

KES

Fly Wheel Inertial Moment Design Standard

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Contents

1. Scope of Application
2. Purpose
3. Definition of Terms
4. Fly Wheel Design Flow Chart
5. Abstract
6. Calculation for Fly Wheel Inertia
7. Program
8. Sample Output
9. Comparison for Inertial Moment and
Volume of Engine Fly Wheel



1. Scope of Application

The estimating method for the required quantity of the inertial moment shall be applicable equally to the gasoline engines and diesel engines, and the standard value of design shall be applicable differently to the gasoline engines and the diesel engine.

2. Purpose

The purpose of this standard is to set the design standard by estimating the required value of the fly wheel inertial moment depended on the given engine specification.

3. Definition of Terms

δ : Speed Fluctuation Coefficient

E : Excess Energy

J : Flywheel Inertial Moment

W : Rotation Angular Speed (Rad/sec)

T : Rotation Torque or Temperature

P : Cylinder Pressure

ϕ : Rotation Angle of Crankshaft

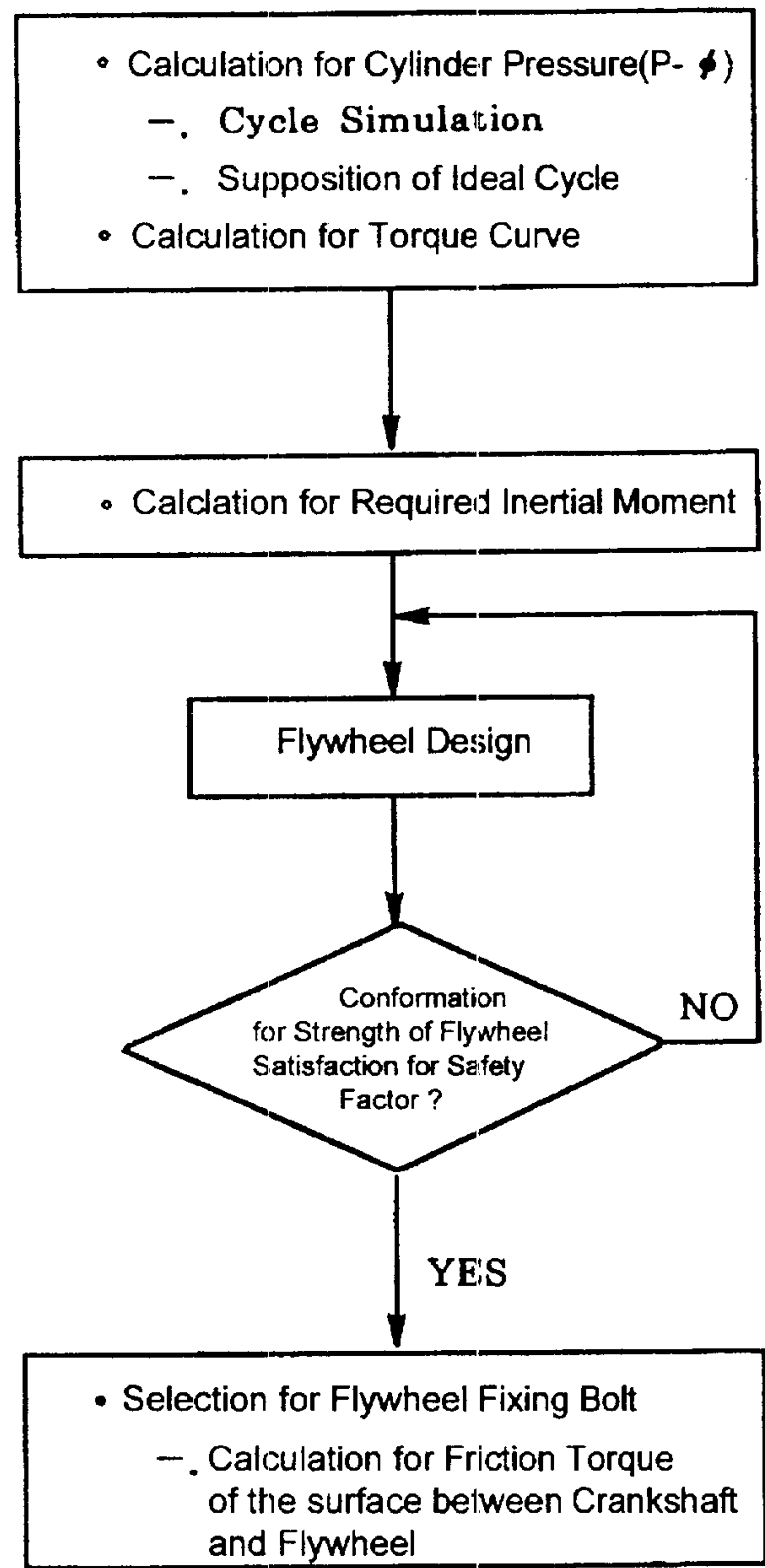
Cv : Specific Heat at Constant Volume

ξ : Pressure Raise Ratio

φ : Injection Ratio

Cp : Specific Heat at Constant Pressure

4. Fly Wheel Design Flow Chart



5. Abstract

