Flow coefficient measurements for an engine cylinder head under transient flow conditions with continuous valve lift change

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Abstract— A flow coefficient measurement system which is operated under an unsteady intake flow condition in the intake port of a diesel engine cylinder head was developed. In order to determine the actual engine intake flow condition, the valve lift of the intake valve, whose rod is in contact with the camshaft, is varied continuously by rotating the camshaft directly. While varying the rotation speed of the camshaft, the flow coefficients were calculated by measuring various sensor signals, in this case the surge tank pressure, differential pressure in the flow meter, the valve lift when synchronized with the camshaft angle position, and the intake air temperature. The measurement of the flow coefficient was automated using a DAQ board and a computer. The flow coefficients change with the valve lift, and the effects of inertia of the intake flow on the flow coefficients are identified. The mean flow coefficients are obtained by integrating flow coefficients over the camshaft angle position.

Keyword-flow coefficient, intake port, cylinder head, valve lift, camshaft

I. INTRODUCTION

The rapid mixing of air and fuel in a diesel engine is one of the most important parameters affecting the performance of this type of engine, and this is especially true for a direct injection diesel engine. The main parameters affecting the air-fuel mix of a diesel engine are the fuel injection pressure and timing [1, 2], the shape of the combustion chamber [3, 4] and the swirl flow within the combustion chamber [5]. The swirl flow, which forces the intake air to move in a tangential direction during the compression stroke, is typically generated from a helical intake port in the engine cylinder head [6]. Highly pressurized injected spray jets are deflected and dispersed by the tangential flow in the combustion chamber, which aids the mixing of the air and the fuel in the combustion chamber [7].

In general, the swirl flow characteristic of the intake port in a diesel engine is evaluated in terms of both the swirl intensity and flow coefficient. The swirl intensity generated by the intake port is measured with either a torque meter or a rotating paddle existing in a cylinder [8, 9]. The flow coefficient of the intake port in the engine cylinder head is the parameter used to evaluate the degree of flow restriction through the intake port.

The swirl flow measuring equipment currently used by automotive manufacturers is operated manually by adjusting the valve lift several times. In the manual measurement method, the swirl flow is maintained in a steady state for each adjusted valve lift. However, the measurement of the swirl flow in an actual engine is very difficult due to both the limitation of the measuring probe when to access the combustion bowl and the highly unsteady flow condition. In order to determine the actual engine operating intake air flow condition, the adjustment of the valve lift was automated by rotating the camshaft, whose profile causes the valve lift to vary continuously.

This study concentrates on flow coefficient measurements in an unsteady operating condition. The measurement of the flow coefficient by controlling the valve lift with the profile of a high-speed rotating camshaft is a better match of the operating conditions of an actual engine. Oh and Lee [10] measured the flow coefficients in a quasi-steady flow condition by rotating a camshaft at a very low speed. Kim and Lee [11] measured the swirl intensity in a quasi-steady flow condition with automated measurement equipment. The automatic measurement of the flow coefficient of an intake port in an unsteady air flow condition was not investigated enough in earlier work. The valve lift of a cylinder head is controlled by a rotating camshaft connected to a step motor in this study. Oh and Lee [10] rotated the camshaft at very low speeds, i.e., 5, 10 and 15 rpm. In this study, the rotating speed of the camshaft was speeded up to 180 rpm. With the high rotating speed of the camshaft in this study, the unsteady flow and flow inertia effects are evaluated when measuring the flow coefficients of the intake port.

II. EXPERIMENTS

Fig. 1 shows the experimental setup used to measure the flow coefficient. The measurement system developed in this study was a modification of traditional flow measuring equipment in which a micro-meter for control of the valve lift is substituted for a camshaft driven by a step motor and several sensors, enabling the automatic measurement of the flow coefficient. Two differential pressure sensors were used to measure the differential pressure in an averaging Pitot tube (APT) flow meter and a surge tank pressure, respectively. The step motor that drives the camshaft allows the automatic adjustment of the valve lift with the camshaft profile. An LVDT (linear variable differential transformer) sensor was used to measure the valve lift. An encoder was used to measure the camshaft angle position.

