Basic *Practical* diesel cycle

define some units

$kN := 10^3 \cdot N$ $kPa := 10^3 \cdot Pa$

$MPa := 10^6 Pa$ $kJ := 10^3 \cdot J$

$kmol := 10^3 mol$

The textbook Diesel cycle is represented by all heat addition at constant pressure. The Otto cycle which is implemented by the spark ignition internal combustion engine adds all heat at constant volume. We will model a combined or dual (Seiliger) cycle with a portion of the heat added at constant volume, the remainder at constant pressure. Setting some parameters to be defined = 1 will reduce to either the Otto or Diesel cycle.

This model will use an ideal air standard cycle with air as an ideal gas with constant specific heats and reversible processes to represent the behavior. The **gas relationships** are useful.

air-standard cycles ...
1. air as ideal gas is working fluid throughout cycle - no inlet or exhaust process
2. combustion process replaced by heat transfer process
3. cycle is completed by heat transfer to surroundings
4. all processes internally reversible
5. usually constant specific heat (page 311)

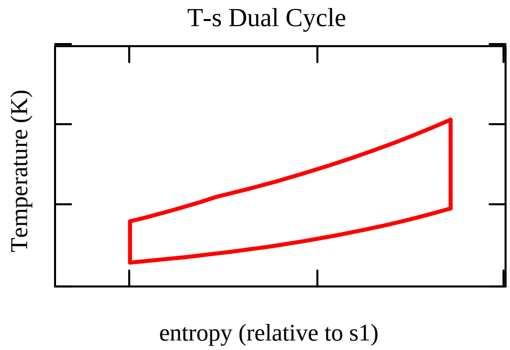
basic practical diesel cycle

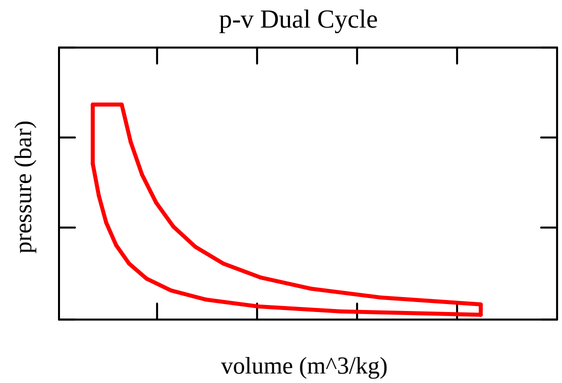
Assumptions for analysis ...
1. reversible cycle with all reversible processes
2. working fluid is air assumed to be a perfect gas with constant specific heats, $\gamma = c_p/c_v = 1.4$
3. mass of air in cylinder remains constant
4. combustion processes are represented by heat transfer from an external source. Constant volume or constant pressure pocesses are done.
5. cycle is completed by cooling heat transfer to the surroundings until the air temperature and pressure return to the initial conditions of the cycle (constant volume process).

   1-2 isentropic compression
   2-3 constant volume heat addition
   3-4 constant pressure heat addition
   4-5 isentropic expansion
   5-1 constant volume cooling

data for plot

this is the shape ...





next we will put numbers on the plots => themodynamic analysis of dual (Seiliger) cycle

The original notes are sourced from VanWylen and Sonntag. They could be revised to use the form of some of the relationships from Woud, but at considerable effort. Rather what follows is the application of the equations developed in the gas relationships lecture applied to the combined air-standard cycle deriving the relationships summarized in Table 7.3 Analytical prediction of the Selinger process on page 245 of the text.

