The effect of aspect ratio on heat loss from a swirling flow within a cylinder

Syed Wahiduzzaman* and Colin R. Ferguson
Purdue University, School of Mechanical Engineering,
West Lafayette, IN 47907, USA

Received 29 October 1986 and accepted for publication 8 July 1987

Measurements have been made of the total rate of heat loss and the half radius swirl velocity of an unsteady, turbulent swirling flow within a cylinder for different aspect ratios. The instantaneous heat loss correlates with the half radius swirl velocity by a Nusselt-Reynolds number power law. The correlation is independent of aspect ratio if the filling of the cylinder results in a flow field which is axi-symmetric and shows no axial variation outside the boundary layers.

Keywords: fluid flow; heat transfer; swirl; unsteady

Introduction

The modeling of heat transfer in internal combustion engines can be divided into two categories: those that use Nusselt number Reynolds number correlations and resolve little, if any, spatial detail, and those that use wall functions or boundary layer models. The former class of models is reviewed by Watson and Janota[1]. One of the many problems with these correlations is that no matter how an engine is configured the only characteristic length that enters the correlation is the bore or cylinder diameter. For example, in the special case where the swirl velocity is much larger than the piston speed and in the absence of combustion, Woschni's[2] correlation reduces to

$$\mathrm{Nu} = 0.012\mathrm{Re}^{0.8} \tag{1}$$

In this form of Woschni's equation the Reynolds number is based on the swirl speed and the radius of the bore; the Nusselt number is based on the radius of the bore. Interestingly enough, Equation 1 was developed using a diesel engine, and it agrees very well with the correlation of Wahiduzzaman and Ferguson[3], developed using a constant volume cylindrical vessel. In any case, neither correlation has included the effect of aspect ratio. The main purpose of this paper is to develop a correlation for flow in a cylinder that includes aspect ratio or to establish the circumstances under which it has no effect as presupposed by Equation 1. In conclusion, a suggestion will be offered pertinent to computation of the distribution of local heat flux.

Apparatus

All measurements reported were obtained in a 102-mm-diameter right circular cylindrical vessel of variable width. Argon is suddenly introduced tangentially into the initially evacuated cylinder through a rapid-acting intake valve. Measurements are made of the gas pressure and of the swirl velocity from the time of inlet valve closure to 375 ms later. The vessel was designated to allow simulation of diesel combustion; see Oren, Wahiduzzaman, and Ferguson[4].

The vessel is shown in Figures 1 and 2. The planar walls of the cylindrical test space are formed by two steel blanks that can be interchanged with large quartz windows of the same dimensions or with special blanks that allow varying the width of the test space, as will be discussed. The intake valve is actuated by compressed air in response to signals issued by a sequence timer integral to a computer control system that will also be discussed. It is very important that the induction process be reproducible, and considerable development was done to ensure that this was so, using as a discriminator records of the intake valve velocity as a function of time. In the experiments reported here, the intake valve velocity profile is invariant as aspect ratio varies, and the valve is open for 120 ms. Note the inlet port on the valve, which is orientable and in these experiments admits the flow tangentially; its width relative to the width of the cylinder will later be concluded as an important feature of the flow.

