ENGINEERING

BASIC THEORY

Thermodynamics (Basic heat technology)

Isothermal condition/ phase	$Pv = \text{constant}$	P	pressure	Pa
		v	volume	m^3
Adiabatic condition/ phase	$Pv^{\kappa} = \text{constant}$	κ	adiabatic index/ exponent	1
Polytropic condition/ phase	$Pv^{n} = \text{constant}$	n	polytropic index/ exponent	1
Equation of condition	$\frac{Pv}{T} = \text{constant}$	T	absolute temperature	K

Ideal processes

The Otto-process	$\eta_o = 1 - \frac{1}{\epsilon_n^{\kappa-1}}$	η_o	ideal thermodynamic efficiency	1
		ϵ_n	nominal degree of compression	1
Nominal degree of compression	$\epsilon_n = \frac{V_1}{V_2}$	V_1	cylinder-volume above piston in lower dead point	m^3
		V_2	cylinder-volume above piston in upper dead point	m^3
Diesel process	$\eta_o = 1 - \frac{1}{\epsilon_n^{\kappa-1}} \cdot \frac{\rho^{\kappa-1}}{\kappa(\rho-1)}$	ρ	volume condition during combustion	1
Adiabatic index	$\kappa = \frac{c_p}{c_v}$	c_p	specific heat capacity at constant pressure	J/kg · K
		c_y	specific heat capacity at constant volume	J/kg · K

Volume condition during combustion	$\Delta V = \frac{V_3}{V_2}$	ΔV	volume condition during combustion	1
		V_3	cylinder-volume above piston at the end of combustion	m^3

Real processes

Pressure of compression	$p_k = p_{s1}\, \epsilon^n$	p_k	pressure of compression	Pa
		p_{s1}	pressure at start of compression	Pa
		ϵ	degree of compression	1
		n	politrop index	1
Compression temperature	$T_k = T_{s1}\, \epsilon^{n-1}$	T_k	compression temperature	K
		T_{s1}	temperature at beginning of compression	K

Efficiency and fuel consumption

Ideal thermodynamic efficiency	$\eta_o = \frac{W_o}{Q_t}$	η_o	ideal thermodynamic efficiency	1
		W_o	thermo work	J
		Q_t	supplied heat	J
Indicated thermodynamic efficiency	$\eta_i = \frac{W_i}{Q_t} = \frac{P_i}{\dot{Q}_t} = \frac{P_i}{\dot{m}_B h_g} = \frac{1}{b_i h_g}$	η_i	indicated thermodynamic efficiency	1
		W_1	work developed in cylinder (indicated work)	J
		Q_t	supplied heat	J
		P_i	indicated effect	W
		$\dot{Q}_t$	supplied energy per time unit	J
		$\dot{m}_B$	fuel consumption	kg/s
		h_g	upper fuel value	J/kg
		b_i	indicated specific fuel consumption	kg/J
	$\eta_i = \eta_o\, \eta_g$	η_g	degree of goodness (inner efficiency)	1

Effective thermodynamic efficiency	$\eta_e = \frac{W_e}{Q_t} = \frac{P_e}{\dot{Q}_t} = \frac{P_e}{\dot{m}_B h_g} = \frac{1}{b_e h_g}$	η_e	effective thermodynamic efficiency	1
		W_e	work supplied to motor shaft/axis (axis work)	J
		p_e	shaft/axis effect	W
		b_e	effective specific fuel consumption	kg/J
	$\eta_e = \eta_i \eta_m$	η_m	mechanic efficiency	1
Degree of goodness	$\eta_g = \frac{W_i}{W_o}$	η_g	degree of goodness	1
		W_o	thermodynamic work	J
Mechanical efficiency of engine	$\eta_m = \frac{W_e}{W_i} = \frac{P_e}{P_i}$	η_m	mechanical efficiency of engine	1
Propeller shaft mechanical efficiency	$\eta_a = \frac{W_p}{W_e} = \frac{P_p}{P_e}$	η_a	propeller shaft mechanical efficiency	1
		W_p	propeller work	J
		W_e	shaft work	J
		P_p	propeller effect	W
Fuel consumption	$b_i = \frac{\dot{m}_B}{P_i}$	b_i	indicated specific fuel consumption	kg/J
	$b_e = \frac{\dot{m}_B}{P_e}$	b_e	effective specific fuel consumption	kg/J