For the measurement of the flow coefficient of the intake port in the cylinder head, air is sucked by a blower through the intake port over a valve with an adjusted lift, past the cylinder liner and surge tank, and into the flow nozzle, following the arrows shown in Fig. 1. The pressure drop between the atmosphere and the surge tank is equal to the pressure loss in the intake port and valve, as there is no significant pressure loss in the cylinder liner. The pressure loss, ΔP, across the APT flow meter is measured with a calibrated differential pressure sensor.

The valve lift of the cylinder head is varied continuously and has a profile identical to that of an actual engine with the rotation of the camshaft with the step motor directly. The digital output ports on the DAQ board can generate a square wave pulse with consecutive on/off (5 V/0 V) operations. The rotation speeds of the camshaft are set 10, 20, 30, 60, 120, 180 rpm.

In a traditional steady flow rig, the surge tank pressure is held constant during the flow coefficient measurement of the valve lift. The surge tank pressure is held constant by adjusting the by-pass valve. A typical setting value that corresponds to the surge tank pressure is 200 mmH_2O or 400 mmH_2O depending on the valve lift. However, in the flow coefficient measurement rig developed in this research, the surge tank pressure is changed continuously because the valve lift varies with the camshaft profile, which is more similar to a real engine. The intake flow induced by the continuous valve movement is closer to that of a real engine.

The measurement of the flow coefficient was made automatically using a high-speed DAQ system. LabView® was used for the automatic measurement and control. The process of the measurement of the flow coefficient is as follows. The step motor is rotated at a constant speed and the blower is always operated at its maximum speed for all of the experiments. When the flow parameter in the measurement system become stable, the surge tank pressure, the differential pressure at the APT flow meter, the intake air temperature, and the valve lift are measured and stored in a data file with encoded timing.

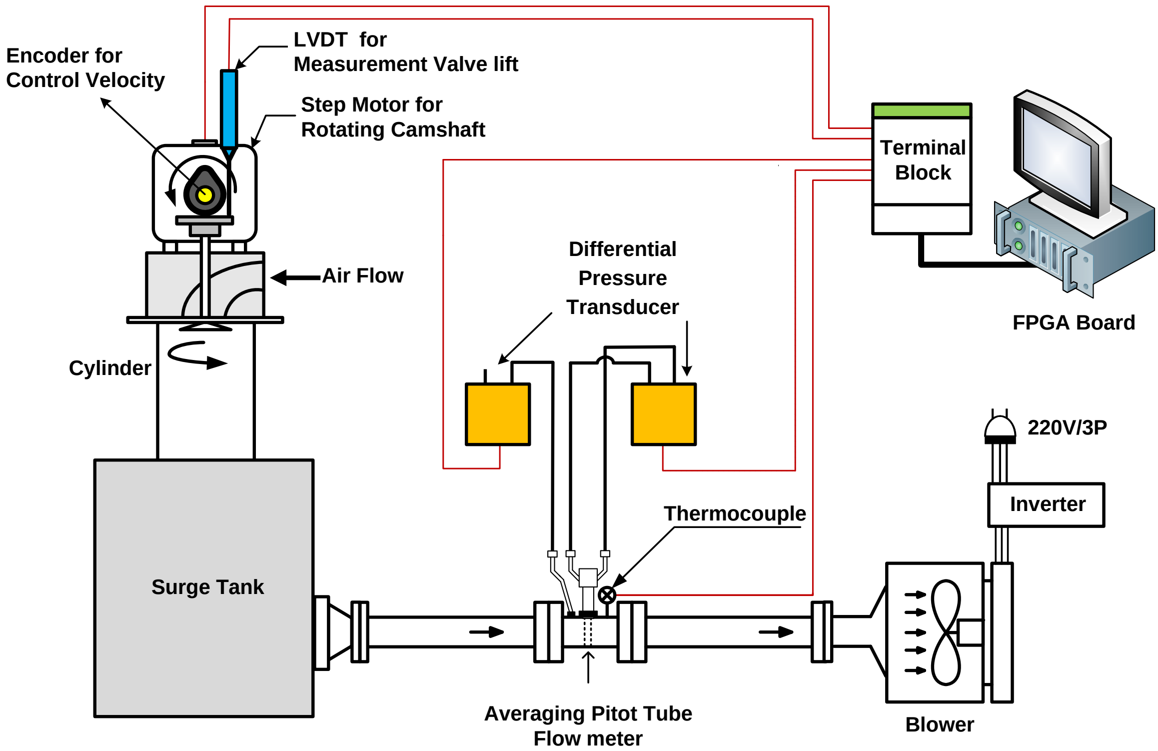

Fig. 1. Experimental setup for measuring the flow coefficients of an intake port in an engine cylinder