The driving torque generated at the crankshaft of engines is caused by the explosion of the cylinders. So, the torque in engines composed the limited numbers of cylinders has the discontinuous variation. The flywheel is adopted so as to moderate the discontinuous variation of the torque.

The excessive torque generated when the mixed gas is exploded increases the rotation speed of the flywheel, and is stored partially as the rotation energy and discharged again as the compression work of the cylinder during the compression stroke. That is, the flywheel prevents the excessive torque change of the crankshaft by absorbing and discharging the rotation energy.

If the inertia of the flywheel is increased, the quantity of absorbing and discharging the rotation energy would increase and the change of the torque or the rotation velocity would decrease.

But, the increase of the flywheel inertia cause the increase of the entire weight of the engine and the disadvantage when the engine is installed in a car.

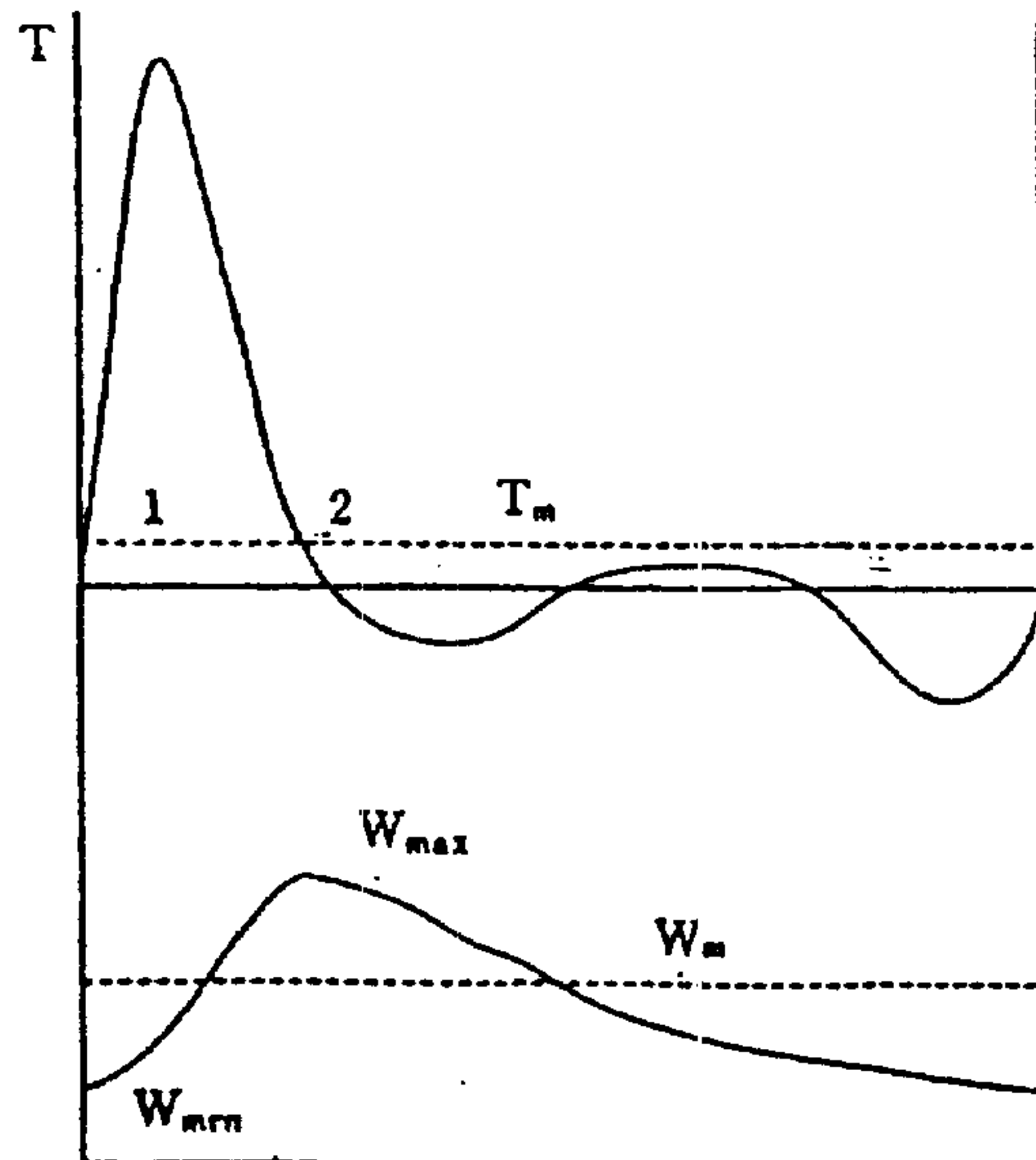
Considering the decrease of the acceleration performance or the deterioration of the fuel consumption and the emission, at present the designers make an effort to reduce the weight of the cars or the engines.

