Topics #6 & #3

Mechanical Design, Exhaust Heat Recovery, Friction and Materials

- Engine Stretch Efficiency Colloquium
- Southfield, MI
- March 3 2010

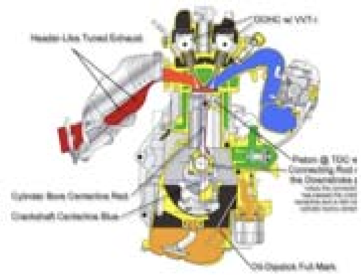
- John M. Clarke

Two thoughts:

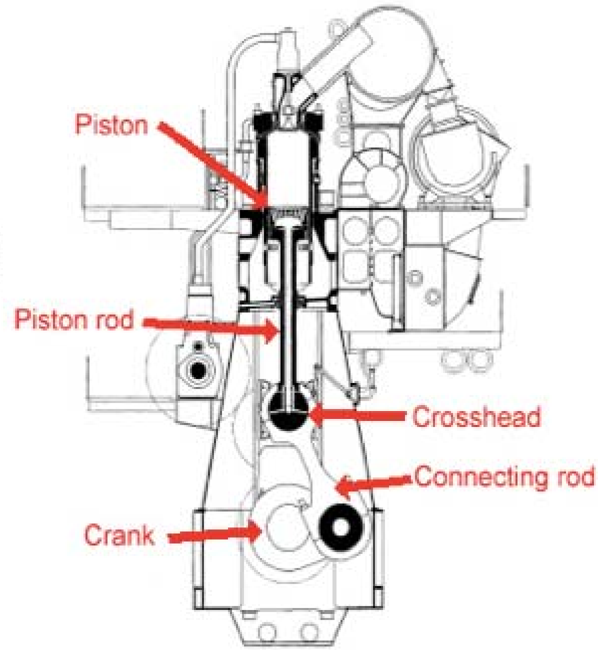
- Neither the design fundamentals nor the efficiencies of our SI and CI engines have changed much in 40 years
- Stupidity: doing the same thing and expecting a different result

Model

Prius

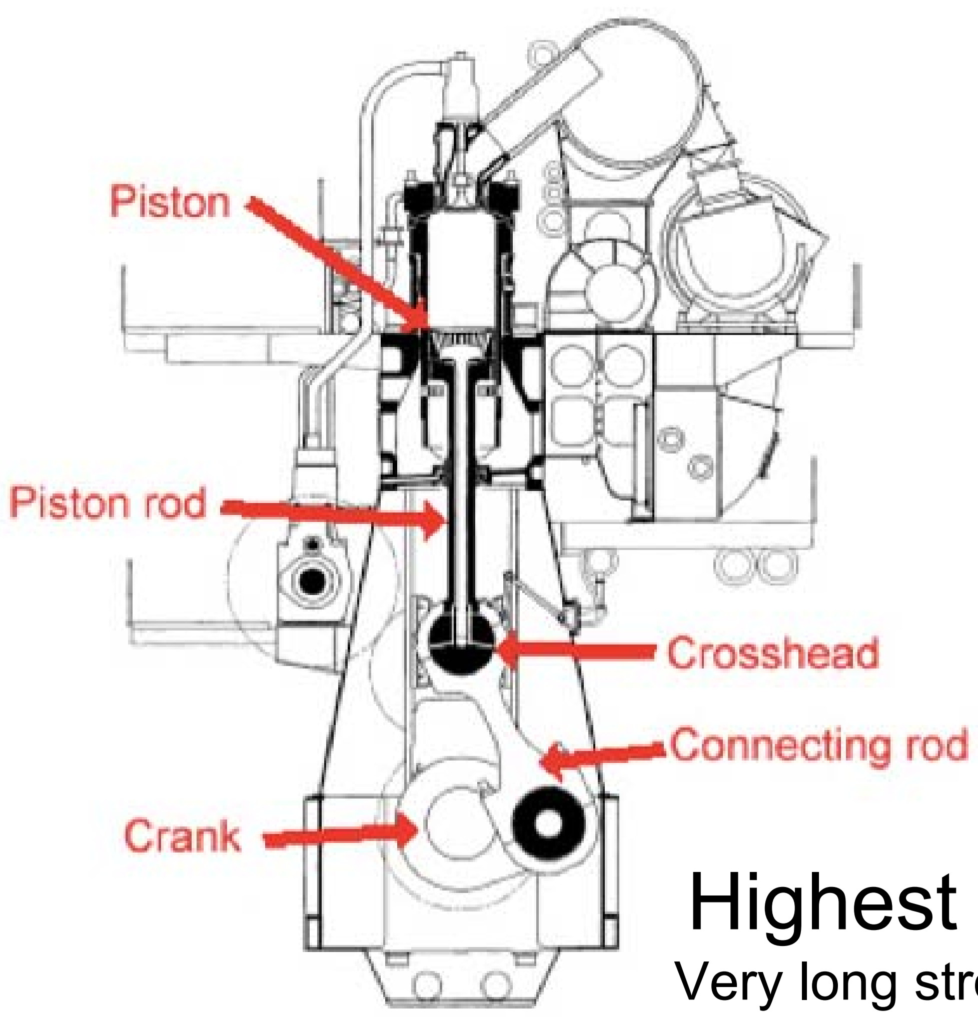


Marine



Power, kW	0.37	73	81000
Mean Piston Speed, m/s	9.3	15 (6 at best efficiency)	8.5
Power/Piston Area, MW/m^2	1.8	3.6	7.9 (turbo 2-stroke)

Across all engine sizes mean piston speed is similar.
Hence engine power is proportional to piston area.
But engine height is proportional to stroke.



Highest efficiency because:

Very long stroke - good combustion shape
Low speed crank - less bearing friction
Efficient large turbocharger
Water cooled intercooler
Direct propellor drive - no transmission

For scaled engines Power $\propto D^2$ but Engine Volume $\propto D^3$
eliminating the dimension (size) yields

$$\frac{\text{Power}}{(\text{Engine Volume})^{2/3}} \text{ is constant}$$

More specifically for scaled 4-stroke engines:

$$\frac{\text{Power}}{(\text{Displacement})^{2/3}} = \frac{P\, V_p\, C^{1/3}}{S^{2/3}}$$