III. RESULTS AND DISCUSSIONS

Fig. 2 shows the intake valve lift with the angle position of the camshaft. The measurement of the valve lift was repeated with 9° cam angle intervals. One measurement cycle consists of one revolution of the camshaft. The measurement cycle was repeated 39 times. The rotation speeds of the camshaft were controlled as 10, 20, 30, 60, 120 and 180 rpm. The valve lift ranges from 0.15 mm to 8.5 mm according to the camshaft angle. Even if the intake valve is in closing position, the valve lift maintained at 0.15mm, which made air flow into the cylinder. The minimum valve lift was maintained to avoid excessive vacuum pressure in the cylinder, which causes to overload the pressure sensor in the cylinder.

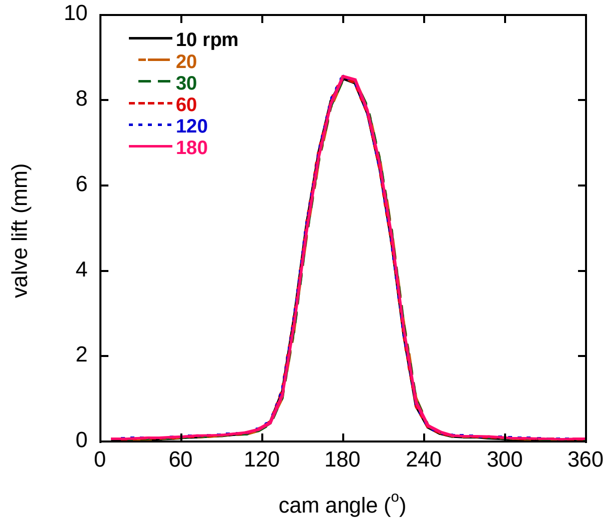

Fig. 2. The measured valve lifts according to the cam angle using an LVDT

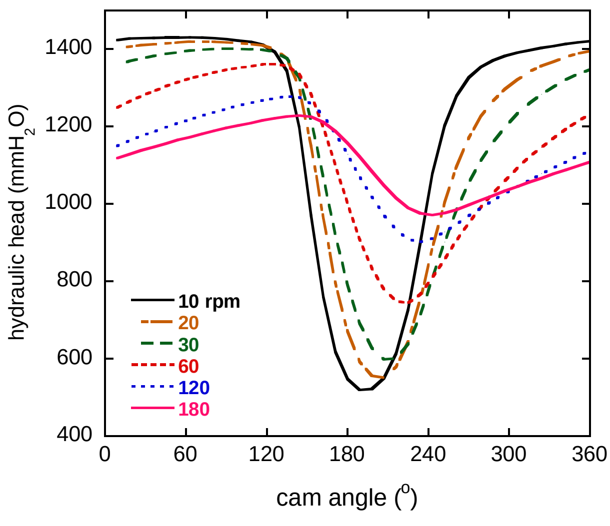

Fig. 3. The vacuum pressure below atmospheric pressure at the surge tank

Fig. 3 shows the measured differential hydraulic heads using the U-tube which senses the differential pressure between atmospheric and surge tank pressure with increasing the camshaft angle position. The differential hydraulic heads represent the magnitude of the vacuum pressure below the atmospheric pressure. The larger value of the differential hydraulic head means the larger vacuum pressure in the surge tank. At the camshaft rotation speed of 10 rpm, the measured differential hydraulic heads are nearly 1400 mmH_2O at the cam angle ranges 0°-120° and 240°-360° where the valve lifts is nearly zero (0.15 mm). The hydraulic heads decrease as the cam angle increase from 120° to 180° due to the increase of the valve lift and then the hydraulic heads increase as the cam angle increase from 180° to 240°, due to the decrease of the valve lift. The minimum hydraulic head is expected at maximum valve lift, however, its location shifted a little bit to the right from cam angle 180°, due to the intake flow inertia effect. The flow inertia effect increases as the rotation speed of the camshaft increase. The larger inertia effect at the high camshaft rotation speed causes a slower recovery of the surge tank pressure due to the shorter time of one revolution time of the camshaft. As the camshaft rotation speeds increase from 10 rpm to 180 rpm step by step, the differential hydraulic heads decrease for all camshaft angles due to the increase of the flow restriction. Also, the camshaft angle