On the contrary, if the inertia is decreased, the torque change would increase and cause overwork of the entire engine drive parts. So, the flywheel inertia shall be selected properly considering the above two requirements.

6. Calculation for Flywheel Inertia

6.1 Required Quantity of Inertia

The torque change operated at the crankshaft and the change of the angular speed is shown at Figure 1.



<Figure 1> Torque & Angular Speed Curve

The one cylindered engine is expressed so as to explain easily. But, in case of the several cylindered engine, overlap the curves considering the phase difference of the cylinders.

T_m expresses the average of the torque in Figure 1. In case that the torque is bigger than T_m , the rotation force is transferred to the flywheel. On the contrary, the rotation energy is discharged from the flywheel under the average of the torque.

The level of velocity change during one cycle of the engine is defined as the speed fluctuation coefficient δ .

$$\delta = \frac{\omega_{\max} - \omega_{\min}}{\omega_m}$$

The flywheel inertia shall be determined so that the speed fluctuation coefficient should be under proper value. The rotation energy is stored in the section between the point 1 and the point 2 in Figure 1, and the stored excess energy E is same with the followings.

$$\begin{aligned}
 E &= \frac{1}{2} J \omega_{\max}^2 - \frac{1}{2} J \omega_{\min}^2 \\
 &= \frac{1}{2} J (\omega_{\max} + \omega_{\min}) (\omega_{\max} - \omega_{\min}) \\
 &= \frac{1}{2} J (2\omega_m) (\delta \omega_m) \\
 &= J \delta \omega_m^2
 \end{aligned}$$

