LOW COST TRANSIENT DISCHARGE COEFFICIENT MEASURE SYSTEM

Bruno Soriano, soriano915@hotmail.com
Automotive Mechanical Engineering Graduate Student, Lutheran University of Brazil

Charles Rech, charlesrech@uol.com.br
Automotive Mechanical Engineering Department, Lutheran University of Brazil

Abstract. *This paper analyses the discharge coefficient in prediction of transient flow in an internal combustion engine, four-stroke spark-ignition, working in a motorized mode, with a low cost measure system. Considering discharge coefficient as the engine breathing capacity, the transient flow that occurs in the intake system was investigated in a standard Honda GX35 engine, with 39.00mm bore and 30.00mm stroke. An experimental apparatus was mounted with a hot film anemometer to measure the transient air discharge. Using a rotameter, the anemometer was calibrated to ensure the results. The response time curves of the anemometer were quantified through the use of an electrical fan controlled by a varivolt. The angular velocity was measured with a photodiode sensor connected to the crankshaft. The engine was driven by an electrical motor, that provides the desired angular velocity, 663, 1444, 2260 and 3065. Results revealed a good method to quantify the discharge coefficient and show the effect of inertia and compressibility of air in the intake stroke.*

Keywords: *internal combustion engine, discharge coefficient measurement, hot wire anemometer*

1. INTRODUCTION

In internal combustion engines, the flow conditions inside the cylinder are critical for the combustion process (Heywood, 1988). These are determined by the air flowing into the cylinder through the intake valves during the induction process and by its evolution during the compression stroke. The discharge coefficient measures the flow permeability in the engine intake system.

A valve and its associated port are said efficient if there is minimal discrepancy between the effective or actual flow area and the geometrical flow area. This efficiency is quantitated by means of discharge or flow coefficient defined as the ratio of the actual flow area to the geometrical flow area (Ferguson, 1985). The discharge coefficient (C_D) of the inlet valve is influenced by the following factors: valve seat width, valve seat angle, rounding of seat corners, port design and cylinder head shape (Heywood, 1998). The discharge coefficient for each valve lift increases with increasing lift. The air flow rate through the intake valve varies with intake pressure ratio, increasing as the pressure ratio increases (Rech *et al*. 2008, Zancanaro *et al* 2010 a, b). Deep and detailed research on the in-cylinder gas flow produced during the intake process is helpful for achieving its efficient control and utilization in order to improve combustion, enhance performance and reduce emissions when developing engines.

Among other parameters, the mixture formation in internal combustion Otto cycle is related to the flow before and after entering the cylinder. The induction process and discharge is a consequence of the geometry of the intake and exhaust manifold, the geometry of the combustion chamber and engine speed. These parameters influence the magnitude of secondary flows and turbulence intensity, which operates significantly in the combustion process of fuel-air mixture.

There are many techniques to analyze the flow into the cylinder from experimental measures, for example, the measurement of the velocity field in the steady flow test rig using laser Doppler velocimetry (Uzkan *et al.* 1983). This method provides high quality results and is more aptly used to measure the velocity field inside the cylinder while the engine is working, although this requires expensive equipment and good optical access to the combustion chamber (Zur *et al.*1989, Payri *et al.*1996, Rask *et al.*1985, Jaffri *et al.*1997, Fansler *et al.*1993, Corcione *et al.*1994, Bopp *et al.*1986). Hadded *et al.*, 1991, used a laser Doppler to characterize the movement of mass air during the intake and compression strokes. Stier and Falco, 1994, analyzed the behavior of the flow using the technique of LIPA (Laser Induced Photochemical Anemometry). There were three openings of valves with water at 20 rpm (corresponding to 340 rpm with air). The authors obtained the velocity field with the formation of re-circulation, considering the magnitude of the vortex.

Witze et al., 1980, compared the turbulence measured in the cylinder, using the hot wire anemometer and Doppler laser. The author's conclusion was that the use of laser Doppler allows a better resolution of the measurement, due to a larger scan of the geometry studied. Liu et al., 1994a, measured the velocity profile and turbulence intensity in the discharge of a typical engine with spark ignition by hot wire anemometer in steady operation. Data were collected from different valve openings. The authors concluded that the velocity profile and turbulence intensity are strongly dependent on the valve opening and the geometry of the intake port. Liu et al., 1994b, measured with the same process, the magnitude of angular momentum and swirl ratios in the admission process for each speed related with opening of valves.