position where the minimum value of the differential hydraulic head appears shifted to the right much more as the camshaft rotation speed increases. At the camshaft rotation speed of 10 rpm, the inertia effect nearly does not appear. Thus, the flow coefficient measured at the camshaft speed below 10 rpm is nearly same as that at the steady or quasi-steady state condition. Considering the real engine operating condition, the flow coefficient should be measured at high speed of camshaft as the real intake flow is unsteady.

The intake air mass flow rate passed through the intake valve was measured using the APT flow meter. The mass flow rate of the APT flow meter [12] was calculated from the measured differential pressure $\Delta P_{up\text{-}down}$ between the upstream and downstream pressure tap. A parameter H based on the $\Delta P_{up\text{-}down}$ is introduced to evaluate the flow rate characteristics [13]. The H-parameter can be calculated from Eq. (1) based on the differential pressure $\Delta P_{up\text{-}down.}$ P_{static} is also measured using the U-tube.

$$H = \frac{P_{static}}{101.3(kPa)} x \frac{293.15(K)}{T_{avg}} \sqrt{\frac{\Delta_{up-down}}{\rho_{std}}} \tag{1}$$

P_{static}: static pressure at the APT flow meter (kPa)

T_{avg} : average temperature at the APT flow meter $(T_1+T_2)/2$ (K)

ρ_{std} : density of the air at standard conditions of 101.3 kPa and 293.15 K (kg/m^3)

$\Delta P_{up\text{-}down}$: differential pressure between upstream and downstream of the APT flow meter (kPa)

$$\dot{m} = 13.16 + 162.0H \tag{2}$$

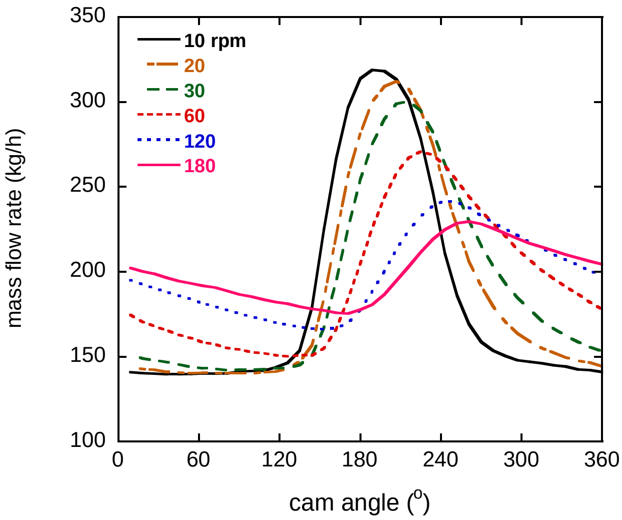

Fig. 4. Mass flow rate measured with the APT flow meter according to the cam angle

The intake air mass flow rate can be calculated from Eq. (2). Figure 4 shows the measured intake air mass flow rate with the camshaft angle position for the various camshaft rotation speeds. The intake air mass flow rate curve shown in Fig. 4 is overall inversely proportional to the differential hydraulic head shown in Fig. 3. The larger differential hydraulic head is correspondent to the smaller valve lift, which results in larger flow restriction, thus cause the smaller mass flow rate. The intake mass flow rate curves shows mirror shapes of the differential hydraulic heads curves with respect to the x-axis. The inertia effect with the rotation speed of the camshaft on the intake air mass flow rate is completely similar to that on the differential hydraulic heads.