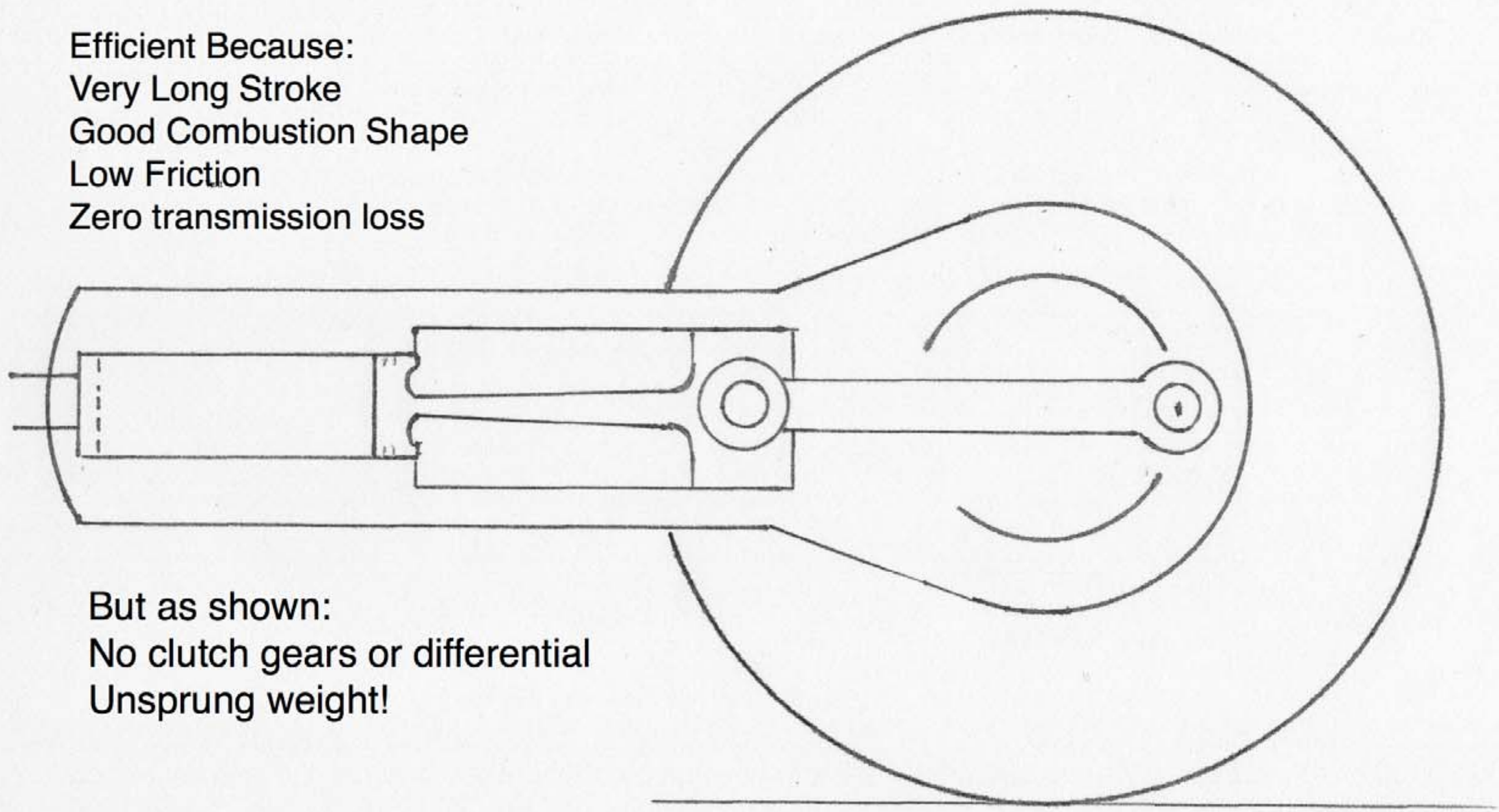
where

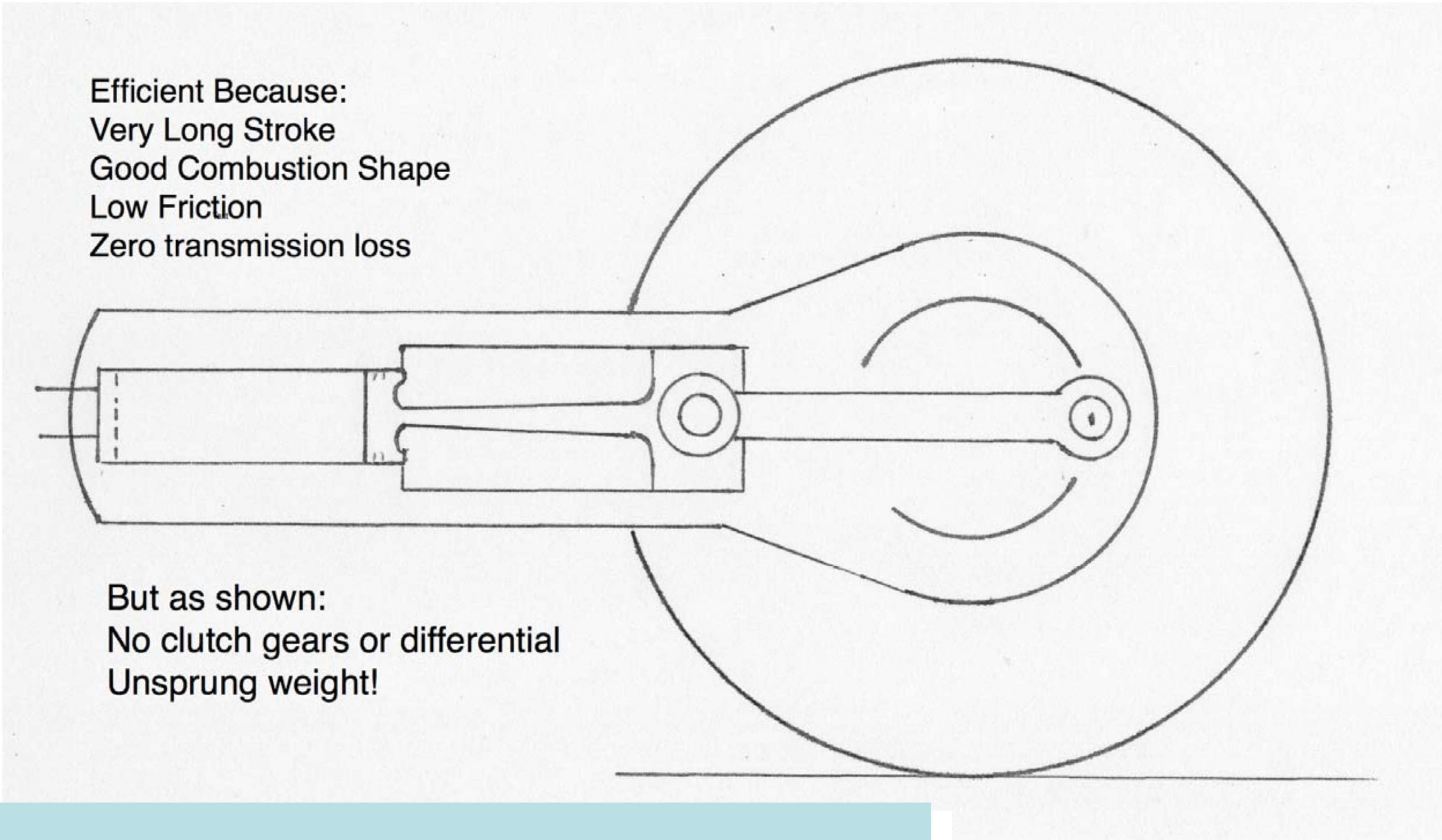
P is a coefficient proportional to BMEP with dimensions of pressure
V_p is mean piston speed
C is the number of cylinders
S is the Stroke / Bore ratio.