In this work, experimental measurement of transient air-mass flow in the intake system are made from an engine motored by an electrical motor that provides the desired angular velocity. The MAF (Measurement of Air Flow) measures the air-mass flow, this instrument consist in a hot film anemometer. The results of air-mass flow for different velocities were treated and converted to discharge coefficient. The curves of C_D were plotted in the same graphic related to angular velocity and valve opening.

2. MATHEMATICAL METHODOLOGY

2.1 The Discharge Coefficient

The impact of a blockage on the engine breathing is assessed through a discharge coefficient C_D that relates the actual mass flow rate through the intake valve to the isentropic mass flow rate. Therefore, the equation assumes the following form (Heywood, 1988; Ferrari ,2005).

$$C_{D\_actual} = \frac{\dot{m}_{actual}}{\frac{\pi d_V^2}{4} \frac{p_{st}}{\left(RT_o\right)^{1/2}} \left(\frac{p_{out}}{p_{st}}\right)^{1/\gamma} \left\{ \frac{2\gamma}{\gamma-1} \left[1 - \left(\frac{p_{out}}{p_{st}}\right)^{(\gamma-1)/\gamma} \right] \right\}^{1/2}} \tag{1}$$

where $\dot{m}_{actual}$ is obtained from the numerical solution, or experimentally, R is the gas (air) constant, T_o the stagnation (inlet) absolute temperature, d_v is the inner valve diameter and γ the specific heat ratio.

2.2 Response Time of Air Flow Measurement

The dynamic response of a measuring instrument is the change in the output caused by a change in the input. Both are functions of time and can be written in a differential form.

$$a_n \frac{d^n x}{dt^n} + a_n \frac{d^{n-1} x}{dt^{n-1}} + \ldots a_1 \frac{dx}{dt} + a_0 = F(t) \tag{2}$$

The order of instruments can be zero, first, second and more. A first order linear instrument has an output which is given by a non-homogeneous first order linear differential equation:

$$\frac{a_1}{a_0} \frac{dx}{dt} + x = \frac{F(t)}{a_0} \tag{3}$$

when $F(t)=0$ to $t=0$ and $F(t)=\mathrm{A}$ to $t>0$ the Eq. 3 can be written:

$$x(t) = \frac{A}{a_0} + \left(x_0 - \frac{A}{a_0} \right) e^{-t/\tau} \tag{4}$$

where τ is a constant, called the constant time of the instrument.

Considering $A/a0=x\infty$, the Eq. 4 can be written:

$$\frac{x(t) - x_\infty}{x_0 - x_\infty} = e^{-t/\tau} \tag{5}$$

Hot film anemometer for measuring air mass is first-order instrument (Holman, 1994). The constant time of a measurement of air flow is determined by the thermal capacity of the hot film and the thermal contact between hot film and air flow that is being measured. The constant time depends on the anemometer's moment of inertia. When t is equal to τ, has a constant time, which represents 63.2 % of the time needed for the event to establish the initial condition until the end. The constant time is dependent on the characteristics of the measuring instrument and the mean on which it is being used. For the case of 90 % of the variability imposed, we have that $e^{-t/\tau} = 0{,}1$ or $t = 2.303\tau$. Or, provide two constants time (1 – 0.135), 86.5 %, 95 % contained three, and so on. Usually, 5τ for the system to stabilize the final condition, which represents 99.3 %, is used (Holman, 1994; Beckwith, 1995).

To verify the constant time of hot film anemometer was construct a test bench showed in the Fig. 1. To air flow equal zero, the voltage of output of anemometer is about 1.5 V, and the maximum air flow the voltage is about 3 V. The air flow in the pipe was blocked five times and set free instantaneously, to get the constant time showed in the Fig. 2.

