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Combustion of Pulverized Coal in Vortex Structures

Grant No. DE-FG22-93PC93221

Quarterly Progress Report No. 3

Period Covered: April 1, 1994 - June 30, 1994

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July 1994

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Abstract

This third quarterly report describes the activities and accomplishments of the research team at the University of Oklahoma, Norman, Oklahoma, related to the project entitled "Combustion of Pulverized Coal in Vortex Structures" during the period April 1, 1994 to June 30, 1994. The work performed in this quarter consisted of the following four tasks: (i) further experiments with smoke visualization, (ii) measurements and data analysis of the homogeneous shear layer, (iii) setting up and photography with schlieren system, and (iv) design and fabrication of the particulate feeding system. In the next quarter, we plan to complete schlieren flow visualization of the shear layer and velocity field measurements with and without nonreacting particulates.

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I. INTRODUCTION

This third quarterly progress report covers the overall objectives, the specific objectives for the reporting period, the organizational details, the work that has been accomplished during the reporting period, the work planned for the next quarter, and an assessment of the anticipated problems.

II. OVERALL OBJECTIVES

The overall objectives of the project are: (i) to investigate the changes in the characteristics of large scale vortex structures in the shear layer caused by the introduction of inert solid particles in one of the feed streams; (ii) to understand the effects of pyrolyzing solids on the shear layer behavior; (iii) to study the effect of combustion of the pyrolysis products on the shear layer structure, heat release rate, and pollutant emission characteristics; and (iv) to study the effect of modifying the shear layer characteristics on the ensuing flame behavior.

III. SPECIFIC OBJECTIVES FOR THE REPORTING PERIOD

The specific objectives for the reporting period were: (i) to process the velocity field data presented in the previous report (ii) to develop a heating system to increase the temperature of one of the streams, (iii) to design and fabricate the particulate feeding system, and (iv) to develop schlieren instrumentation for flow visualization and obtain pictures of the flow field in the test section for different ratios of the initial velocities of the mixing streams.

IV. ORGANIZATIONAL DETAILS

Mr. Nelson Butuk, a graduate student in the School of Aerospace and Mechanical Engineering, pursuing his Ph. D. degree program continued to work as a research assistant assisting the principal investigator, Professor S. R. Gollahalli. In addition, Mr. Azfar Kamal and Mr. Subramanian Thenappan, also graduate students, were involved in various phases of construction and testing. The mechanical engineering technician of the School, Mr. Bill Hill, and the machinist, Mr. Steve Dean helped the research team during the reporting period. Also, the college of Engineering machine shop headed by Mr. Donald Burroughs helped in the fabrication of the particulate system.

V. WORK ACCOMPLISHED DURING THE REPORTING PERIOD

VA. Flow Field Data Analysis and Results

Figure A shows the nomenclature and the coordinate system employed in representing the experimental data. The measurements reported in the pervious quarterly report include the mean velocity profiles in the cross-stream direction (y) of the shear layer at several streamwise locations (x) for various ratios of the velocities of the two streams (U_1/U_2). These locations were at 0, 6.3, 10, 14, 16, 20, 24, 28, 32, and 36 cm from the splitter plate. The velocity U_2 was set at a constant value of 19.5 m/s while varying U_1 at 3.6, 6.2, and 14.5 m/s yielding three velocity ratios.

To analyze the results of the homogeneous plane mixing layer, the following parameters were defined following the landmark paper by Brown and Roshko (1974):

$\eta = y/(x-x_0)$ dimensionless cross-stream distance
 x_0 virtual origin which is not at the end of the splitter plate but located upstream because of the boundary layer development on the splitter plate

$r = U_1/U_2$ velocity ratio or strength of mixing layer

$\partial_w = (U_2 - U_1) / (\partial U / \partial y)_{\max}$ velocity-profile maximum slope thickness (vorticity thickness)

$\partial'_w = d\partial_w / dx = \partial w / (x-x_0)$ x derivative of vorticity thickness

$\lambda = (U_2 - U_1) / (U_2 + U_1)$

∂'_w was used to represent the important mixing layer parameter, the spreading rate, commonly denoted by σ related to ∂'_w by the relation $\sigma \partial'_w = \pi^{1/2}$ (Spencer and Jones, 1971).

