Five Stroke Internal Combustion Engine

A new concept for internal combustion engines

by Gerhard Schmitz, St.Vith 2011, Belgium

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1 Introduction

This document deals with a new concept of internal combustion engines, the five-stroke internal combustion engine, developed by Gerhard Schmitz.

The first section describes this new concept. Then, a detailed theoretical analysis follows, where the new 5-stroke cycle is compared to the classical 4-stroke cycle, both producing equivalent torque characteristics.

An **appendix** is added, where the same comparison has been analysed by Dr. H. Alten from **ILMOR Engineering Ltd**.

"Thanks to ILMOR Engineering Ltd. for making this detailed study."

2 A new concept for internal combustion engines

"Don't throttle the engine down, load it up!"

The piston displacement of current internal combustion engines is dimensioned for a **power regulation**, where the admission is **throttled down**, when partial load is needed. This leads to pumping losses and low mechanical efficiency's at partial load and rather "big volumes" to satisfy the peak power requirements.

In order to **increase the power density**, turbo- or supercharged four-stroke cycles has made appearance. The load pressures, however, where limited by thermal and mechanical stress considerations, as well as the non controlled ignition for gasoline cycles. The problem is due to the fact, that the single reciprocating device has a compression stroke which is equal to the expansion stroke. On one hand, you need a high expansion stroke in order to convert the maximum of thermal energy into work. On the other hand, you need a rather low compression stroke, in order to limit the thermal and mechanical stresses, as well as the non controlled ignition for gasoline cycles. This leads to the situation, that the four-stroke cycles should only be run with a rather small load pressure range (absolute load pressure = 1.2 ... 2 bar), still requiring throttling for low loads.

The only way to overcome the above mentioned compromise would be a cycle, where compression stroke and expansion stroke are different.

The **low compression ratio** (5...7) will allow a large range of load pressures (absolute pressure = 1.0 ... 5.0 bar), large enough to cover the power range of the currently throttled four-stroke cycle. The engine load would then be, in some way, controlled by the "variable overall compression stroke", variable compression of the supercharging device followed by the piston's constant compression ratio. The piston compression stroke has just to be high enough to enable the combustion of the air (spontaneous or ignited).

The **high expansion ratio** (15...19) will ensure a "high" conversion of the thermal energy into mechanical work.

Such a cycle is realised using the turbo- or supercharged **five**-stroke internal combustion engine or "***Six-stroke internal combustion engine with variable compression***", where the different tasks are assigned to different devices.

- *One device designed to increase and control the breathing (i.e. the power)...*

  ... *the turbo- or supercharging device (load pressure 1...5 bar)*

- *One device where the primary task is to burn this air...*

  ... *the high pressure cylinder of the 5-Stroke-Engine*

- *One device to complete the conversion of the thermal energy into mechanical work...*

  ... *the low pressure cylinder of the 5-Stroke-Engine.*

3 The “Five-stroke cycle”

3.1 Overview

The five-stroke cycle consists in the following steps:

1. Admission in the high pressure (HP) cylinder
2. Compression, followed by the ignition
3. First expansion of the burned gases
4. Second expansion of the burned gases
5. Exhausting of the burned gases.

These five strokes will be realised inside of a three cylinder engine, where a supercharging device is used to feed the high pressure cylinder. This device may be mechanical driven or by a turbine, using the residual energy of the exhaust gases.