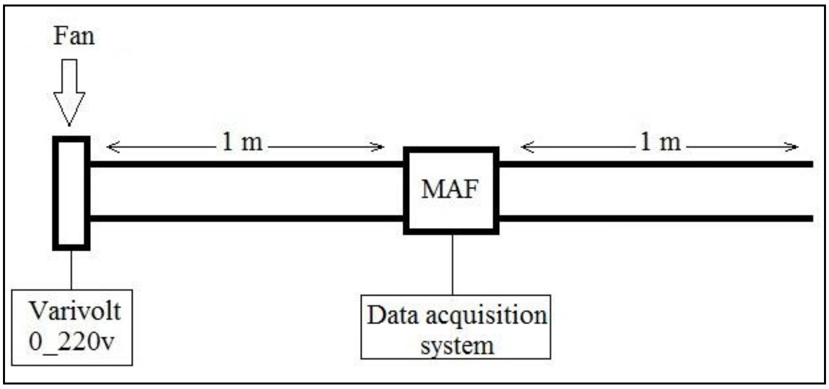

Figure 1 – Representation of test bench to verify the constant time

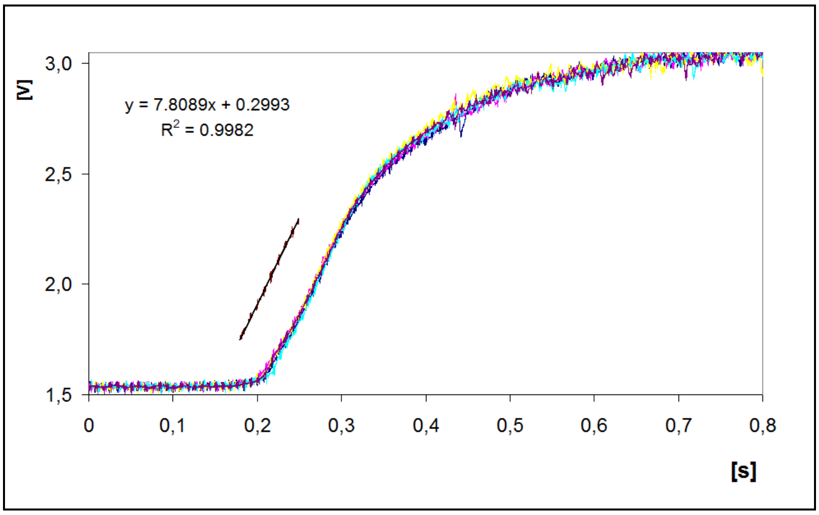

Figure 2 – Sequence of 5 measurements to determine the constant time of MAF: the maximum standard deviation was 0.027 V.

The constant time found is about 120 ms (15 ms/g). The maximum air flow is about 75 crank angle degree, in the maximum velocity piston of 5.0 m/s at 3065 rpm. Considering a quasi-static system the air mass flow is about 1.73 mg/s in this point. In this case, the constant time of hot film anemometer is 8 times greater than necessary to measurement.

2.3 Uncertainly of Measurement

Uncertainty is usually expressed in terms of standard uncertainty, the combined uncertainty or expanded uncertainty. The standard uncertainty of a random data is the estimated equivalent of one standard deviation of action of this effect on the nomination. The combined uncertainty of a measurement process is estimated considering the simultaneous action of all sources of uncertainty and still represents a standard deviation of the resulting distribution. The expanded uncertainty associated with the measurement process, is estimated from the combined uncertainty multiplied by the Student t appropriated (Gonçalves Jr, 2008).

In this article, 30 intake processes were analyzed for each angular velocity. So, the standard deviation can be used.

The measurement system composed by MAF was calibrated with a rotameter and the uncertainly of calibration was 0.25 % (Rech, 2010).

3. EXPERIMENTAL METHODOLOGY

Experimental measurements in the intake system were made on a single cylinder four stroke motored engine. The specifications of the engine are given in the Table 1.

