講演番号 15

Experiment and Simulation of Transient Behavior of Marine Diesel Engine

環境･動力系　環境エンジン研究グループ
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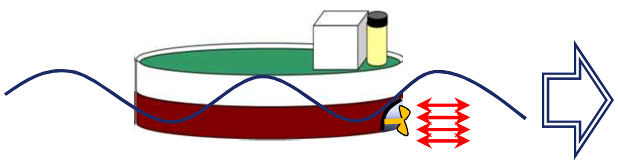
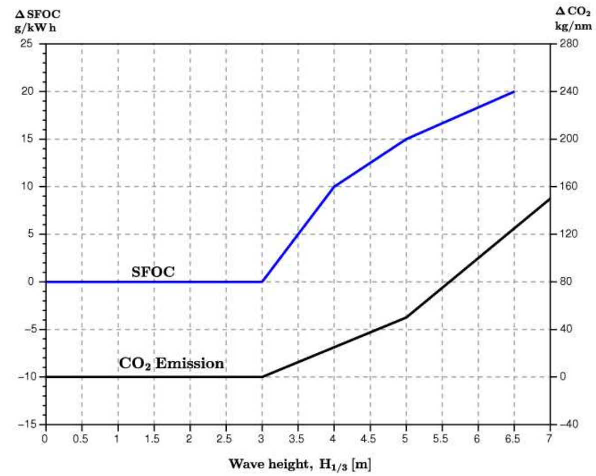
Research Objective

NMRI



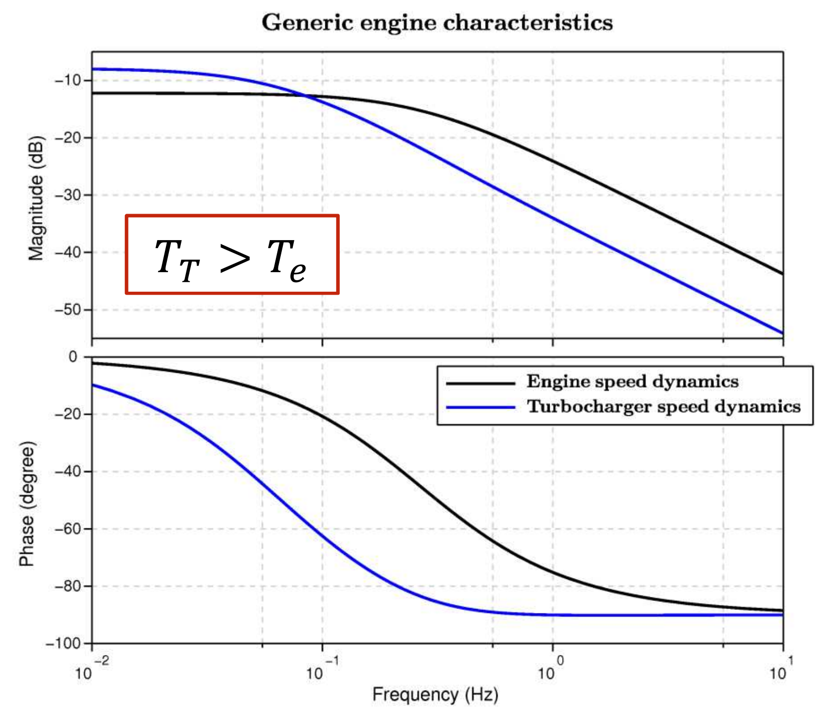


Fuel Oil Consumption (SFOC) in actual sea inevitably increases and differs from steady-state SFOC map

Hypothesis:

Engine dynamics: $$n_e\Big|_{n_{TC_0}} = \frac{K_e}{T_e p + 1} u_f$$

TCH dynamics: $$n_{TC}\Big|_{n_{e_0}} = \frac{K_{TC}}{T_T p + 1} u_f$$



Owing to qualitatively different dynamics of engine and turbocharger (TCH) an ample air supply for fuel combustion in rough sea ceases to hold, since air pressure $P_s \propto (n_{TC})^2$. This study aim at reveal effect of steady-state and fluctuating components of air supply on engine performance.

Experiment Engines Particulars

Four-stroke Medium Speed Diesel Engine

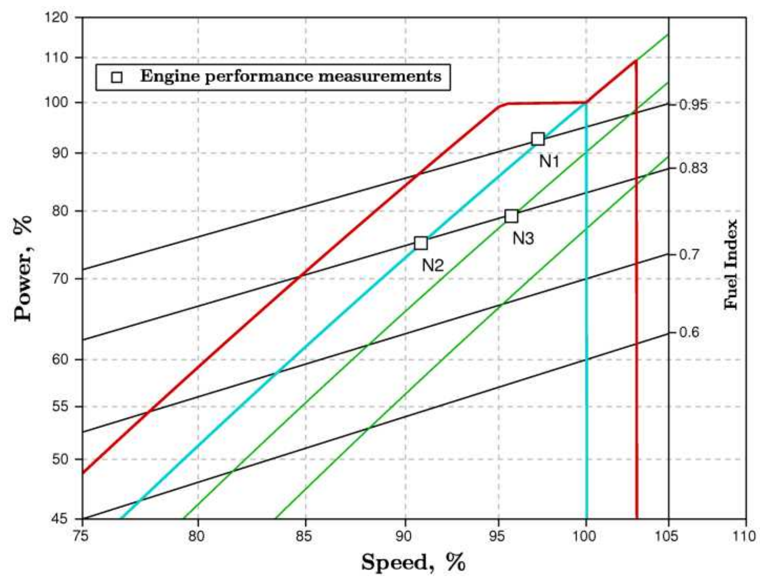
Two-stroke Slow Speed Diesel Engine

Niigata 6L19HX		
No of Cylinders	--	6
Bore/Stroke	mm	190/260
Speed/Power	rpm/kW	1000/750
Scav. Air Pressure	barA	2.9
Scav. Air Flow	Nm^3/h	4180

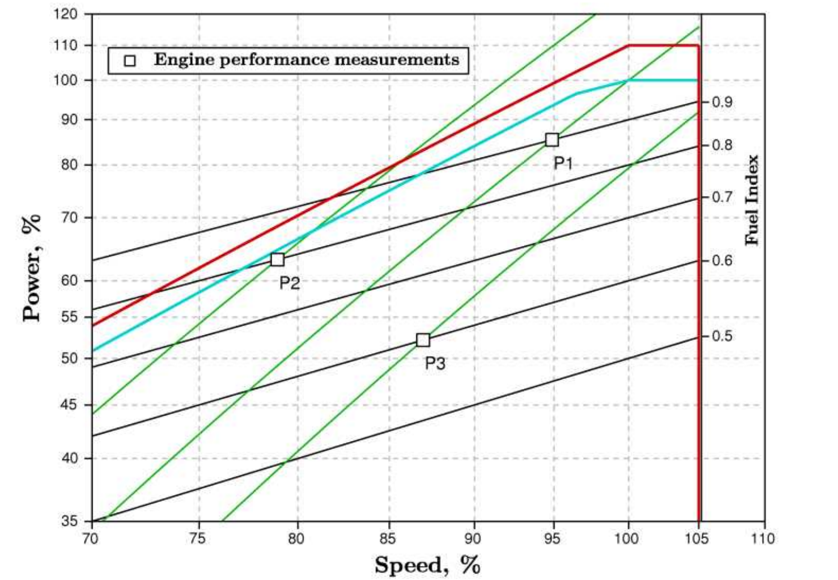
Mitsui-MAN 4S50ME-T9.2		
No of Cylinders	--	4
Bore/Stroke	mm	500/2214
Speed/Power	rpm/kW	117/7120
Scav. Air Pressure	barA	4.4
Scav. Air Flow	Nm^3/h	40932