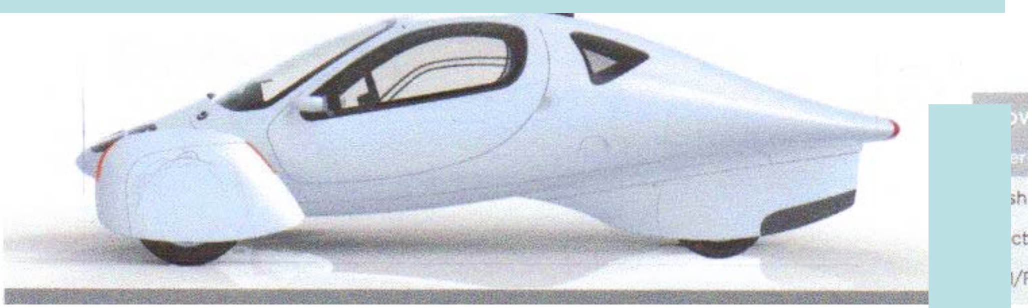
$$P = \frac{1}{4}\left(\frac{\pi}{4}\right)^{1/3} \eta_{brake}\, \eta_{vol}\, \rho_{in}\, \text{FAR LHV}$$

where

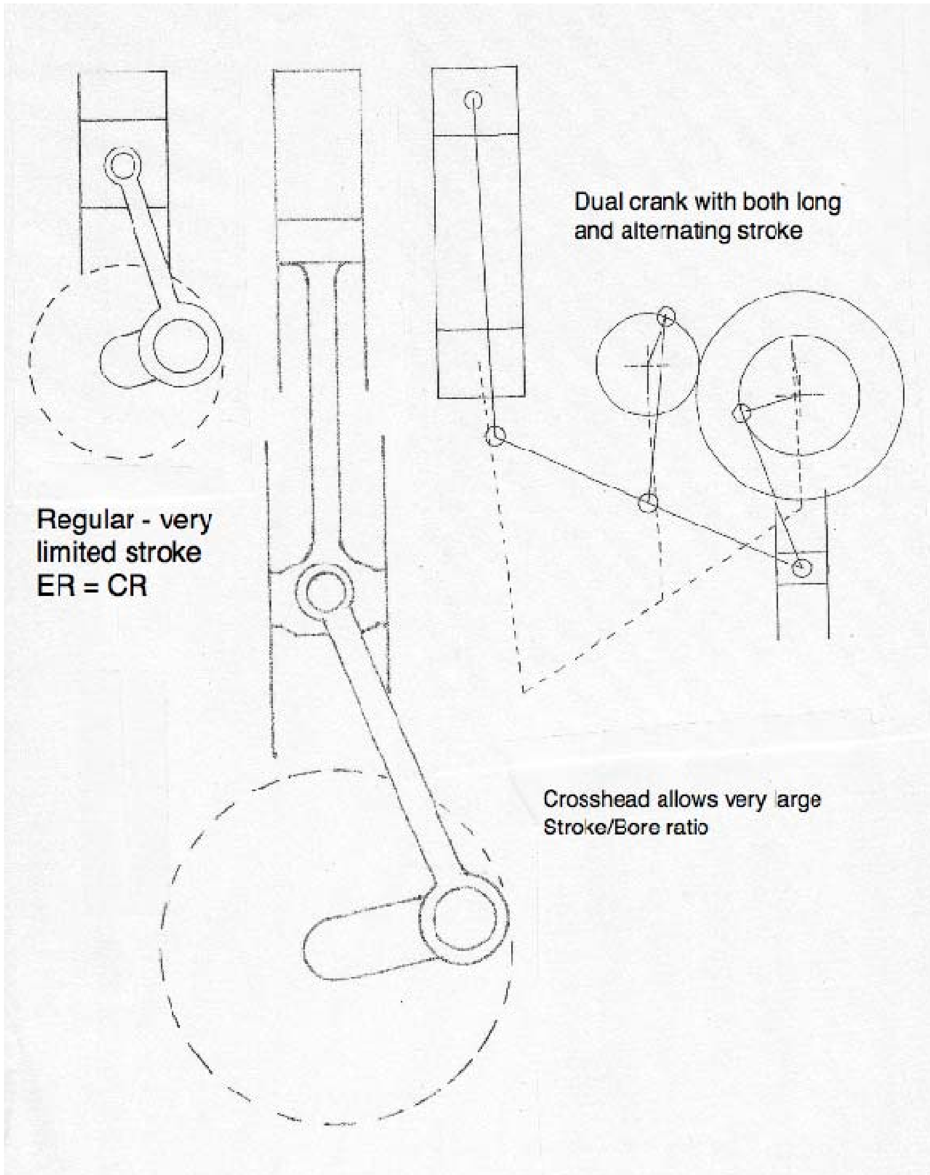
η_{brake} is brake thermal efficiency
η_{vol} is volumetric efficiency
ρ_{in} is inlet air density
FAR is fuel / air mass ratio
LHV is fuel lower heating value


Efficient Because:
Very Long Stroke
Good Combustion Shape
Low Friction
Zero transmission loss
But as shown:
No clutch gears or differential
Unsprung weight!



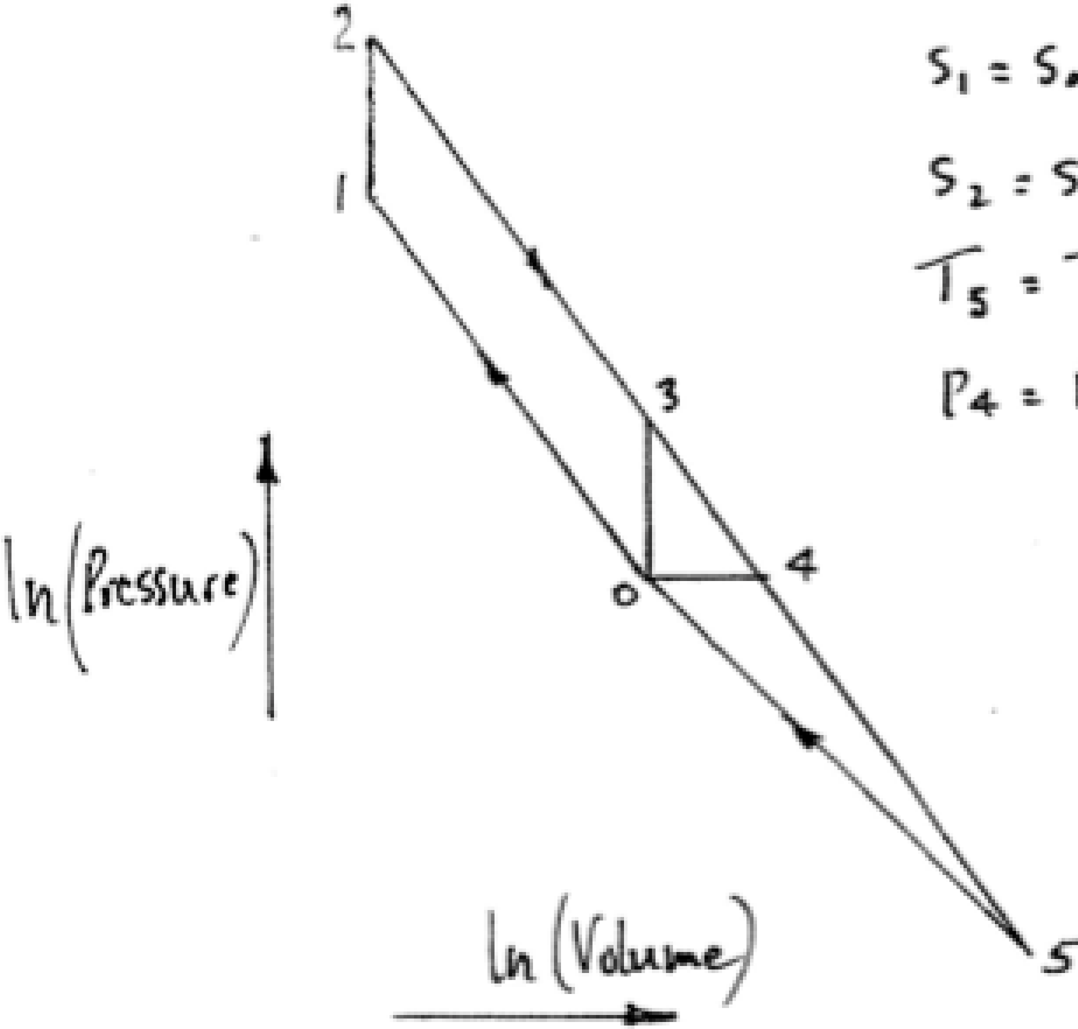


No differential!