$$r_c, a, b \qquad r_c = \frac{v_1}{v_2} \qquad a = \frac{p_3}{p_2} \qquad b = \frac{v_4}{v_3}$$

stage 1-2
isentropic adiabatic compression (expansion) ____________________________________
volume ratio known

$$r_c = \frac{v_{initial}}{v_{final}} = \frac{v_1}{v_2} \qquad p_{final} = p_{initial}\cdot\left(\frac{v_{initial}}{v_{final}}\right)^{\gamma} = \left(\frac{v_1}{v_2}\right)^{\gamma} = r_c^{\gamma} \qquad T_{final} = T_{initial}\cdot\left(\frac{v_{initial}}{v_{final}}\right)^{\gamma-1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1} = r_c^{\gamma-1}$$

$$\frac{v_1}{v_2} = r_c \qquad \frac{p_{final}}{p_{initial}} = r_c^{\gamma} \qquad \frac{T_{final}}{T_{initial}} = r_c^{\gamma-1}$$

stage 2-3
heat transfer at constant volume .... ____

$$\frac{p_3}{p_2} = a \qquad p_{initial} = \frac{R\cdot T_{initial}}{v_{constant}\cdot 100} \qquad p_{final} = \frac{R\cdot T_{final}}{v_{constant}\cdot 100} \qquad \frac{T_{final}}{T_{initial}} = \frac{p_{final}}{p_{initial}} = \frac{p_3}{p_2} = a$$

$$\frac{v_1}{v_2} = 1 \qquad \frac{p_3}{p_2} = a \qquad \frac{T_{final}}{T_{initial}} = a$$

stage 3-4
heat transfer at constant pressure .... ____

$$b = \frac{v_{final}}{v_{initial}} = \frac{v_4}{v_3} \qquad v_{initial} = \frac{R\cdot T_{initial}}{p_{constant}\cdot 100} \qquad v_{final} = \frac{R\cdot T_{final}}{p_{constant}\cdot 100} \qquad \frac{T_4}{T_3} = \frac{T_{final}}{T_{initial}} = \frac{v_{final}}{v_{initial}} = b$$

$$\frac{v_4}{v_3} = b \qquad \frac{p_4}{p_3} = 1 \qquad \frac{T_4}{T_3} = b$$

stage 4-5
isentropic adiabatic compression (<u>expansion</u>) ____________________________________
volume ratio known

$$\frac{v_5}{v_4} = \frac{v_5}{v_3}\cdot\frac{v_3}{v_4} = \frac{v_5}{v_3}\cdot\frac{v_3}{v_4} = \frac{v_1}{v_2}\cdot\frac{v_3}{v_4} = \frac{r_c}{b}$$

as $v_5 = v_1$ and $v_2 = v_3$ [W 7.68 & 7.69]

$$p_{final} = p_{initial}\cdot\left(\frac{v_{initial}}{v_{final}}\right)^{\gamma} = \left[p_4\cdot\left(\frac{v_4}{v_5}\right)\right]^{\gamma} = p_4\cdot\left(\frac{1}{\frac{r_c}{b}}\right)^{\gamma} = p_5$$

$$T_{final} = T_{initial}\cdot\left(\frac{v_{initial}}{v_{final}}\right)^{\gamma-1} = T_4\cdot\left(\frac{v_4}{v_5}\right)^{\gamma-1} = T_4\cdot\left(\frac{1}{\frac{r_c}{b}}\right)^{\gamma-1} = T_5$$

$$\frac{v_5}{v_4} = \frac{r_c}{b} \qquad \frac{p_4}{p_5} = \left(\frac{r_c}{b}\right)^{\gamma} \qquad \frac{T_4}{T_5} = \left(\frac{r_c}{b}\right)^{\gamma-1}$$

N.B. ratios are inconsistent 5/4 ... 4/5

stage 5-1
heat transfer at constant volume ....

$$\frac{v_5}{v_1} = 1 \qquad p_{initial} = \frac{R\cdot T_{initial}}{v_{constant}\cdot 100} \qquad p_{final} = \frac{R\cdot T_{final}}{v_{constant}\cdot 100}$$

so ...