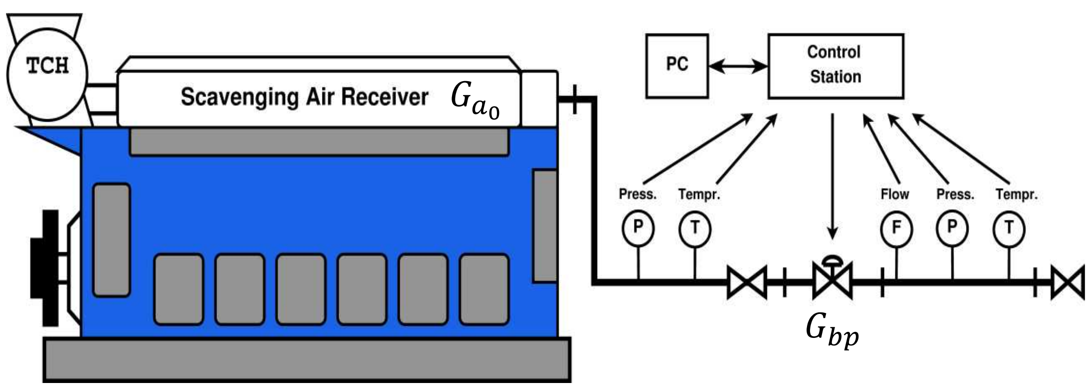
Experiment Test Bench & Conditions

4st Engine



2st Engine



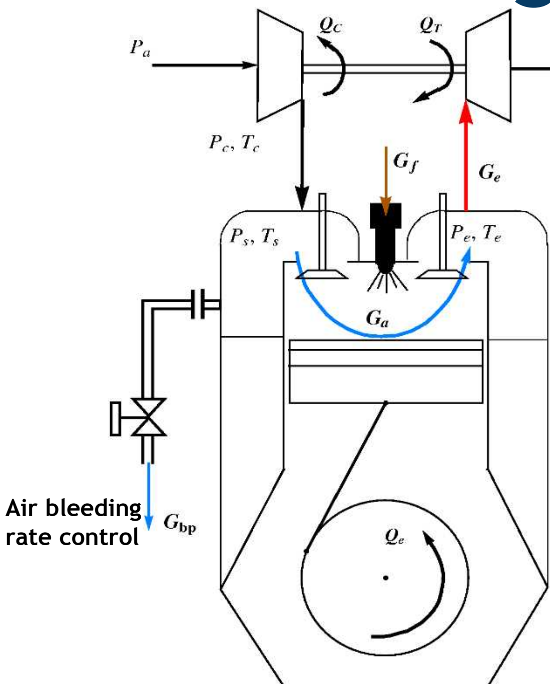


Scavenging air by-pass system allow to reproduce steady-state and fluctuating components of engine air supply.

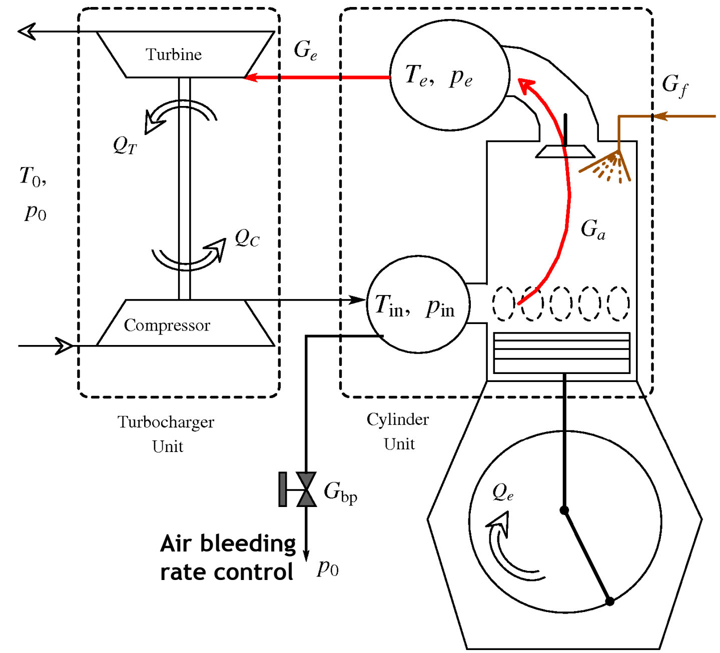
Experiment Conditions

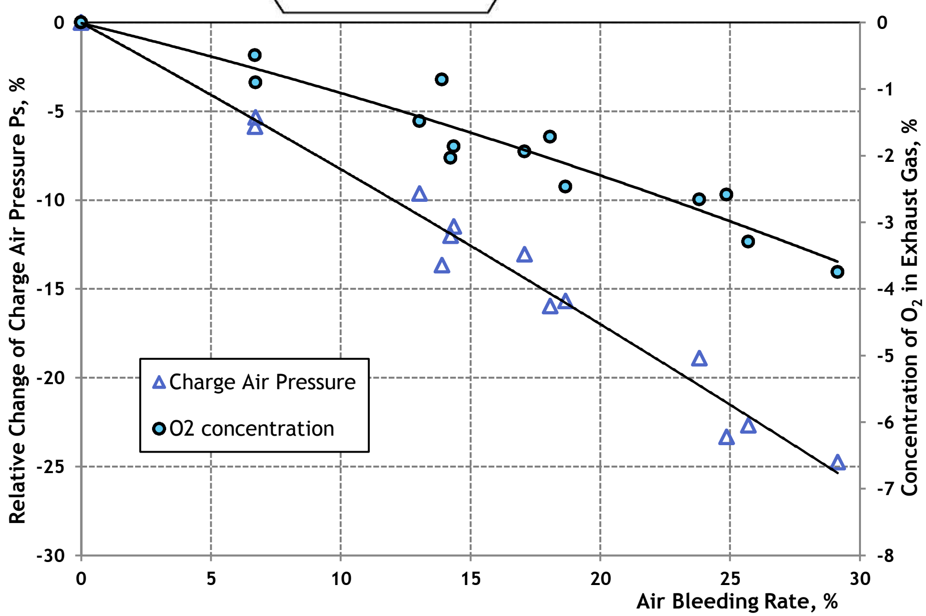
	4st engine	2st engine
Air bleeding rate G_{bp}/G_{a_0}, %	7,14,18, 25,30	5,10,15
By-pass fluctuation period, sec	7,10,15	10,12,15
By-pass fluctuation amplitude, %	25,30,40, 50	20,30

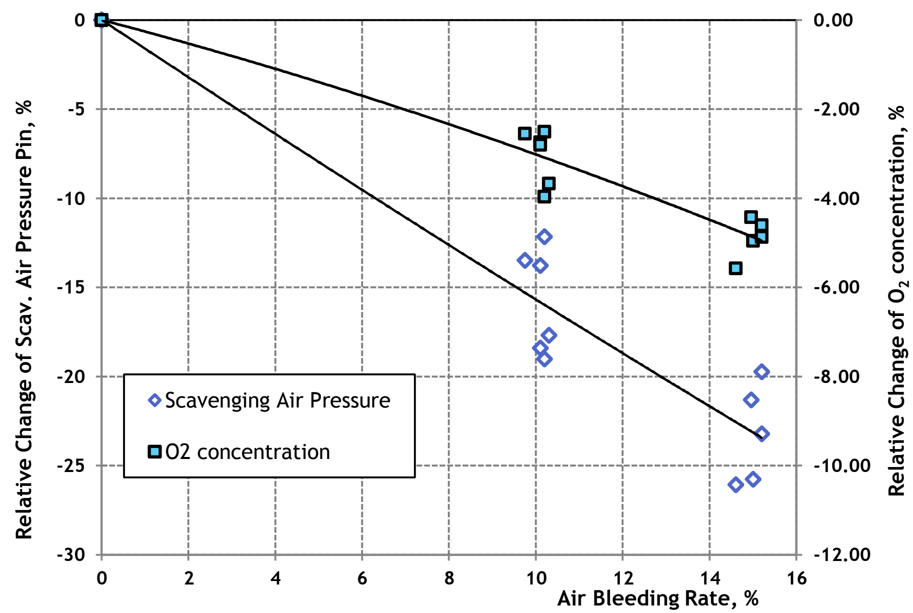
Air Bleeding Effect on Engine Performance