Regular - very
limited stroke
ER = CR
Dual crank with both long
and alternating stroke
Crosshead allows very large
Stroke/Bore ratio

The comments in this talk relate to engine **shape** not size. They apply to all sizes.

Cycles……….



$S_1 = S_0$

$S_2 = S_3 = S_4 = S_5$

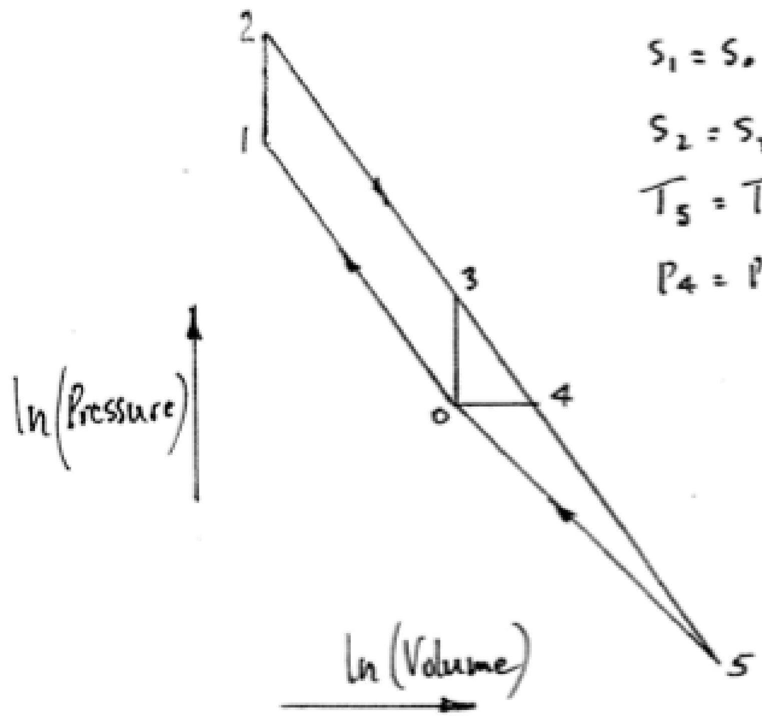
$T_5 = T_0$

$P_4 = P_0$

$c = \frac{T_1}{T_0}$

$h = \frac{T_2}{T_1}$

Formula for Efficiency of 3 Important Cycles



$s_1 = s_0$

$s_2 = s_3 = s_4 = s_5$

$T_5 = T_0$

$P_4 = P_0$

$c = \dfrac{T_1}{T_0}$

$h = \dfrac{T_2}{T_1}$

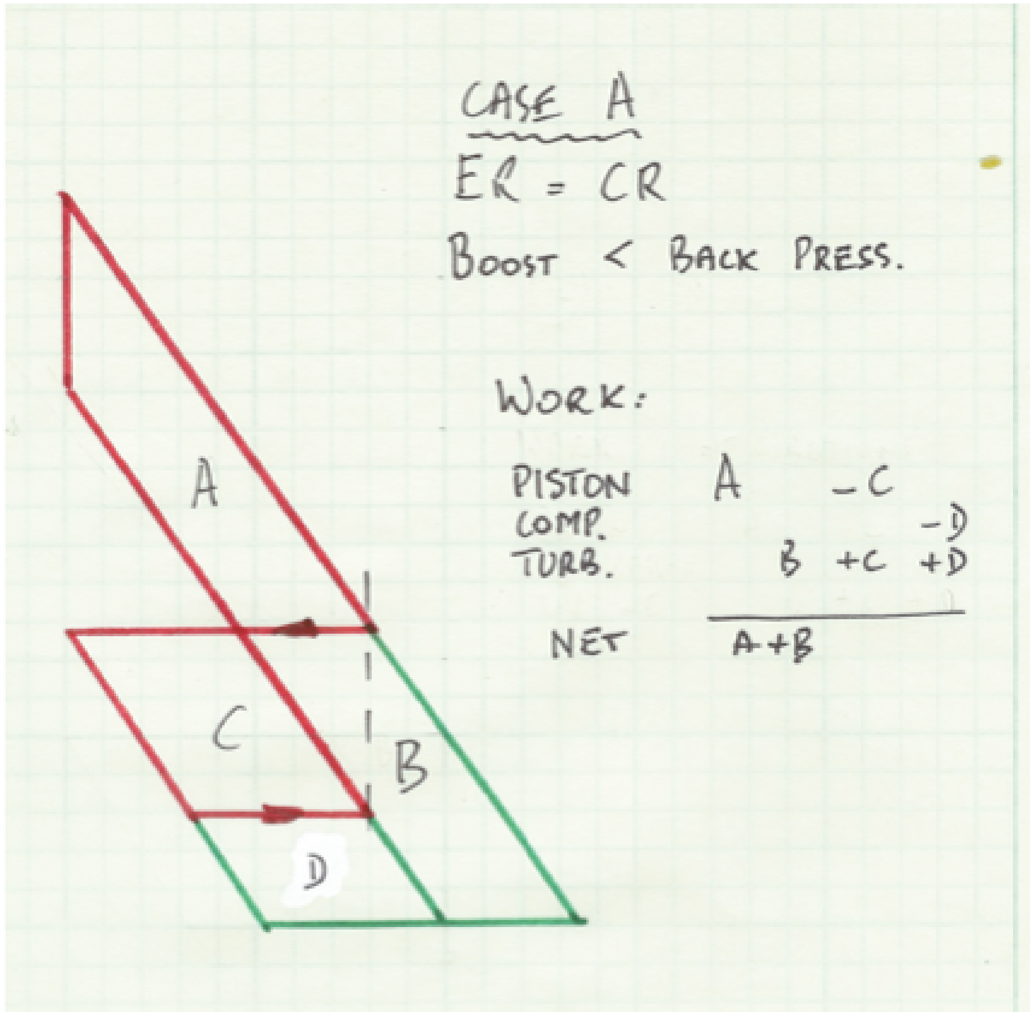
$$\text{Efficiency} = 1 - \frac{1}{c}\left\{ \frac{\ln(h)}{h-1} + \left(1 - \frac{\gamma\left(h^{1/\gamma}-1\right)}{h-1}\right) + \left(\frac{\gamma\left(h^{1/\gamma}-1\right) - \ln(h)}{h-1}\right) \right\}$$