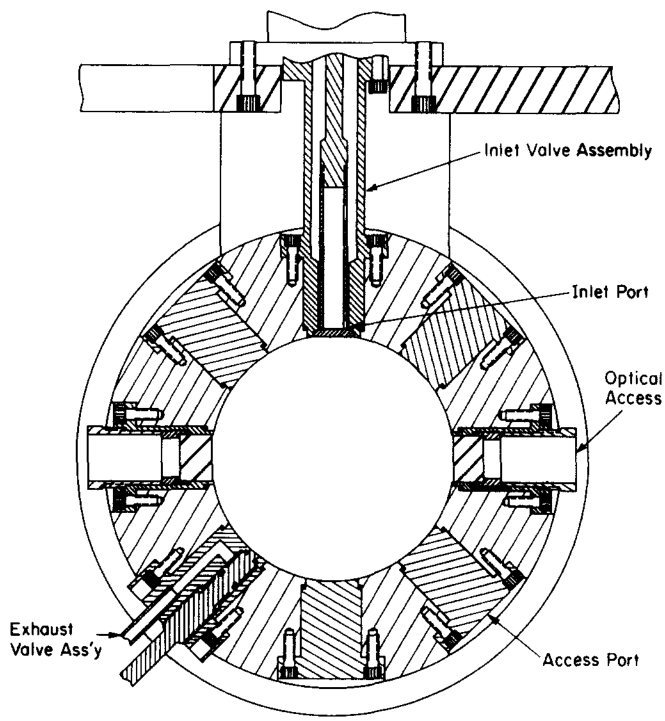

Figure 1 Schematic of the cylindrical test vessel. The initially evacuated vessel is filled by dumping heated argon stored in the prechamber through a rapid acting inlet valve

* Now at Integral Technologies Inc., Westmont, IL.

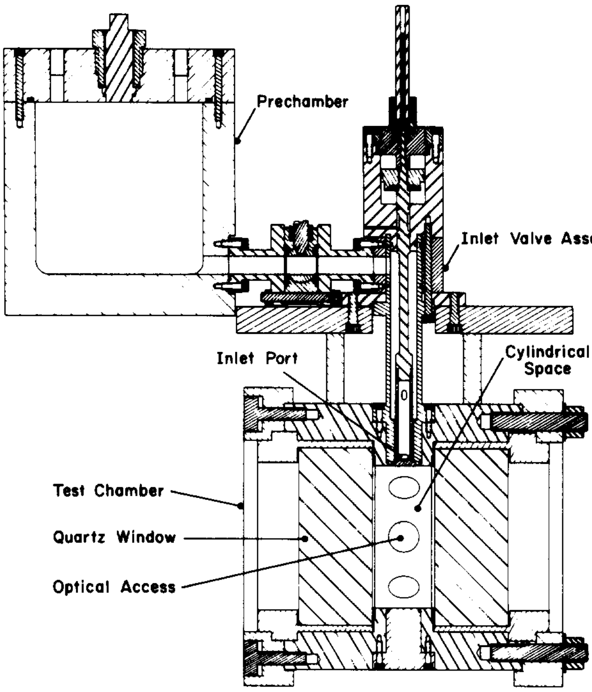

Figure 2 Another view of the cylindrical test section

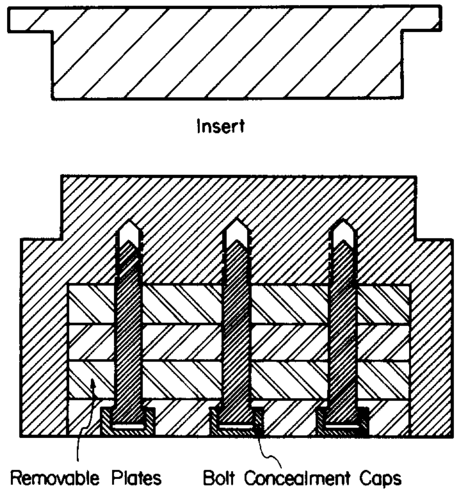

Figure 3 Special blanks interchangeable with the quartz windows, Figure 2, that allow varying the width of the test section

The special blanks that allow varying the width of the test space are depicted in Figure 3. To reduce the width of the cylinder, the insert is used; to increase the width, the "disk stack" is used; different widths are obtained by the number of disks stacked. As aspect ratio varies, the intake valve and the access ports are always centered between the planar walls.

The computer control and data acquisition system is shown schematically in Figure 4. The control of the intake valve was already mentioned. The sequence timer is a device designed to provide TTL (transistor-transistor logic) signals at precise and programmable intervals. These signals are used to drive relays, inhibit processes, initiate data acquisition, trigger scopes, and provide an event marker. The minimum interval between two states of the TTL signal is 0.1 ms, with an accuracy of 10 μs. The power control interface switches power by means of 16 solid-state relays triggered by the sequence timer.

The signal from the photomultiplier tube (PMT) of the laser Doppler velocimeter is processed by a counter-type processor operated in the N-cycle mode. Three 16-bit words describe a single realization: the number of cycles, the time elapsed during the eight cycles counted, and the time between the last and the present realizations. The data inhibit signal prevents data being collected prior to times of interest so that the limited memory of the minicomputer (PDP 11/03) is reserved only for the data of interest.