$$\frac{p_{initial}}{p_{final}} = \frac{T_{initial}}{T_{final}} = \frac{p_5}{p_1} = \frac{T_5}{T_1}$$

$$\frac{p_5}{p_1} = \frac{p_5}{p_4}\cdot\left(\frac{p_4 = p_3}{p_1}\right) = \frac{p_5}{p_4}\cdot\frac{p_3}{p_2}\cdot\frac{p_2}{p_1} = \frac{1}{\left(\frac{r_c}{b}\right)^{\gamma}}\cdot a\cdot r_c^{\gamma} = a\cdot b^{\gamma}$$

$$\frac{v_5}{v_1} = 1 \qquad \frac{p_5}{p_1} = a\cdot b^{\gamma} \qquad \frac{T_5}{T_1} = a\cdot b^{\gamma}$$

this one is initial/final

Now, applying the gas relationships to the calculation of states around the air-standard combined cycle

constants ... $\gamma := 1.4 \quad c_v := 0.7165\frac{kJ}{kg\cdot K} \quad c_p := 1.0035\frac{kJ}{kg\cdot K} \quad R := 0.287\frac{kJ}{kg\cdot K}$

given ... $T_1, v_1(calc), s_1, p_1, r_v, r_p, r_c$

$T_1 := 295K \quad s_1 := 1\frac{kJ}{kg} \quad p_1 := 1bar \quad r_v := 12.5 \quad r_p := 1.38 \quad r_c := 1.86 \quad v_1 := \frac{R\cdot T_1}{p_1} \qquad v_1 = 0.847\frac{m^3}{kg}$

r_v = compression ratio r_c in text
r_p = pressure ratio during constant volume heat addition = a in text
r_c = cut-off ratio. portion of stroke during which constant pressure heat addition occurs = b in text

$$r_v = \frac{v_1}{v_2} = r_c \qquad r_p = \frac{p_3}{p_2} = a \qquad r_c = \frac{v_4}{v_3} = b$$

1-2 isentropic compression of air

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{v_1}{v_2}\right)^{\gamma-1}$$

(7.35) this .. for reversible adiabatic process

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1} \qquad p_2 = p_1\cdot\left(\frac{v_1}{v_2}\right)^{\gamma}$$

$$s_2 := s_1 \qquad v_2 := \frac{v_1}{r_v} \qquad T_2 := T_1\cdot\left(\frac{v_1}{v_2}\right)^{\gamma-1} \qquad p_2 := \frac{R\cdot T_2}{v_2}$$

$$v_2 = 0.068\frac{m^3}{kg} \qquad T_2 = 810.188\,K \qquad p_2 = 34.33\,bar$$

later we will plot on T-s and p-v so the relationships for intermediate states is shown. Any state value can serve as the plot parameter, but we will use temperature.

$T_1 \le T\_plot \le T_2$ $\quad s = s_1 = s_2 = \text{constant}$

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1} \quad \text{and ...} \quad \frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} \quad \text{so ...} \quad v\_plot = v_1 \cdot \left(\frac{T_1}{T\_plot}\right)^{\frac{1}{\gamma-1}} \quad \text{and ...} \quad p\_plot = p_1 \cdot \left(\frac{T\_plot}{T_1}\right)^{\frac{\gamma}{\gamma-1}}$$

2-3 constant volume heat addition using r_p during constant volume portion of heat addition ...

$v_3 := v_2$ $\quad p_3 := p_2 \cdot r_p$ $\quad p_3 = 47.375\,\text{bar}$ $\quad$ need to calculate T_3 $\quad v_2 = v_3$

$p \cdot v = R \cdot T$ **(3.2)** $\quad \dfrac{p_1 \cdot v_1}{T_1} = \dfrac{p_2 \cdot v_2}{T_2}$ **(3.5)** $\quad \dfrac{p_3}{T_3} = \dfrac{p_2}{T_2}$ $\quad T_3 := T_2 \cdot \dfrac{p_3}{p_2}$ $\quad T_3 = 1.118 \times 10^3\,\text{K}$

