

Exercise IV: Idle regulation of a S.I Engine

Solutions:

1. Approximation of the mixing phenomena by an isothermal expansion from a thermodynamic state "0" (exhaust valve = open / intake valve = close) to a thermodynamic state "1" (exhaust valve = close / intake valve = open).

$$V_{eg,0} = V_{TDC}$$

$V_{eg,1}$ = volume taken by the exhaust gases (residual gases) into the cylinder during the intake stroke:

Ideal gas law:
$$M_{eg,0} = M_{eg,1} = cte \rightarrow \frac{P_{exh} \cdot V_{eg,0}}{r \cdot T_{eg,0}} = \frac{P_{coll} \cdot V_{eg,1}}{r \cdot T_{eg,1}}$$

Isothermal expansion relation:
$$T_{eg,0} = T_{eg,1} = cte$$

Then:
$$V_{eg,1} = \frac{P_{exh} \cdot V_{TDC}}{P_{coll}} = \frac{P_{exh}}{P_{coll}} \cdot \frac{V_u}{\varepsilon - 1} \quad \text{with} \quad V_{TDC} = \frac{V_u}{\varepsilon - 1}$$

Air mass introduced into the cylinder if volumetric efficiency is known:

$$M_{air} = \eta_{vol} \cdot \underbrace{\frac{P_{coll}}{r \cdot T_{coll}}}_{\rho_{air}} \cdot V_u$$

and if η_{vol} is not known:
$$M_{air} = \frac{P_{coll}}{r \cdot T_{coll}} \cdot \underbrace{(V_u + V_{TDC} - V_{eg,1})}_{=\eta_{vol} \cdot V_u} \quad \text{using } V_{eg,1} \text{ and } V_{TDC}$$

$$M_{air} = \underbrace{\left(\frac{\varepsilon}{\varepsilon - 1} \cdot \frac{V_u}{r \cdot T_{coll}} \right)}_A \cdot P_{coll} + \underbrace{\left(- \frac{P_{exh}}{r \cdot T_{coll}} \cdot \frac{V_u}{\varepsilon - 1} \right)}_B \quad \text{with} \quad \varepsilon = \frac{V_u + V_{TDC}}{V_{TDC}}$$

b) Numerical application: $A = 6.18 \cdot 10^{-9} \quad B = -6.26 \cdot 10^{-5}$

c) On a real engine, these 2 parameters are strongly depending of the valve timing and the scavenging process. The intake valve opening / closing and the exhaust valve opening / closing crank angle can improve (or reduce) the internal gas recirculation. We use these properties for increasing the effective power or for pre-treatment means (NOx reduction).

2. Fundamental equation of dynamic in steady state conditions:
$$\sum C = J_{mot} \cdot \underbrace{\frac{d\omega}{dt}}_{=0} = 0$$

$$C_i^- + C_i^+ - C_{friction} = J_{mot} \cdot \frac{d\omega}{dt} = 0$$

Indicated work of low pressure loop is defined by: $E_i^- = 4 \cdot \pi \cdot C_i^- = (P_{coll} - P_{exh}) \cdot V_u$

Then
$$C_i^- = \frac{(P_{coll} - P_{exh}) \cdot V_u}{4 \cdot \pi}$$

Indicated work of high pressure loop is defined by:
$$E_i^+ = 4 \cdot \pi \cdot C_i^+ = \eta_i \cdot \underbrace{\frac{M_{air}}{R_{A/F} \cdot \lambda}}_{M_F} \cdot \Delta h_i^0$$

Then
$$C_i^+ = \frac{\eta_i \cdot (A \cdot P_{coll} + B) \cdot \Delta h_i^0}{4 \cdot \pi \cdot R_{A/F} \cdot \lambda} = C_{friction} - C_i^-$$

$$P_{coll} = \frac{4 \cdot \pi \cdot C_f + P_{exh} \cdot V_u - \frac{\eta_i \cdot B \cdot \Delta h_i^0}{R_{A/F} \cdot \lambda}}{\frac{\eta_i \cdot A \cdot \Delta h_i^0}{R_{A/F} \cdot \lambda} + V_u}$$