COMBUSTION BLOWDOWN EXH. HEAT

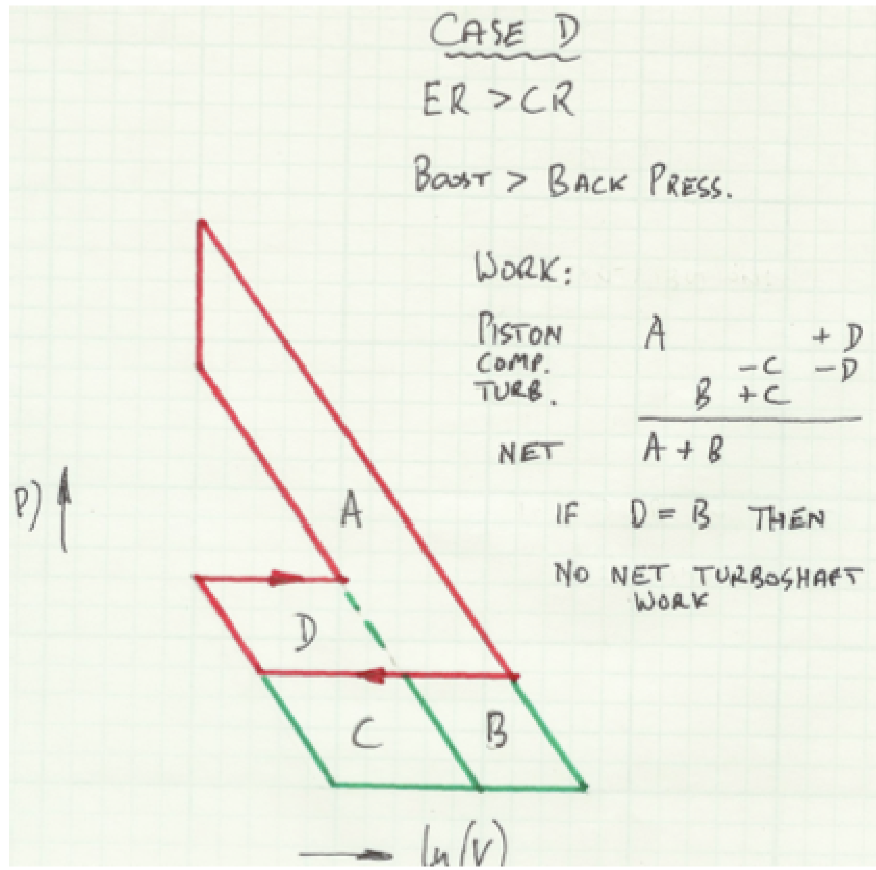
e.g. $h = 3$ $\{ 0.549 + 0.166 + 0.285 \}$

$\gamma = 7/$[illegible] $h = 5$ $\{ 0.402 + 0.245 + 0.353 \}$

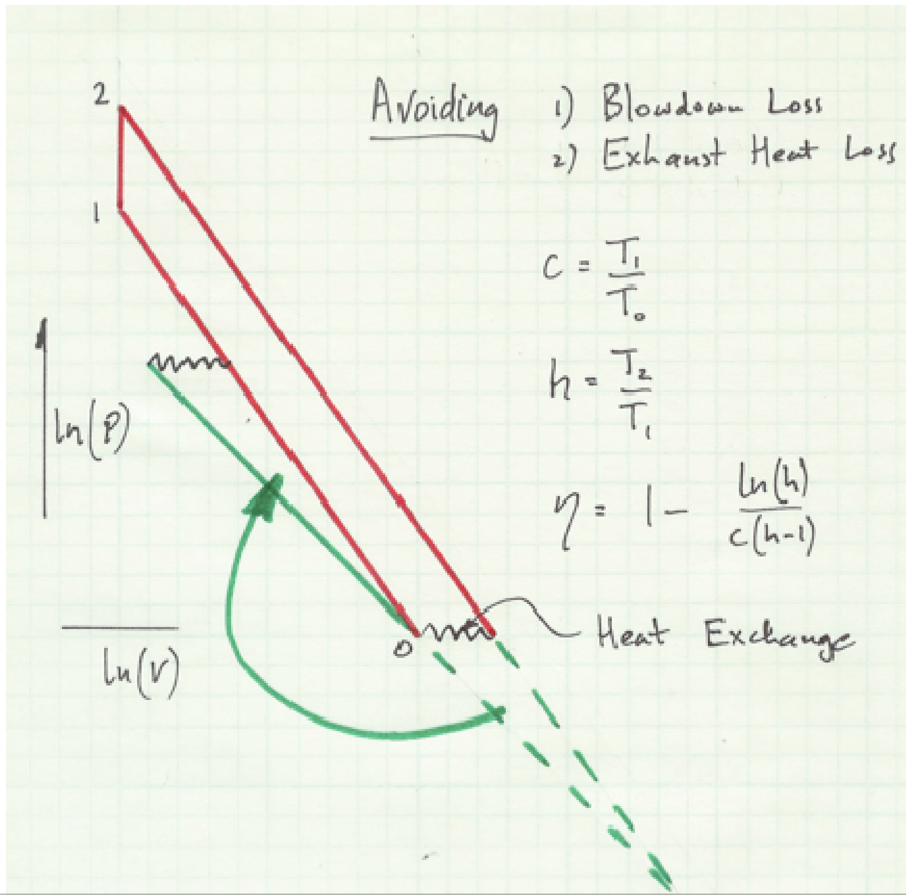
Turbocompound



Compressor and Turbine Work Balance



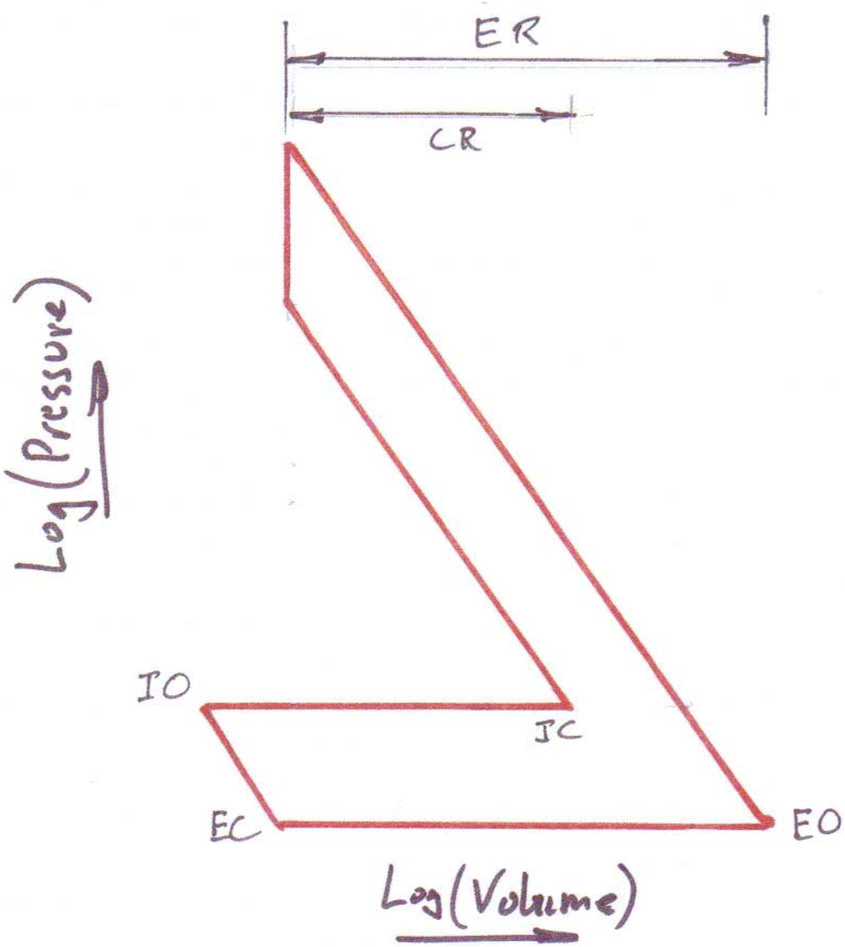
Exhaust heat recovery could be merged with all the cases



	Efficiency ,%	Compress'n Ratio	Expans'n Ratio
Otto	70	20	20
Diesel	74	44	44
Atkinson	75	20	44
Brayton	78	44	97
Extreme Expansion	85	6	97
Carnot	90		

All these **ideal** cycles have the same maximum pressure and temperature.
Pmax=20 MPa, Tmax=3000 K.