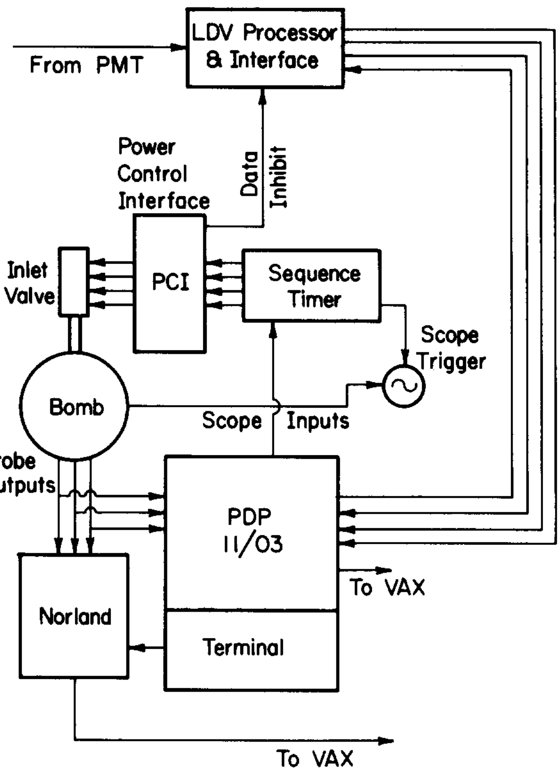

Figure 4 The computer control and data acquisition flow diagram

Notation

D	Diameter of cylinder
L	Height or width of cylinder
m	Mass
Nu	Nusselt number
p	Pressure
$\dot{Q}_l$	Total heat loss rate
R	Gas constant
Re	Reynolds number
t	Time
$\bar{T}$	Mass average temperature
V	Volume

Greek symbols

γ	Ratio of specific heats

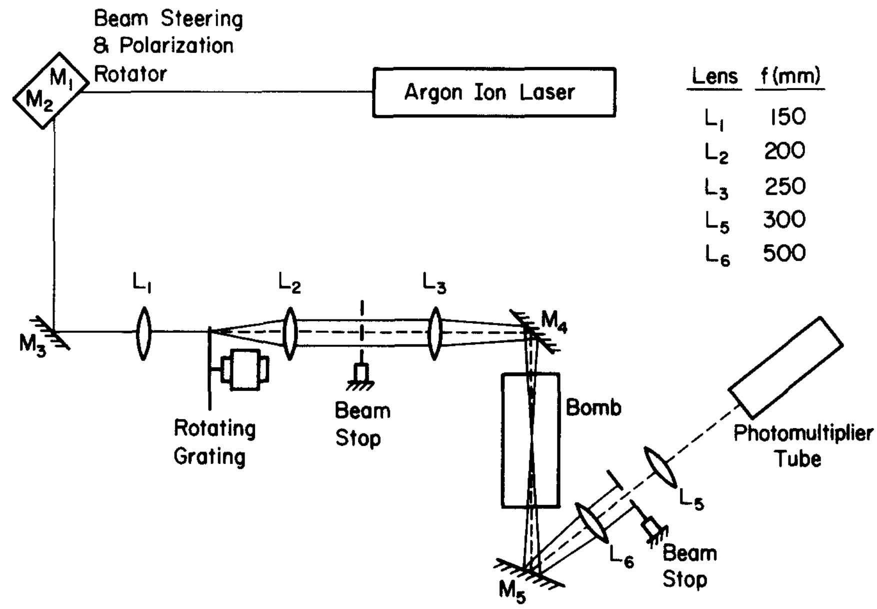

Figure 5 Forward scattering laser Doppler velocimeter used to measure the swirl velocity