Numerical application:
$$P_{coll} = 284 \text{ mbar}$$

3. Air flow mass through the throttle valve: $\dot{M}_{air} = 0.003 \text{ kg/s}$

Relation between air flow mass and air into the cylinder:
$$\dot{M}_{air} = n_c \cdot \frac{N}{120} \cdot M_{air}$$

With the result obtained in point 1) and 2):

$$M_{air} = 6.18 \cdot 10^{-9} \cdot 284 \cdot 100 - 6.28 \cdot 10^{-5} = 1.13 \cdot 10^{-4} \text{ kg}$$

$\Rightarrow N = 796 \text{ rpm}$

4. Mass of fuel injected in each cylinder (injector):
$$M_{fuel} (mg) = \frac{M_{air} (kg) \cdot 10^6}{R_{A/F} \cdot \lambda}$$

Lower injector opening time:

$$t_{inj,low} (ms) = 0.358 \cdot \frac{M_{air} (kg) \cdot 10^6}{R_{A/F} \cdot \lambda_{high}} + 0.97 = 3.76 \text{ ms}$$

Higher injector opening time:

$$t_{inj,high} (ms) = 0.358 \cdot \frac{M_{air} (kg) \cdot 10^6}{R_{A/F} \cdot \lambda_{low}} + 0.97 = 3.88 \text{ ms}$$

Only 120 μ s of difference guarantee a proper 3 ways catalyst regulation.

5. At full load operation:
$$M_{air,FL} = 6.18 \cdot 10^{-9} \cdot 980 \cdot 100 - 6.28 \cdot 10^{-5} = 5.43 \cdot 10^{-4} \text{ kg}$$

$$M_{fuel} (mg) = 46.7 \text{ mg}$$

$$t_{inj,FL} (ms) = 17.68 \text{ ms}$$

Injector opening period:
$$\alpha_{inj} = \frac{N \cdot 360}{60} \cdot \frac{t_{inj,FL} (ms)}{1000} = 721^\circ \text{ c.a}$$

The injector has no time left to close itself again \Rightarrow continuous injection.

6. AC system switched on \Rightarrow An increase of the friction torque from 20 Nm to 30 Nm per cylinder

$$P_{coll} = \frac{4 \cdot \pi \cdot 30 + 1013 \cdot 100 \cdot 500 \cdot 10^{-6} - \frac{0.84 \cdot 6.26 \cdot 10^{-5} \cdot 43000 \cdot 1000}{14.2 \cdot 1.0}}{\frac{0.84 \cdot 6.18 \cdot 10^{-9} \cdot 43000 \cdot 1000}{14.2 \cdot 1.0} + 500 \cdot 10^{-6}} = 361 \text{ mbar}$$

At idle speed, the throttle valve is at sonic conditions, it means that the air flow mass is constant if the ECU do not change the throttle position.

$$\dot{M}_{air} = cte = 0.003 \text{ kg / s} \quad \text{if} \quad \mathcal{G}_{throttle} = cte$$

Then
$$N = \frac{\dot{M}_{air} \cdot 120}{n_c \cdot M_{air}} = \frac{0.003 \cdot 120}{4 \cdot (A \cdot 361 + B)} = 559 \text{ rpm}$$

7. Air flow needed in order to maintain a minimum engine speed of 700 rpm.

$$\dot{M}_{air} = n_c \cdot \frac{N}{120} \cdot M_{air} = 0.0038 \text{ kg / s}$$

And now, imagine how much complicated is the engine control management considering:

- An exhaust gas recirculation system
- A variable nozzle turbo-compressor unit
- A variable direct injection pressure system
- A complete post-treatment system including a 3-ways catalyst and a NO_x Absorber
- An On-Board Diagnostic system (mandatory since EURO 4)
- ... And an electric motor to control in the case of a hybrid powertrain application