Generalized 4-stroke cylinder process



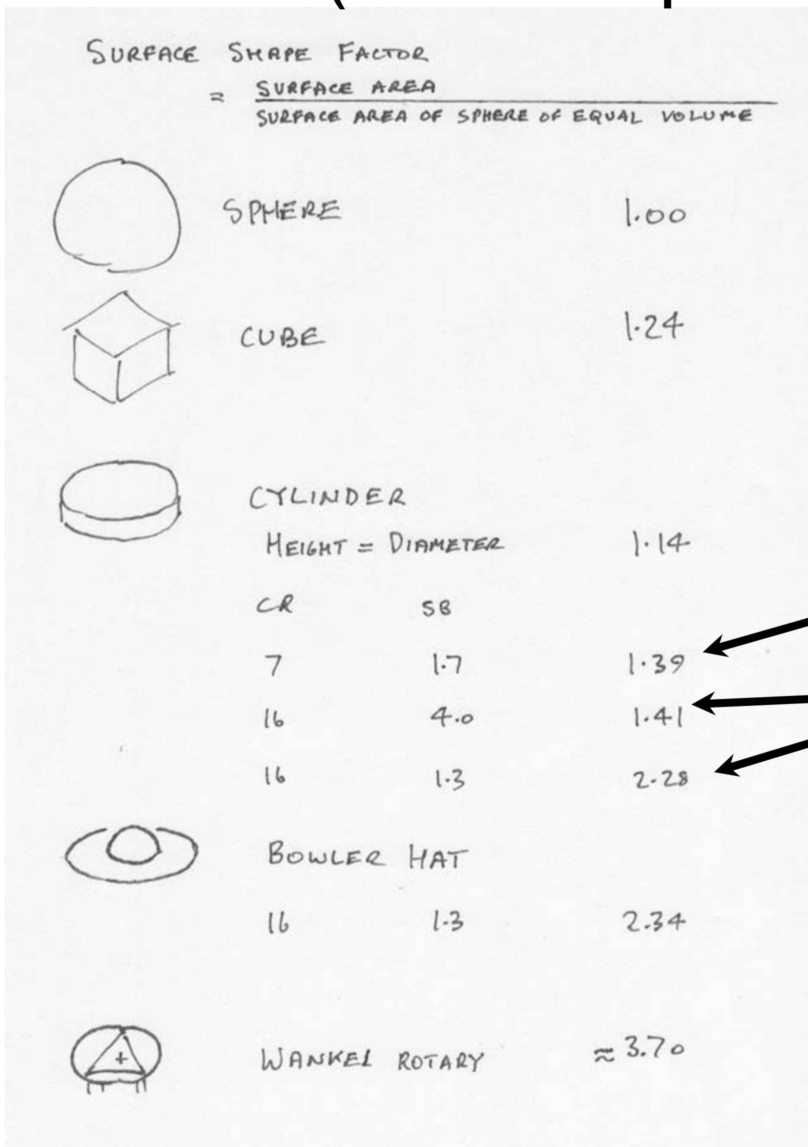
Heat Loss Comments

It is often asserted that the heat loss is dependent on the surface/volume ratio of the combustion chamber.

I dislike the use of this parameter - numerically it is size and unit dependent. When applied over a range of engine sizes it yields nonsense.
It ignores the role of time.

Instead I recommend.......

Surface shape factor
=area/(area of sphere of equal volume)



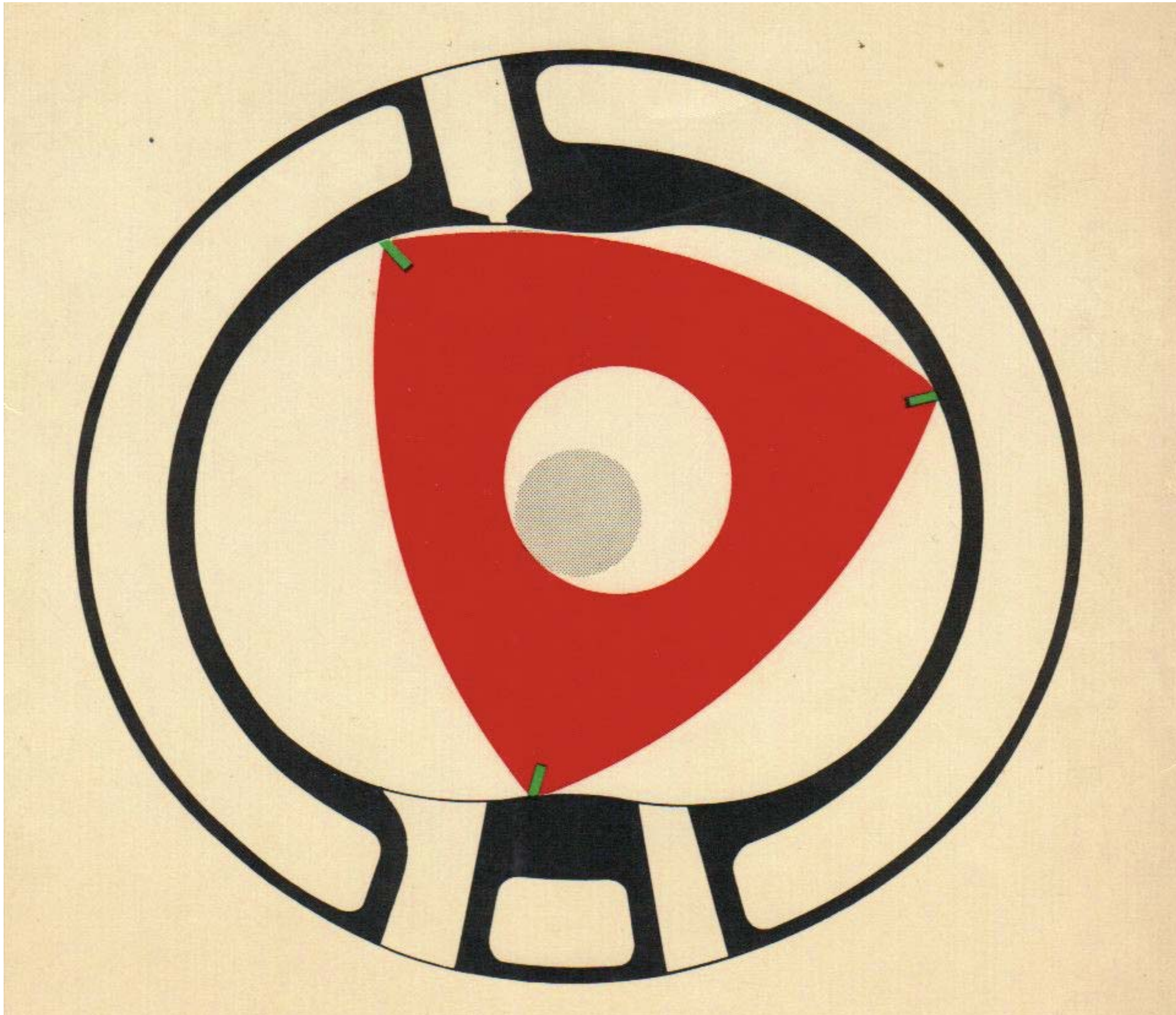
SURFACE SHAPE FACTOR

$$= \frac{\text{SURFACE AREA}}{\text{SURFACE AREA OF SPHERE OF EQUAL VOLUME}}$$

SPHERE		1.00
CUBE		1.24
CYLINDER		
HEIGHT = DIAMETER		1.14
CR	SB	
7	1.7	1.39
16	4.0	1.41
16	1.3	2.28
BOWLER HAT		
16	1.3	2.34
WANKEL ROTARY		≈ 3.70