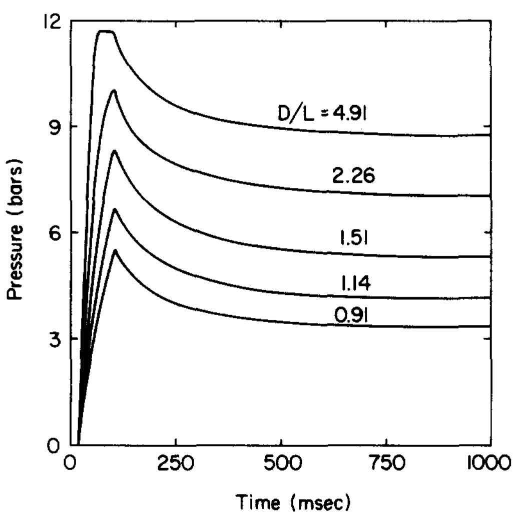

Figure 6 Pressure in the cylinder during filling and after valve closure at 125 ms

The laser velocimeter is used to measure the swirl velocity at the half-radius point in the symmetry plane of the cylinder. The optical train is shown in Figure 5. To obtain maximum fringe contrast, a polarization rotator is employed. The laser beam is split by focusing it into a rotating diffraction grating, which also provides a frequency shift and allows discrimination of positive and negative velocities. The primary beam and all but the first-order beams from the rotating grating are blocked off by a beam stop. Lenses L_2 and L_3 collimate and direct the first-order beams into the test chamber, creating an ellipsoidal probe volume. This arrangement suffers from the narrow beam angle required to pass the beams through a rather small window. The major axis of the probe volume, aligned radially, is 2.75 mm or 5.4% of the cylinder's radius. This poor resolution can be tolerated only because it has already been shown that the velocity profile is nearly flat at the half-radius point[3].

By mapping the entire flow field in terms of velocity, turbulence intensity, and temperature as well as spatially resolving the local heat flux on the walls, Wahiduzzaman and Ferguson[3] were able to show that when $D/L=2.26$ the swirl velocity in the midplane and at the half-radius point adequately characterized the flow. It characterizes the flow because the flow proved to be one-dimensional. Therefore, in this work all velocity measurements are made at the same half-radius point as the aspect ratio (D/L) is varied.

Once the inlet valve closes, the pressure in the cylinder is spatially uniform, so it does not matter where it is measured. The pressure history is recorded with a piezoelectric transducer and is the basis from which the total heat loss from the gas is determined. Because the pressure is uniform and because argon has constant specific heats, the instantaneous rate of heat loss is

$$\dot{Q}_l = \frac{-V}{\gamma-1}\frac{dp}{dt} \tag{2}$$

The pressure record is digitally filtered prior to differentiation to eliminate random errors.

Results

The pressure records as a function of aspect ratio are given in Figure 6. As the width of the cylinder increases, so does its volume. The filling process was done with conditions in an upstream filling reservoir and with the duty cycle of the inlet valve held constant. As a result, the mass entering the cylinder is a weak function of the aspect ratio, and the density at time zero is dominated by the changing volume. Therefore the pressure levels decrease as the aspect ratio decreases. The flatness of the peak at $D/L=4.91$ is caused by pressure equilibrium being realized between the filling reservoir and the cylinder prior to closure of the inlet valve. It occurs in this case only due to the small cylinder volume at this aspect ratio.

The heat transfer determined from the pressure records is given in Figure 7. The only clear feature of the dependence on aspect ratio is that at $D/L=4.91$ the heat loss is significantly less than in any other case. Recognize that several variables are changing simultaneously, including the swirl velocity and the mass average temperature driving the heat loss.