To analyze the results, it was first necessary to determine x_0 . This was done by calculating ∂_w , the vorticity thickness at each x location and plotting the results versus x . Figures 1, 2 , and 3 show the plots for the three velocities used. The point x_0 was determined from the location os for $y = 0$ after fitting data with the best regressed curve. The parameter ∂_w was determined by using Lagrangian interpolation to the velocity data points and using the formula

$$f'_{x_0} = \{4f(x_0 + h) - 3f(x_0) - f(x_0 + 2h)\} / 2h$$

to approximate dU/dy for a suitable step size h at each data point. The maximum value of dU/dy was then obtained. The calculated results for x_0 for each velocity ratio were

(i) for $U_2 - U_1 = 14.5 \text{ m/s}$ and $\lambda = 0.6$
 $y = 6.753 \times 10^{-3} + 9.134 \times 10^{-2} x$
 $x_0 = -0.074 \text{ m}$

(ii) for $U_2 - U_1 = 6.2 \text{ m/s}$ $\lambda = 0.2$
 $y = 5.3186 \times 10^{-3} + 6.6297 \times 10^{-2} x$
 $x_0 = -0.08 \text{ m}$

(iii) for $U_2 - U_1 = 3.6 \text{ m/s}$ $\lambda = 0$.
 $y = 6.753 \times 10^{-3} + 9.134 \times 10^{-2} x$
 $x_0 = -0.09 \text{ m}$

Having determined x_0 , the velocity profiles of U/U_2 versus η were plotted. Figures 4, 5, and 6 show these plots. The spreading parameter $\delta'w$ was next determined and is shown in Figs. 7, 8, and 9 at each x location for each value of λ .

VB. Discussion

An important parameter for comparison of mixing layer is the spreading rate parameter, popularly known as σ . This parameter is normally obtained by fitting experimental data to analytical results. The well-known analytical solution of a plane shear layer assuming similarity (Schlichting, 1968) reduces the boundary layer equations to a simple third-order ordinary differential equation

$$f'''(\eta) + 2\sigma^2 f(\eta) f''(\eta) = 0$$

with boundary conditions

$$f' = 1 \pm \lambda \text{ at } \eta = \pm\infty$$

where $\eta = \sigma y/x$

$$\lambda = (U_2 - U_1) / (U_2 + U_1) \text{ and } f' = U/U_2$$

This leads to the general series solution in powers of λ

$$U = (1/2)(U_1 + U_2) [1 + \lambda \operatorname{erf}(\eta + d) + \dots] \quad (\text{Ruderich R. 1986})$$

This equation requires the determination of two constants σ and d . The constant s which is a measure of the spreading rate of the shear layer, depends on the eddy viscosity and must be determined experimentally. Because of this σ is defined in such a way that the use of η as abscissa brings the velocity profiles closest to the error function. The second constant d takes care of the missing third boundary condition.

Figures 7, 8, and 9 showing the spreading rate parameter $\sigma'w$ defined above indicates slightly different values for each location of x . This probably indicates the presence of a nonfully developed flow. For the velocity ratio $r = 0.26$, which is close to the value $r = 0.34$ Brown and Roshko, the value of s is 0.089 in agreement with the value shown in Fig. 7.

In shear layers it is not easy to distinguish between developed, developing, or transitional flows. If the velocity ratio, r is zero (ie., one stream is stagnant, then Bradshaw (1966) gives a rule of thumb for estimating the distance required to achieve self similarity based on the initial momentum thickness at the splitter plate. That rule is not applicable for the situation for $r > 0$ since the flow becomes complex. The flow then develops from two boundary layers which will in general have two different momentum thicknesses. In general, the length required for the flow to become fully developed will increase with increasing velocity ratio.

Because it was difficult to determine from our velocity profiles whether the flow is fully developed and has achieved self similarity, it was decided to investigate the analytical solution using two different approaches: (i) PHOENICS flow code which solves the full time-averaged Navier-Stokes equations, (ii) Solutions of simplified boundary-layer equations using similarity transformation principles. These two approaches will also serve to complement each other.

The PHOENICS code was run and some results were obtained during this reporting period. See figure 10 for the velocity profile development. Computer programs to implement the second approach have been written and are currently being debugged.

VB. Development of a Heating System to Increase the Temperature of One of the Streams

For obtaining schlieren or shadowgraph pictures of the shear layer one needs to have a density difference between the two streams of the shear layer. First, we considered adding

a lighter gas like helium to one of the streams. Since, the estimated cost of the gas requirement was prohibitive, we decided to heat one of the streams. Some preliminary calculations indicated that the electrical power requirement to obtain sufficient temperature increase was not available in the laboratory, we decided to employ direct heat addition by burning a natural gas flame in one of the streams.

For this purpose we used a Mecker burner supplied with compressed natural gas from a storage bottle. The burner was located in the duct immediately downstream of the blower and was well upstream of the flow straightening devices and thus the shape of the initial velocity profiles of the two streams was not affected by heating. A flame stabilizer was included to prevent the flame from being blown-out at high velocities.