Effect and mean pressure

Stroke volume per cylinder (displacement per cylinder)	$V_h = \frac{\pi D^2}{4} S$	V_h	stroke volume per cylinder	m^3
		D	diameter of cylinder (bore)	m
		S	stroke	m

Indicated effect of a two-stroke engine	$P_i = i W_i n_a = i V_h p_{mi} n$	P_i	indicated effect	W
		i	number of cylinders	1
		W_i	indicated work	J
		n_a	number of work processes per second and per cylinder	s^{-1}
		p_{mi}	indicated mean pressure	Pa
		n	frequency of rotation	s^{-1}
		$n_a = n$ for a two-stroke engine		
Indicated effect of a four-stroke engine	$P_i = i W_i n_a = i V_h p_{mi} \frac{n}{2}$	$n_a = {}^{n}/_{2}$ for a four-stroke engine		
Indicated mean pressure	$p_{mi} = \frac{W_i}{V_h}$	p_{mi}	indicated mean pressure	Pa

$$\boxed{p_{mi} = \frac{\text{area of } pV\text{-diagram in mm}^2}{\text{length of } pV\text{-diagram in mm}} \quad \text{(scale factor of pressure shaft)}}$$

Shaft effect of two-stroke engine	$P_e = i W_e n_a = i V_h p_{me} n$	P_e	shaft effect	W
		W_e	shaft work	J
		P_{me}	effective mean pressure	Pa
		$n_a = n$ for two-stroke engine		
	$P_e = P_i \eta_m$	η_m	mechanic efficiency of engine	1
Shaft effect of four-stroke engine	$P_e = i W_e n_a = i V_h p_{me} \frac{n}{2}$ $P_e = P_i \eta_m$	$n_a = {}^{n}/_{2}$ for four-stroke engine		

Equation for effective mean pressure

$$p_{me} = \frac{\rho_i h_g}{(L/B)_r} \quad \frac{\eta_m \eta_i \gamma_f}{\lambda_f}$$

P_{me}	effective mean pressure	Pa
ρ_i	density of dry air outside engine	kg/m^3
h_g	oil's heating value	J/kg
$(L/B)_r$	reaction equivalent mixture of air and fuel	kg/kg
η_i	indicated thermo efficiency	1
γ_f	degree of air-filling of cylinder	1
λ_f	air factor related to air filling of cylinder	1

$$p_{me} = \eta_m p_{mi}$$

p_{mi}	indicated mean pressure	Pa

$$T = \frac{P_e}{\omega} = \frac{P_e}{2\pi n}$$

Torque moment

T	torque moment	Nm
ω	angle velocity	rad/s

Mean piston velocity

$$c_{ms} = 2 S n$$

c_{ms}	mean piston velocity	m/s
S	length of stroke	m

COMBUSTION

Theoretic air demand

$$v_{Lr} = \frac{22.4}{0.21} \left(\frac{c}{12} + \frac{h}{4} + \frac{s}{32} \right)$$

v_{Lr}	theoretic need for air	$\frac{\text{Nm}^3 \text{ air}}{\text{kg fuel}}$

Nm^3 – normal cubic meter – not SI-unit

c	mass of carbon	kg
h	mass of hydrogen	kg
s	mass of sulfur	kg

$$(L/B)_r = 1.293 \cdot \frac{22.4}{0.21} \left(\frac{c}{12} + \frac{h}{4} + \frac{s}{32} \right)$$

$(L/B)_r$	theoretic need of air	$\frac{\text{kg air}}{\text{kg fuel}}$

Real air usage

$$L/B = \lambda \, (L/B)_r$$

L/B	real air usage	$\frac{\text{kg air}}{\text{kg fuel}}$
λ	air factor related to air usage	1

Specific air usage

$$l_e = b_e\,\lambda\,(L/B)_r$$

l_e	specific air usage	kg air/J
b_e	specific fuel usage	kg/J

Engine's air usage

$$\dot{m}_L = P_e\,l_e = P_e\,b_e\,\lambda\,(L/B)_r$$

$\dot{m}_L$	air usage of engine	kg/s
P_e	shaft effect	W

$$\dot{m}_L = \dot{m}_B\,\lambda\,(L/B)_r$$

$\dot{m}_B$	fuel usage	kg/s

$$\dot{m}_L = \gamma_L\,i\,V_h\,\rho_i\,n_a$$

γ_L	degree of air usage	1
i	number of cylinders	1
V_h	displacement per cylinder	m^3
ρ_i	air density outside	kg/m^3
n_a	number of work processes per second	s^{-1}