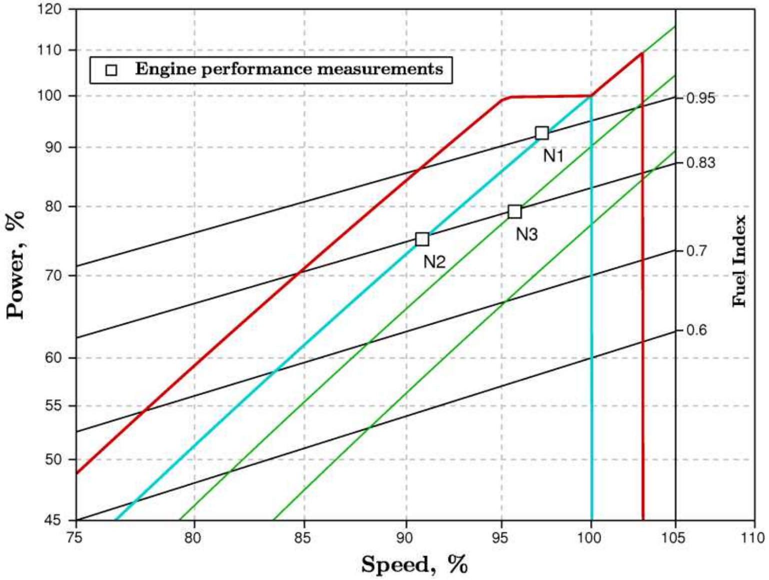
As air bleeding rate increases the scavenging air pressure and air to fuel ratio drops, that is indicated by O_2 concentration, thus fuel combustion worsens and SFOC inevitably increases.