$s_2 - s_1 = c_{vo} \cdot \ln\left(\dfrac{T_2}{T_1}\right) + R \cdot \ln\left(\dfrac{v_2}{v_1}\right)$ **(7.21)** $\quad c_{vo} = \text{constant}$ $\quad s_3 := \left(s_2 + c_v \cdot \ln\left(\dfrac{T_3}{T_2}\right) \cdot K\right)$ $\quad s_3 = 1.231\,\dfrac{kJ}{kg}$

for later plotting

$T_2 \le T\_plot \le T_3$ $\quad s\_plot = s_2 + c_v \cdot \ln\left(\dfrac{T\_plot}{T_2}\right) \cdot K$

p-v are end points v = constant (straight lines) although intermediate states would be determined from the state equation ...

$$p\_plot = \frac{R \cdot T\_plot}{v_2}$$

3-4 heat added at constant ***pressure*** with r_c

$v_4 := v_3 \cdot r_c$ $\quad p_4 := p_3$ $\quad T_4 := \dfrac{p_4 \cdot v_4}{R}$

$v_4 = 0.126\,\dfrac{m^3}{kg}$ $\quad p_4 = 47.375\,\text{bar}$ $\quad T_4 = 2.08 \times 10^3\,\text{K}$

$s_2 - s_1 = c_{po} \cdot \ln\left(\dfrac{T_2}{T_1}\right) - R \cdot \ln\left(\dfrac{p_2}{p_1}\right)$ **(7.23)** $\quad c_{po} = \text{constant}$ $\quad s_4 := \left(s_3 + c_p \cdot \ln\left(\dfrac{T_4}{T_3}\right) \cdot K\right)$ $\quad s_4 = 1.854\,\dfrac{kJ}{kg}$

for later plotting

$T_3 \le T\_plot \le T_4$ $\quad s\_plot = s_3 + c_p \cdot \ln\left(\dfrac{T\_plot}{T_2}\right) \cdot K$

p-v are end points v = constant (straight lines) although intermediate states would be determined from the state equation ...

$$v\_plot = \frac{R \cdot T\_plot}{p_2}$$

4-5 isentropic expansion

$v_5 := v_1$ $\quad s_5 := s_4$ $\quad s_5 = 1.854\,\dfrac{kJ}{kg}$

$\dfrac{T_4}{T_5} = \left(\dfrac{v_5}{v_4}\right)^{\gamma-1}$ $\quad T_5 := T_4 \cdot \left(\dfrac{v_4}{v_5}\right)^{\gamma-1}$ $\quad T_5 = 970.553\,\text{K}$ $\quad p_5 := \dfrac{R \cdot T_5}{v_5}$ $\quad p_5 = 3.29\,\text{bar}$

as with isentropic compression above using T as the plot parameter ...

$T_4 \ge T\_plot \ge T_5$ $\quad$ decreasing ... $\quad s = s_4 = s_5 = \text{constant}$

$$\frac{T_5}{T_4} = \left(\frac{v_4}{v_5}\right)^{\gamma-1}$$ and ... $$\frac{T_5}{T_4} = \left(\frac{p_5}{p_4}\right)^{\frac{\gamma-1}{\gamma}}$$ so ... $$v\_plot = v_4 \cdot \left(\frac{T_4}{T\_plot}\right)^{\frac{1}{\gamma-1}}$$ and ... $$p\_plot = p_4 \cdot \left(\frac{T\_plot}{T_4}\right)^{\frac{\gamma}{\gamma-1}}$$

5-1 constant volume cooling

$$s_1 := \left(s_5 + c_v \cdot \ln\left(\frac{T_1}{T_5}\right) \cdot K\right)$$

check closure of s_1 $\quad s_1 = 1\,\frac{kJ}{kg}$

and for later plotting ...

