Engines course

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

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

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

   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: $$M_{air} = \underbrace{\frac{P_{coll}}{r \cdot T_{coll}}}_{\rho_{air}} \cdot \underbrace{\left(V_u + V_{TDC} - V_{eg,1}\right)}_{=\eta_{vol} \cdot V_u}$$ using $V_{eg,1}$ and V_{TDC}

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

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

   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: $E_i^- = 4 \cdot \pi \cdot C_i^- = \left(P_{coll} - P_{exh}\right) \cdot V_u$

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

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

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

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

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):

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

$\Rightarrow$ $$N = 796\ rpm$$

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:

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

Higher injector opening time:

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

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

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

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

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

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

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

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

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.

$$\dot{M}_{air} = cte = 0.003 \ kg/s \qquad \text{if} \qquad \vartheta_{throttle} = cte$$

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

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

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

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