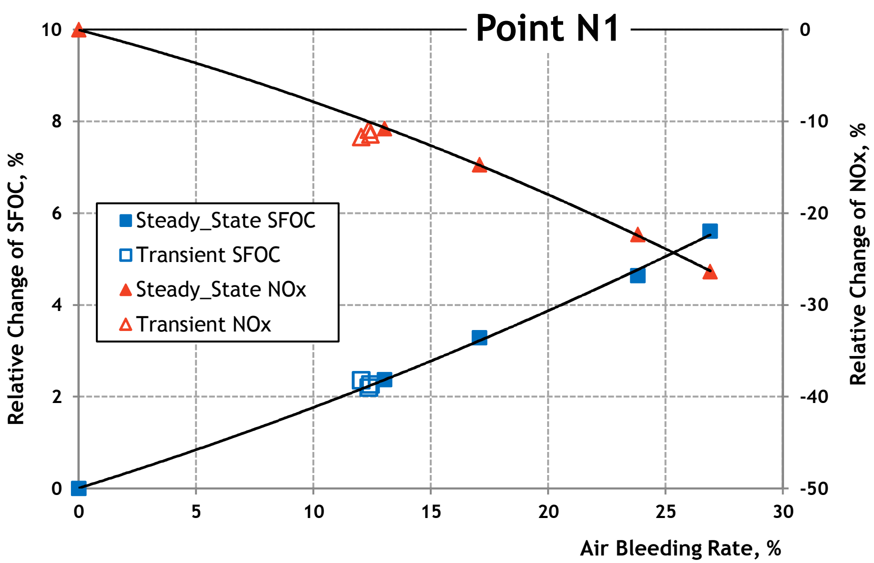


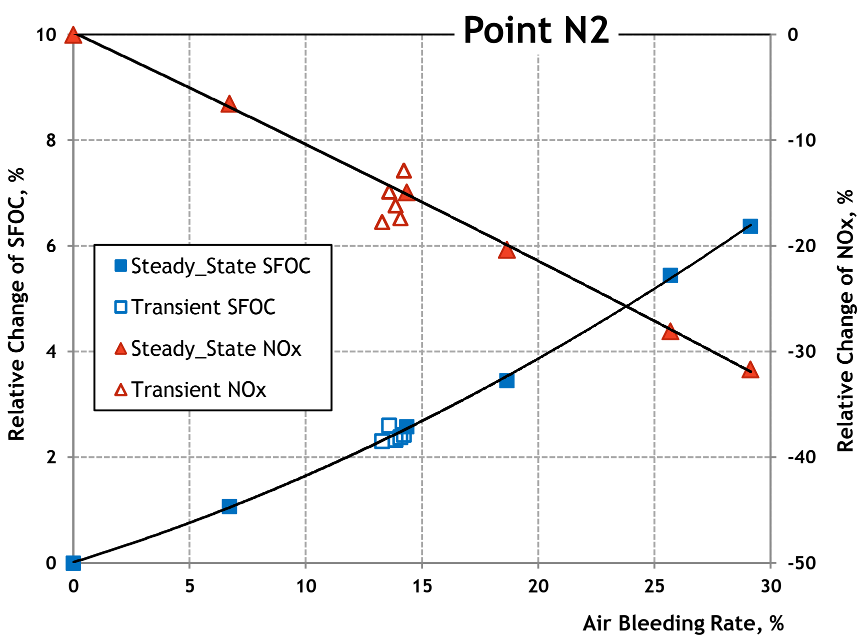


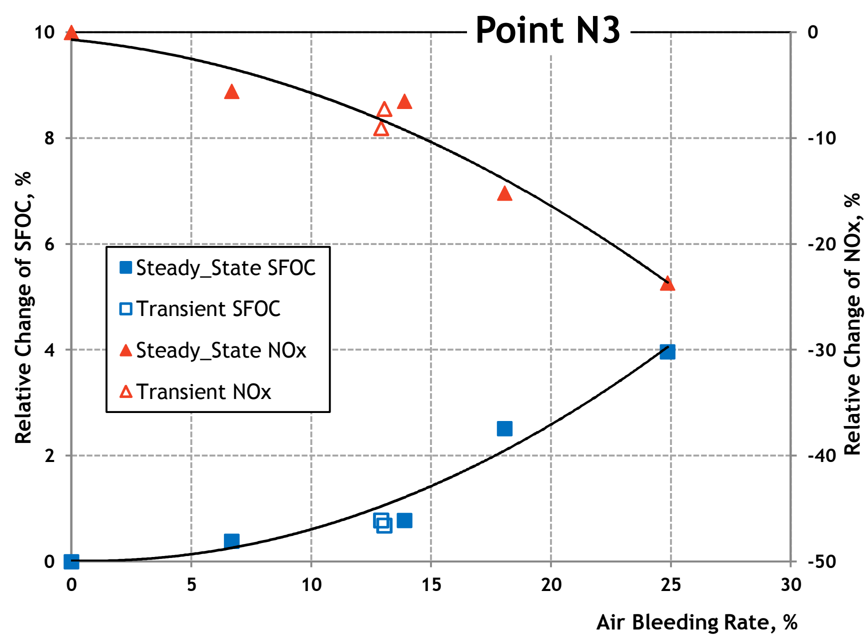


4st Engine Experiment Results









2st Engine Experiment Results

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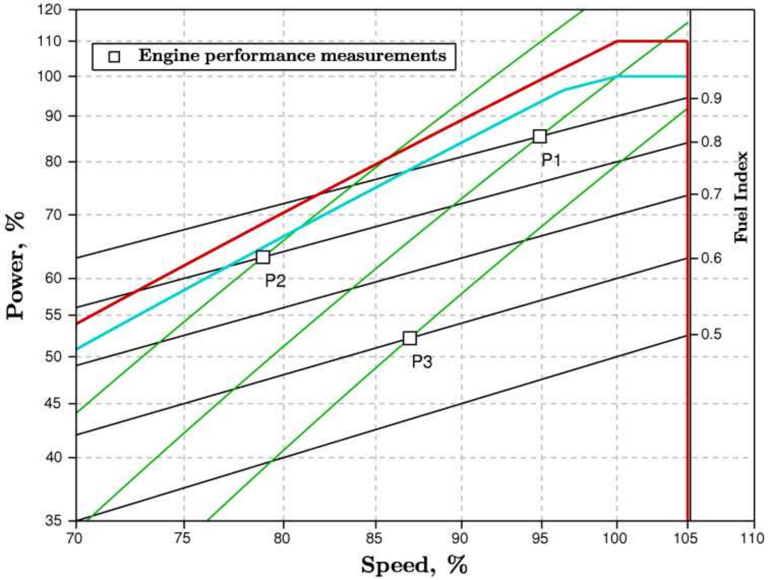
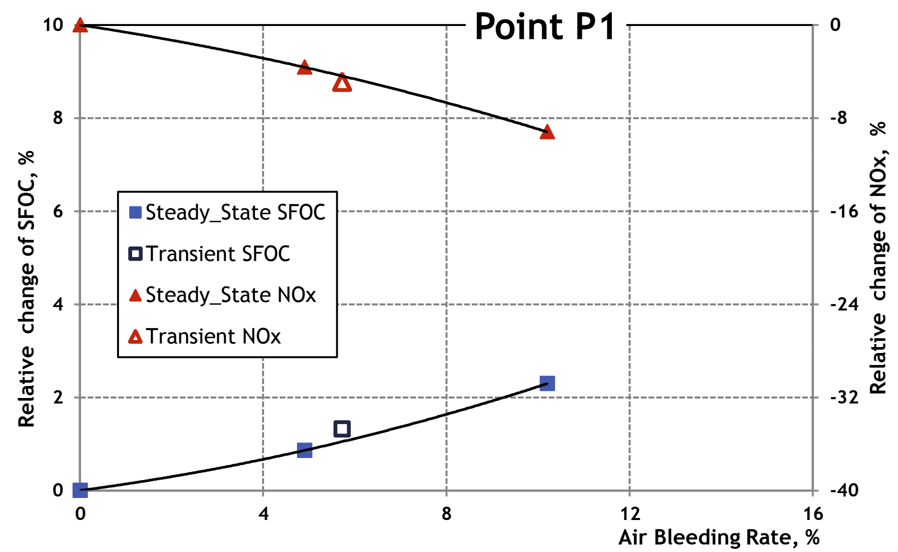
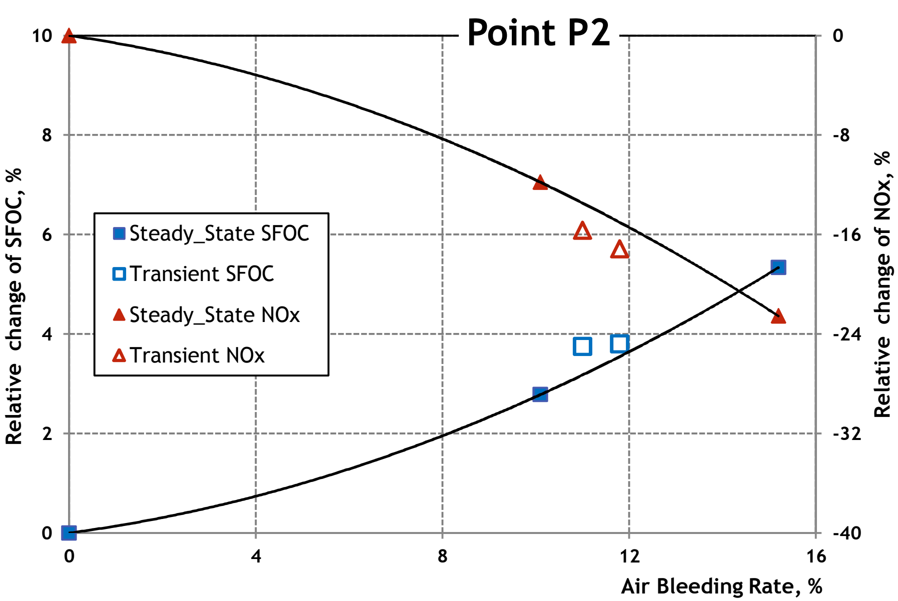
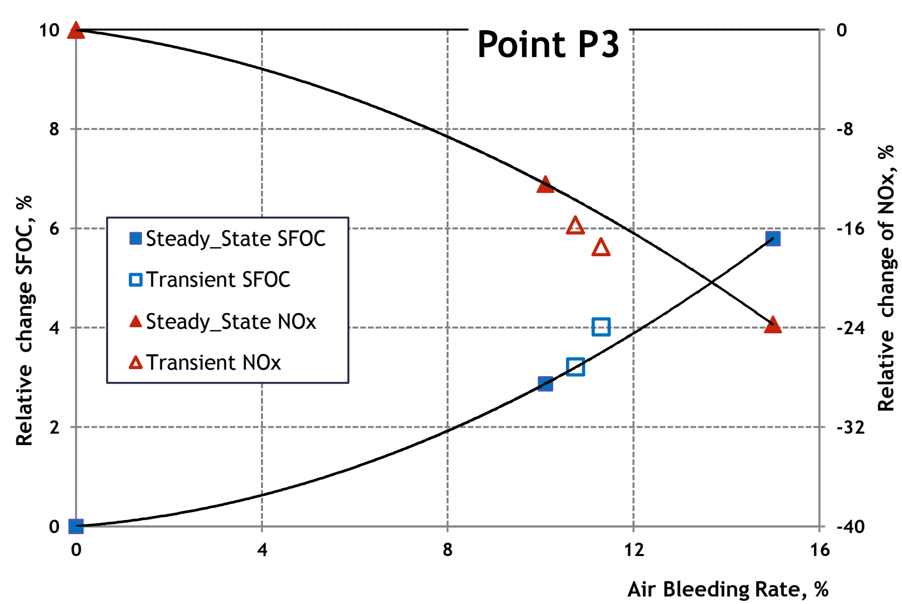