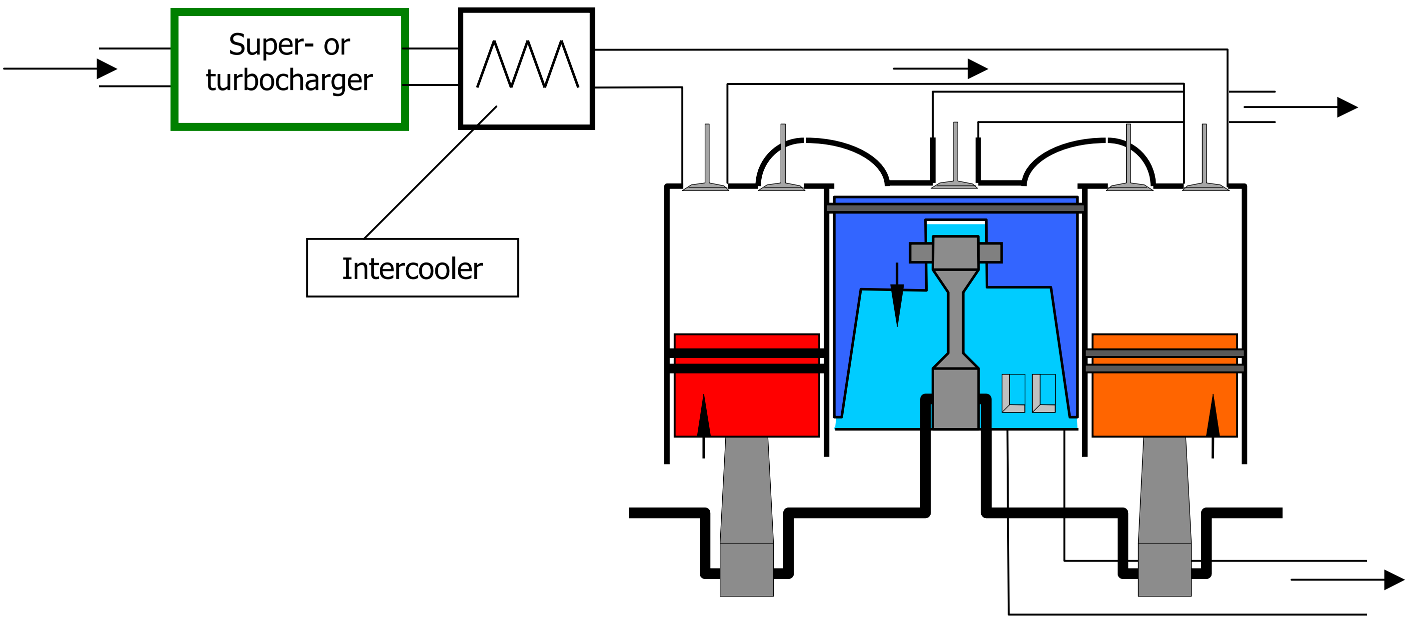


Figure 1: Three cylinder 5-Stroke engine

3.2 Details of cycle evolution

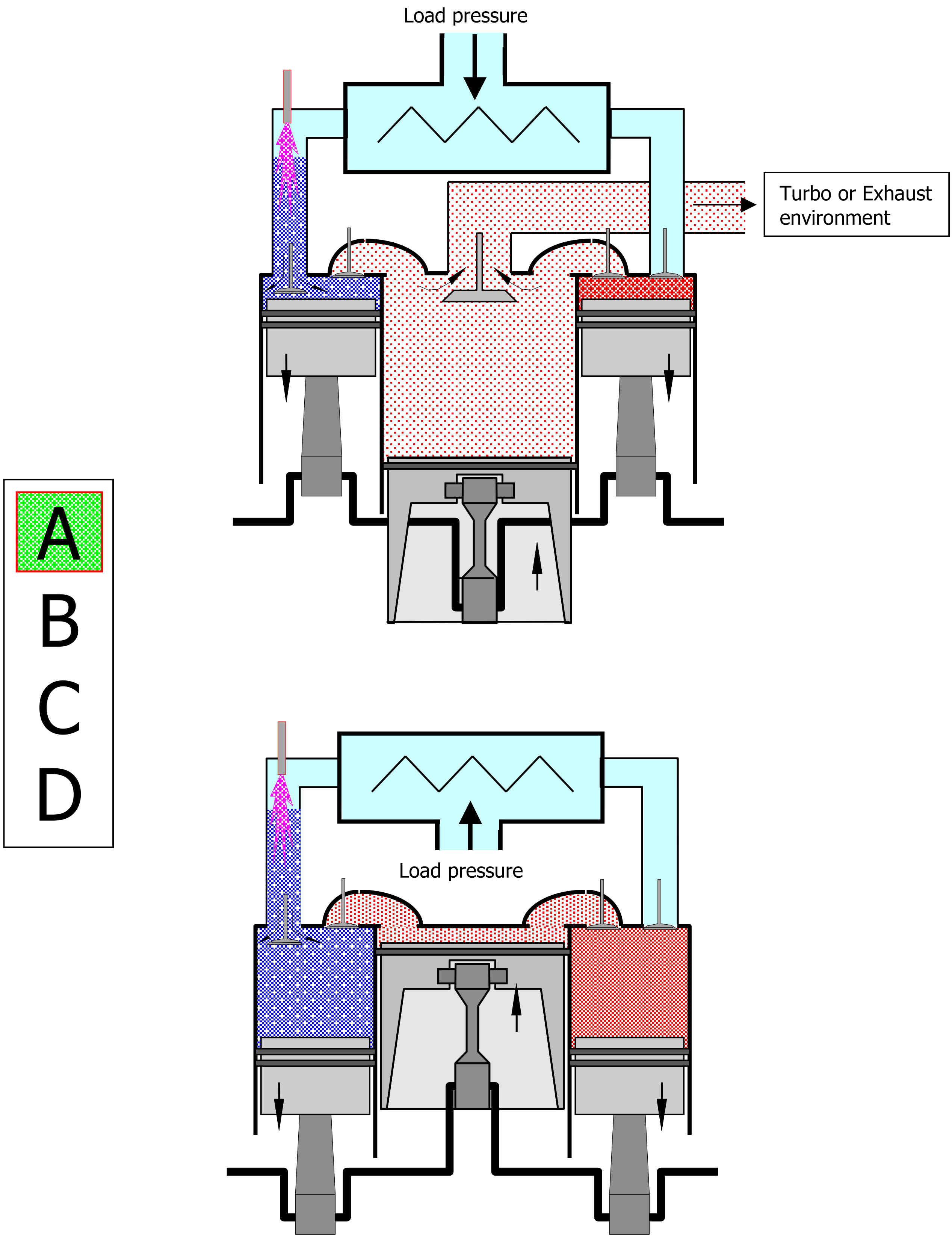


Figure 2: 5-Stroke cycle – Phase A

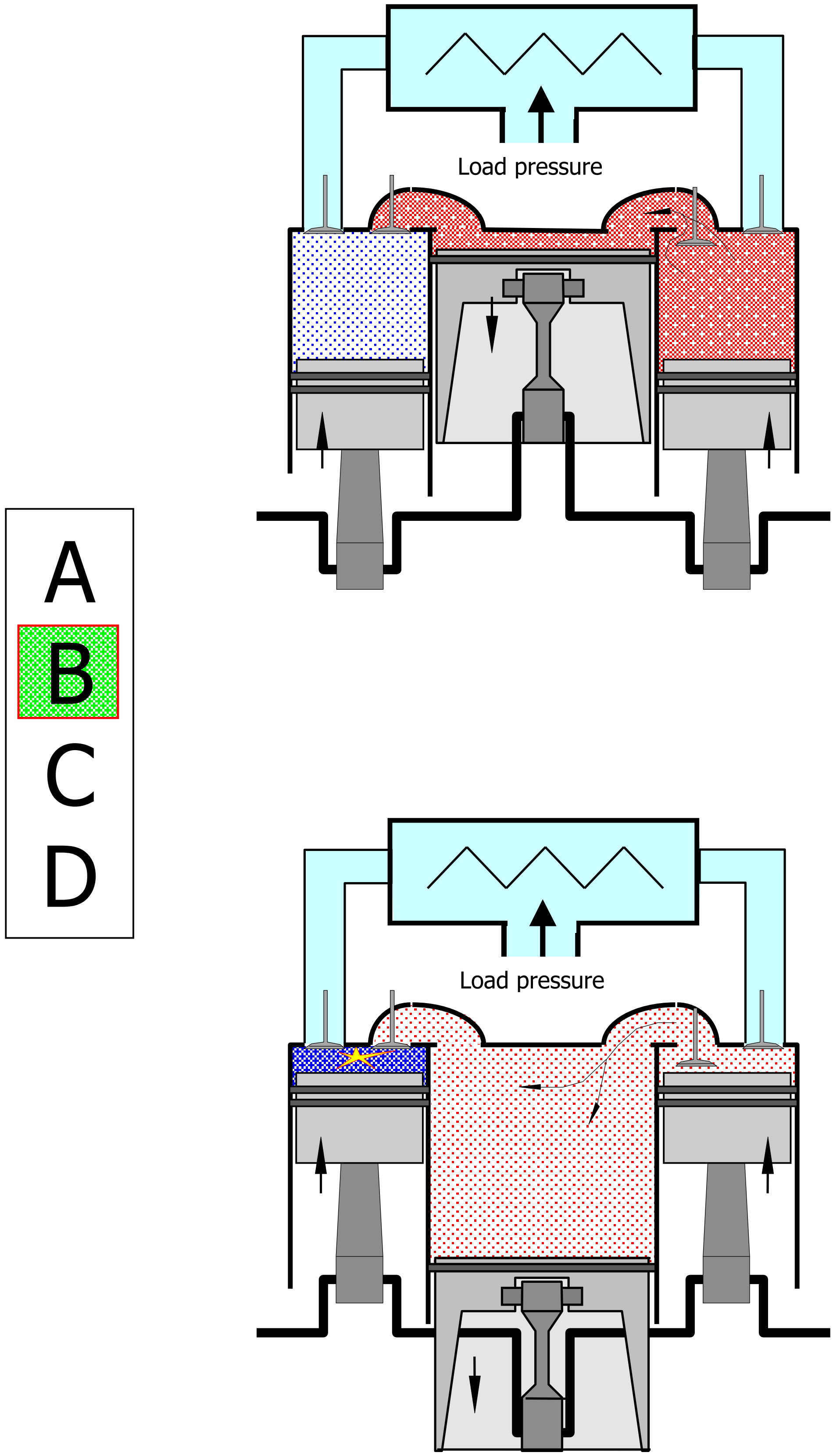


Figure 3: 5-Stroke cycle – Phase B

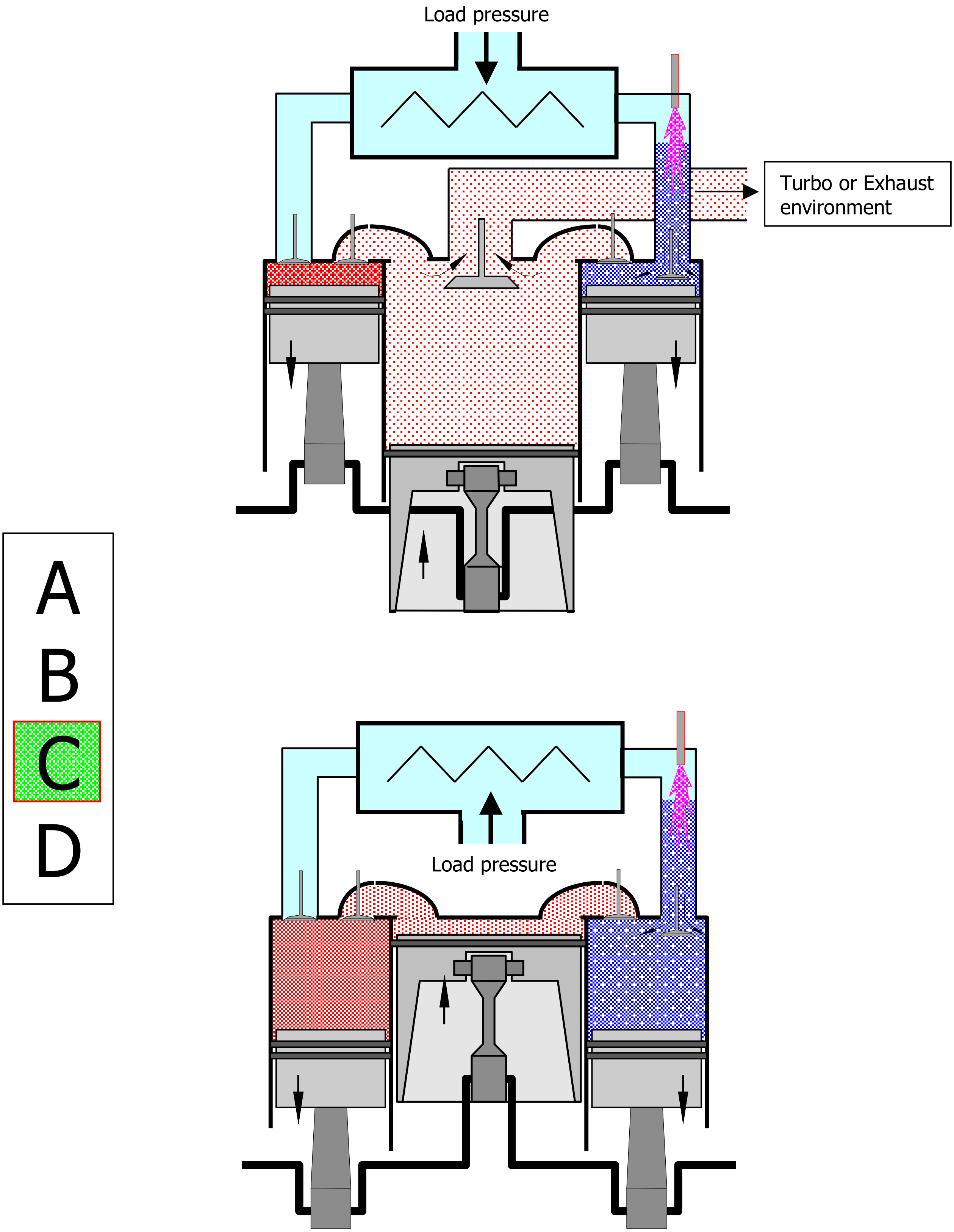


Figure 4: 5-Stroke cycle – Phase C

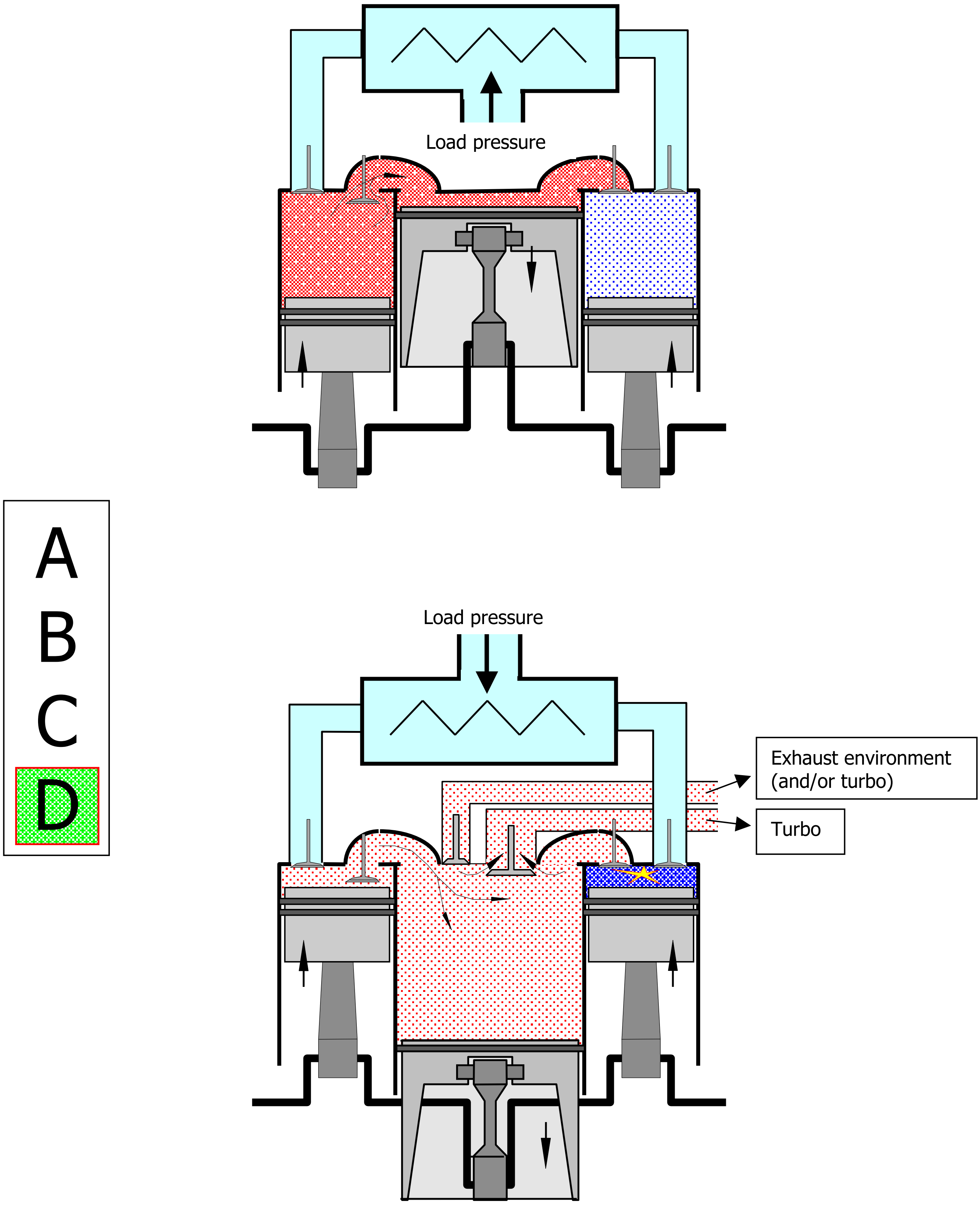


Figure 5: 5-Stroke cycle – Phase D

Note: In Figure 5: 5-Stroke cycle – Phase D, a more complex exhaust valve system for the low pressure cylinder (or second expansion cylinder) has been included into the drawing.

This is optional and allows, at partial load, the back pressure on the piston of the low pressure cylinder during the exhaust stroke to be reduced to the environmental pressure.

4 Five-stroke vs. Four-stroke cycle

4.1 Overview

In the following chapter, the new five-stroke cycle will be compared to the “classical” four-stroke cycle. The analysis will be done by a calculation code especially designed by G. Schmitz for this purpose. The model used for both cycles includes gas flow friction losses across valve sections and pipes/ports as well as heat losses inside the cylinder and connecting pipes.

The two engines, that will be compared, are designed to provide nearly identical torque and power characteristics.

The partial load in the case of the 4-stroke cycle is obtained by throttling the admission and in the case of the 5-stroke cycle by reducing the load pressure of the turbocharger in a first step and then for very small loads, a throttling of the admission will be necessary.

4.2 Technical data

The 750 ccm five-stroke engine is designed to produce equivalent torque/power, i.e. **46kW/110Nm at 4000 rpm**, than the 1200 ccm four-stroke engine.

4.2.1 The four-stroke engine

4.2.1.1 Summary

Number of cylinders:	4
Supercharged:	No
Global piston displacement:	1202 ccm
Individual piston displacement:	300.5 ccm
Bore:	72.6 mm
Stroke:	72.6 mm
Compression ratio:	10:1
Number of intake valves:	1
Intake valve, diameter:	26 mm
Number of exhaust valves:	1
Exhaust valve diameter:	26 mm

Valve lift (see details in Figure 6, page 17)

Intake valve duration:	177 °CA (0.5 mm to 0.5 mm eff. lift)
Max. lift:	9 mm at 90°CA ATDC
Exhaust valve duration:	177 °CA (0.5 mm to 0.5 mm eff. lift)
Max. lift:	9 mm at 90°CA BTDC

4.2.1.2 Details of thermodynamic data for computer simulation

```
Input data "4t99load"          Date & time:   05.05.2000 10:09:11:37

Four- (HP-data) or Five-stroke engine?           4
Engine speed (RPM):                     4000.00000

Combustion in HP cylinder
Duration (msec):                           2.00000
Mixture part burned at TDC (./.):          0.35000
Heat input per kg mixture (J):       3000000.00000