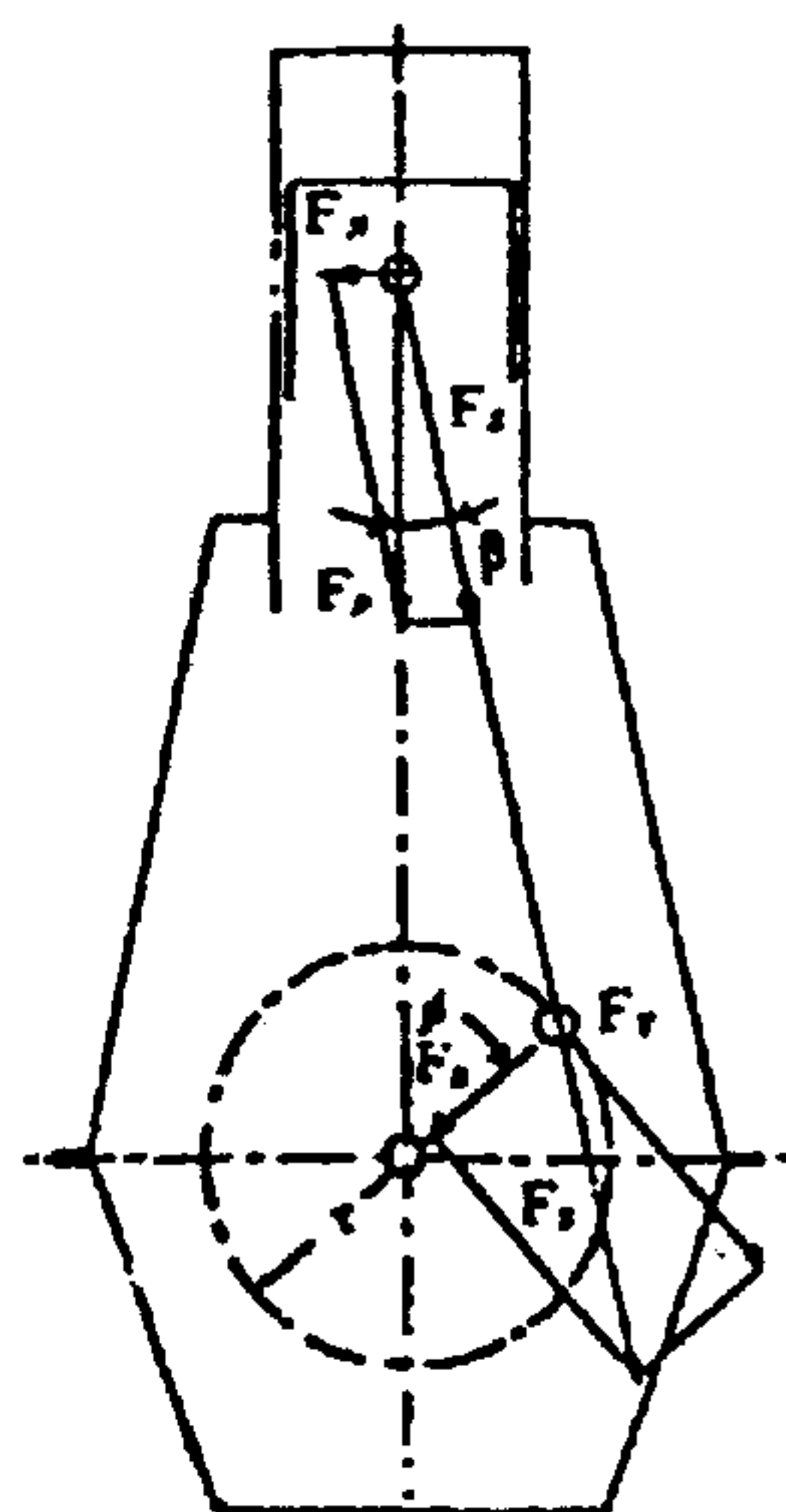
Therefore, the flywheel inertial moment J is calculated from the following equation

$$J = \frac{E}{\delta \omega_m^2}$$

The actual rotation inertia is produced by the flywheel as well as the crankshaft, the oil pump and the pulley. But, calculate it considering that all inertia is concentrated at the flywheel.

6.2 Excess Energy

The torque caused by the gas pressure in the cylinder and the inertia force torque of the reciprocating mass comprises the driving torque of the crankshaft. F_p is the force acting on the piston in Figure 2.



<Figure 2> Force Diagram

$$F_p(\phi) = F_G(\phi) + F_{osc}(\phi) = A_p(P(\phi) - P_o) + F'_{osc}(\phi)$$

A_p = Piston Area

P_o = Atmospheric Pressure

$P(\phi)$ = Explosion Pressure at Crank Angle ϕ

$$F_{osc}(\phi) = \text{Inertial Force by Reciprocating Mass} = -m_{osc} r \omega^2 (\cos \phi + \lambda \cos 2\phi)$$