$T_5 \geq T\_plot \geq T_1$

decreasing ...

$$s\_plot = s_5 + c_v \cdot \ln\left(\frac{T\_plot}{T_5}\right) \cdot K$$

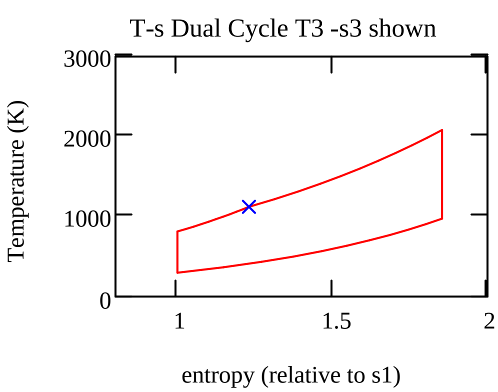
p-v are end points v = constant (straight lines) although intermediate states would be determined from the state equation ...

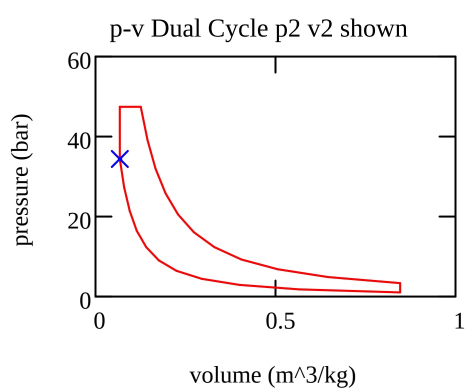
$$p\_plot = \frac{R \cdot T\_plot}{v_2}$$

$$\begin{pmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_1 \end{pmatrix} = \begin{pmatrix} 295 \\ 810 \\ 1118 \\ 2080 \\ 971 \\ 295 \end{pmatrix} K \qquad \begin{pmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \\ s_5 \\ s_1 \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \\ 1.231 \\ 1.854 \\ 1.854 \\ 1 \end{pmatrix} \frac{kJ}{kg} \qquad \begin{pmatrix} p_1 \\ p_2 \\ p_3 \\ p_4 \\ p_5 \\ p_1 \end{pmatrix} = \begin{pmatrix} 1 \\ 34.33 \\ 47.375 \\ 47.375 \\ 3.29 \\ 1 \end{pmatrix} bar \qquad \begin{pmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \\ v_5 \\ v_1 \end{pmatrix} = \begin{pmatrix} 0.847 \\ 0.068 \\ 0.068 \\ 0.126 \\ 0.847 \\ 0.847 \end{pmatrix} \frac{m^3}{kg}$$

now for plotting, including the intermediate values ... details in area below, relationships developed above

parameterization of T-s, p-v





now for calculations of efficiency

r v = compression ratio $r_v = \frac{v_1}{v_2}$

r p = pressure ratio during constant volume heat addition $r_p = \frac{p_3}{p_2} = \frac{T_3}{T_2}$ at constant volume (ideal gas law pv=RT)

r c = cut-off ratio. portion of stroke during which constant pressure heat addition occurs $r_c = \frac{v_4}{v_3} = \frac{T_4}{T_3}$ at constant pressure (ideal gas law pv=RT)

1-2 isentropic compression of air

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{v_1}{v_2}\right)^{\gamma-1}$$ **(7.35)** this .. for reversible adiabatic process

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1} = r_v^{\gamma-1} \qquad p_2 = p_1\cdot\left(\frac{v_1}{v_2}\right)^{\gamma} = p_1\cdot r_v^{\gamma}$$

2-3 constant volume heat addition using r_p during constant volume portion of heat addition ...

$$Q_{H1} = m\cdot c_v\cdot(T_3 - T_2) = m\cdot c_v\cdot T_2\cdot\left(\frac{T_3}{T_2} - 1\right) = m\cdot c_v\cdot T_2\cdot(r_p - 1)$$