External constant conditions:
Pressure (bar):                            1.00000
Temperature (°C):                         15.00000
Purity (1=air, 0=burned gas):              1.00000

Engine geometry's:
Cylinder volume at TDC (ccm):             33.40000
Cylinder bore (mm):                       72.60000
Piston stroke (mm):                       72.60000
Connecting rod length (mm):              140.00000

Engine bloc temperatures:
Cylinder head temperature (°C):          180.00000
Piston upper face temperature (°C):      250.00000
Cylinder wall temperature (°C):          120.00000

Valve control:          Effective valve lift law [°KW,lift(mm)]
Admission:                           D:\fuenftak\db\lift-4-5.ven
Exhaust port:                        D:\fuenftak\db\lift-4-5.ven

                                       Intake     Exhaust
Number of valves:                     1.00000     1.00000
Valve diameter (mm):                 26.00000    26.00000
Max. lift pos. (0°CA=Adm. TDC HP):   90.00000   -90.00000
Valve/cam clearance (mm):             0.20000     0.20000
Lift multiplicator (./.):             1.00000     1.00000
Angle multiplicator (./.):            1.00000     1.00000


Supercharging device exists ?                    N
```

4.2.1.3 Details of mechanical friction data for computer simulation

The parameter used in this section are those used by the engine simulation program SIMOTTO (http://www.euregio.net/simotto).

```
Mechanical friction data "4t-motor"

Engine bloc
        nocyl:          4         nocrab:          5            hd:  0.35000
r2wrod (/100):    1.80000 clpist (/1e3):    1.00000        fdrypr:  0.20000
r2wcra (/100):    2.00000 clcrab (/1e3):    1.00000    mu (Ns/m²):  0.01000

Piston rings
    pel (bar):    1.00000
        norin:          2             b1:    0.01500            b2:  0.01700

Valve control
```

```
     nocamb:        10     dcamb (mm):  27.00000        fdryct:  0.20000
cltap (/1e3):  1.00000     wcamb (mm):  15.00000  stival (N/mm):50.00000
   htap (mm): 25.00000         clcamb:   1.00000    preval (mm):  5.00000
  rcami (mm): 15.00000     rcame (mm):  15.00000
```

4.2.2 The five-stroke engine

4.2.2.1 Summary

Number of cylinders:	3
Supercharged:	Yes
Global piston displacement:	750 ccm

High pressure area (HP):

Number of cylinders:	2
Individual piston displacement:	150 ccm
Bore:	60 mm
Stroke:	53 mm
Compression ratio:	7:1
Number of intake valves:	1
Intake valve, diameter:	21 mm
Number of exhaust valves:	1
Exhaust/Transfer valve diameter:	21 mm

Valve lift (see details in Figure 6, page 17)

Intake valve duration:	177 °CA (0.5 mm to 0.5 mm eff. lift)
Max. int. lift:	9 mm at 90°CA ATDC
Exh./Tran. valve duration:	177 °CA (0.5 mm to 0.5 mm eff. lift)
Max. exh./tran. lift:	9 mm at 90°CA BTDC