Exhaust gases

$$V_{CO_2} = \frac{22.4\,(c/12)\cdot 100}{22.4\,(c/12) + v_{Lr}\,(\lambda - 0.21)}$$

V_{CO_2}	volume % CO_2 (efficiency CO_2) in dry exhaust	%
c	mass of carbon	kg

$$V_{O_2} = \frac{0.21\,v_{Lr}\,(\lambda - 1)\cdot 100}{22.4\,(c/12) + v_{Lr}\,(\lambda - 0.21)}$$

V_{O_2}	volume % O_2 (efficiency O_2) in dry exhaust	%

$$V_{N_2} = \frac{0.79\,v_{Lr}\,\lambda\cdot 100}{22.4\,(c/12) + v_{Lr}\,(\lambda - 0.21)}$$

V_{N_2}	volume % N_2 (efficiency N_2) in dry exhaust	%

Air factor

$$\lambda = \frac{22.4\,(c/12)\,(100 - V_{CO_2})}{V_{CO_2}\,v_{Lr}} + 0.21$$

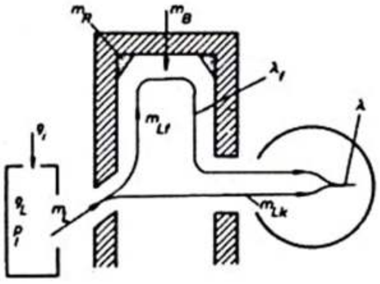
λ	air factor related to air usage	1

GAS CHANGING IN TWO-STROKE ENGINES

Degree of air usage

$$\gamma_L = \frac{m_L}{m_{Lt}}$$

$$m_{Lt} = \rho_i\,V_h$$

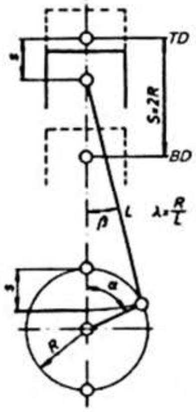


γ_L	degree of air usage	1
m_L	quantity of air used	kg
m_{Lt}	theoretic quantity of air filling	kg
ρ_i	density of suctioned air	kg/m^3
V_h	displacement (stroke volume)	m^3

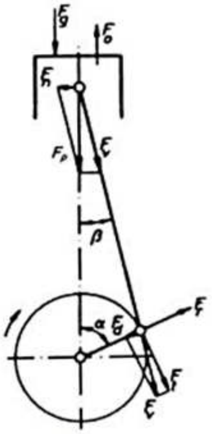
Degree of air filling	$\gamma_f = \frac{m_{Lf}}{m_{Lt}} = \gamma_L \; (1 - \gamma_k)$	γ_f	degree of air filling	1
		m_{Lf}	quantity of air filled/ suctioned	kg
		γ_k	degree of short circuit	1
Degree of scavenging air	$\gamma_R = \frac{m_{Lf}}{(m_{Lf} + m_R)}$	γ_R	degree of scavenging air	1
		m_R	quantity of residual gasses	kg
Air factor related to air filling	$\lambda_f = \lambda \; (1 - \gamma_k)$	λ_f	air factor related to air filling	1
		λ	air factor related to air usage	1
Degree of short circuit	$\gamma_k = \frac{m_{Lk}}{m_L}$	γ_k	degree of short circuit	1
		m_{LK}	loss owing to short circuit + expelling	kg
	$m_L = m_{Lf} + m_{Lk}$	m_L	quantity of air usage	kg