Table 1. Specifications of the engine (Honda, 2011)

Honda GX35 engine	
Bore x Stroke (mm)	39 x 30
IVO/IVC (ATDC)	22/78
Displacement (cm^3)	35.8
Maximum valve lift (mm)	3.00
Intake air system	Naturally aspirated
Compression ratio	8:1

To experimental date the engine, it was instrumented with data acquisition, sensors of angular position and air flow as show the Fig. 3. The angular position of the crankshaft was measured with a photodiode sensor connected to the crankshaft and supplied one pulse per revolution. This point was adjusted to be the Top Dead Center (TDC). The time required for the sensor to go from 0 (when the passage of light is blocked) to 5 volts (when the passage of light is removed) is 5 μs (Photonic, 2011).

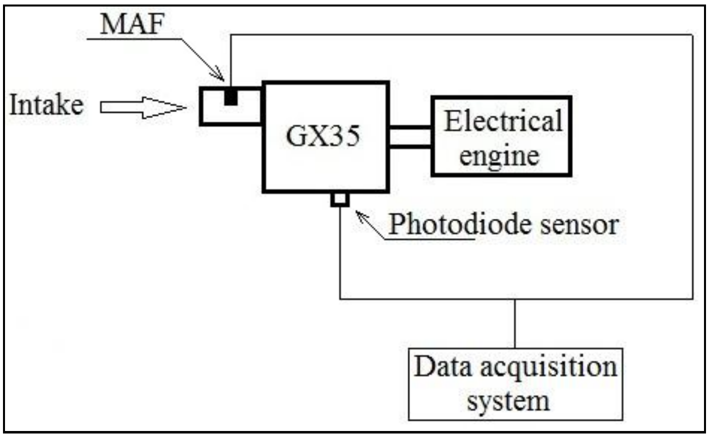

Figure 3 – Schematic picture of measurement system

The air-mass flow was measured with an automotive hot film anemometer. (MAF - Bosch 0 280 218 002). This sensor has an input voltage of 5 and 12 V. The output analogic signal is related to the air flow in the intake process. The heated sensor element in the air-mass meter dissipates heat to the incoming air. The higher the air flow, the more heat is dissipated. The resulting temperature differential is a measure for the air mass flowing past the sensor. An electronic hybrid circuit evaluates this measuring data so that the air-flow quantity can be measured, and its direction of flow. Only part of the air-mass flow is registered by the sensor element. The total air mass flowing through the measuring tube is determined by means of calibration, known as the characteristic-curve definition (Bosch, 2011). The hot film anemometer was about 150 mm of the valve port.

The data was acquired with a commercial data acquisition board (National instruments 6124) and its original software Labview (2008). The values of voltage and frequency were collected and processed with the correspondent calibration curves of each sensor and converted into units of mass flow and angular position. It was acquired 20000 samples for second.

4. RESULTS AND DISCUSSION

The air-mass intake in internal combustion engine motored was measurement by hot film anemometer. Figure 4 shows the results of 30 cycles, with 3065 rpm, obtained in voltage versus time units in the MAF sensor. The black and thicker line of Fig. 4 represents the arithmetic mean of the 30 measurements. The maximum standard deviation mean in this case was about 0.04 V, with good repeatability. The angular velocity had a small change, so the standard deviation of the air-mass is related with the variation of the engine speed. This variation of electrical engine speed can be associated with the energy necessary to rotate the GX35 in relation to cylinder filling.

Another phenomenon that may interfere for the flow to not be the same is residual gas that not goes out of the cylinder in the exhaust phase. This residual gas affects the oncoming intake stroke.