Low pressure area (LP):

Number of cylinders:	1
Individual piston displacement:	449 ccm
Bore:	83 mm
Stroke:	83 mm
Compression ratio:	17,7:1
Number of exhaust valves:	1
Exhaust valve diameter:	45 mm

Valve lift (see details in Figure 6, page 17)

Exhaust valve duration:	177 °CA (0.5 mm to 0.5 mm eff. lift)
Max. exhaust. lift:	9 mm at 110°CA BTDC

4.2.2.2 Details of thermodynamic data for computer simulation

```
Input data "5t99load"          Date & time:   05.05.2000 10:54:12:77

Four- (HP-data) or Five-stroke engine?            5
Engine speed (RPM):                        4000.00000
```

Combustion in HP cylinder	
Duration (msec):	2.00000
Mixture part burned at TDC (./.):	0.25000
Heat input per kg mixture (J):	3000000.00000

External constant conditions:	HP	LP
Pressure (bar):	3.90000	calculated
Temperature (°C):	calculated	1000.00000
Purity (1=air, 0=burned gas):	1.00000	0

Engine geometry's:	HP	LP
Cylinder volume at TDC (ccm):	24.98000	11.00000
Cylinder bore (mm):	60.00000	83.00000
Piston stroke (mm):	53.00000	83.00000
Connecting rod length (mm):	130.00000	130.00000

Engine bloc temperatures:	HP	LP
Cylinder head temperature (°C):	180.00000	180.00000
Piston upper face temperature (°C):	250.00000	250.00000
Cylinder wall temperature (°C):	120.00000	120.00000

Valve control:	Effective valve lift law [°KW,lift(mm)]
HP admission:	D:\fuenftak\db\lift-4-5.ven
HP exh. or Transfer port:	D:\fuenftak\db\lift-4-5.ven
LP exhaust:	D:\fuenftak\db\lift-4-5.ven

	HP adm	Transfer	LP exh
Number of valves:	1.00000	1.00000	1.00000
Valve diameter (mm):	21.00000	21.00000	45.00000
Max. lift pos. (0°CA=Adm. TDC HP):	90.00000	-90.00000	70.00000
Valve/cam clearance (mm):	0.20000	0.20000	0.20000
Lift multiplicator (./.):	1.00000	1.00000	1.00000
Angle multiplicator (./.):	1.00000	1.00000	1.00000

HP->LP Transfer ports:	
Mean port diameter (mm):	26.00000
Mean port length (mm):	30.00000
Port wall temperature (°C):	250.00000

Supercharging device exists ?	**Y**
Type of supercharging:	**turbo**
Atmospheric pressure (bar):	1.00000
Atmospheric temperature (°C):	15.00000
Compressor intake pressure (bar):	1.00000
Compressor intake temperature (°C):	15.00000
Compressor exhaust pressure (bar):	4.00000
Compressor isentropic efficiency (./.):	0.69000
Intercooler efficiency (./.):	0.70000
Primary exhaust pipe length (mm):	200.00000
Primary exhaust pipe wall temp. (°C):	570.00000
Turbine exhaust pressure (bar):	1.00000
Turbine isentropic efficiency (./.):	0.69000
Exhaust mass flow through waste-gate (%):	0

4.2.2.3 Details of mechanical friction data for computer simulation

The parameter used in this section are those used by the engine simulation program SIMOTTO (http://www.euregio.net/simotto).

Mechanical friction data "**te-5t-hp**"

```
Engine bloc
         nocyl:         2        nocrab:         3            hd:  0.35000
r2wrod (/100):    1.80000 clpist (/1e3):   1.00000        fdrypr:  0.20000
r2wcra (/100):    2.00000 clcrab (/1e3):   1.00000    mu (Ns/m²):  0.01000

Piston rings
     pel (bar):   1.00000
         norin:         3            b1:   0.01500            b2:  0.01700

Valve control
        nocamb:         6    dcamb (mm):  27.00000        fdryct:  0.20000
 cltap (/1e3):    1.00000    wcamb (mm):  15.00000 stival (N/mm): 50.00000
     htap (mm):  25.00000        clcamb:   1.00000   preval (mm):  5.00000
    rcami (mm):  15.00000    rcame (mm):  15.00000
```

Mechanical friction data "**te-5t-lp**"

```
Engine bloc
         nocyl:         1        nocrab:         1            hd:  0.35000
r2wrod (/100):    1.80000 clpist (/1e3):   1.00000        fdrypr:  0.20000
r2wcra (/100):    2.00000 clcrab (/1e3):   1.00000    mu (Ns/m²):  0.01000

Piston rings
     pel (bar):   1.00000
         norin:         1            b1:   0.01500            b2:  0.01700

Valve control
        nocamb:         2    dcamb (mm):  27.00000        fdryct:  0.20000
 cltap (/1e3):    1.00000    wcamb (mm):  15.00000 stival (N/mm): 50.00000
     htap (mm):  25.00000        clcamb:   1.00000   preval (mm):  5.00000
    rcami (mm):  15.00000    rcame (mm):  15.00000
```

4.2.3 The valve lift laws

The different valve lift laws are given in effective valve lift in mm vs crankshaft position in °CA, where the reference position (0°CA) is the scavenging TDC of the high pressure piston, in the case of the five-stroke cycle. Note that the second expansion cylinder exhaust valve opens at each rotation of the crankshaft. For the following study, no optimisation has been undertaken concerning the valve lift laws.

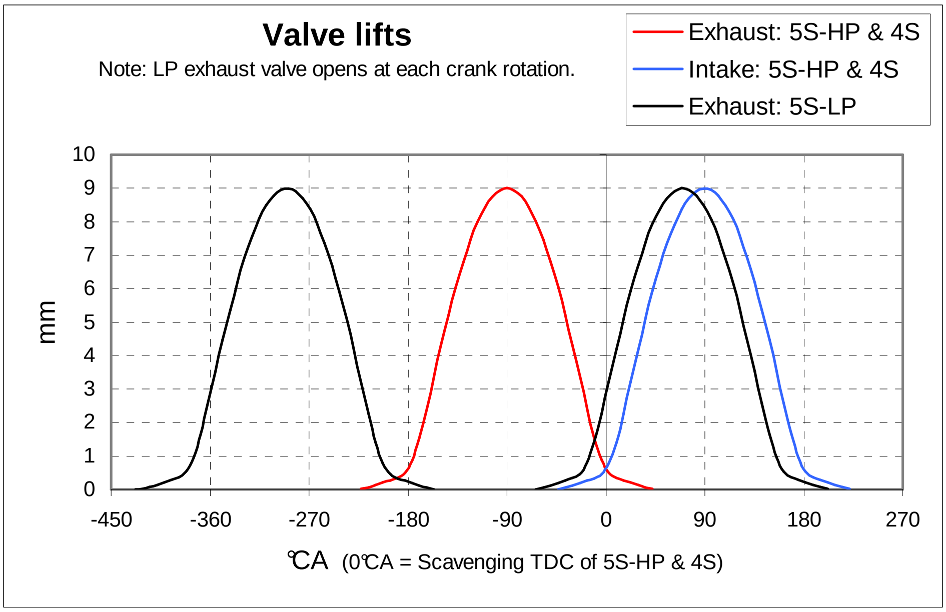


Figure 6: The valve lift laws for 5- & 4-stroke engines

4.3 Calculation results

The computer simulation has been used to analyse the behaviour of both engines, 4- and 5-stroke, at an engine speed of 4000 rpm running at different load percentages, ranging from 5% to 100%.

4.3.1 Load regulation

4.3.1.1 4-Stroke

In the case of the 4-stroke cycle, a simply throttling has been used to reduce the load

Load	Intake pres.	Turbo?
	(bar)	(Y/N)
5	0.1766	N
10	0.2205	N
20	0.3078	N
30	0.39336	N
40	0.48137	N
50	0.56773	N
60	0.65496	N
70	0.743	N
80	0.8294	N
90	0.9158	N
100	1	N

Table 1: Load regulation of the 4-stroke cycle

4.3.1.2 5-Stroke

In the case of the 5-stroke, first the load pressure has been reduced and then, for smaller loads than 26%, a throttling has been applied to the HP-intake.

Load	HP Int. pres.	Load pres.	Comp. Eff.	Turbine Eff.	Exh. pipe temp.	Turbo?	Wastegate
(%)	(bar)	(bar)	(./.)	(./.)	(℃)	(Y/N)	(%)
5	0.418					N	100
10	0.555					N	100
20	0.835					N	100
26	1.000					N	100
30	1.170	1.200	0.63	0.63	390	Y	30
40	1.585	1.625	0.64	0.64	420	Y	25.7
50	1.998	2.048	0.65	0.65	450	Y	21.4
60	2.401	2.461	0.66	0.66	480	Y	17.14
70	2.777	2.847	0.67	0.67	510	Y	12.8
80	3.147	3.227	0.68	0.68	540	Y	8.6
90	3.504	3.594	0.69	0.69	570	Y	4.3
100	3.900	4.000	0.69	0.69	570	Y	0

Table 2: Load regulation of the 5-stroke cycle at 4000 rpm

4.3.2 Main results

4.3.2.1 Fuel economy

The main results concern the behaviour of the 4-stroke and 5-stroke engine running at 4000 rpm at different loads. The fuel economy of the 5-stroke vs the 4-stroke ranges from more than 30% at very low load to 16% at full load.

