of jet characteristics in the initial region is necessary. In pulverized fuel furnaces, one of the most important rate-controlling factors is the rate at which secondary air and recirculating gases are entrained by the primary air-coal jet. Therefore, a study of the mixing characteristics of a concentric jet is helpful in designing pulverized fuel furnaces. Entrainment is also known to cause firestorms around large conflagrations. Many mixing devices in the chemical industry rely on entrainment for their effectiveness. If these processes are to be understood, the factors affecting the entrainment should be known.

In our previous paper (Wall et al., 1980) entrainment in the initial region was measured using the technique suggested by Ricou and Spalding (1961) and we analyzed the results using an equivalent jet approach. The work reported here details the mathematical model of the initial region of a concentric jet, together with measurements of the velocity distribution.

FEATURES OF A CONCENTRIC JET

The details of the development of the initial region of a concentric jet are shown in Figure 1. It comprises of a central potential core of radius r_{1p} enveloped by an inner mixing region with characteristic dimension b_p. Surrounding this shear layer is the annular potential core with inner and outer boundaries represented by the radial distances r_{2p} and r_{1s}, respectively. The outer mixing region is characterized by b_s and the outer radius r_{2s}. The annular potential core is shorter than the central potential core; therefore, the initial region of a concentric jet is taken to end where the boundaries of the annular potential core meet. Downstream from this point, there is a region of transition which is followed by the fully-developed region.

ANALYSIS

For the inner mixing region, on the assumption of a jet issuing in a coflowing external stream, the inner and outer boundaries and the half width line are respectively represented by Eqs. 1, 2 and 3. (See Abramovich, 1963.)

$$\frac{r_{1p}}{r_1} = 1 - K\frac{x}{r_1} \tag{1}$$

$$\frac{r_{2p}}{r_1} = 1 + M\frac{x}{r_1} \tag{2}$$

$$\frac{b_p}{r_1} = N\frac{x}{r_1} \tag{3}$$

where,

$$K = \pm\frac{0.27\,(1-m)\sqrt{0.214+0.144m}}{(1+m)} \tag{4}$$

$$M = \pm\frac{0.27\,(1-m)\,(1-\sqrt{0.214+0.144m})}{(1+m)} \tag{5}$$

$$N = \pm 0.135\frac{(1-m)}{(1+m)} \tag{6}$$

For the outer mixing region, on the assumption of a submerged jet, the inner and outer boundaries are represented by Eqs. 7, 8 and 9, respectively (Abramovich, 1963):

$$\frac{r_{1s}}{r_1} = \frac{r_2}{r_1} - W\frac{x}{r_1} \tag{7}$$

$$\frac{r_{2s}}{r_1} = \frac{r_2}{r_1} - W\frac{x}{r_1} + 2R\frac{x}{r_1} \tag{8}$$

$$\frac{b_s}{r_1} = R\frac{x}{r_1} \tag{9}$$

$$W = 0.111 \tag{10}$$

$$R = 0.135 \tag{11}$$

The entrainment was determined by integration of the velocity profile and was shown earlier (Subramanian, 1980) to be represented by Eq. 12.

$$E_{1+2} = \frac{Q}{Q_0} - 1 = A\left[\frac{x}{r_1}\right] + B\left[\frac{x}{r_1}\right]^2 \tag{12}$$

where

$$Q = \int_0^{r_{2s}} 2\pi\, rU dr \tag{13}$$

$$Q_0 = \pi r_1^2\, U_1\,(1 + mAr) \tag{14}$$

$$A = \pm\frac{0.27(1-m)^2\,(1 - 2\sqrt{0.214+0.144m})}{(1+m)^2} + 0.48m\sqrt{1+Ar} \tag{15}$$

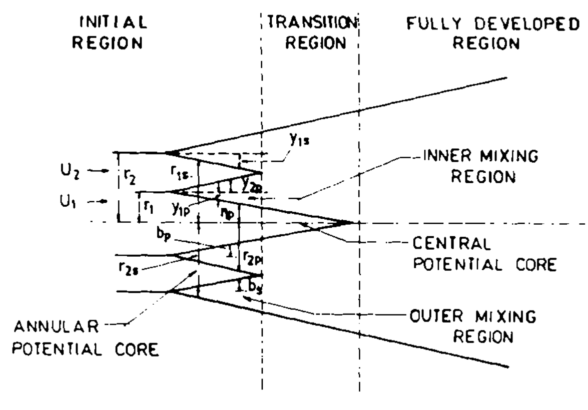

Figure 1. Development of initial region of a concentric jet.