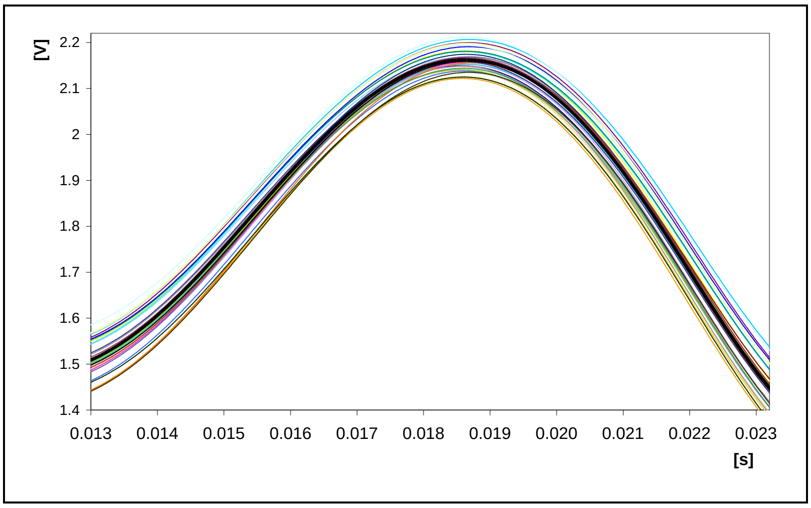

Figure 4 – MAF electrical voltage versus time unit

The right side of Fig. 5 shows the results for the discharge coefficient as a function of the crank angle to four angular velocities. The left side shows the intake valve lift. Effect of inertia and compressibility of the admission air are detected. From the increase of the rotation, minor is the time for cycle and increases the delay of reading of the data in the sensor considering intake valve open angle. The Fig. 5 shows that the discharge coefficient is increasing with angular velocity. The air-mass rate will increase until the maximum volumetric efficiency.

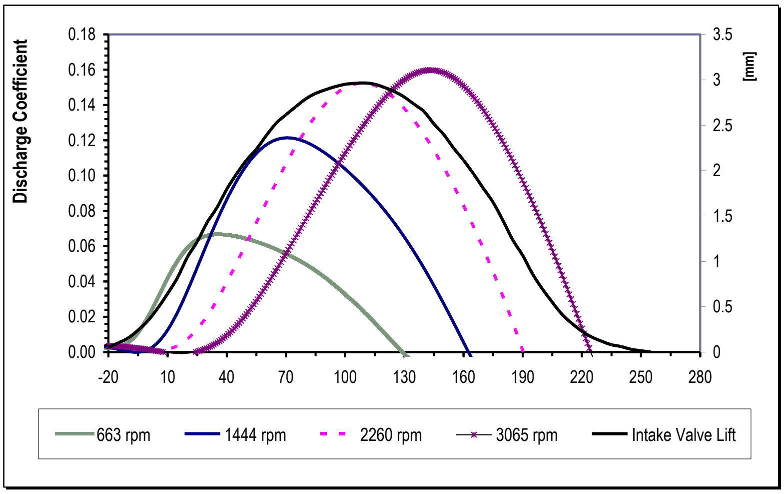

Figure 5 – Evolution along crank angle of the discharge coefficient

5. CONCLUSION

In order to analyze the utilization of hot film anemometer to define the discharge coefficient on the intake stroke of an internal combustion engine in a motored mode, the time response of the sensor was compared with the quasi-static system. The sensor employed produced by Bosch was 8 times greater than the necessary to measure the air-mass flow. The photodiode sensor utilized to measure the angular velocity has a low cost and good time response, about 4000 times faster than the necessary to measure the angular velocity. It demonstrated that the utilized equipment is adequate for the proposal measurement.

The maximum standard deviation mean was small and the results of 30 measurements showed good repeatability. Some deviation in the flow measurement can be associated with the variation of the angular velocity and interference of the last exhaust cycle.

The discharge coefficient increases with rotation until maximum volumetric efficiency. Effect of inertia and compressibility of the admission air are detected.

6. REFERENCES

Baratta, M.; Catania, A.E.; Pesce, F.C.; Spessa, E.; Rech C.; Vielmo, H.A., 2008a "Multidimensional Modeling of a High Swirl-Generating Helical Intake Port for Diesel Engines", 12th Brazilian Congress of Thermal Engineering and Sciences, Belo Horizonte -MG, Proceedings of ENCIT, Rio de Janeiro, RJ: ABCM.

Beckwith, T. G.; Marangoni, R. D.; Leinhard, J.H. 1993 "Mechanical Measurements", 5. ed. Reading: Addison-Wesley.

Bopp S, Vafidis C, Whitelaw JH., 1986 "The effect of engine speed on the TDC flowfield in a motored reciprocating Engine". SAE 860023.

