The Influence of Swirl on the Flow Characteristics of a Reciprocating Piston-Cylinder Assembly[1]

W. C. Reynolds.[2] It would be helpful to have the authors' estimates of the experimental uncertainty in some key results, for example the location of the center of the vortices, the angles of the jet-exit streamlines, and the strength of the recirculations.

L. D. Cloutman.[3] Recent interest by automobile manufacturers in more fuel-efficient engines that produce less pollution has resulted in attempts to model the detailed reacting flows that occur in internal combustion engine cylinders (for example, references [1-3] and the work referenced by the authors). One goal of this effort is to provide engine designers with a tool that can supplement their expensive and time-consuming experiments. It is necessary to validate these complex numerical fluid dynamics programs by comparing computed results with analytic solutions and carefully performed and documented experiments.

In the present paper and its reference [1], the authors have made a significant contribution to the validation process. These experiments are attractive for code validation because of their simplicity. One especially useful aspect of this experiment is its axisymmetric nature. Most of the present detailed engine programs are limited to two dimensions. In addition, it is a relatively simple turbulent fluid flow without complicating features such as combustion. A reliable engine model must be able to simulate such an experiment accurately before it makes sense to worry about chemistry, fuel sprays, etc.

To be useful to numerical modelers, the documentation of an experiment must include enough information to allow the computations to be done without guessing at any parameters: geometry of the experiment, thermodynamic state and composition of the fluid(s), initial conditions, and boundary conditions (including possible time dependence). The report by Dyer [4] on a constant volume bomb experiment is a good example of a sufficiently well-documented study. However, authors almost invariably leave out some critical piece of information or include some complication that makes it impossible to simulate the experiment numerically. The present paper is marginal in this regard, as the thermodynamic state and composition of the working fluid are not specified. In general, this omission would render the results useless for numerical simulations. However, in this particular case, the omission is not serious as the flow is basically isothermal and incompressible, and therefore probably insensitive to these details. Gosman, et al. [5] have attempted to simulate some of these experiments, and their discussion elaborates on some of the problems encountered in trying to compare even these relatively simple experiments with calculations. Additional simple, well-documented experiments, perhaps each emphasizing one physical process such as combustion or fuel sprays, would be most welcome.

Additional References

1 Butler, T. D., Cloutman, L. D., Dukowicz, J. K., and Ramshaw, J. D., "CONCHAS: An Arbitrary Lagrangian-Eulerian Computer Code for Multi-component Chemically Reactive Fluid Flow at All Speeds," Los Alamos Scientific Laboratory report LA-8129-MS, 1979.

2 Butler, T. D., Cloutman, L. D., Dukowicz, J. K., Ramshaw, J. D., and Krieger, R. B., "Toward a Comprehensive Model for Combustion in a Direct-Injection Stratified-Charge Engine," in *Combustion Modeling in Reciprocating Engines,* ed. J. N. Mattavi and C. A. Amann, General Motors Research Laboratories, New York, Plenum Press, 1980.

3 Cloutman, L. D., Dukowicz, J. K., and Ramshaw, J. D., "Numerical Simulation of Reactive Flow in Internal Combustion Engines," *Proc. of the Seventh Intern. Conf. on Numerical Methods in Fluid Dynamics,* in press, 1980.

4 Dyer, T. M., "Characterization of One- and Two-Dimensional Homogeneous Combustion Phenomena in a Constant Volume Bomb," Sandia Laboratories report SAND78-8704, 1978.

5 Gosman, A. D., Johns, R. J. R., and Watkins, A. P., "Assessment of a Prediction Method for In-Cylinder Processes in Reciprocating Engines," in *Combustion Modeling in Reciprocating Engines,* ed. J. N. Mattavi and C. A. Amann, General Motors Research Laboratories, New York, Plenum Press, 1980.

Authors' Closure

Reply to W.C. Reynolds, Stanford University

The enquiry requests estimates of the experimental uncertainty on three topics - (i) the location of the centers of the vortices, (ii) the strength of the recirculations, and (iii) the angles of the jet-exit streamlines. These are considered in turn.

(i) The primary vortices occupy the bulk of the flow space, are stronger and are much more accurately defined than the secondary vortices which form in the corners near the cylinder head and piston face and in the near-axis region behind the head. The vortices were plotted by joining up contours of the stream function ψ, obtained by integration of the mean axial velocity values, and adding or subtracting small amounts of mass (typically up to ±10 percent of the net mass flux) to correct for departures of the measurements from continuity requirements.