The intake air mass flow rate through the valve can be described by well-known compressible flow equation for mass flow rate $\dot{m}$ through a converging nozzle. The flow coefficient C_f based on the valve throat area for a valve lift position is defined by Eq. (3).

$$\dot{m} = C_f \rho_v V_{is} A \tag{3}$$

Where V_{is} is calculated from Eq. (4) which is an isentropic relation for a flow in a converging nozzle emptying into a plenum, ρ_v is air density calculated by Eq. (5) and here, flow area A through the valve is assumed to be constant value of the valve seat area.

$$V_{is} = \sqrt{\frac{2k}{k-1} x \frac{P_0}{\rho_0}\left[1-\left(\frac{P_d}{P_0}\right)^{\frac{k-1}{k}}\right]} \tag{4}$$

$$\rho_v = \rho_0\left(\frac{P_d}{P_0}\right)^{\frac{1}{k}} \tag{5}$$

By Substituting Eq. (4) and Eq. (5) into Eq. (3), Eq. (6) is obtained.

$$\dot{m} = \frac{C_f A P_0}{\sqrt{RT_0}}\sqrt{\frac{2k}{k-1}\left(\left(\frac{P_d}{P_0}\right)^{\frac{2}{k}}-\left(\frac{P_d}{P_0}\right)^{\frac{k+1}{k}}\right)} \tag{6}$$

Where the subscript o and d mean stagnation values at port inlet and downstream of the valve, respectively. P_o and P_d can be substituted by atmospheric pressure and surge tank pressure, respectively. If $\dot{m}$, P_o and P_d are measured, flow coefficient C_f can be calculated from Eq. (5). Mean flow coefficient C_{fmean} is equal to the sum of the flow coefficient between cam angle α_1 and α_2 divided by the angle difference (α_1 - α_2) as Eq. (7)

$$C_f = \frac{\int_{\alpha_1}^{\alpha_2} C_f(\alpha)d\alpha}{\alpha_1 - \alpha_2} \tag{7}$$

Figure 5 shows the V_{is} calculated by Eq. (4) with the camshaft angle position as the camshaft rotation speed increases. The characteristics of the V_{is} curves show similar trends of the differential hydraulic heads. At the camshaft rotation speed of 10 rpm, the V_{is} varies from 160m/s to 80 m/s. The valve lift correspondent to the V_{is} of 160m/s is the minimum lift of 0.5mm, and the V_{is} of 80m/s to the maximum lift of 8.5mm. As the rotation speed of the camshaft increases, the V_{is} variation band width reduces. At 180 rpm of the camshaft rotation speed, the V_{is} varies approximately from 140 m/s to 130m/s. The intake flow inertia effects also appear in the V_{is} as similar to the results of the hydraulic heads.

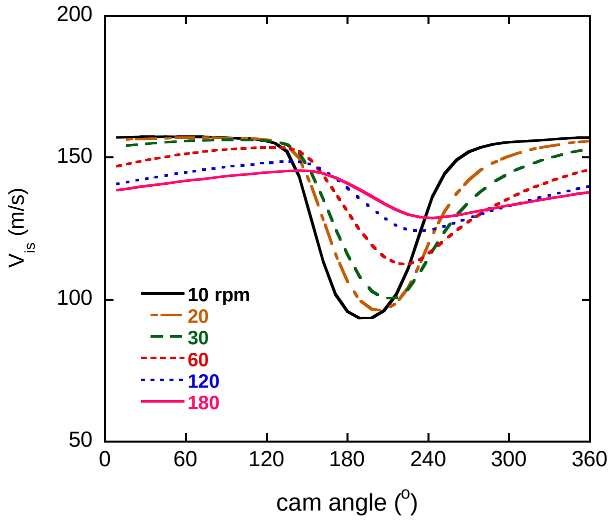

Fig. 5. V_{is} (isentropic flow velocity) passing through the intake valve as calculated from the differential pressure between the atmosphere and the surge tank pressure

Figure 6 shows the measured flow coefficients by Eq. (6) with the camshaft angle position for the various camshaft rotation speeds. The flow coefficient curves in Fig. 6 shows similar trends with those of the mass flow rate shown in Fig. 5. At the camshaft rotation speed of 10 rpm, the flow coefficients C_f varies from approximately 0.1 to 0.38. As the rotation speed of the camshaft increases, the C_f variation band width reduces. At 180 rpm of the camshaft rotation speed, the C_f varies approximately from 0.14 to 0.2. The intake flow inertia effects also appear in the C_f as similar to the results of the mass flow rates.