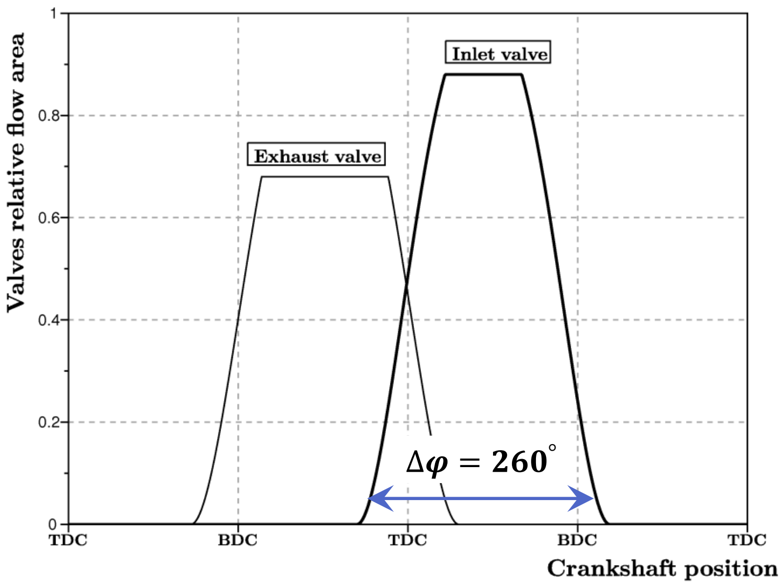






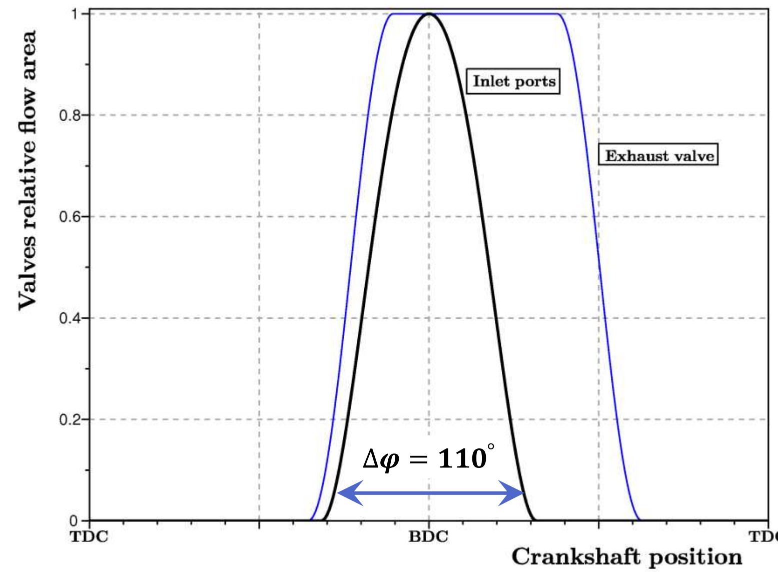
Engine Scavenging vs Fluctuating Air Supply

Scavenging duration of 4st Engine



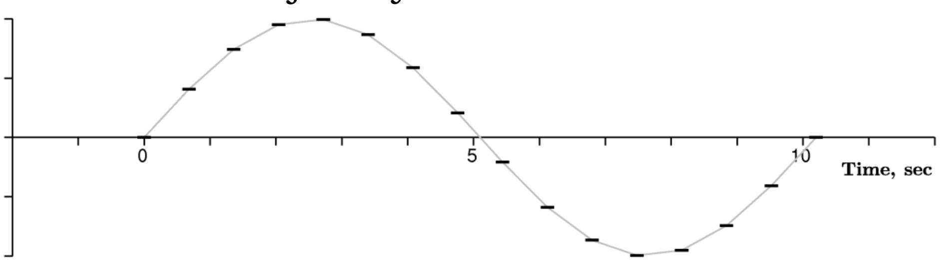
$$\Delta t = \frac{\Delta\varphi^{\circ}}{6\, n_e[rpm]} = \frac{260}{6\{910\sim970\}} = \{0.048\sim0.045\}sec$$

Scavenging duration of 2st Engine



$$\Delta t = \frac{\Delta\varphi^{\circ}}{6\, n_e[rpm]} = \frac{110}{6\{91\sim111\}} = \{0.200\sim0.165\}sec$$

Transient Trajectory



The transient trajectory is assumed to be made up of series of steady-state points as engine dynamics and, in particular scavenging process is much faster than fluctuation of air supply. This justifies quasi-steady approach for engine simulation.

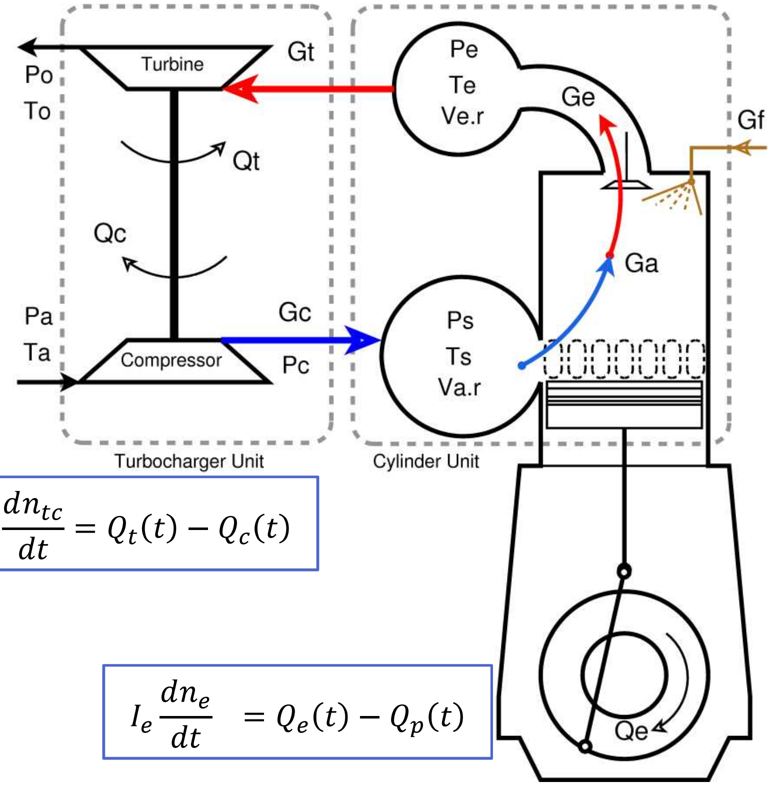
Quasi-Steady Modeling of 2st Diesel Engine

Engine Torque:

$$Q_e = Q_i - Q_{fr}$$

$$Q_i = \frac{z\, i\, V_s}{2\,\pi} \underbrace{\eta_c\, P_{i_0}\, h_p}_{P_{mep}} \qquad \because \eta_c = f\left(\frac{\dot{G}_a}{\dot{G}_f}\right)$$

$$Q_{fr} = \frac{z\, i\, V_s}{2\,\pi} 10^5 \left[k_{fr_2} \left(\frac{n_e}{N_{e_0}}\right)^2 + k_{fr_1} \left(\frac{n_e}{N_{e_0}}\right) + k_{fr_0} \right]$$



$$I_{tc} \frac{dn_{tc}}{dt} = Q_t(t) - Q_c(t)$$

$$I_e \frac{dn_e}{dt} = Q_e(t) - Q_p(t)$$

Compressor Torque:

$$Q_c = \frac{C_{p_{air}}\, T_a\, G_a}{2\,\pi\, n_{tc}\, \eta_{ic}} \left(\pi_c^{\frac{k_a - 1}{k_a}} - 1\right) \qquad \because \pi_c = \frac{P_c}{P_a}$$

Turbine Torque:

$$Q_T = \frac{C_{p_{exh}}\, T_e\, G_t\, \eta_{it}}{2\,\pi\, n_{tc}} \left(1 - \pi_T^{\frac{k_e - 1}{k_e}}\right) \qquad \because \pi_T = \frac{P_0}{P_e}$$

State Variables
n_e
n_{tc}

⇨

Thermodynamic Variables	
G_a,	G_t
P_e,	P_c
T_e,	T_s

Simplified Model for Thermodynamic Variables

Pressure speed relation of compressor:

$$\pi_c = \left\{\left[\pi_{c_0}^{\frac{k_a-1}{k_a}} - 1\right]\left(\frac{n_{tc}}{n_{tc_0}}\right)^2 + 1\right\}^{\frac{k_a}{k_a-1}}$$

Temperature after compressor:

$$T_c = T_a\left[\frac{1}{\eta_{ic}}\left(\pi_c^{\frac{k_a-1}{k_a}} - 1\right) + 1\right]$$

Charging air temperature :

$$T_s = T_{sw} + (T_c - T_{sw})\frac{T_{s_0} - T_{sw_0}}{T_{c_0} - T_{sw_0}}\left(\frac{G_a}{G_{a_0}}\right)^{\frac{1}{3}}$$