Marine

Regular



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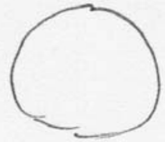
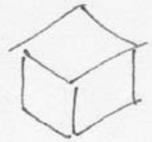


SPHERE 1.00



CUBE 1.24

CYLINDER

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WANKEL ROTARY ≈ 3.70

Heat Loss During Combustion

Heat transferred at high temperature to the walls of the combustion chamber is a major loss to the system performance. The following analysis not reproduced here suggests the dependence of this loss on geometry, maximum cylinder pressure and compression ratio.

$$\frac{\text{Heat Transferred}}{\text{Fuel Energy Released}} \propto \frac{A_{cc}}{A_p} \frac{P_{max} \arccos\left(1 - \frac{1}{CR-1}\right)}{\rho_{in} \eta_{vol} \text{ FAR LHV}}$$

where

$\frac{A_{cc}}{A_p}$ = Combustion Chamber Surface Area / Piston Area

P_{max} = Maximum Cylinder Pressure

CR = Compression Ratio

(this influences the time available for combustion within the cycle)

ρ_{in} = Inlet Air Density

η_{vol} = Volumetric Efficiency

FAR = Fuel / Air mass ratio

LHV = Fuel Lower Heating Value

"Back of the envelope" analysis for vehicle surface cooling potential

Analysis suggests that vehicle surfaces can provide sufficient cooling effect and so often avoid the drag associated with radiators.

Cooling should be sufficient at steady speeds on level road below

$$V = \sqrt{\frac{c_p A_h \Delta T}{K A_f N}}$$

where

c_p is specific heat of air

A_h / A_f is the heat rejection area / drag surface area

ΔT is the air to surface temperature difference

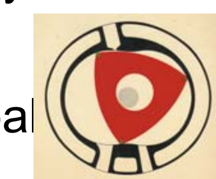
K is the ratio of heat rejection to power at the wheels

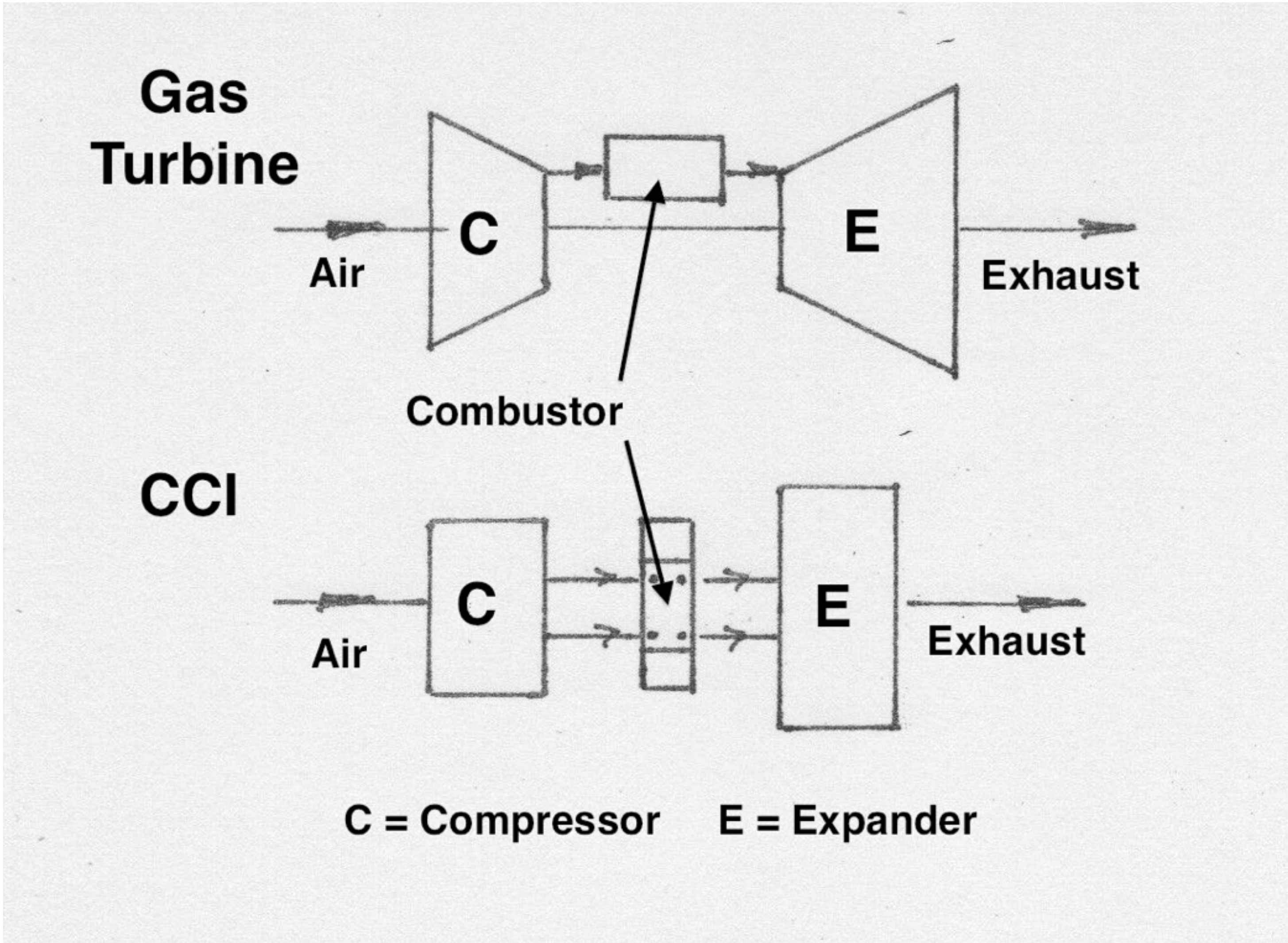
N is a dimensionless number related to Reynolds' s analogy ($\tau c_p / hV$) of order 2