ENGINE DYNAMICS

Crank-operation



Connecting rod ratio	$\lambda = \frac{R}{L}$	λ	connecting rod ratio	1
		R	crank radius	m
		L	length of connecting rod	m
Length of stroke	$s = R \; (1 - \cos\alpha + \frac{\lambda}{2} \sin^2\alpha)$	s	length of stroke	m
		α	angle of crank	rad
Piston velocity	$c = R \; \omega \; (\sin\alpha + \frac{\lambda}{2} \sin 2\alpha)$	c	piston velocity	m/s
		ω	angle velocity of crank	rad/s
Piston acceleration	$a = R\omega^2 \; (\cos\alpha + \lambda \cos 2\alpha)$	a	piston acceleration	m/s^2
Piston acceleration in top and bottom dead centers	$a_{TD} = R\omega^2 \; (1 + \lambda)$	a_{TD}	piston acceleration in top dead center	m/s^2
	$a_{BD} = -R\omega^2 \; (1 - \lambda)$	a_{BD}	piston acceleration in bottom dead center	m/s^2



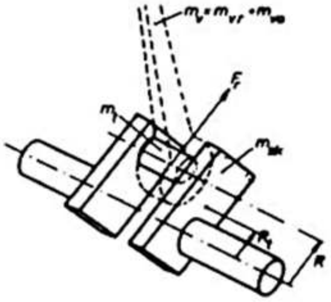
Oscillating force	$F_o = (m_s + m_{vo})\, a$	F_o m_s m_{vo}	oscillating force mass of whole piston oscillating part of mass of connecting rod	N kg kg
Gas force	$F_g = \frac{\pi d^2}{4}\, p$	F_g d p	gas force piston diameter difference of pressure on upper and lower side of piston	N m Pa
Piston force	$F_p = F_g + F_o$	F_p	piston force	N
Normal force	$F_n = F_s \operatorname{tg} \beta$	F_n β	normal force angle of connecting rod	N rad
Connecting rod force	$F_v = \frac{F_p}{\cos \beta}$	F_v	connecting rod force	N
Tangential force	$F_t = F_v \sin(\alpha + \beta)$ $F_t = \frac{F_p \sin(\alpha + \beta)}{\cos \beta}$	F_t	tangential force	N
Work per revolution	$W_i = F_{tm}\, 2\pi R$	W_i F_{tm}	work mean tangential force	J N
Mean indicated torque	$T_i = F_{tm} R$	T_i	torque	N · m
Radial force	$F_d = F_v \cos(\alpha + \beta)$	F_d	radial force	N
Rotating force	$F_r = m_r R\, \omega^2$	F_r m_r	rotating force mass of crank journals/pin + mass of counter-weights related to crank radius + rotating part of connecting rod mass m_{vr}	N kg

Mass forces in a one-cylinder engine

Rotating mass forces

$$F_r = m_{vr} R \omega^2 + m_t R \omega^2 + 2 m_{sk} R_t \omega^2$$

F_r	rotating mass forces	N
m_{vr}	rotating mass part of connecting rod	kg
R	crank radius	m
ω	angle of velocity	rad/s
m_t	mass of the crankshaft pin	kg
m_{sk}	mass of the crank counterweight	kg
R_t	the radius of the center of gravity of the counterweight	m



$$F_r = m_r R \omega^2$$

$$m_r = m_{vr} + m_t + 2 m_{sk} \frac{R_t}{R}$$

m_r	mass of crankshaft/ journal pin + mass of counter-weights related to crank radius + rotating part of connecting rod mass m_{vr}	kg

Oscillating mass forces

$$F_o = m_o R \omega^2 \ (\cos\alpha + \lambda \cos 2\alpha)$$

F_o	oscillating mass forces	N
m_o	total oscillating mass	kg
α	angle of crank	rad
λ	connecting rod ratio	1

$$m_o = m_p + m_{vo}$$

m_p	mass of complete piston	kg
m_{vo}	oscillating mass of connecting rod	kg

$$F_{01} = m_o R \omega^2 \cos\alpha$$

F_{01}	mass forces of first order	N

$$F_{02} = \lambda m_o R \omega^2 \cos 2\alpha$$

F_{02}	mass forces of second order	N

Centrifugal force of counter weights

$$F_k = F_r + \frac{1}{2} F_{01\,\mathrm{maximum}}$$

F_k	counter weights' centrifugal force	

Two counter weights

$$2 m_k R_k \omega^2 = m_r R \omega^2 + \frac{1}{2} m_o R \omega^2$$

m_k	mass per counter weight	kg
R_k	point of gravity radius	m
m_r	rotating mass	kg
m_o	oscillating mass	kg