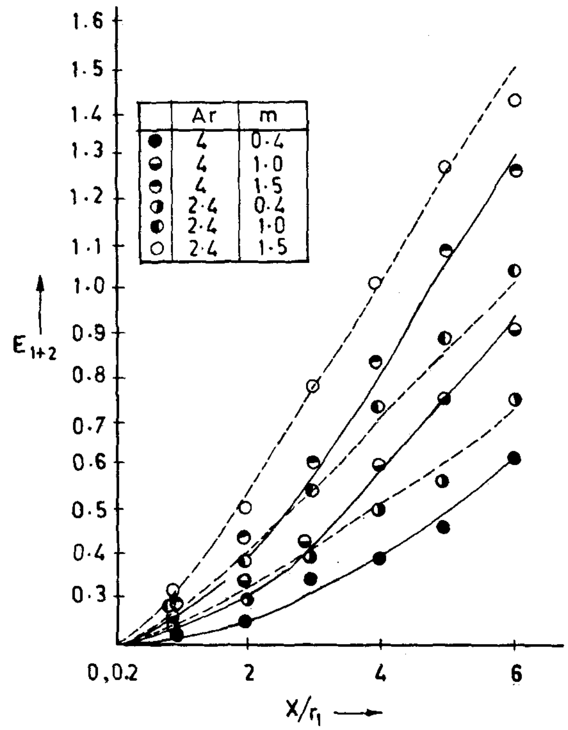

Figure 2. Plot of entrainment ratio vs. axial distance.

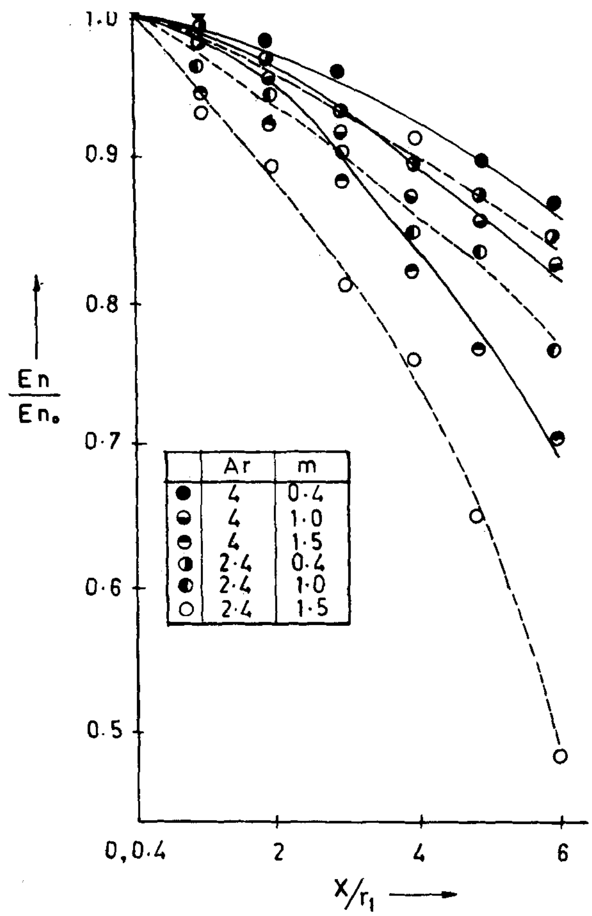

Figure 3. Plot of energy distribution vs. axial distance.

$$B = \frac{(0.27)^2 (1-m)^3 (0.509 + 0.144m - \sqrt{0.214 + 0.144m})}{(1+m)^2} + 0.0004m \quad (16)$$

The energy is represented by Eq. 17

$$En = \int_0^{r_{2s}} \tfrac{1}{2}\rho\, U^3 2\pi r dr \quad (17)$$

and the energy at the nozzle is given by Eq. 18

$$En_0 = \tfrac{1}{2}\rho U_1^3 \pi\, r_1^2 (1 + m^3 Ar) \quad (18)$$

Therefore,

$$\frac{En}{En_0}(1 + m^3 Ar) = (1 + m^3 Ar) + C\left[\frac{x}{r_1}\right] + D\left[\frac{x}{r_1}\right]^2 \quad (19)$$

where

$$C = -2K + N(1.26 + 0.72m + 0.78m^2 + 1.24m^3) - 2m^3 M - 2m^3 W\frac{r_2}{r_1} + 1.26\, Rm^3 \frac{r_2}{r_1} \quad (20)$$

$$D = K^2 - NK(1.26 + 0.72m + 0.78m^2 + 1.24m^3) + N^2(0.48 + 0.66m + 0.78m^2 + 2.08ma^3) + m^3(W^2 - M^2 + 0.48R^2 - 1.26RW) \quad (21)$$