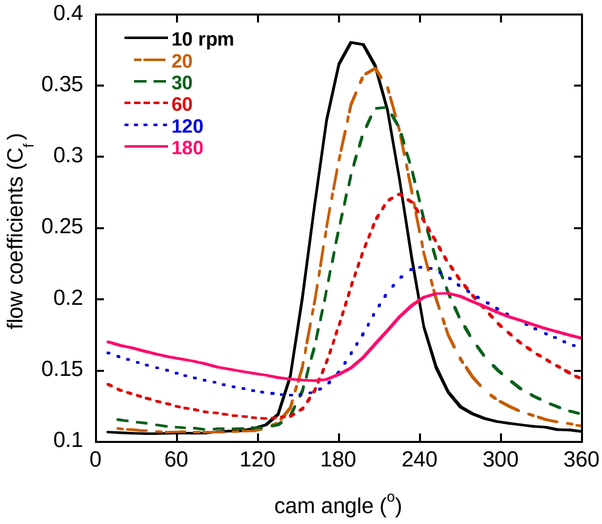

Fig. 6. Flow coefficient of the intake port in the engine cylinder head according to the cam angle

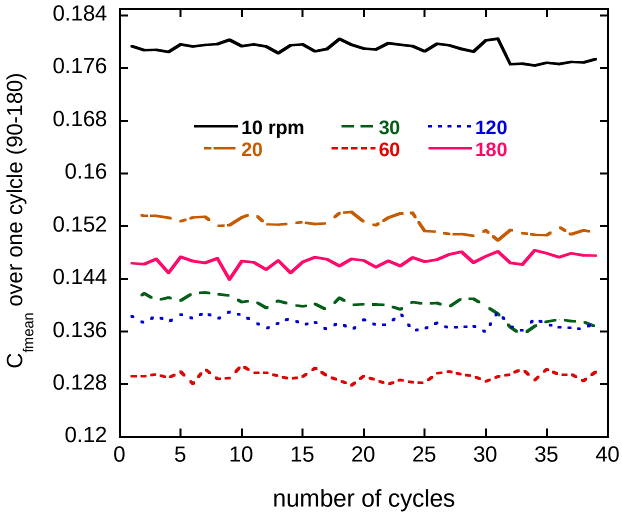

Fig. 7. Mean flow coefficients (C_{fmean}) over the crank angle integration range of 90° to 180°

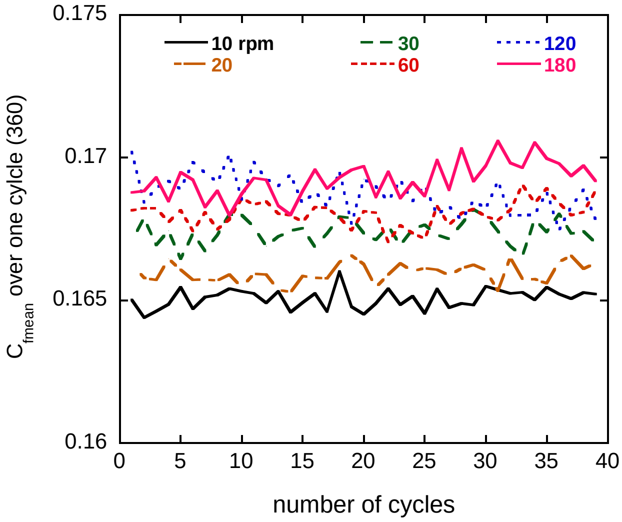

Fig. 8. Mean flow coefficients (C_{fmean}) over the crank angle integration range of 0° to 360°

Figure 7 shows the mean value of the flow coefficients (C_{fmean}) over one measurement cycle which has integration range in crank angle from 90° to 180°. The crank angle range 90°-180° corresponds to the valve lift

0.15mm-8.5mm whose range represents the intake process range. The C_{fmean} measurement was repeated 39 times. At the each rotation speed of the camshaft, the C_{fmean} varies up or down for each measurement cycle. Figure 7 shows the C_{fmean} variation for the various rotation speed of the camshaft. As the rotation speed increases, the C_{fmean} decreases in the rotation speed ranges 10-60 rpm and increases again in 90-180 rpm ranges. Figure 8 shows the mean value of the flow coefficients (C_{fmean}) over another measurement cycle which has integration range in the angle position from 0° to 360°.