The vortex centers can however be located since the value of the stream function is either a maximum or a minimum at these points. Thus, for the centers.,

$$\text{at constant } x, \frac{d\psi}{dr} = 0, \text{ i.e. } \bar{U} = 0,$$

$$\text{and at constant } r, \frac{d\psi}{dx} = 0, \text{ i.e. } \bar{V} - 0.$$

Hence, the vortex centers may be determined by plotting the loci of points (at constant x) where $\bar{U} = 0$ and (at constant r) where $\bar{V} = 0$. The point of intersection gives the vortex center. Interpolation is necessary in the latter case due to the relative coarseness of the axial spacing. An example is shown on Fig. A for the profiles at 90 deg ATDC and S = 1.20 (see Figs. 2(*a*) and 3(*c*) of the paper). The location of the center of the primary vortex is almost exactly as shown in the paper, while that of the vortex in the corner between the cylinder head and wall is in the correct radial position but slightly further from the wall than shown in Fig. 2(*c*). No information can be obtained for the center of the third vortex since there is no region near the axis in Fig. 3(*c*) where $\bar{V} = 0$ (except at the axis itself). This confirms that the center of this vortex must be nearer to the wall (i.e. as shown) than z = 10 mm. For the primary vortex, therefore, the contours presented in the paper are consistent with the mean values of the radial velocity. The

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[1] By A. A. Morse, J. H. Whitelaw, and M. Yiameskis, published in the Dec. 1980 issue of the ASME JOURNAL OF FLUIDS ENGINEERING, Vol. 102, No. 4, pp. 478–480.

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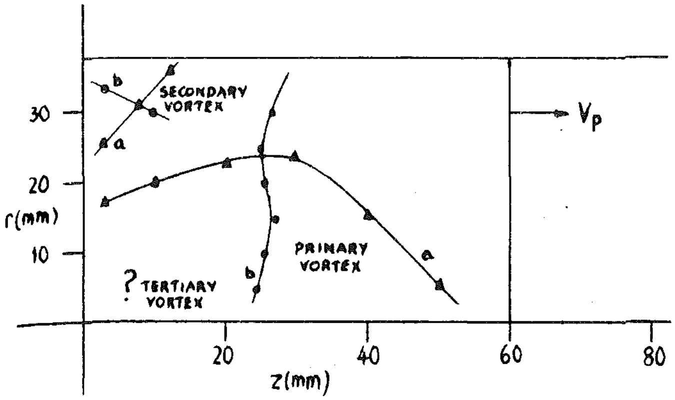

Fig. A Determination of vortex centers (S = 1.20, 90 deg ATDC). (*a*) Loci of points at constant x where $\bar{U} = 0$, (*b*) loci of points at constant r where $\bar{V} = 0$. Location of vortex centers. Primary vortex—from above: $z = 25.1$ mm, $r = 23.8$ mm. From 80-WA/FE-8: $z = 23.5$ mm, $r = 22.7$ mm. Secondary vortex—from above: $z = 7.6$ mm, $r = 31.2$ mm. From 80-WA/FE-8: $z = 5.5$ mm $r = 31.3$ mm

same confirmation of the location of the centers cannot however be drawn for the secondary vortices since there are not enough data points in the volumes occupied by the vortices for clear definition. In general, the estimated location of the vortex centers is accurate to within ±2 mm in both the axial and radial directions so that, as a rough guide, the innermost contour for each vortex may be considered as representing the area of uncertainty for the true center of rotation.

(ii) The quoted values for the mass flux recirculated by each vortex are probably more accurate for the secondary vortices than for the primary vortex since corrections to the mass balances to satisfy continuity were always made in the regions of large velocity, i.e. in the primary vortex and the indrawn jet. The quoted strengths of the primary vortices are accurate, therefore, to the same order as the extent of the corrections required to adjust the mass balances (i.e. an upper limit of ±10 percent). The secondary vortices were drawn on the basis of integration from the nearest boundary at which the stream-function values was known, i.e. from the wall or the axis as appropriate, and *no corrections to the measured velocity values were made*. Thus, the accuracy of the quoted vortex strengths is that of the measurements themselves, i.e. ±3 percent.

(iii) The angles of the jet-exit streamlines are subject to appreciable uncertainty in the zero swirl case (Figs. 1(*a*), 2(*a*), and 4(*a*)) since the nearest station of measurement to the cylinder head was at z = 10mm. Interpolation across the initial 10mm of flow space is difficult in view of the steep gradients of axial velocity (and hence of the stream function) which prevail. The situation is improved for the cases with swirl since the profiles at z = 3mm were also measured.

Reply to L. D. Cloutman, Los Alamos Scientific Laboratory

Dr. Cloutman's remarks about our paper (80-WA/FE-8) indicate a philosophy which is essentially the same as we have adopted at Imperial College in the alliance of measurements in simple "engine-like" configurations to the development of computer codes to predict the flow field in reciprocating systems of increasing complexity. Consequently, as he realizes, we have endeavoured in our measurements to provide the computor with sufficient information to simulate the experiments numerically without major uncertainties concerning the initial and boundary conditions or the working state of the fluid. We have provided in the paper, data which show the increasing effect of swirl on the in-cylinder flow processes and should assist in the development of numerical procedures and turbulence models to predict the basic flow field in the absence of complicating effects such as compression and combustion. A more comprehensive statement of the data is available in the report cited in the paper.

Following on from the data presented, we have now made measurements in a similar swirling flow configuration with different clearance volumes and bore-to-stroke ratios. These demonstrate clearly the effects of such parameters on the growth and decay of the vortex structure. The effect of off-setting the inlet valve to produce a three-dimensional flow has also been explored. Both sets of data are available in the form of Imperial College reports. Measurements are currently being performed in similar plexiglass configurations but with the addition of compression ratio – 3.5, and the program has been supported by data obtained in a practical diesel engine of compression ratio 17.5.