Load (%)	Effective Torque		Global Efficiency		BSFC (gr/kWh)		Economy (%)
	4-Stroke	5-Stroke	4-Stroke	5-Stroke	4-Stroke	5-Stroke	5S vs 4S
5	5.5	5.5	0.111	0.178	757.9	471.3	37.8
10	11.1	10.9	0.176	0.264	478.3	318.6	33.4
20	22.1	22.0	0.248	0.352	338.6	239.2	29.4
30	32.9	33.0	0.287	0.382	292.8	220.2	24.8
40	44.0	43.8	0.312	0.390	269.4	215.8	19.9
50	55.0	54.7	0.329	0.397	255.7	211.7	17.2
60	66.0	65.7	0.341	0.405	246.7	207.5	15.9
70	77.1	76.7	0.350	0.414	240.3	203.0	15.5
80	88.1	87.9	0.357	0.423	235.7	198.9	15.6
90	99.1	98.8	0.362	0.431	232.3	195.2	16.0
100	110.0	109.9	0.366	0.436	229.6	192.9	16.0

Table 3: Fuel economy of the 5-troke vs. 4-stroke cycle at 4000 rpm

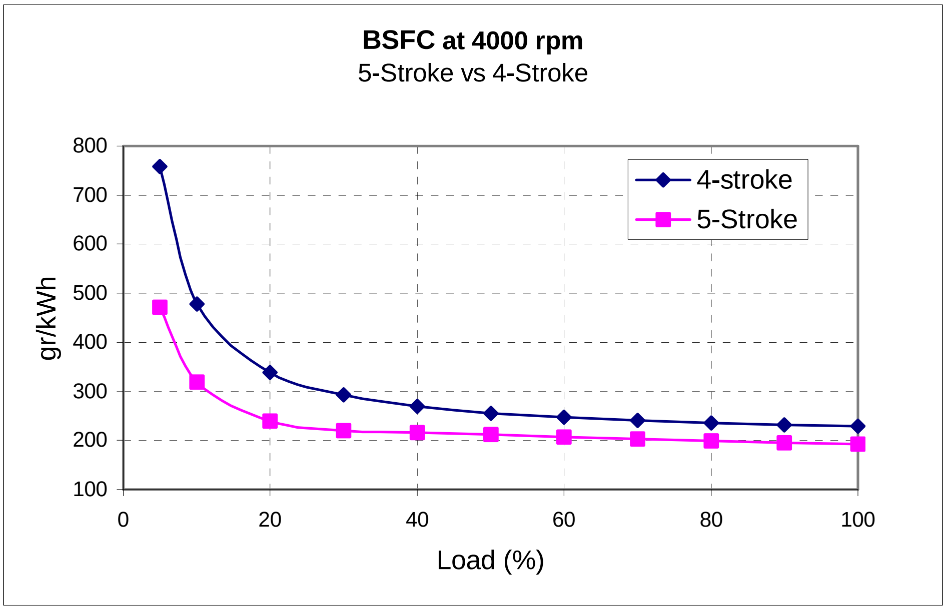


Figure 7: BSFC of the 4- and 5-stroke engines at 4000 rpm

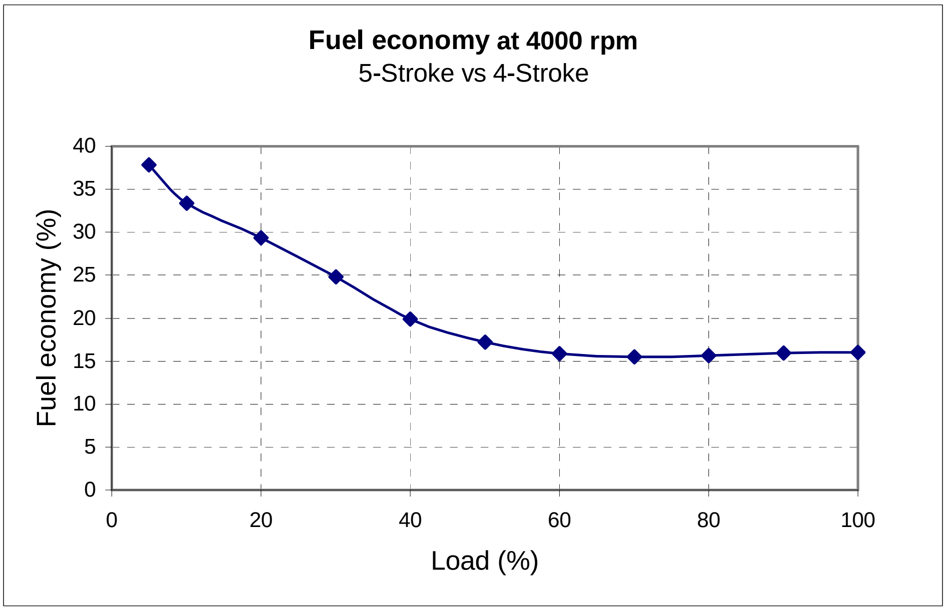


Figure 8: Fuel economy of the 5-stroke cycle vs. 4-stroke cycle

Note: The in the appendix included “Report: TD-103” concerning a comparison of this new 5-stroke versus the classical 4-stroke engine, which has been edited by Mr. Hans Alten from Ilmor Engineering Ltd. and where a completely different calculation code has been used, leads finally to similarly results, where a economy of 22% at low load and 20% at full load has been estimated.
It’s to be noted, that the 5-stroke engine analysed by Mr. Alten has identical HP cylinders as the engine analysed one this document, but the LP cylinder has a piston displacement of 655 ccm in place of 450 ccm and the load pressure at full load is only 3.2 bar in place of 3.9.

Finally Mr. Alten made an analysis for both, 2000 and 4000 rpm.

4.3.2.2 Work distribution

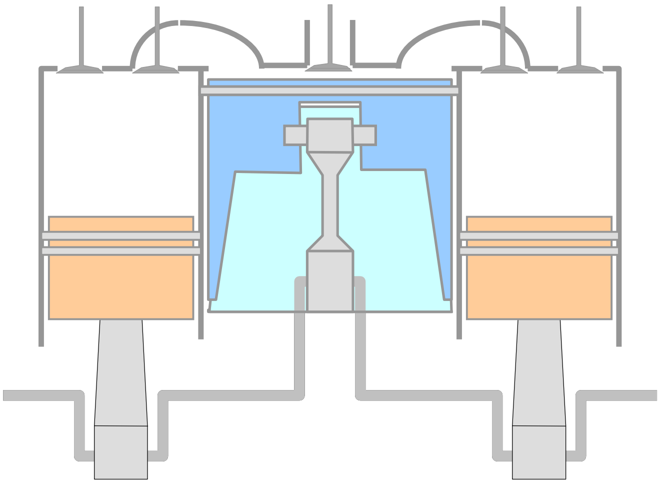
This chapter deals with the distribution of the engine work over the different strokes in the 4- and 5-stroke engine, as well the distribution of the engine work over the different pistons in the case of the 5-stroke engine.

Load (%)	Intake	Com.	Expan.	Exh.	Total
5	3.5	-18.1	79.3	-27.5	**37.2**
10	4.7	-22.6	100.4	-27.4	**55.0**
20	6.9	-31.6	142.5	-27.4	**90.5**
30	9.2	-40.3	184.2	-27.8	**125.3**
40	11.6	-49.4	227.3	-28.5	**161.1**
50	13.9	-58.2	269.9	-29.4	**196.2**
60	16.2	-67.2	313.2	-30.5	**231.7**
70	18.6	-76.2	357.1	-32.0	**267.5**
80	21.0	-85.1	400.5	-33.6	**302.8**
90	23.3	-94.0	444.3	-35.5	**338.1**
100	25.6	-102.7	487.9	-37.6	**373.2**

Table 4: Internal work (in Joule) over one 4-stroke cycle

Load (%)	HP Int.	HP com.	HP exp.	HP exh.	LP exp.	LP Exh.	Tot.HP	Tot.LP	Total
5	5.4	-17.3	86.0	-11.6	43.6	-46.8	62.5	-3.2	59.3
10	7.2	-23.0	115.2	-15.0	56.3	-46.9	84.4	9.4	93.8
20	10.9	-34.6	175.6	-22.1	82.5	-47.1	129.8	35.4	165.2
30	15.3	-48.3	243.5	-30.7	114.1	-58.2	179.7	55.9	235.6
40	20.7	-65.1	320.0	-40.9	152.1	-80.7	234.8	71.4	306.2
50	26.2	-81.8	394.6	-50.8	188.8	-100.3	288.2	88.5	376.7
60	31.5	-98.0	466.5	-60.3	223.6	-115.8	339.8	107.8	447.6
70	36.5	-113.2	534.7	-69.0	256.0	-126.3	388.9	129.7	518.6
80	41.3	-128.1	601.7	-77.5	287.2	-134.0	437.4	153.3	590.7
90	46.1	-142.5	665.1	-85.5	316.3	-138.7	483.3	177.6	660.9
100	51.3	-158.4	732.7	-94.2	348.2	-147.8	531.5	200.3	731.9