3-4 heat added at constant ***pressure*** with r_c

$$Q_{H2} = m\cdot c_p\cdot(T_4 - T_3) = m\cdot c_p\cdot T_3\cdot\left(\frac{T_4}{T_3} - 1\right) = m\cdot c_p\cdot T_3\cdot(r_c - 1) = m\cdot c_p\cdot T_2\cdot\frac{T_3}{T_2}\cdot(r_c - 1) = m\cdot\gamma\cdot c_v\cdot T_2\cdot r_p\cdot(r_c - 1)$$

substituting $\gamma = c_p/c_v$ and $r_p = T_3/T_2$

5-1 constant volume cooling

$$Q_L = -m\cdot c_v\cdot(T_5 - T_1) = -m\cdot c_v\cdot T_1\cdot\left(\frac{T_5}{T_1} - 1\right)$$

$$\frac{T_5}{T_1} = \frac{p_5}{p_1} = \frac{p_5}{p_4}\cdot\frac{p_4}{p_3}\cdot\frac{p_3}{p_2}\cdot\frac{p_2}{p_1} = \left(\frac{v_4}{v_5}\right)^{\gamma}\cdot 1\cdot r_p\cdot\left(\frac{v_1}{v_2}\right)^{\gamma} = \left(\frac{v_4}{v_3}\right)^{\gamma}\cdot r_p = r_p\cdot r_c^{\gamma} \quad \Rightarrow \quad Q_L = -m\cdot c_v\cdot T_1\cdot\left(r_p\cdot r_c^{\gamma} - 1\right)$$

^
as $v_5 = v_1$ and $v_2 = v_3$

combining these for thermal efficiency of the cycle ...

$$\eta_{th} = 1 + \frac{Q_L}{Q_H} = 1 - \frac{T_1\cdot\left(r_p\cdot r_c^{\gamma} - 1\right)}{T_2\cdot\left[(r_p - 1) + \gamma\cdot r_p\cdot(r_c - 1)\right]} = 1 - \frac{r_p\cdot r_c^{\gamma} - 1}{r_v^{\gamma-1}\cdot\left[(r_p - 1) + \gamma\cdot r_p\cdot(r_c - 1)\right]}$$

$r_v = 12.5$

$r_p = 1.38$

$$\eta_{th} := 1 - \frac{r_p\cdot r_c^{\gamma} - 1}{r_v^{\gamma-1}\cdot\left[(r_p - 1) + \gamma\cdot r_p\cdot(r_c - 1)\right]}$$

$\eta_{th} = 0.592$

$r_c = 1.86$

and we could calculate the work per cycle

$$W = Q_{H1} + Q_{H2} + Q_L = m\cdot c_v\cdot(T_3 - T_2) + m\cdot c_p\cdot(T_4 - T_3) - m\cdot c_v\cdot(T_5 - T_1)$$

$m := 1$ for per unit mass calculation in mcd

$Q_{H1} := m\cdot c_v\cdot(T_3 - T_2)$ $\quad Q_{H1} = 220.59\,\frac{kJ}{kg}$

$Q_{H2} := m\cdot c_p\cdot(T_4 - T_3)$ $\quad Q_{H2} = 964.897\,\frac{kJ}{kg}$

$Q_L := -m\cdot c_v\cdot(T_5 - T_1)$ $\quad Q_L = -484.034\,\frac{kJ}{kg}$

$W := Q_{H1} + Q_{H2} + Q_L$ $\quad W = 701.453\,\frac{kJ}{kg}$ $\quad W = 701.453\,\frac{kW}{\frac{kg}{s}}$

can also express as ...

$W1 := \eta_{th}\cdot(Q_{H1} + Q_{H2})$

$W1 = 701.296\,\frac{kW}{\frac{kg}{s}}$

N.B. this specific power is more than double LM 2500

another parameter describing diesel engines

some diesel examples ...

wartsila 32 (four stroke)

wartsila 64 (four stroke)

Sulzer RT-flex96C, Sulzer RTA96C (two stroke)