M_{osc} = Reciprocating Mass

~ Mass of Piston Ass'y + $\frac{1}{3}$ Mass of conn. rod

r = Crank Radius

$\lambda = r/l = \text{Crank Radius} / F_s(\phi)$, Force to the direction of Conn. rod

$$F_s(\phi) = F_p(\phi) / \cos \beta \quad (F_{sc} \phi) = \text{Force to the direction of Conn. rod}$$

$$F_T(\phi) = F_s(\phi) \sin(\beta + \phi)$$

$$= \frac{F_p(\phi)}{\cos \beta} (\sin \beta \cos \phi + \sin \phi \cos \beta)$$

$$= F_p(\phi) \left(\sin \phi + \cos \phi \frac{\sin \beta}{\cos \beta} \right)$$

$$\sin \beta = \lambda \sin \phi, \quad \cos \beta = \sqrt{1 - \lambda^2 \sin^2 \phi}$$

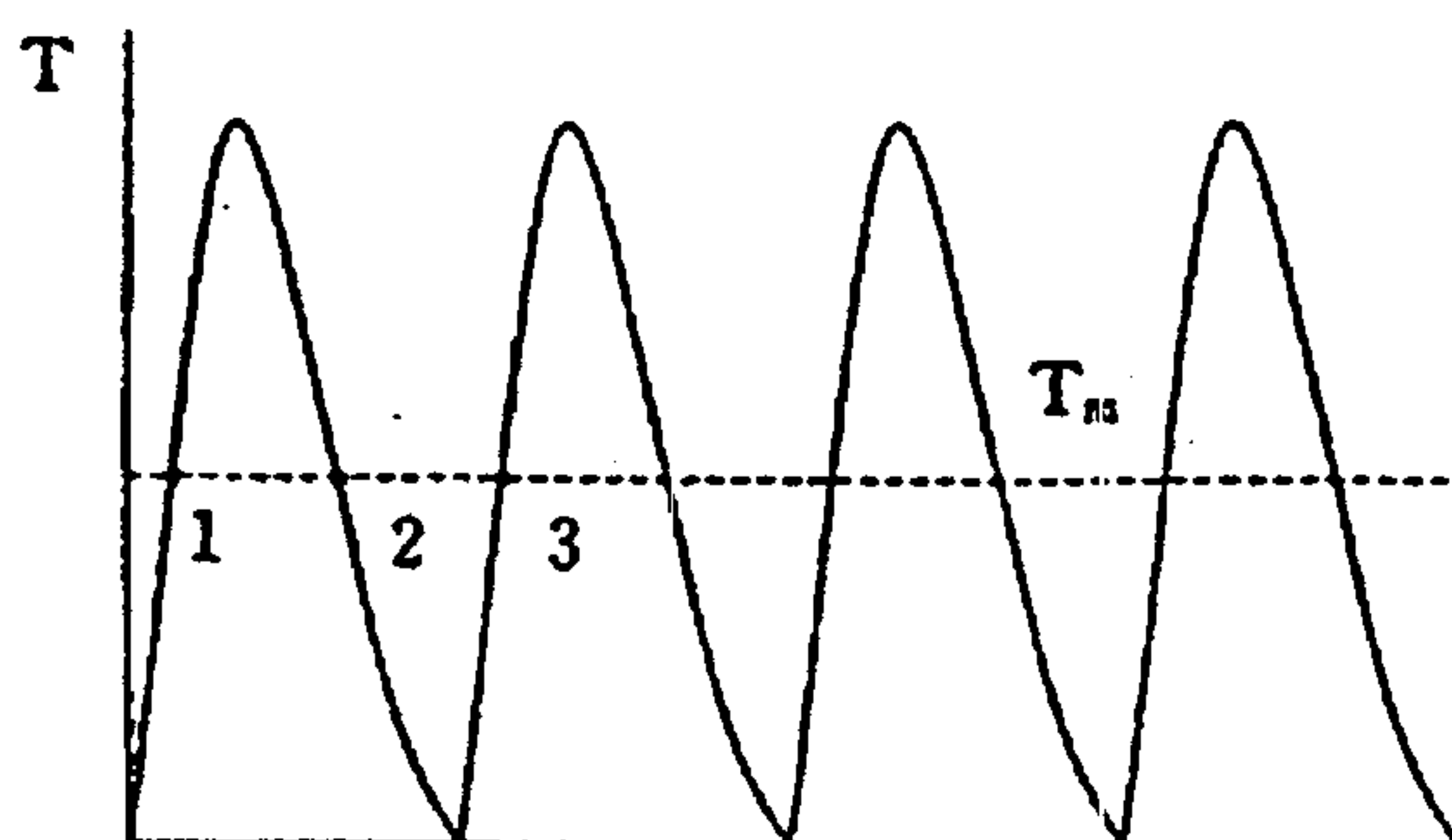
$$F_T(\phi) = F_p(\phi) \left(\sin \phi + \cos \phi \frac{\lambda \sin \phi}{\sqrt{1 - \lambda^2 \sin^2 \phi}} \right)$$