Torque swings

Swing frequency

$$f_{n1} = \frac{1}{2\pi}\sqrt{\frac{G\,I_p}{L}\cdot\frac{I_1 + I_2}{I_1 \cdot I_2}}$$

f_{n1}	frequency	Hz
G	shearing module of shaft	N/m^2
I_p	polar inertia moment of shaft	m^4
L	shaft length	m
I_1	inertia moment of flywheels	kg/m^2
I_2	inertia moment of flywheels	kg/m^2

Plane pressure in bearings

$$p = \frac{\frac{\pi}{4} d_v^2 \cdot p_f}{D_v L_{ve}}$$

p	bearing pressure	Pa
d_v	cylinder diameter	m
p_f	maximum combustion pressure	Pa
D_v	diameter of bearing journal	m
L_{ve}	effective bearing length (with deduction for eventual grease tracks)	m

PROPULSION IN WATER

Effect needed

Propulsion effect (towing effect)

$$P_E = F_T v$$

P_E	propulsion effect	W
F_T	propulsion resistance	N
v	ship velocity	m/s

Pushing power/force

$$F_p = F_T + F_M$$

F_p	pushing force	N
F_M	additional resistance from propeller	N

Propeller's delivered effect (pushing effect)

$$P_s = F_s v_r$$

P_s	pushing effect	W
v_r	propeller's velocity in propulsion direction related to water	m/s

$$\textbf{current coefficient} = \frac{v - v_r}{v}$$

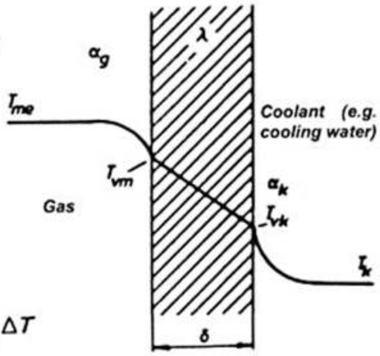
v_r	relative velocity of propeller	

Current coefficient 0.20 – 0.25

Propeller efficiency	$\eta_p = \frac{P_s}{P_p}$	η_p	propeller efficiency	1
		P_p	effect supplied to propeller	W
Propulsion efficiency	$\eta_f = \frac{P_E}{P_p} = \frac{P_E}{P_s} \frac{P_s}{P_p} = \eta_{sg} \eta_p$	η_f	propulsion efficiency	1
		η_{sg}	shape of hull (degree of goodness of hull)	1
	$\eta_{sg} = \frac{P_E}{P_s}$			
Shaft mechanical efficiency	$\eta_a = \frac{P_p}{P_e}$	η_a	shaft mechanical efficiency	1
		P_e	shaft effect from engine	W
Ship's theoretical speed	$v_t = s\, n_p$	v_t	ship's theoretical velocity	m/s
		s	propeller thread/ rise	m
		η_p	propeller rotating frequency	s^{-1}
Slip	$\text{slip} = \frac{(v_t - v)\, 100}{v_t}$			
	$P_e = P_e^* \left(\frac{n}{n^*}\right)^3 = P_e^* \left(\frac{v}{v^*}\right)^3$	P_e	shaft effect	W
		p_e^*	shaft effect at normal operation	W
		n	rotation frequency	s^{-1}
		n^*	rotation frequency at normal operation	s^{-1}
		v^*	velocity at normal operation	m/s
	$P_e = \Delta^{\frac{2}{3}} \frac{v^3}{A}$	Δ	displacement	ton
		A	admiralty constant	

HEAT TRANSFER AND HEAT LOAD

Heat flow $\dot{Q} = \alpha_g A \, \Delta T$



$\dot{Q}$	heat flow	J/s = W
α_g	heat transfer coefficient	$W/(m^2 \cdot K)$
A	area to which heat is transferred	m^2
ΔT	temperature difference between gas and surface material	K

Heat flux $\dot{q} = \frac{\dot{Q}}{A} = \alpha_g \, \Delta T$

$\dot{q}$	heat flux (density of heat flow)	

Eichelberg's formula $\alpha_g = 2.1 \sqrt{pT} \, \sqrt[3]{c_{ms}}$

α_g	heat transfer coefficient	$kcal/m^2h$
	Eichelberg's formula is based on the technical system.	
p	absolute gas pressure	kp/cm^2
T	gas temperature	K
c_{ms}	mean piston velocity	m/s