Indicated Mean Effective Pressure; Imep

$$Imep = \frac{work\_per\_stroke}{swept\_volume} = \frac{work}{V_1 - V_2} \qquad m = \frac{p_1\cdot V_1}{R\cdot T_1}$$

$$Imep = \frac{W\cdot m}{V_1 - V_2} = \frac{W\cdot\frac{p_1\cdot V_1}{R\cdot T_1}}{V_1 - V_2} = \frac{W\cdot\frac{p_1}{R\cdot T_1}}{1 - \frac{V_2}{V_1}} = \frac{W\cdot\frac{p_1}{R\cdot T_1}}{1 - \frac{1}{r_v}}$$

in this example ... $Imep := \frac{W\cdot\frac{p_1}{R\cdot T_1}}{1 - \frac{1}{r_v}}$ $\quad Imep = 9.005\,bar$

consider indicated power, ref: Woud 7.4.2-3 $\quad n_e = engine\_rpm$

$power\_per\_cyl = \frac{work\_per\_cycle}{unit\_time}$ $\quad$ time is period of power strokes = 1/freq = 1/(n_e=engine_rpm)

2-stroke n_e = # power strokes/time $\quad P_i = \frac{W_i}{period\_power\_stroke} = \frac{W_i}{\frac{1}{freq} = \frac{1}{n_e = engine\_rpm}} = W_i\cdot n_e$

4-stroke n_e = 2*# power strokes/time $\quad P_i = W_i\cdot\frac{n_e}{2}$ $\quad k = if(stroke = 2, 1, 2)$

with ... $i = number\_of\_cylinders$ $\quad$ engine power is ... $\quad P_i = W_i\cdot\frac{n_e\cdot i}{k} = Imep\cdot V_S\cdot\frac{n_e\cdot i}{k}$

brake power P_B, power at engine drive flange, after mechanical losses in engine see Woud (7.12) and 7.4.1

$$W_e = \frac{effective\_work}{unit\_mass} = \frac{W_i}{mass} \cdot \eta_{mechanical}$$

$$P_e = W_e \cdot \frac{n_e \cdot i}{k} = mep_e \cdot V_S \cdot \frac{n_e \cdot i}{k}$$ $$P_e = constant \cdot mep_e \cdot n_e$$ for later discussion

$$mep_e = mean\_effective\_pressure = brake\_mean\_effective\_pressure = BMEP$$

$$mep_e = \frac{P_e \cdot k}{V_S \cdot n_e \cdot i} = \frac{P_e}{V_S \cdot \frac{n_e}{k} \cdot i} = \frac{power\_per\_cyl}{V_S \cdot \frac{n_e}{k}}$$

COLT-PIELSTICK PC4.2B DATA
Configuration Vee Only
Bore 570 mm
Stroke 660 mm
Engine Version 60 Hz Propulsion
Cylinder (nos) 10-12-16-18
Output Range (kW) 12,500-22,500 13,250-23,850
Speed (rpm) 400 400/430
Mean Eff. Pressure (bar) 22.3 22.3/22.0
Mean Piston Speed (m/s) 8.8 8.8/9.5
Output/cyl kW (hp) 1250 (1676) 1250 (1676)/1325 (1777)
from: page 16 of **Fairbanks Morse medium speed diesel handbook**

$power\_per\_cyl := 1250kW$ $n_e := \frac{400}{min}$ $n\_stroke := 4$ $k := if(n\_stroke = 2, 1, 2)$ $bore := 570mm$ $stroke := 660mm$

$V_S := \frac{\pi}{4} \cdot bore^2 \cdot stroke$ $V_S = 5.948\ ft^3$ $mep_e := \frac{power\_per\_cyl}{V_S \cdot \frac{n_e}{k}}$ $mep_e = 22.266\ bar$ as stated in data above

two special cases (can be calculated above setting r_p and r_c appropriately ...