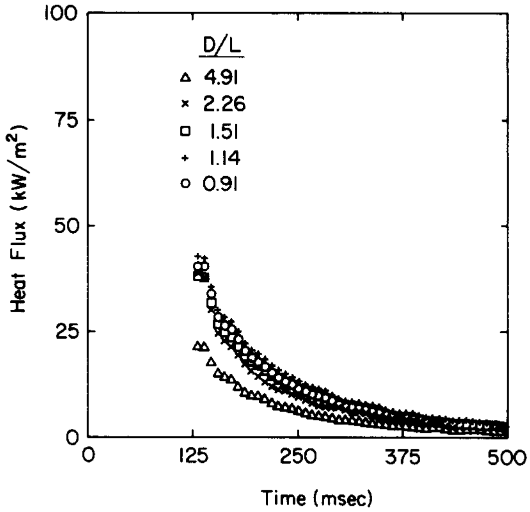

Figure 7 Heat loss per unit wall area for different aspect ratios

The swirl velocity records are given in Figure 8. These are the ensemble mean velocities, and hence they are free from the turbulent fluctuations seen in an individual realization. The velocity decreases with increasing aspect ratio. It was already mentioned that at $D/L=4.91$ pressure equilibration is realized during the filling process between the cylinder and the filling reservoir. In the limit of $D/L \ll 1$, the flow through the inlet valve would always be choked during the fill cycle. Hence, it can be seen that the average velocity of the entering gas, which will fix the initial swirl, will decrease with increasing aspect ratio.

Error analysis

Examples of systematic errors in the velocity measurements are errors due to inaccuracy of the fringe spacing measurement and slippage of the seed particles relative to the gas speed. The seed particles used have a nominal diameter of 0.3 microns. A posteriori calculations showed that the slip velocity, derived by equating the drag force on a particle to the maximum fluid acceleration, was smaller than the resolution of the laser velocimeter and thus of no concern.

Errors in fringe spacing are the results of errors in measuring the beam intersection angle. That angle is determined by removing the collection optics and measuring the distance between two spots at a known distance far away from the probe volume. Each of these two distances is determined to within 1.0%, resulting in a 2.0% error in the fringe spacing.

Another systematic error is due to velocity bias, which occurs because in a given time interval more high-velocity particles than low-velocity particles pass through the probe volume, causing the resultant mean to be higher than the true mean. In order to obtain a bias-free measurement, individual velocity realizations must be made at equal time intervals (Stevenson, Thomson, and Roesler[6]), which was not possible in this case. The velocity bias is difficult to estimate. Based on the work of McLaughlin and Tiederman[7], the bias error is estimated to be less than 2.0%.

One of the most important sources of random errors is due to variance in the filling process from experiment to experiment. The standard variation in the mean velocity of an individual experiment at time zero is about 4.0%.

Another source of random error is fluctuations of the digital mantissa used to compute the Doppler frequency. These fluctuations may be caused by noise or digital rounding off of an analog signal. This error is estimated by the general method of Kline and McClintock[8], and for this problem is about 2.0%.

Computing the overall uncertainty as the square root of the sum of squares of individual uncertainties finally yields the estimate that the mean velocity is uncertain by less than 5.0%.

The rate of heat loss is determined by a pressure measurement. There are systematic errors in the derivation of Equation 2, but they are small. For example, the rate of kinetic energy decay is neglected, and the pressure in the vessel is assumed uniform. These cause errors of 0.2% and 1.0%, respectively.

By far the most important error is random error in the time derivative of the pressure. Again applying the general method of error anlaysis[8] to this problem, we estimate this error to be 23%. Accounting for all other errors, including uncertainties in the transducer calibration, leakage of charge from the piezoelectric crystal, leaking of argon from the cylinder, and variance in the filling processes increase that estimate by only 0.5%.

Dimensional analysis

To define a Nusselt number, we assume the mass average temperature of the gas to drive the heat transfer. Since the pressure is uniform and argon has constant specific heats, it can be determined from the measured pressure and knowledge, determined from the presure when the gas reaches thermal equilibrium with the walls, of the mass of gas in the cylinder. It can be shown that

$$\bar{T}=pV/mR \tag{3}$$

Evaluating gas properties at the mass average temperature, choosing the characteristic length to be the radius and the characteristic velocity to be the measured swirl velocity at the half-radius point, we have plotted the Nusselt number against the Reynolds number for $D/L=2.26$ in Figure 9. If all the data obtained are correlated by a power law independent of the aspect ratio, we obtain

$$\mathrm{Nu}=0.086\mathrm{Re}^{0.68} \tag{4}$$

with a standard error of 35 in the Nu. The goodness of fit can be improved, but a multiplicative factor dependent upon aspect ratio will not work. The standard error in fitting Equation 4 is as