Table 5: Internal work (in Joule) over one 5-stroke cycle



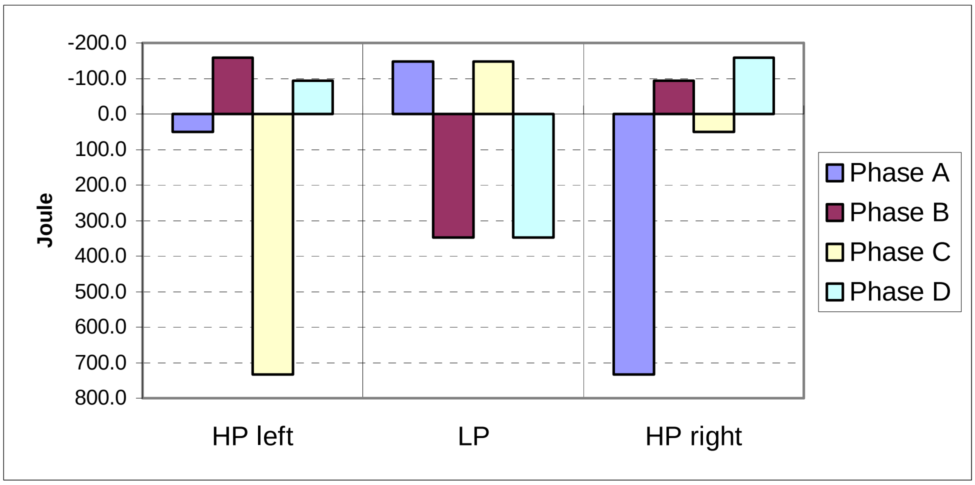


Figure 9: Indicated work over two crank rotations in the 5-stroke engine

Note: Please refer to Details of cycle evolution, page 7, for the description of the different phases A to D.

Load (%)	Tot. inter. work (J)		Mechanical friction work				Total effective work (Joule)			
	4-Stroke	5-Stroke	4-Stroke	HP 5-Str.	LP 5-Str.	5-Stroke	**4-Stroke**	HP 5-Str.	LP 5-Str.	**5-Stroke**
5	74.5	59.3	39.8	14.8	9.9	24.6	**34.7**	47.7	-13.1	**34.7**
10	110.1	93.8	40.6	15.4	10.0	25.4	**69.5**	69.0	-0.5	**68.4**
20	180.9	165.2	42.2	16.7	10.1	26.8	**138.8**	113.1	25.3	**138.4**
30	250.5	235.6	43.8	18.2	10.4	28.6	**206.8**	161.5	45.5	**207.1**
40	322.1	306.2	45.4	19.9	10.7	30.7	**276.7**	214.8	60.7	**275.5**
50	392.4	376.7	47.1	21.6	11.1	32.7	**345.3**	266.5	77.4	**344.0**
60	463.3	447.6	48.7	23.3	11.4	34.6	**414.6**	316.5	96.5	**413.0**
70	535.0	518.6	50.4	24.8	11.6	36.4	**484.6**	364.1	118.1	**482.2**
80	605.5	590.7	52.1	26.3	11.9	38.2	**553.4**	411.1	141.4	**552.5**
90	676.3	660.9	53.8	27.7	12.1	39.8	**622.4**	455.5	165.5	**621.1**
100	746.5	731.9	55.5	29.3	12.3	41.6	**690.9**	502.2	188.0	**690.3**

Table 6: Effective Work over one 5- and 4-stroke crank rotation

Note: This table shows, that the work is distributed as follows at full load (100%) between the different pistons of the three cylinder 5-stroke engine:

HP left:	**36.4 %**
LP (centre):	**27.2 %**
HP right:	**36.4 %**

So, even in the very non uniform 5-stroke cycle, the engine power is nearly equally distributed over the three cylinders!

4.3.2.3 Heat loss density

This chapter deals with the heat losses inside the engines, running at 4000 rpm and at different loads.

Load (%)	Heat Input	Tot. heat loss	Heat loss density		
			Cyl.	Head	Piston
	(Joule)	(Joule)	(W/cm²)	(W/cm²)	(W/cm²)
5	156.5	-51.8	-4.1	-12.1	-11.3
10	197.6	-59.7	-4.7	-14.1	-13.2
20	279.3	-74.3	-5.7	-17.8	-16.7
30	359.9	-88.7	-6.8	-21.4	-20.0
40	443.1	-103.3	-7.8	-25.0	-23.4
50	525.0	-117.4	-8.9	-28.4	-26.6
60	608.0	-131.6	-10.0	-31.9	-29.9
70	692.2	-145.8	-11.0	-35.3	-33.1
80	775.4	-159.7	-12.1	-38.6	-36.2
90	859.3	-173.6	-13.2	-41.9	-39.3
100	943.1	-187.3	-14.2	-45.2	-42.4

Table 7: Heat loss density in the 4-stroke engine at 4000 rpm

Load (%)	Heat Inp.	Heat loss	Heat loss density						
			HP cyl.	HP head	HP pist.	LP cyl.	LP head	LP pist.	Transfer
	(Joule)	(Joule)	(W/cm²)	(W/cm²)	(W/cm²)	(W/cm²)	(W/cm²)	(W/cm²)	(W/cm²)
5	194.4	-85.6	-6.3	-15.3	-14.3	-5.9	-10.2	-9.1	-4.0
10	259.3	-102.9	-8.0	-19.4	-18.1	-6.6	-11.3	-10.2	-5.1
20	393.5	-135.5	-11.3	-27.3	-25.5	-7.6	-13.3	-12.0	-7.1
30	542.1	-176.3	-14.9	-35.8	-33.5	-9.7	-17.1	-15.4	-9.4
40	706.7	-225.4	-18.8	-45.1	-42.3	-12.7	-22.3	-20.2	-12.0
50	865.7	-270.6	-22.5	-53.9	-50.5	-15.4	-27.0	-24.5	-14.4
60	1018.7	-311.8	-25.9	-62.0	-58.3	-17.7	-31.1	-28.3	-16.6
70	1163.9	-348.5	-29.1	-69.6	-65.4	-19.6	-34.5	-31.4	-18.6
80	1306.7	-382.9	-32.2	-76.9	-72.3	-21.2	-37.5	-34.1	-20.6
90	1441.0	-413.9	-35.0	-83.6	-78.6	-22.6	-40.0	-36.5	-22.4
100	1582.8	-448.3	-38.0	-90.8	-85.4	-24.4	-43.1	-39.3	-24.3

Table 8: Heat loss density in the 5-stroke engine at 4000 rpm

The peak thermal stress at the piston surface of the 4-stroke cycle at full load reaches 42.4 W/cm², while the peak values in the case of the 5-stroke cycle is 85.4 W/cm² for the HP piston and 43.1 W/cm² for the LP piston, which are nearly equivalent to those of the 4-stroke piston. The HP-> LP transfer port has to support 39.3 W/cm². The HP piston has to evacuate about the double of the heat power than the 4-stroke piston, so its cooling has to be well designed.

4.3.2.4 Turbocharger random conditions

Load (%)	Gas temperature in ℃ at ...						Pres. (bar)
	Comp. Exh	Interc. Exh	4-str. exh.	LP exh.	Turb. inlet	Turb .outlet	Turb. Inlet
5	15	15	1082.1	764.8	735.8		
10	15	15	1119.6	760.1	733.3		
20	15	15	1077.2	709.4	691.4		
30	39.6	22.4	1040.9	719.6	679.8	651.3	1.24
40	82.2	35.2	1011.6	750.2	712.3	639.3	1.71
50	116.1	45.3	989.0	769.6	734.3	630.9	2.13
60	143.7	53.6	970.9	781.0	748.8	624.3	2.46
70	165.6	60.2	956.2	786.1	757.4	619.1	2.69
80	184.4	65.8	944.4	787.3	762.1	613.9	2.85
90	200.3	70.6	934.6	785.0	763.6	608.7	2.95
100	219.2	76.3	926.6	787.8	766.5	603.2	3.14

Table 9: Turbocharger random conditions at 4000 rpm and full load

4.3.3 Detailed results at 30 and 100% load

4.3.3.1 Integrated results at 30 % load

4.3.3.1.1 The four-stroke engine

```
Result of "4t30load"

Date & Time:            05.05.2000 15:09:35:17

Cycle type:                                  4

Engine speed (RPM):                 4000.00000

Turbocharger exists ?                        N

Heat Input (J):                      359.92920
Total indicated work (J):            125.27290

Heat transfer density (W/cm²) at...
                ...cylinder head:      -21.379
           ... piston upper face:      -20.008
                ...cylinder wall:       -6.755

Effective torque (Nm):                    32.9
Effective power (kW):                     13.8
```