Figure 11 shows the transverse temperature profiles at various distances from the splitter plate for a given energy input to the burner. Figure 12 to 14 show the development of velocity profiles for a given value of the velocity ratio r . It is noticed that the magnitudes of the velocity in stream 2 used as the normalizing factor is higher in the heated case, and hence the U/U_2 profile falls below the curves for the unheated case. The magnitudes of the shear layer parameters found for the heated case are compared with those for the unheated case. It is seen that the spreading rate of the shear layer is higher in the case of the heated stream. This effect may be attributed to the density and viscosity changes in the heated stream.

VC Design of Particulate Feeding System

Figure 15 shows the details of the particulate feeding system designed to supply solid particles to one of the shear layers. It consists of an inverted open trapezoidal trough. The side walls of this container can be positioned at different angles such that the width of the linear slit opening at the bottom can be varied. Powder material will be placed in the trough. A cylindrical shaft with a linear groove along its length controls the amount of powder fed to the slit opening. The shaft is run by a variable speed direct current electric motor with a large reduction gear. The speed of the motor can be varied by varying the armature current. The trough will be connected to the top channel so that the linear slit opening is in communication with the top stream at the position of the contraction venturi. As a result of the venturi, the local static pressure in the channel will be negative, and thus the particulate matter that falls into the stream will be sucked into the stream and carried into the test section. By adjusting the rpm of the motor and the width of the slit opening we expect to vary the concentration of particulate matter in the upper gas stream.

This device was designed and fabricated during the reporting period.

VD. Design and Installation of the Schlieren Flow Visualization System

After several preliminary trials, it was decided to use a schlieren/shadowgraph system to visualize the shear layer as the smoke pattern photographs could yield only a limited amount of information. During the reporting period, we have constructed two optical stands to mount the light source and collecting optics. We have also purchased a fiber optic light source. We have conducted some preliminary trials to determine the alignment and camera timings to freeze the motion of the shear layer.

VI. WORK PLANNED FOR THE NEXT QUARTER

In the next quarter, we plan to pursue the following tasks: (i) install schlieren instrumentation for flow visualization of shear layer, (ii) test and debug the particulate feeding system, (iii) obtain schlieren photographs of the homogeneous shear layers and shear layers having nonreacting particles, and (iv) extend the velocity field measurement to particulate-laden shear layers.

VII. ANTICIPATED PROBLEMS

Although currently we do not expect any major problems in the execution of the project in the next quarter, we expect some difficulties in the working of particulate feed system and obtaining an uniform flow rate. Further we may run into some problems with the intensity and duration of the flash light source to freeze the motion and obtain good exposures with the available high speed photographic films.

VIII. CONCLUDING REMARKS

During the third quarter we have completed the tasks as planned. We designed and constructed a new particulate feeding system. We have completed the velocity field measurements in homogeneous shear layers and analyzed the data. The results show good agreement with the data available in literature and hence provide us confidence with the capabilities and precision of our apparatus. We have also started assembling schlieren visualization system and designed a heating system to obtain the density gradients in the test section required for flow visualization. In the next quarter, we expect to conduct flow visualization experiments and conduct detailed velocity measurements in nonreacting particulate laden shear layers.

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Figures

Coordinate System

Figure A

Graph of Shear Layer Thickness vs stream wise distance,x for U2-U1=14.53m

Figure 1

Graph of shear layer thickness vs stream-wise distance, x for $U_2 - U_1 = 6.2 \text{ m}$

Figure 2

Graph of shear layer thickness vs stream-wise distance, x for U2-U1=3.61m

Figure 3

Velocity profiles. $U_2 - U_1 / U_2 + U_1 = 0.6$ vs dimensionless Y-distance

Figure 4

Velocity Profiles $U_2 - U_1 / U_2 + U_1 = 0.2$ vs dimensionless Y-distance

Figure 5

Velocity Profiles. $U_2 - U_1 / U_2 + U_1 = 0.1$ vs dimensionless Y-distance

Figure 6

Spreading rate. $U_2 - U_1 / U_2 + U_1 = 0.6$ vs Stream wise Distance X

Figure 7

Spreading rate. $U_2 - U_1 / U_2 + U_1 = 0.2$ vs Stream wise Distance X

Figure 8

Spreading rate. $U_2 - U_1 / U_2 + U_1 = 0.1$ vs Stream wise Distance X

Figure 9

Figure 10

—> : 94.5 m/s.

PLANE SHEAR LAYER K-E MODEL Y-X POS

PHOENICS

Temperature Profiles for heated experiment.r=0.33

Figure 11

Cold and Heated Results at X=200mm

Figure 12

Cold and Heated results at X=140mm

Figure 13

Experimental and Phoenix Results at X=320mm

Figure 14

Schematic Of the Particle Feeding System Arrangement

Figure 15

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