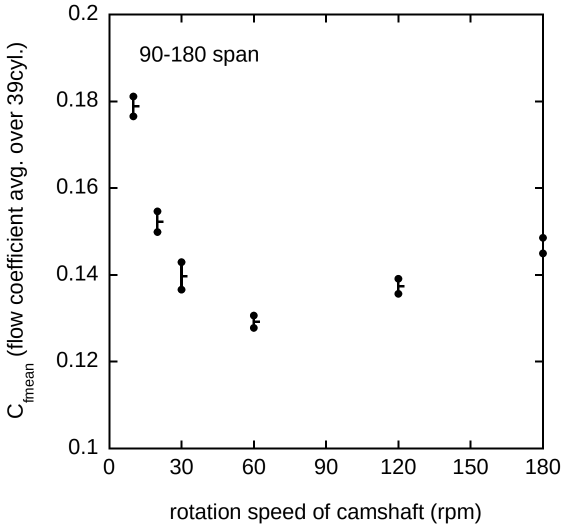

Fig. 9. The bandwidth of the mean flow coefficients (C_{fmean}, crank angle integration range of 90° to 180°) with the rotation speed of the camshaft

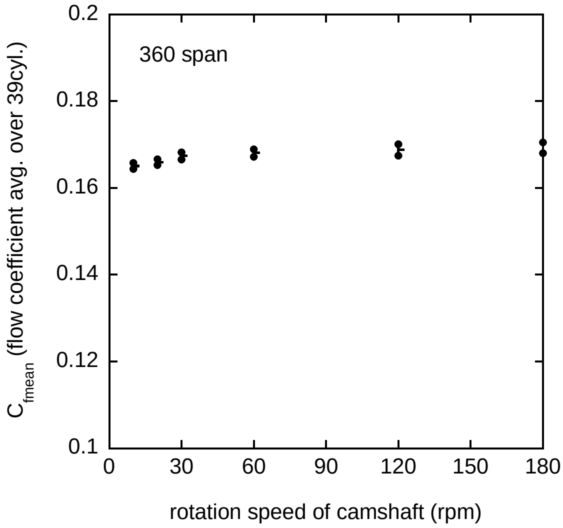

Fig. 10. Mean flow coefficients (C_{fmean}, crank angle integration range 0°-360°) with the rotation speed of the camshaft

Figures 9 and 10 show the C_{fmean} variation band width as the rotation speed of the camshaft increases. Figure 9 shows the C_{fmean} with the crank angle integration range 90°-180° and it displays a parabola curve with increase of the rotation speed of the camshaft. Figure 10 shows the C_{fmean} with the crank angle integration range 0°-360° and it displays nearly constant value with increase of the rotation speed of the camshaft. The C_{fmean} with the crank angle integration range 90°-180° cannot include the real intake flow process due to the intake flow inertia effect. Even if the C_{fmean} with the crank angle integration range 0°-360° include the flow coefficient values which are measured in the valve lift of nearly zero, the contribution to the C_{fmean} with the crank angle integration range 0°-360° is relatively small, because the mass flow rate at the valve lift of nearly zero is small. Thus, the C_{fmean} with the crank angle integration range 0°-360° is more effective in evaluating the flow coefficients of the intake valve than the C_{fmean} with the crank angle integration range 90°-180°.

IV. CONCLUSION

A valve lift control scheme which can determine the intake air flow condition of an engine under operation was automated by rotating a camshaft whose profile causes the valve lift to vary continuously. The flow coefficients of the intake port were measured while increasing the camshaft rotation speed in a stepwise manner, and the following conclusions were obtained.

(1) The flow coefficients of the intake port increase as the valve lift increases with a constant camshaft rotation speed.

(2) As the camshaft rotation speed increases, the inertia effect of the intake flow on the flow coefficients increases.

(3) The mean flow coefficients, which are averaged values over the integration range of 0 to 360 can remove the inertia effect on the flow coefficients and obtain a value of 0.165 nearly irrespective of the rotation speed of the camshaft.

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