$$= F_p(\phi) \sin \phi \left(1 + \frac{\lambda \cos \phi}{\sqrt{1 - \lambda^2 \sin^2 \phi}} \right)$$

Driving Torque $T(\phi)$

$$T(\phi) = r F_T(\phi) = r F_p(\phi) \sin \phi \left(1 + \frac{\lambda \cos \phi}{\sqrt{1 - \lambda^2 \sin^2 \phi}} \right)$$

The typical form of the torque curve of the 4-cylindered engine is same with Figure 3.

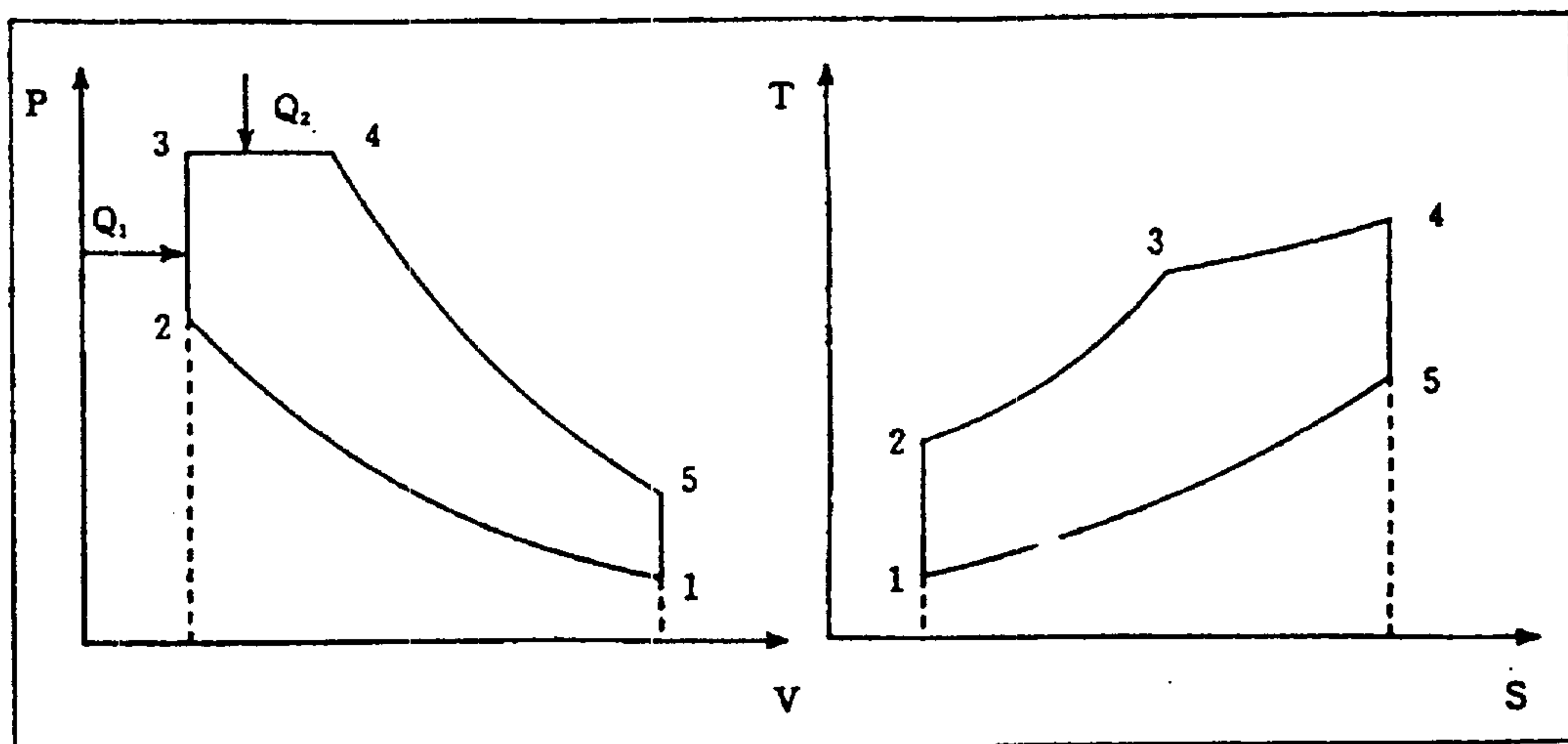


<Figure 3> 4-CYL. Torque Curve

$$T_m = \frac{1}{720^\circ} \int_0^{720^\circ} T(\phi) d\phi$$

Excess Energy, E

$$E = \int_1^2 [T(\phi) - T_m] d\phi = - \int_2^5 [T(\phi) - T_m] d\phi$$



<Figure 4> Dual Cycle P-V T-S Diagram

6.3 Cylinder Pressure

To calculate the excess energy E, at first the cylinder pressure P (ϕ) should be estimated accurately. If the data measured from an actual engine is available, the accurate calculation may be possible. But, the accurate calculation is not possible in the beginning of design before manufacturing a proto engine and the estimating method shall be used. In case of using the performance estimating program requiring enormous input data, the calculation supposed as simple ideal cycle is easy because the preparation for the input data takes much time and the quantity of the calculation is excessive.

The thermodynamic cycle of engines can be expressed generally with the dual cycle of Figure 4.

1-2 : Isentropic Compression Stroke

$$P(\phi) = P_1 \left[\frac{V_{sw} + V_c}{V(\phi) + V_c} \right]^{kc} \quad kc = \text{Isentropic Index} \sim 1.38$$