Bosch , 2010 "Hot-film air-mass meter, type HFM 2" http://apps.bosch.com.au/motorsport/downloads/sensors_airmass.pdf

Corcione FE, Valentino G., 1994 "Analysis of in-cylinder flow processes by LDA". Combust Flame;99:387–94.

Fansler T.D., 1993 "Turbulence production and relaxation in bowl-in-piston engines". SAE 930479.

Ferguson, Colin R., 1985 "Internal combustion engine". New York: J. Wiley.

Ferrari, G., 2005, "Motori a Combustione Interna", Torino, Ed il Capitello, (in italian).

Golçalves Jr, A. A.; Sousa, A. R., 2008 "Fundamentos de metrologia científica e Industrial", São Paulo: Manole.

Hadded, O.; Denbratt, I., 1991 "Turbulence characteristics of tumbling air motion in 4-valve SI engines and their correlation with combustion parameters", SAE Paper 910478.

Heywood, J.B., 1988, "Internal Combustion Engines", McGraw-Hill Inc.

Holman, J. P., 1994 "Experimental methods for engineers", 6th ed. United States of America: McGraw-Hil Inc.,.

Honda Engines GX35, 2011, "model-detail/gx35" http://engines.honda.com/models/model-detail/gx35

Jaffri K, Hascher HG, Novak M, Lee K, Schock H, Bonne M, et al., 1997 "Tumble and swirl quantification within a motored four-valve SI engine cylinder based on 3-D LDV measurements". SAE 970792.

Labview, 2008 "user guide" National Instruments

Liu R., Xiao F., Guan L., and X. L. Jilin, 1994a "An Investigation into Air Flow Characteristics through Inlet Valve of Directed Ports", SAE Paper 941753.

Liu X., Liu R., Xiao F., , and Guan L., 1994b "A Microscopic Analysis of In-Cylinder Swirl Generated by Directed Ports", SAE Paper 941754.

Manual Photo Diodo 2011 "Chaves Optoeletrônicas Transmissivas" www.politronic.com.br/ especs/cha/PHCTX0X.pdf

Payri F, Desantes JM, Pastor JV., 1996 "LDV measurements of the flow inside the combustion chamber of a 4-valve D.I. Diesel engine with axisymmetric piston bowls". Experiments in Fluids; Vol. 22:118–28.

Rask RB, Saxena V., 1985 "Influence of the geometry on flow in the combustion chamber of a direct-injection Diesel Engine". ASME Winter Annual Meeting. p. 19–28.

Rech, C., Zancanaro, F. V, Wildner, F. D., Vielmo, H.A., Oliveira A. M. Jr., 2010 "Experimental and Numerical Analysis of Gas Motion in a Standard Cooperative Fuel Research Engine", 13th Brazilian Congress of Thermal Engineering and Sciences, Uberlândia - MG. Proceedings of ENCIT, Rio de Janeiro, RJ: ABCM.

Stier B., and Falco R.E., 1994 "Application of LIPA (Laser Induced Photochemical Anemometry) to the Water Analog Model of a Four-Stroke IC Engine", SAE Paper 940282.

Uzkan T, Borgnakke C, Morel T., 1986, "Characterization of flow produced by a high-swirl inlet port" SAE Paper 830266.

Witze, P. O.; Hall, M. J.; Wallace, J. S., 1988 "Fiber-optic instrumented spark plug for measuring early flame development in spark ignition engines", SAE Paper 881638.

Zancanaro, F. V. Jr., 2010a "Simulação Numérica do Escoamento Turbulento em Motores de Combustão Interna", Porto Alegre, UFRGS, Dissertação de mestrado.

Zancanaro, F. V. Jr.,Vielmo, H.A., 2010b "Intake Flow and Time Step Analysis in the Modeling of a Direct Injection Diesel Engine", 13th Brazilian Congress of Thermal Engineering and Sciences, Uberlândia - MG. Proceedings of ENCIT, Rio de Janeiro, RJ: ABCM.

Zur Loye AO, Siebers DL, Mckinley TL, Ng HK, Primus RJ., 1989, "Cycle-resolved LDV measurements in a motored Diesel engine and comparison with k–e model predictions" SAE 890618.

10. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.