One-dimensional transfer $\dot{q}_m = \frac{\lambda}{\delta} \left(T_{vm} - T_{vk} \right)$

$\dot{q}_m$	mean heat flux	W/m^2
λ	thermo conductivity	$W/(m^2 \cdot K)$
δ	material thickness	m
T_{vm}	mean wall temperature on gas side	K
T_{vk}	mean wall temperature on refrigerant side	K

$\dot{q}_m = \alpha_k \left(T_{vk} - T_k \right)$

α_k	heat transfer coefficient	$W/(m^3 \cdot K)$
T_k	refrigerant temperature	K

Heat transfer through wall $\dot{q}_m = k \left(T_{me} - T_k \right)$

k	heat transfer coefficient	$W/(m^3 \cdot K)$
T_{me}	mean effective gas temperature	K

Heat transfer coefficient

$$\frac{1}{k} = \frac{1}{\alpha_{gm}} + \frac{\delta}{\lambda} + \frac{1}{\alpha_k}$$

α_k	heat transfer coefficient gas-surface	$W/(m^2 \cdot K)$
α_k	heat transfer coefficient material-refrigerant	$W/(m^2 \cdot K)$

Any boiler scale shall be added $\frac{\delta_{ks}}{\lambda_{ks}}$.

AUXILIARY SYSTEMS

Cooling water system

Necessary quantity of cooling water

$$\dot{v} = \frac{\Sigma r_k}{\Delta T_{tot}\ c\ \rho\ \eta_e}$$

$\dot{v}$	specific cooling water quantity	m^3/J
Σr_k	heat quantity transferred in cooler, in percentage of supplied energy	%
ΔT_{tot}	temperature difference	K
c	specific heat capacity	$J/(kg \cdot K)$
ρ	density	kg/m^3
η_e	effective thermo efficiency	1

$$\dot{v} = \frac{\Sigma r_k\ \dot{m}_B\ h}{\Delta T_{tot}\ c \rho P_e}$$

$\dot{m}_B$	fuel consumption	kg/s
h	calorific value	J/kg

$$\dot{V} = \dot{v}\ P_e$$

$\dot{V}$	water quantity	m^3/s
P_e	shaft efficiency	W

Freshwater coolers

Heat flow

$$\dot{Q} = r_{kf}\,\dot{m}_B\,h = r_{kf}\,h\,b_e\,P_e = r_{kf}\,\frac{P_e}{\eta_e}$$

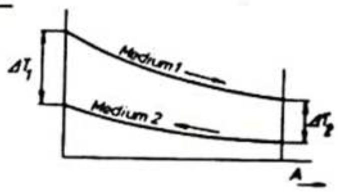
$\dot{Q}$	heat flow	J/s = W
r_{kf}	heat quantity carried off in freshwater coolers in percentage of supplied energy	%
$\dot{m}_B$	fuel consumption	kg/s
h	calorific value	J/kg
b_e	effective specific fuel consumption	kg/J
p_e	shaft efficiency	W
η_e	effective thermo efficiency	1

$$\dot{Q} = k\,A\,\Delta T$$

k	heat transfer coefficient	$W/(m^2 \cdot K)$
A	cooling area	m^2
ΔT	logarithmic mean temperature difference	K

Logarithmic mean temperature difference

$$\Delta T = \frac{\Delta T_1 - \Delta T_2}{\ln\dfrac{\Delta T_1}{\Delta T_2}}$$



ΔT	logarithmic mean temperature difference	K
ΔT_1	temperature difference	K
ΔT_2	temperature difference	K

Lubricating coolers

Heat flow

$$\dot{Q} = r_{ks}\,\dot{m}_B\,h = r_{ks}\,h\,b_e\,P_e = r_{ks}\,\frac{P_e}{\eta_e}$$

$\dot{Q}$	heat flow	J/s = W
r_{ks}	transferred heat quantity in lubricating coolers in percentage of supplied energy	%
P_e	shaft effect	W

Effect needed for lubricating pump

$$P = \frac{\Delta p\,\dot{V}}{\eta} = \frac{\Delta p\,\dot{v}\,P_e}{\eta}$$

P	effect needed	W
Δp	increased pressure in pump	Pa
$\dot{V}$	oil quantity	m^3/s
η	pump efficiency	1
$\dot{v}$	oil quantity	m^3/J