Thermodynamic efficiency (./.):	0.34805
Mechanical efficiency (./.):	0.825
Global efficiency (./.):	0.287
BSFC (gr/kWh):	**292.8**

4.3.3.1.2 The five-stroke engine

Result of "**5t30load**"

Date & Time:	05.05.2000 15:27:52:86		
Cycle type:	**5**		
Engine speed (RPM):	**4000.00000**		
Turbocharger exists ?	**Y**		
Turbo type:		turbo	
Temp. at compressor outlet (°C):		39.55338	
Compressor work (J):		-9.68422	
Temp. at intercooler outlet (°C):		22.36603	
Temp. at LP exhaust port (°C):		719.60390	
Temp. (°C), pres. (bar) turbine intake:		679.77360	1.23583
Temperature turbine outlet (°C):		651.27540	
Heat Input (J):	542.11740		
Total indicated work (J):	235.63380		

Heat transfer density (W/cm²) at...	**HP**	**LP**
...cylinder head:	-35.799	-17.070
... piston upper face:	-33.538	-15.367
...cylinder wall:	-14.861	-9.716
...transfer pipe:		-9.378

Effective torque (Nm):	33.0
Effective power (kW):	**13.8**
Thermodynamic efficiency (./.):	0.43465
Mechanical efficiency (./.):	0.879
Global efficiency (./.):	0.382
BSFC (gr/kWh):	**220.2**

4.3.3.2 Integrated results at 100 % load

4.3.3.2.1 The four-stroke engine

Result of "**4t99load**"

Date & Time:	05.05.2000 10:09:41:36
Cycle type:	**4**
Engine speed (RPM):	**4000.00000**
Turbocharger exists ?	**N**
Heat Input (J):	943.05020

```
Total indicated work (J):              373.23060

Heat transfer density (W/cm²) at...
                 ...cylinder head:       -45.168
            ... piston upper face:       -42.378
                 ...cylinder wall:       -14.228

Effective torque (Nm):                    110.0
Effective power (kW):                      46.1

Thermodynamic efficiency (./.):         0.39577
Mechanical efficiency (./.):              0.926
Global efficiency (./.):                  0.366
BSFC (gr/kWh):                            229.6
```

4.3.3.2.2 The five-stroke engine

```
Result of "5t99load"

Date & Time:             05.05.2000 10:56:20:97

Cycle type:                                   5

Engine speed (RPM):                  4000.00000

Turbocharger exists ?                         Y
                                Turbo type:       turbo
          Temp. at compressor outlet (°C):    219.21260
                       Compressor work (J):  -236.79580
         Temp. at intercooler outlet (°C):     76.26376
            Temp. at LP exhaust port (°C):    787.76880
    Temp. (°C), pres. (bar) turbine intake:   766.45170       3.13854
          Temperature turbine outlet (°C):    603.21780

Heat Input (J):                      1582.82500
Total indicated work (J):             731.87630

Heat transfer density (W/cm²) at...          HP                  LP
                 ...cylinder head:      -90.776             -43.084
            ... piston upper face:      -85.358             -39.329
                 ...cylinder wall:      -38.029             -24.398
                 ...transfer pipe:                          -24.342

Effective torque (Nm):                    109.9
Effective power (kW):                      46.0

Thermodynamic efficiency (./.):         0.46239
Mechanical efficiency (./.):              0.943
Global efficiency (./.):                  0.436
BSFC (gr/kWh):                            192.9
```