MEASUREMENT OF VELOCITY

Two different geometries were investigated having secondary to primary area ratios of 4 and 2.4. The primary air jet issued vertically downwards through tubes of size 12.5- and 20-mm diameter and the secondary through concentric tubes having 19.1- and 37.6-mm diameter, respectively, the air for the secondary coming through an air chamber having a honeycomb section for obtaining a flat velocity profile as it enters the annulus. Measurements of velocity were made using a total head tube 1 mm in diameter. The probe was calibrated in the potential core of a submerged jet using a standard pilot tube. Adjustments of the probe position at any radial distance could be made with an accuracy of 0.025 mm. To do this, a sliding mechanism with a vernier scale was used. A micromanometer was used in the actual measurement. The Reynolds number for the primary was equal to 2.8×10^4. The velocity ratios of a secondary to primary chosen were 0.4, 1.0 and 1.5. Experiments were done to a distance of $6r_1$ at regular axial distances equal to r_1.

RESULTS

Experimental measurement of velocity showed that the inner and outer mixing regions exhibit similarity of velocity distribution which closely follows the cosine form given below:

$$f(\eta) = \tfrac{1}{2}\left(1 + \cos\frac{\pi\eta}{2}\right) \quad (22)$$

where

$$\eta = \frac{r - r_{1p}}{b_p} \text{ (for the inner mixing region)} \quad (23a)$$

$$= \frac{r - r_{1s}}{b_s} \text{ (for the outer mixing region)} \quad (23b)$$

$$f = \frac{U - U_2}{U_1 - U_2} \text{ (for the inner mixing region)} \quad (24a)$$

$$= \frac{U}{U_2} \text{ (for the outer mixing region)} \quad (24b)$$

Entrainment of air by a concentric jet, normalized with respect to the total air flow (primary plus secondary), is a function of the axial distance from the efflux section and the velocity and area ratios. Figure 2 shows the curves for entrainment which have been obtained from Eq. 12. The experimental points have been obtained by integration of the velocity profile and substituting measured values of velocity. There is a general agreement between experimental and theoretical values based on Abramovich's correlations. With increase in the value of m, there is an increase in the entrainment; with increase in Ar, there is a reduction in mixing. In pulverized fuel applications a better mixing is desired, and our work shows that by increasing the secondary velocity a better efficiency is achieved. Also keeping the annular area low, compared to the primary area, is beneficial for combustion.

Figure 3 shows the energy distributions evaluated from Eq. 19. With increase in m, the ratio En/En_0 decreases. The same trend is seen with a reduction in Ar. Experimental points are obtained by integration of the velocity profile and substituting measured values of velocity. The experimental points approximate the theoretical curves fairly well.

From the energy distribution it is possible to conclude that we can get a short and intense flame for high values of m and low values of Ar, since most of the kinetic energy is depleted in the vicinity of the nozzle and this combination of m and Ar leads to enhanced mixing rates of the recirculating gases.

NOTATION

Ar	= area ratio, ratio of annular area to primary jet area
A,B	= constants, defined by Eqs. 15 and 16, respectively
b	= length scale (m)
C,D	= constants, defined by Eqs. 20 and 21, respectively
d	= diameter (m)
E_{1+2}	= entrainment ratio, defined by Eq. 12
En	= energy (J), defined by Eq. 17
En_0	= energy at nozzle (J), defined by Eq. 18
f	= velocity function, defined by Eq. 22
K,M,N	= constants, defined by Eqs. 4, 5 and 6, respectively
m	= ratio of secondary to primary velocity
Q	= volumetric flow rate (m^3/s)
Q_0	= initial volumetric flow rate (m^3/s)
R	= constant, defined by Eq. 11
r	= radial distance (m)
U	= velocity (m/s)
W	= constant, defined by Eq. 10
x	= axial distance (m)
x_1	= length of potential core (m)

Greek Letters

η	= dimensionless radial distance, defined by Eq. 23
π	= constant
ρ	= density of air (kg/m^2)

Subscripts

$1,p$	= primary
$2,s$	= secondary

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