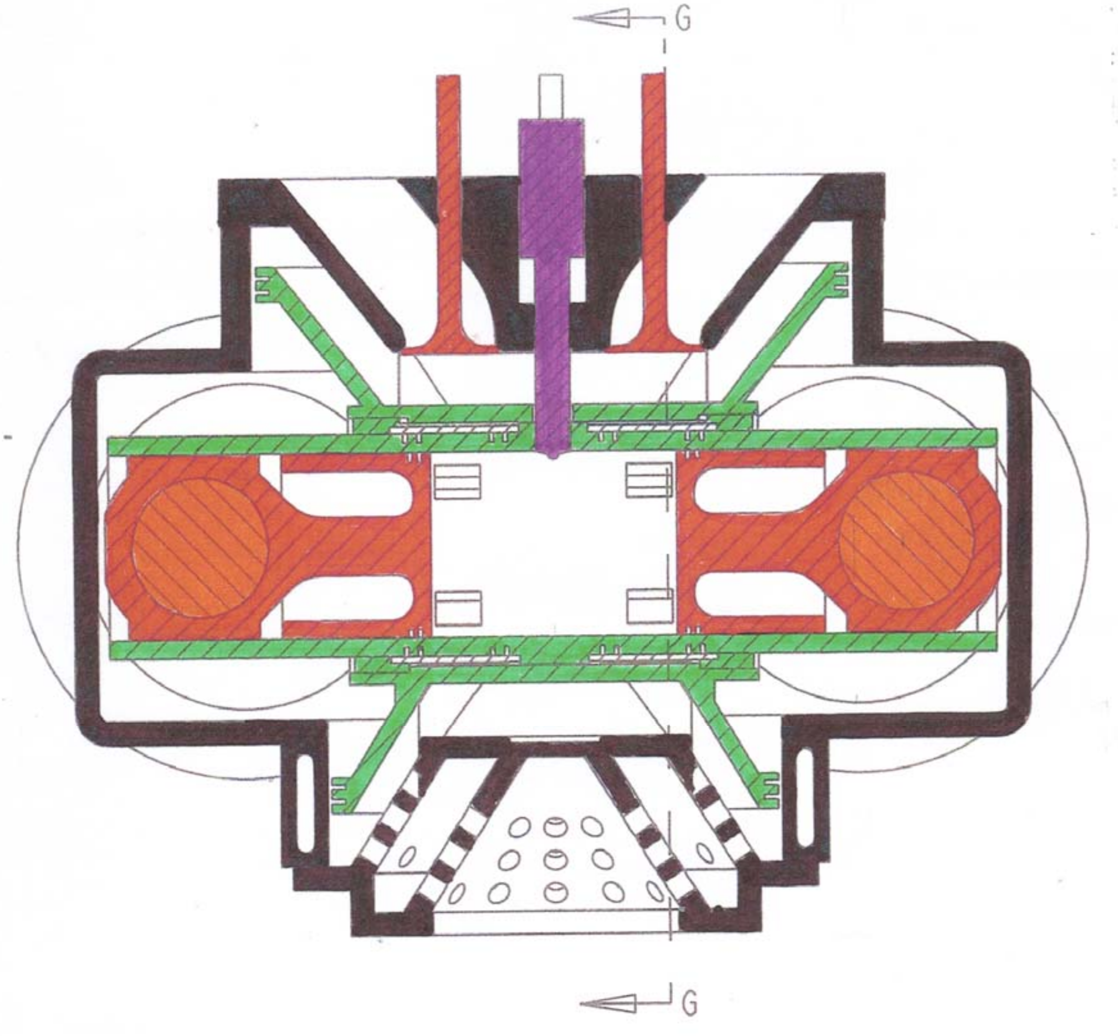
For Example c_p=1005 J/kg/K, A_h / A_f=1/8, ΔT=60 C, N=2, K=1 then

$$V = \sqrt{\frac{1005 \times 60}{1 \times 8 \times 2}} = 60\, m/s$$

Suggestion

- What about an engine with the following features ?
  - Small size - very small stroke/bore ratio
  - Low surface area factor combustion chamber - as for very large stroke/bore ratio
  - Atkinson expansion and more - high cycle efficiency and exceptional turbomachine compatibility
  - Round cylinders - no corner seals !
  - Sinusoidal motion - complete inertia bal  shaft mounted counterweights
  - Dimensions based on ideal Brayton cycle

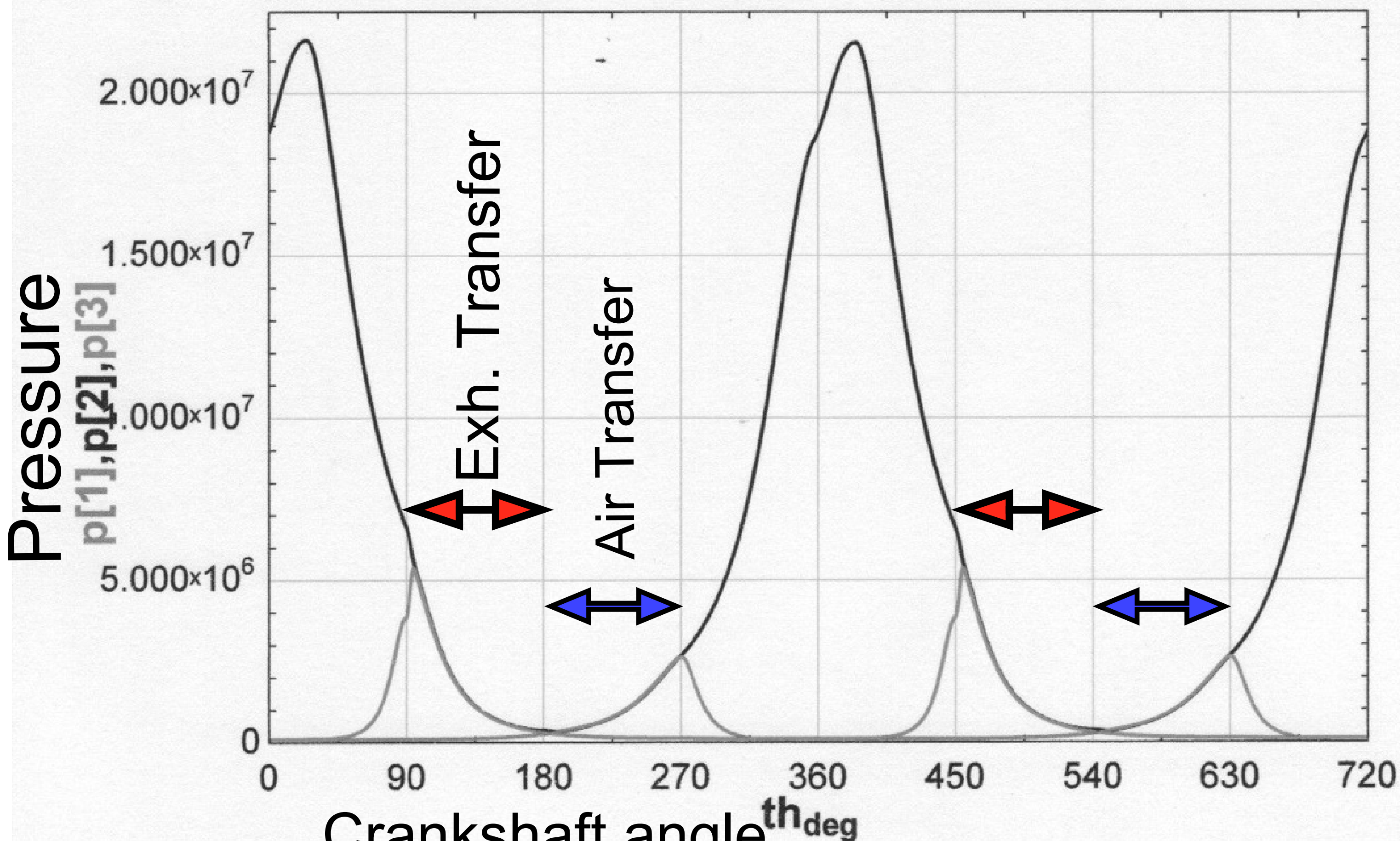

Gas
Turbine
C
E
Air
Exhaust
Combustor
CCI
C
E
Air
Exhaust
C = Compressor
E = Expander



SECTION E-E

Motiv Engines LLC have placed the CCI animation on the web.

http://www.motivengines.com/page6/page6.html



Simulation (adiabatic, perfect gas) of Brayton (NA) cycle in the CCI configuration

Conclusions

- I don’t want to conclude - I want to start!

Next steps.....

- This august body should decide and advise:
  - How much more (if anything) can be gained from automotive combustion engine efficiency
  - Plans involving \$100M+ of DoE funds should include a ‘proper’ mix of low risk low gain and high risk high gain projects

Opinion

- Current CI and SI engines are ‘mature’ and very cost effective.
- Over the years there have been many ‘radically improved’ engine projects that failed
- This does NOT mean there is nothing better
- It does mean that the better something will be different

Opinion - 2

- The Compact Compression Ignition engine I have outlined really is a different approach
- The classic piston and crank mechanism constrains thermodynamic efficiency
- Separating the cylinders allows them to be individually optimized