4.3.3.3 Indicated results

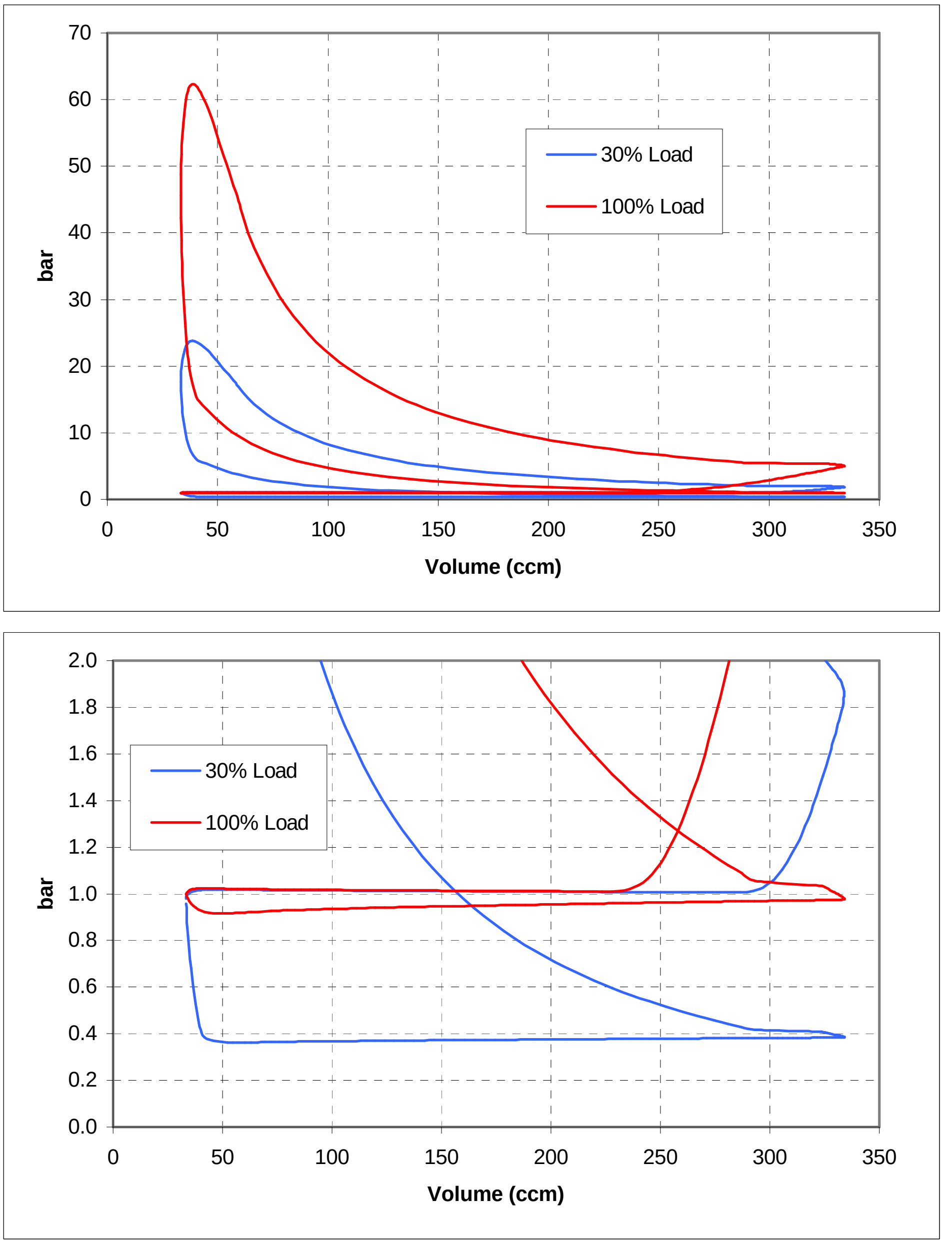


Figure 10: Pressure/Volume diagram of 4-stroke cycle at 4000 rpm

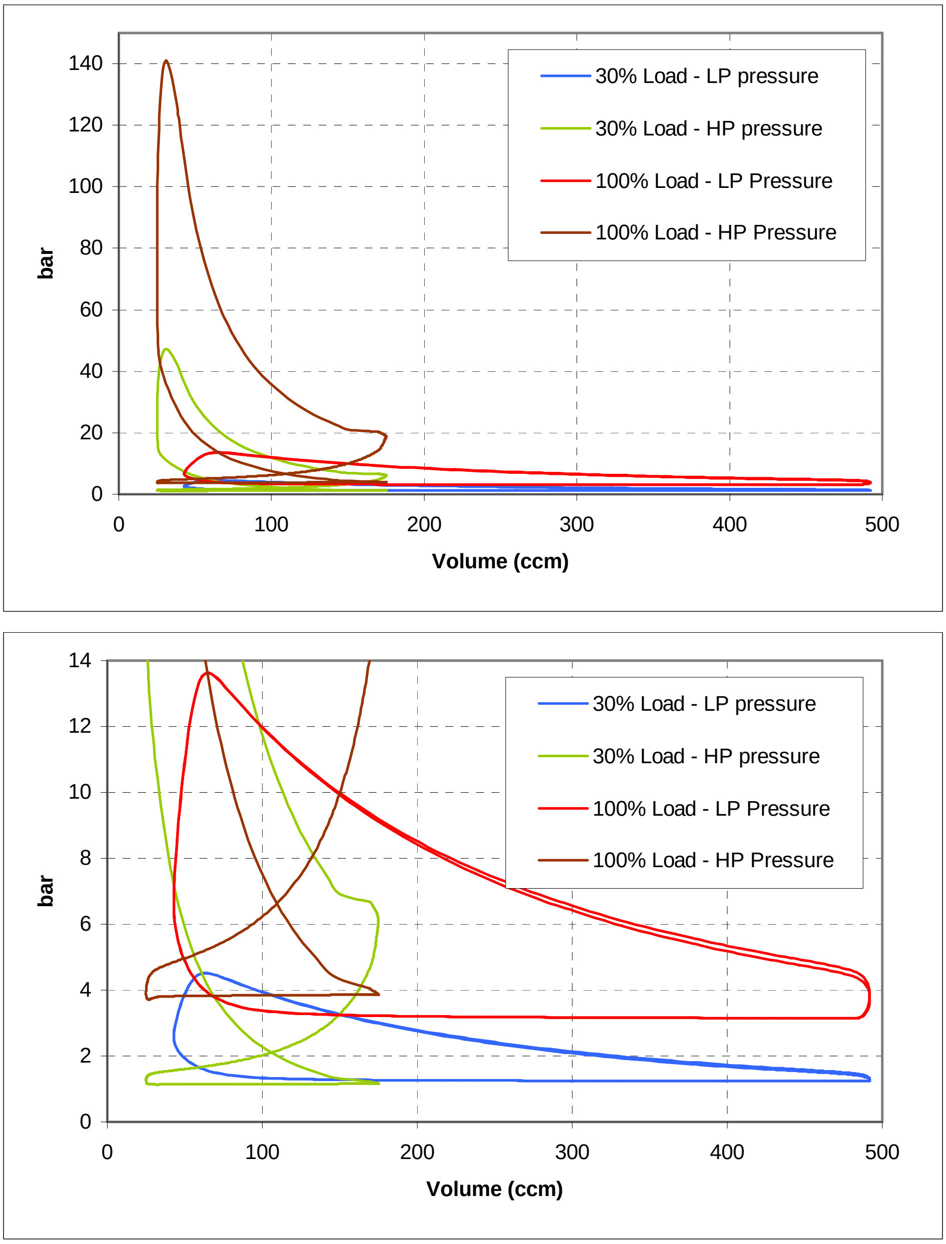


Figure 11: Pressure/Volume diagram of 5-stroke cycle at 4000 rpm

Note: Figure 11 shows, that the LP pv-diagram has no negative loop section, as the classical four-stroke (and the HP) pv-diagram always has. This is due to the fact, that the low pressure cylinder works as a “two-stroke” cycle, i.e. expansion-exhausting-expansion-...

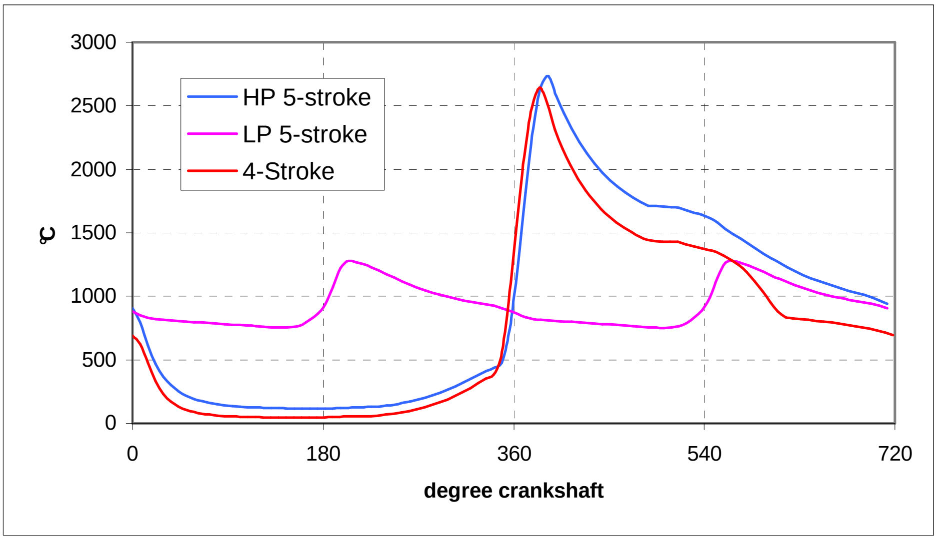


Figure 12: Indicated gas temperature at full load at 4000 rpm

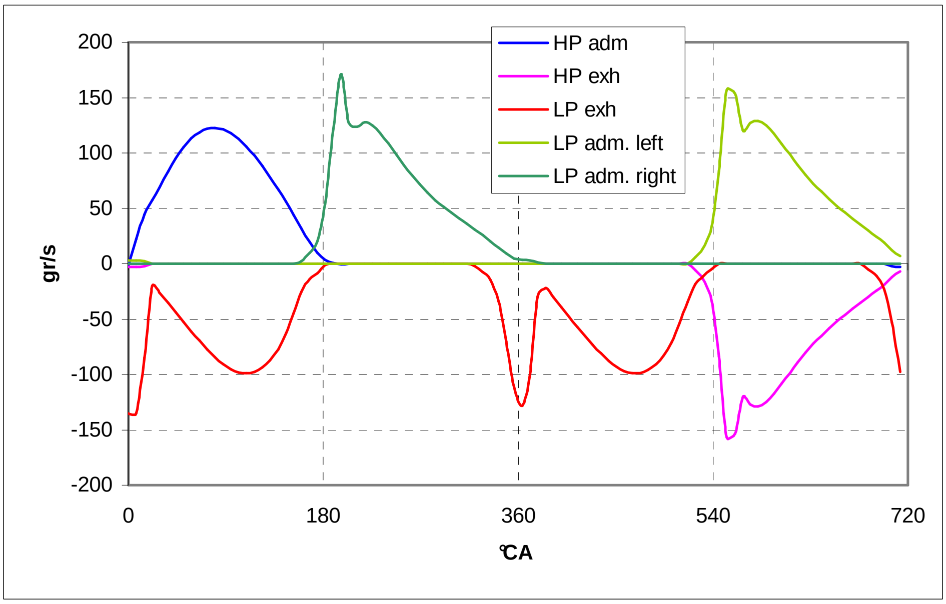


Figure 13: Mass flow rates in the 5-stroke engine at full load at 4000 rpm

Note: In Figure 13 (page 28), the HP flow rates are those of the **left** high pressure cylinder, the flow rates of the right HP cylinder are not shown. The HP exhaust flow equals (minus) the left LP admission flow rate evolution. Indeed, it's the same flow. The minus sign (HP exh.) indicates simply, that the HP exhaust flow is leaving the cylinder, and the plus sign (LP adm. Left) indicates, that the flow is entering the LP cylinder. The LP exhaust flow corresponds to that of a "two stroke" engine.

4.4 Conclusions

The advantages of the 5-stroke cycle versus the 4-stroke engine are:

- **The fuel consumption is reduced from 16% (at full load) up to 30% (at low load).**
- The total piston displacement is reduced by about 37%, i.e. a 750 ccm five-stroke has identical torque characteristic as a 1200 ccm four-stroke.
- The partitioning of the cycle in low and high pressure (and temperature) areas permits a specialisation of each partial cycle, i.e. introduction of new materials in engine building at the low pressure area.
- The low HP compression ratio (...7,0...:1) permits a more compact combustion chamber and reduces its volume variation during combustion, which prevents an excessive temperature drop of the flame towards the end of combustion.
- The heat-exchanger could be by-passed in order to regulate the air/fuel mixture intake temperature, during normal use and during engine starting.
- The high pressure drop at the beginning of the mixture admission in the high pressure cylinder permits high turbulence.
- ...

Problems, which may raise:

- The power regulation is much more sophisticated in the case of the 5-stroke cycle. A combination of turbine regulation using a wastegate and varying the air/fuel ratio of the mixture (see GDI engines) may solve this problem.
- The increased heat loss density of the HP cylinder requires a carefully designed cooling system.
- The different masses (2 small and 1 big piston) requires a carefully designed mass equilibration.
- ...

Finally, it could be stated, that the new five-stroke cycle seems to, all in all, to be a serious alternative choice to the classical four-stroke engine in road cars. He could use all the existing know-how concerning the four-stroke cycle, that is turbo charging, direct injection, ... to combine it into a high-tech combustion engine, that consumes much less primary energy and causes much less environment pollution.

5 Appendix

The appendix consists of the ...

Report: TD-103: „Thermodynamische Untersuchung eines 4-Taktmotors mit Nachexpansion“

by Hans Alten, ILMOR Engineering Ltd., Brixworth, 14.10.1999.

This report concerns in one hand the transient behaviour of the five-stroke engine versus the for stroke engine, where a rather „slow“ response on load change requests of the five-stroke cycle is found out. On the other hand, the fuel economy has been analysed, see figures 15 and 16. An economy of 20 (at full load) ... 22% (at partial load) has been pointed out.

It should be noted, that the power regulation in this study uses conventional throttling and turbine wastegate control, no optimisation has been done to improve the response behaviour of the 5-stroke engine.