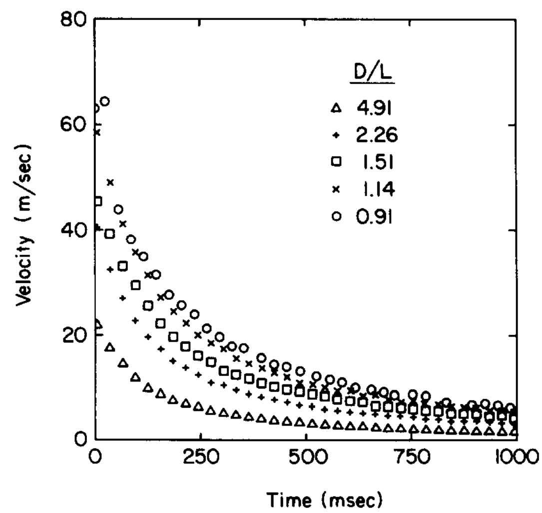

Figure 8 Ensemble average half-radius swirl velocity as a function of time and aspect ratio

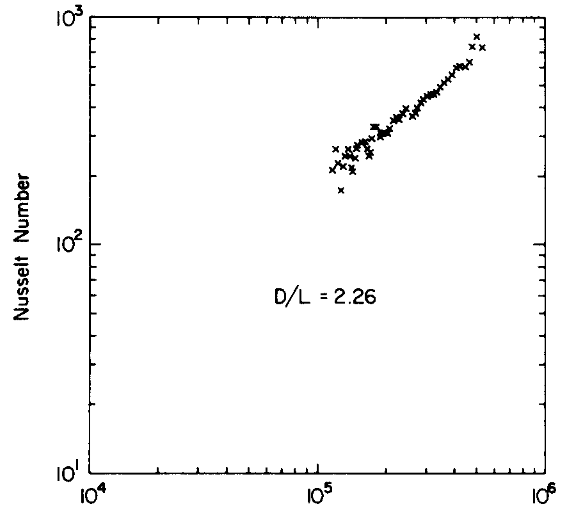

Figure 9 The Nusselt number and Reynolds number are based on the radius, the half-radius swirl, and the mass average temperature

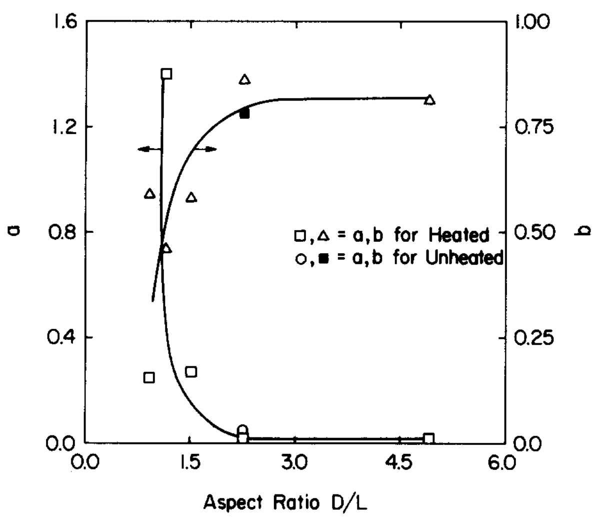

Figure 10 Constants *a* and *b* used to relate the Nusselt number to Reynolds number; see Table 1. For aspect ratios greater than 2, the flow is one-dimensional, and hence the constants are independent of aspect ratio

small as it is partly because the range of Reynolds numbers obtained was limited to one decade and the curves intersect at about $Re = 5 \times 10^5$. It was therefore decided to adopt a power law correlation wherein both the slope and intercept depend upon the aspect ratios. The results are given in Figure 10 and tabulated in Table 1. The standard error for a given aspect ratio is seen in Table 1 to be improved.

Inspection of Figure 10 reveals that for $D/L > 2$ the Nusselt number is independent of aspect ratio. Recall that when choosing the half-radius velocity to characterize the flow, we assume that it is one-dimensional. Because the intake valve can be approximated as a line source during filling only if the filling slot is not small compared to the cylinder width, it is not hard to imagine that the flow at lower aspect ratios is no longer one-dimensional and is the underlying reason for the behavior depicted in Figure 10.