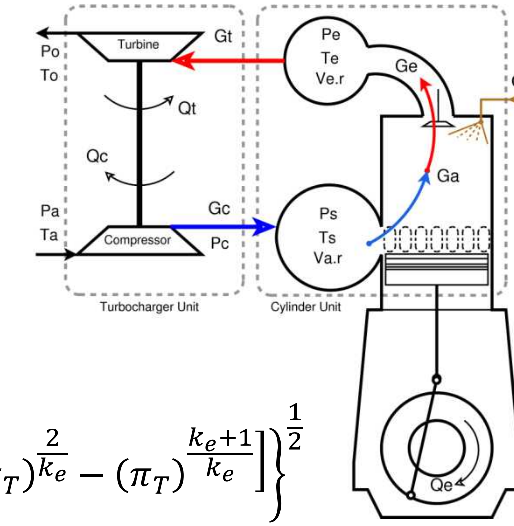
Scavenging Air flow:

$$G_a = \mu f_c \frac{P_s}{\sqrt{R_{air} T_s}}\left\{\frac{2\,k_a}{k_a - 1}\left[\left(\frac{P_e}{P_c}\right)^{\frac{2}{k_a}} - \left(\frac{P_e}{P_c}\right)^{\frac{k_a+1}{k_a}}\right]\right\}^{\frac{1}{2}}$$

Fuel flow:

$$G_f = z\, i\, g_{f_0} h_p \frac{N_e}{60} \qquad \therefore g_{f_0} - \mathit{fuel\ portion\ at\ MCR}$$

Air/Exh.Gas Receivers:



$$G_c \equiv G_a$$

$$G_t \equiv G_e$$

Exhaust Gas flow:

$$G_t = G_a + G_f =$$

$$= a_t \mu f_t \frac{P_e}{\sqrt{R_{exh} T_e}}\left\{\frac{2\,k_e}{k_e - 1}\left[(\pi_T)^{\frac{2}{k_e}} - (\pi_T)^{\frac{k_e+1}{k_e}}\right]\right\}^{\frac{1}{2}}$$

Gas flow correction:

$$a_t = k_{a_2}\left(\frac{P_0}{P_e}\right)^2 + k_{a_1}\left(\frac{P_0}{P_e}\right) + k_{a_0}$$

Energy balance:

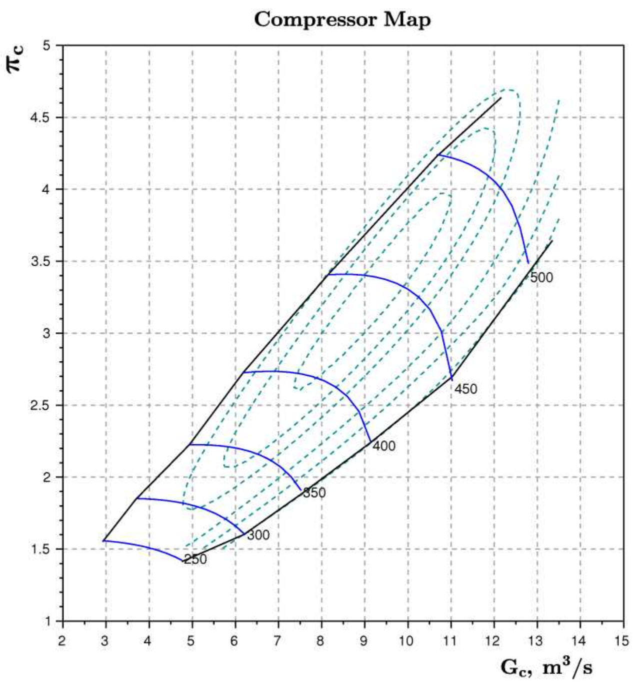
$$(G_a\, C_{p_{air}}\, T_s + G_f\, H_u \xi_a)\eta_{exh} = G_e\, C_{p_{exh}}\, T_e$$

Fraction of Fuel energy in Exh. Gas:

$$\xi_a = k_{\xi_1} P_{mep} + k_{\xi_0}$$

Details on empirical coefficients determination can be found in: “Development of Diesel Engine Simulator for Use with Self-Propulsion Model” Journal of the JIME, Vol.48, No5.

Full Model for Thermodynamic Variables

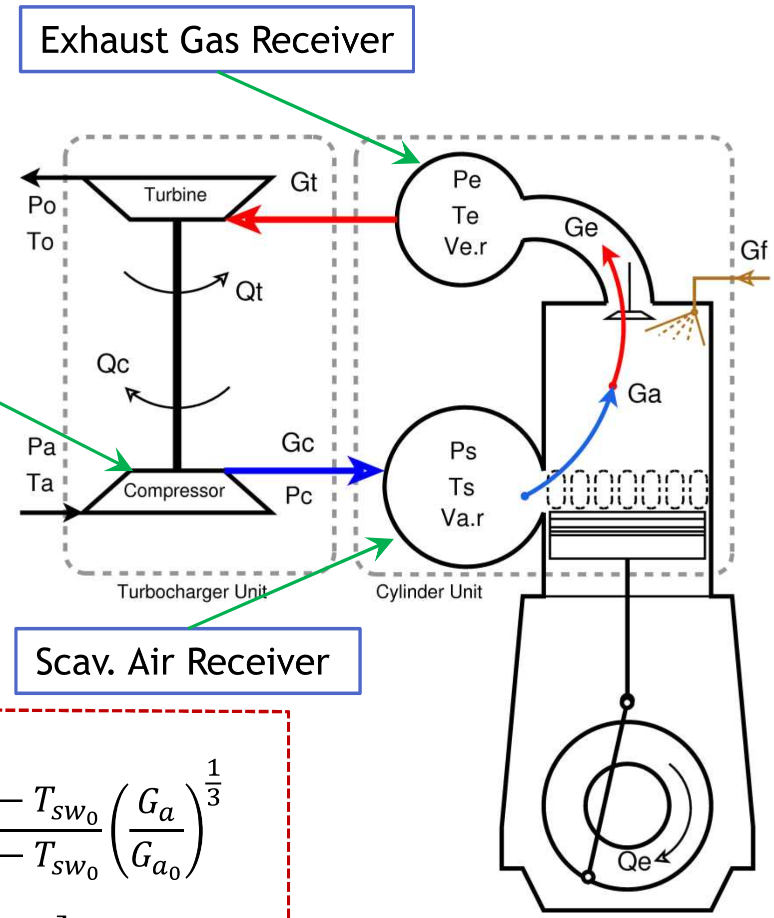


$$\frac{dT_e}{dt} = \frac{k_e}{m_{e.r}C_{p.e}}\left(G_aC_{p.a}T_s + G_fH_u\xi_a\right) - \frac{T_e}{m_{e.r}}\left(G_tk_e + \frac{dm_{e.r}}{dt}\right)$$

$$\frac{dm_{e.r}}{dt} = G_a + G_f - G_t$$

$$P_e = \frac{m_{e.r}R_eT_e}{V_{e.r}}$$

$$\begin{cases} G_c = f(\pi_c, n_{TC}) \\ \eta_{ic} = f(\pi_c, n_{TC}) \end{cases}$$



$$\frac{dP_s}{dt} = \frac{k_aR_aT_s}{V_{a.r}}(G_c - G_a)$$

$$T_s = T_{sw} + (T_c - T_{sw})\frac{T_{s_0} - T_{sw_0}}{T_{c_0} - T_{sw_0}}\left(\frac{G_a}{G_{a_0}}\right)^{\frac{1}{3}}$$

$$T_c = T_a\left[\frac{1}{\eta_{ic}}\left(\pi_c^{\frac{k_a-1}{k_a}} - 1\right) + 1\right]$$