Otto cycle - spark ignition engine heat added at TDC (constant volume) only

extra subscript added for special designation

air-standard Otto cycle: ***spark*** ignition internal-combustion engine
1-2 isentropic compression of air
2-3(=4) heat added at constant ***volume*** (piston momentarily at rest at tdc
4-5 isentropic expansion
5-1 heat rejection at constant volume (piston at crank-end dead center)

from air standard dual cycle above

$$\eta_{th} = 1 + \frac{Q_L}{Q_H} = 1 - \frac{T_1 \cdot \left(r_p \cdot r_c^{\gamma} - 1\right)}{T_2 \cdot \left[\left(r_p - 1\right) + \gamma \cdot r_p \cdot \left(r_c - 1\right)\right]} = 1 - \frac{r_p \cdot r_c^{\gamma} - 1}{r_v^{\gamma - 1} \cdot \left[\left(r_p - 1\right) + \gamma \cdot r_p \cdot \left(r_c - 1\right)\right]}$$

$r_{co} := 1$ $\eta_{th\_otto} := 1 - \frac{r_{po} \cdot r_{co}^{\gamma o} - 1}{r_{vo}^{\gamma o - 1} \cdot \left[\left(r_{po} - 1\right) + \gamma o \cdot r_{po} \cdot \left(r_{co} - 1\right)\right]}$ $\eta_{th\_otto} \rightarrow 1 - \frac{1}{r_{vo}^{\gamma o - 1}}$

$r_c := 1.0$ $r_p := 5$ $r_v := \begin{pmatrix} 5 \\ 10 \\ 15 \end{pmatrix}$ $\eta_{th\_otto} := 1 - \frac{1}{r_v^{\gamma - 1}}$ removing o designation $\eta_{th\_otto} = \begin{pmatrix} 0.475 \\ 0.602 \\ 0.661 \end{pmatrix}$

and ... Diesel cycle ... all heat added at constant pressure

air-standard ***Diesel*** cycle: ***compression*** ignition internal-combustion engine

1-2(=3) isentropic compression of air

3-4 heat added at constant ***pressure*** (gas expanding during heat addition)

4-5 isentropic expansion

5-1 heat rejection at constant volume (piston at crank-end dead center)

$r_{pd} := 1$ $\eta_{th\_diesel} := 1 - \frac{r_{pd} \cdot r_{cd}^{\gamma d} - 1}{r_{vd}^{\gamma d - 1} \cdot \left[\left(r_{pd} - 1\right) + \gamma d \cdot r_{pd} \cdot \left(r_{cd} - 1\right)\right]}$ $\eta_{th\_diesel} \rightarrow 1 - \frac{r_{cd}^{\gamma d} - 1}{r_{vd}^{\gamma d - 1} \cdot \gamma d \cdot \left(r_{cd} - 1\right)}$

$r_c := 2.5$ $r_p := 1$ $r_v := \begin{pmatrix} 10 \\ 15 \\ 20 \end{pmatrix}$ $\eta_{th\_diesel} := 1 - \frac{r_c^{\gamma} - 1}{r_v^{\gamma - 1} \cdot \gamma \cdot \left(r_c - 1\right)}$ $\eta_{th\_diesel} = \begin{pmatrix} 0.506 \\ 0.58 \\ 0.625 \end{pmatrix}$

Relate r_c, a, b to efficiency

$r_v = \frac{v_1}{v_2} = r_c$ $r_p = \frac{p_3}{p_2} = a$ $r_c = \frac{v_4}{v_3} = b$

reset variables

$$\eta_{th} := 1 - \frac{r_p \cdot r_c^{\gamma} - 1}{r_v^{\gamma - 1} \cdot \left[\left(r_p - 1\right) + \gamma \cdot r_p \cdot \left(r_c - 1\right)\right]}$$

substitute, var1 = var2, where var1 is to be replaced

$$\eta_{th} \text{ substitute}, r_v = r_{cc}, r_p = a, r_c = b, \gamma = \kappa \rightarrow 1 - \frac{a \cdot b^{\kappa} - 1}{r_{cc}^{.4} \cdot \left[a - 1 + a \cdot (b - 1) \cdot \kappa\right]}$$

[W 7.87]