$$T(\phi) = T_1 \left[\frac{V_{sw} + V_c}{V(\phi) + V_c} \right]^{(kc-1)}$$

V_{sw} = Stroke Volume

V_c = Clearance Volume

$V(\phi)$ = Volume at Crank Angle ϕ

$$= A_p r [(1 - \cos \phi) + \frac{1}{\lambda} (1 - \sqrt{1 - \lambda^2 \sin^2 \phi})]$$

A_p = Piston Area

$$P_2 = P_1 \varepsilon^{kc}$$

$$T_2 = T_1 \varepsilon^{(kc-1)}$$

$$\varepsilon = \text{Compression Ratio} = \frac{V_{sw} + V_c}{V_c}$$

2-3 : Explosion Stroke at Constant Volume

$$\xi = \text{Pressure raise ratio} = \frac{P_2}{P_3}$$

$$T_3 = \xi T_2$$

P_3 shall be determined from experience by maximum pressure in the clearance volume.
Heating value during explosion stroke, Q_1

$$Q_1 = C_v m T_2 (T_3/T_2 - 1)$$

3-4 : Explosion Stroke at Constant Pressure

Because P_4 is same with P_3 ,

ϕ = Injection Ratio

$$= V_4/V_3 = T_4/T_3$$

$$Q_2 = C_p m T_3 (T_4/T_3 - 1)$$

Crank angle ϕ_4 relevant to V_4 is calculated from the following equation.

$$V(\phi_4) = V_4 - V_c$$

$$\text{Set as } C = 1 + 1/\lambda - V(\phi_4)$$

$$\phi_4 = \text{Arc cos } [c/2 + 1/(2c) - 1/(2c\lambda^2)] + 360^\circ$$

Total Heating Value Q

$$Q = Q_1 + Q_2 = C_v m T_2 (T_3/T_2 - 1) + C_p m T_3 (T_4/T_3 - 1)$$

$$= m C_v [C(T_3/T_2 - 1) T_2 + K_E (T_4/T_3 - 1) T_3]$$

$$= m C_v T_1 \varepsilon^{(kc-1)} [(\xi - 1) + K_E \xi (\phi - 1)]$$

$$K_E = C_p/C_v = 1.35$$

Supposing that H is the lower heat value of the fuel, calculate the total heat value from the fuel and calculate ϕ by setting the above equation as same value with the total heat value.