In the introduction it was mentioned that Woschni's[2]

Table 1 Correlation constants as a function of aspect ratio

a	b	ε	D/L
0.017	0.81	15	4.91
0.011	0.85	28	2.26
0.270	0.58	17	1.51
1.400	0.46	15	1.14
0.250	0.59	11	0.91

$Nu = a\,Re^b$, ε

correlation for heat transfer in an engine agreed in the limit case of no piston motion and no combustion with that obtained by Wahiduzzaman and Ferguson[3] for what can now be identified as the special case here of $D/L = 2.26$. That statement needs qualification. Woschni's swirl speed is based on an instrument that measures the total angular momentum of the steady flow through the intake valve and port when mounted on a flow bench; it is not based on an in-cylinder measurement of the swirl. Wang and Ferguson[9] have shown that the half-radius velocity in a one-dimensional swirling flow is about twice the half-radius velocity of a solid body with the same angular momentum and therefore equal to the peripheral speed needed in Woschni's correlation. That the two correlations have the same exponent is significant; that they have the same premultiplicative factor is fortuitous to the extent that swirl, though in at least one engine is one-dimensional as in this case (Johnston *et al.*[10]), varies with time in an engine, and Woschni characterized it by a single number.

Conclusions

In Ref. 3 it is shown that the heat transfer from a swirling flow within a cylinder is

$$Nu = 0.011 Re^{0.85} \tag{5}$$

Both Nu and Re are based on the radius, and the characteristic velocity used is the half-radius velocity. In this paper Equation 5 is shown to be independent of aspect ratio provided the swirling flow is one-dimensional and in the range $8 \times 10^4 < Re < 7 \times 10^5$. A one-dimensional flow results if the intake flow acts as a line source during the filling of the cylinder.

Equation 5 is for the total heat loss. The spatial distribution in local heat flux can be estimated from the total heat loss using the dimensionless graphs in Ref. 3.

Acknowledgments

This work was supported by the U.S. Department of Energy, Office of Energy Utilization Research, Energy Conversion and Utilization Program. We wish to thank Professors F. P. Incropera and W. H. Stevenson for helpful discussions during the course of this work.

References

1 Watson, N. and Janota, M. S. *Turbocharging the Internal Combustion Engine*. Wiley, New York, 1982, 535–540
2 Woschni, G. P. Die Berechung der Wandverluste und der Thermischen Belastung der Bauteile von Diesselmotoren. *MTZ*, 1970, **31**(12)
3 Wahiduzzaman, S. and Ferguson, C. R. Convective heat transfer from a decaying swirling flow within a cylinder. Eighth Int. Heat Transfer Conf., 1986, Paper 86-IHTC-253, 987–992
4 Oren, D. C., Wahiduzzaman, D. C., and Ferguson, C. R. A diesel

combustion bomb: proof of concept. *SAE Trans.*, 1984, **93**, 5.945–5.460

5 Wahiduzzaman, S. A. H. A study of heat transfer due to a decaying, swirling flow in a cylinder with closed ends. Ph.D. Thesis, Purdue University, 1985

6 Stevenson, W. H., Thompson, H. D., and Roesler, T. C. Direct measurement of laser velocimeter bias errors in a turbulent flow. *AIAA J.*, 1982, **20**, 1720–1732

7 McLaughlin, D. K. and Tiederman, W. G. Biasing correction for individual realization of laser anemometer measurement in turbulent flows. *Phys. Fluids*, 1973, **16**(12)

8 Kline, S. J. and McClintock, F.A. Describing uncertainties in single sample experiments. *Mechanical Engineering*, 1953, **75**

9 Wang, Q. C. and Ferguson, C. R. Multidimensional modeling of the decay of angular momentum and internal energy in a constant volume cylindrical vessel. *J. Heat Transfer*, 1986, **108**(3), 700–702

10 Johnston, S. C., Robinson, C. W., Rorke, W. S., Smith, J. R., and Witze, P. O. Application of laser diagnostics to an injected engine. *SAE Trans.*, 1973, **88**, 353–370