Model Validation at Steady-State

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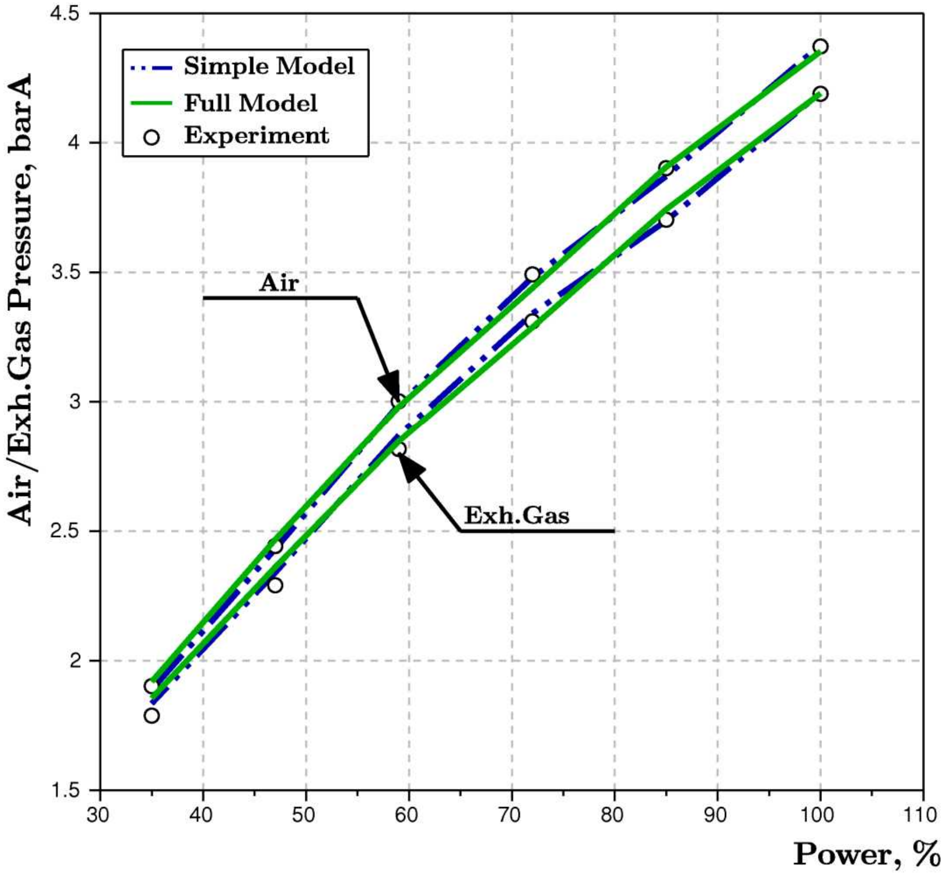
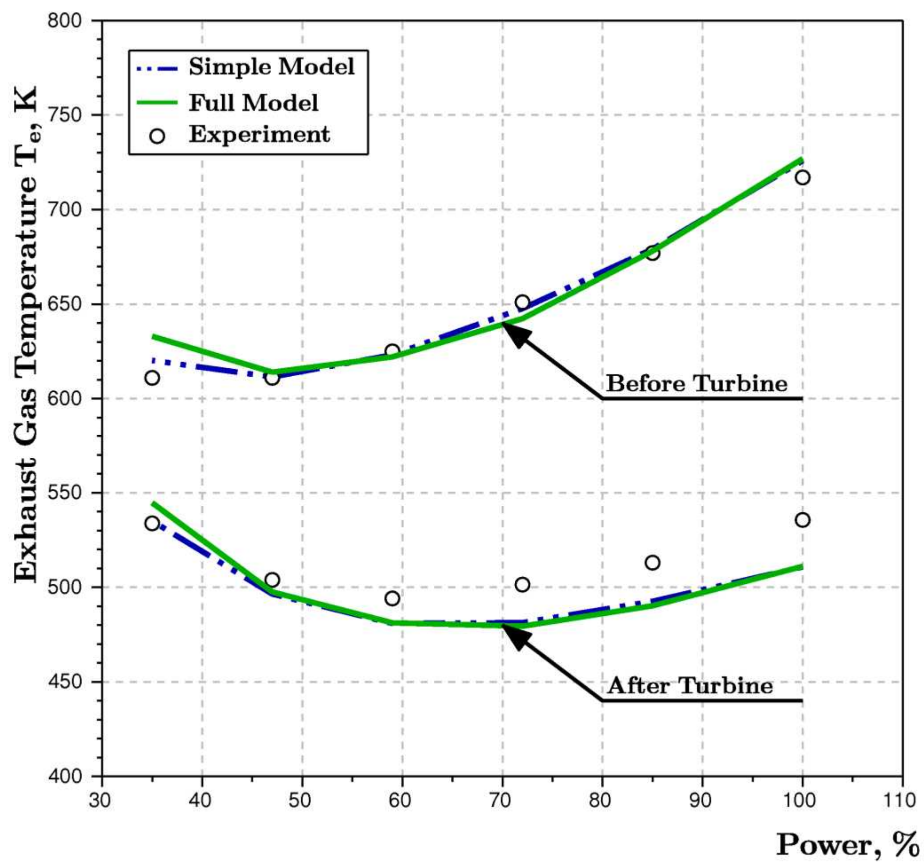
Air/Exh.Gas Receivers Pressure

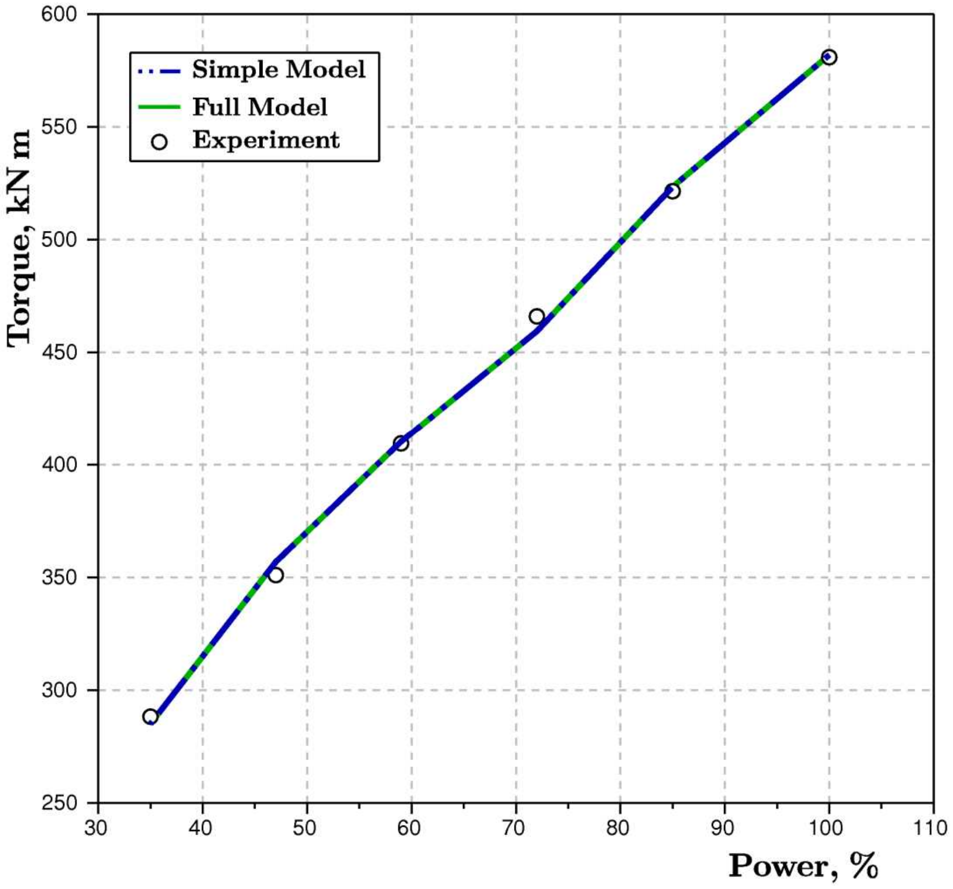


Exh.Gas Temperature at Turbine

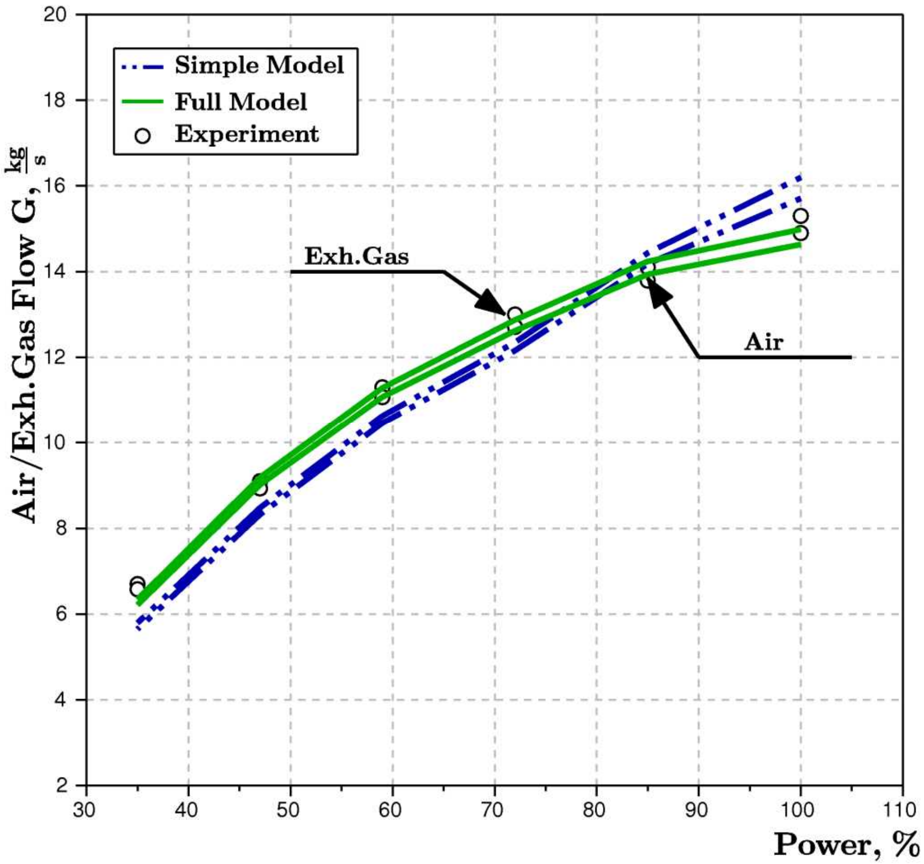


Model Validation at Steady-State

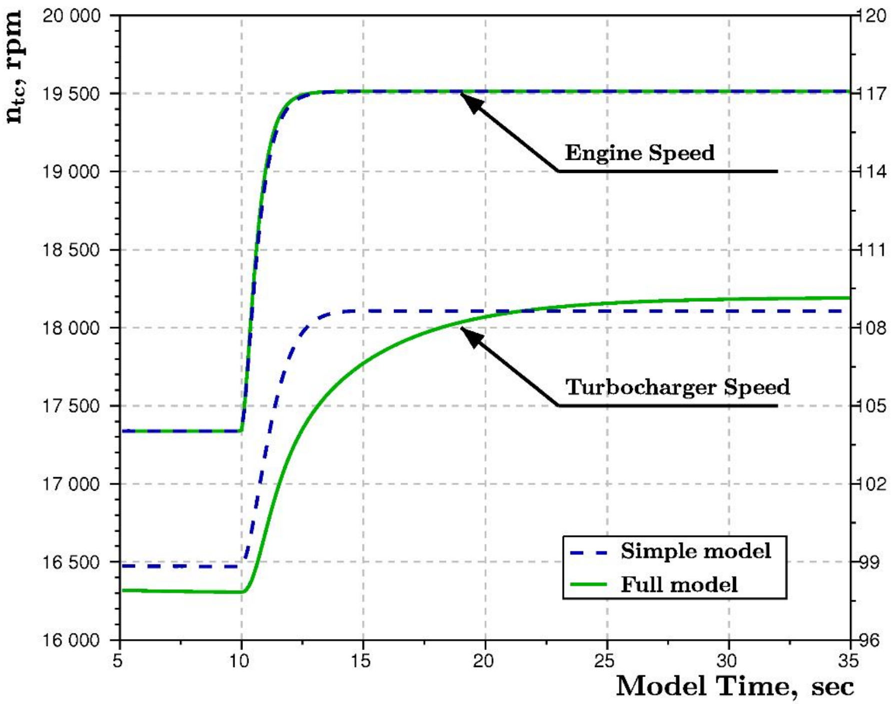
Engine Torque

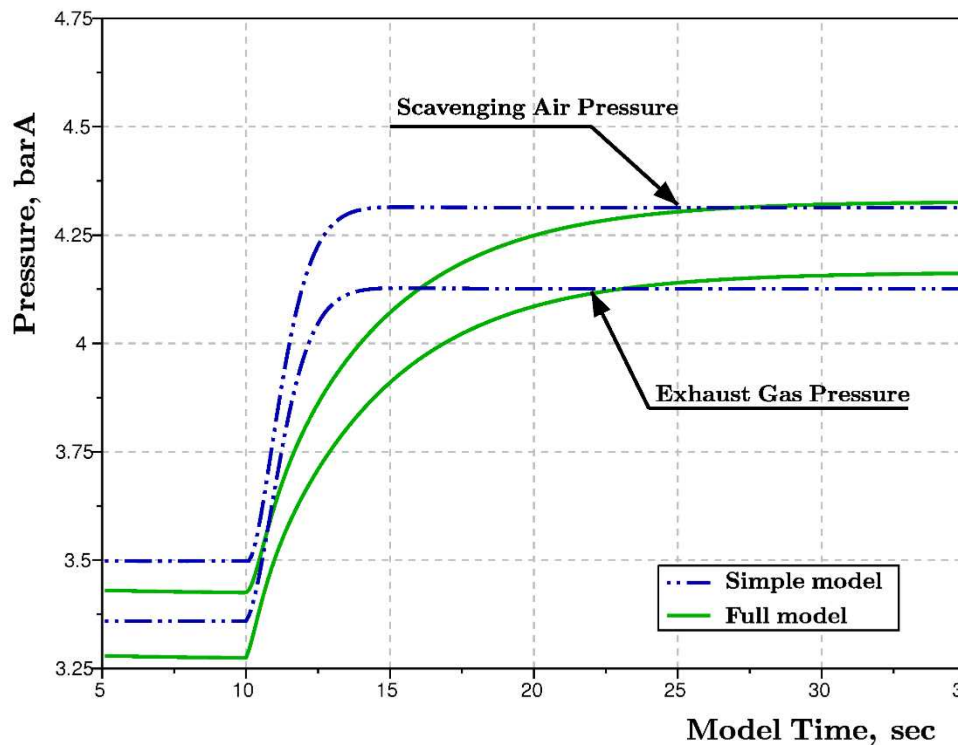


Air/Exh.Gas Flows



Transient Responses





Thermodynamic interconnection between engine combustion process and turbocharger air supply sub-system impose large delay on engine responses, this in turn affects propulsion engine operation in actual sea.

Concluding Remarks

1. The experiments on four-stroke and two-stroke engines revealed effect of scavenging air depletion on engine performance in both the steady-state and transient conditions.

2. As was found, the fluctuating air supply has a tiny effect only on two-stroke engine and no remarkable effect on four-stroke engine. This fact is explained by difference in scavenging processes and higher sensitivity of two-stroke engine to air supply.

3. Combustion process deterioration and resulted SFOC increase is rooted in average decrease of air to fuel ratio due to air supply sub-system delay.

4. Owing to fast engine dynamics with respect to external disturbance, propulsion engine operation can be simulated with quasi-steady approach including air and exhaust gas receivers.

Acknowledgement

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