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« Pneumatic-Combustion Hybrid Engine: A study of the effect of the valve-train sophistication on pneumatic modes. »

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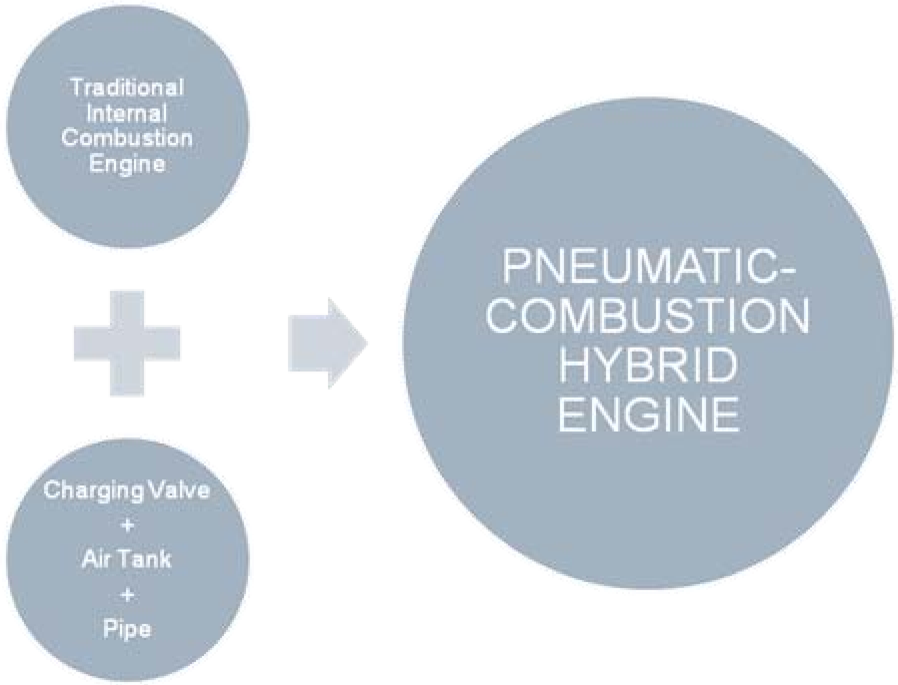
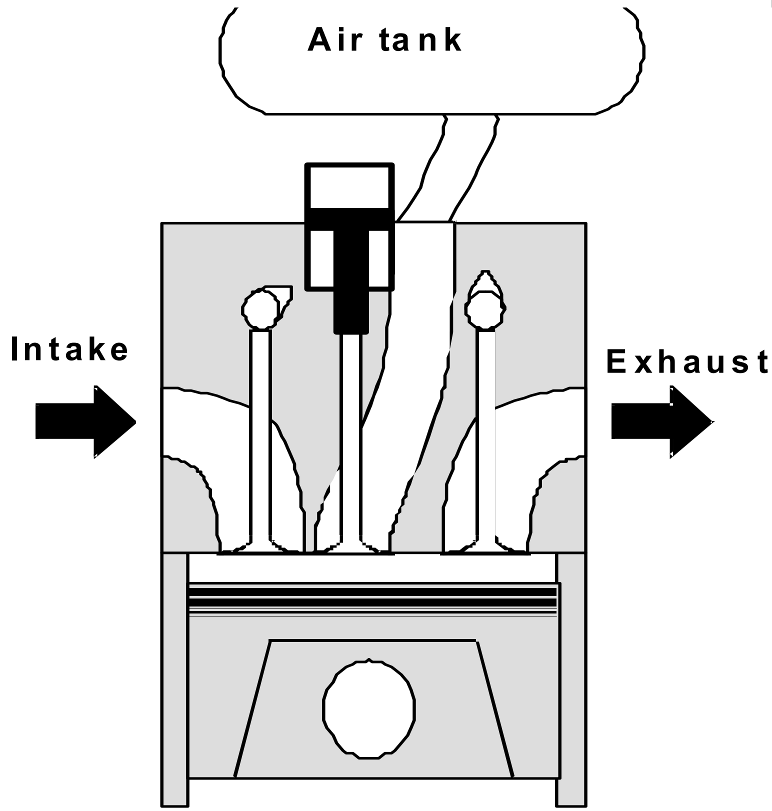
Summary

1. Introduction.
2. Idealized cycles.
3. Kinematic Model of the charging valve.
4. Quasi dimensional Engine model.
5. Simulations Results.
6. Conclusion.

1 - INTRODUCTION

1 - Introduction

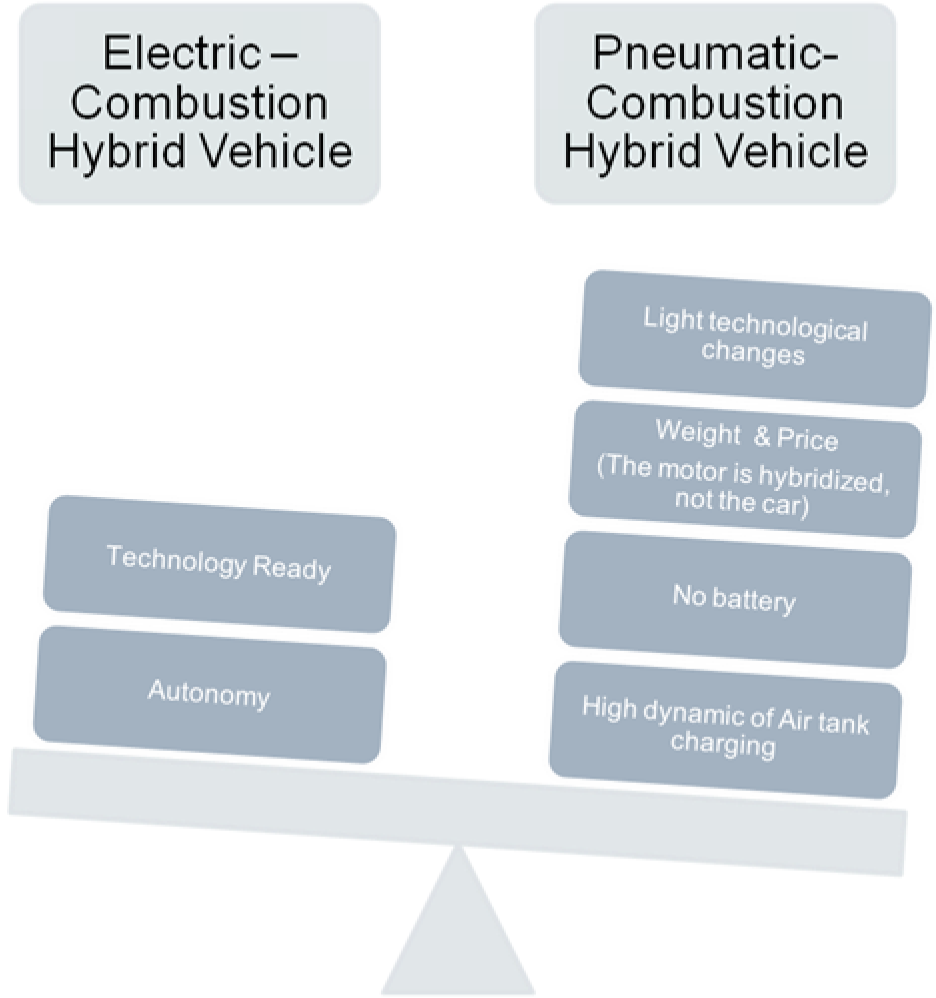




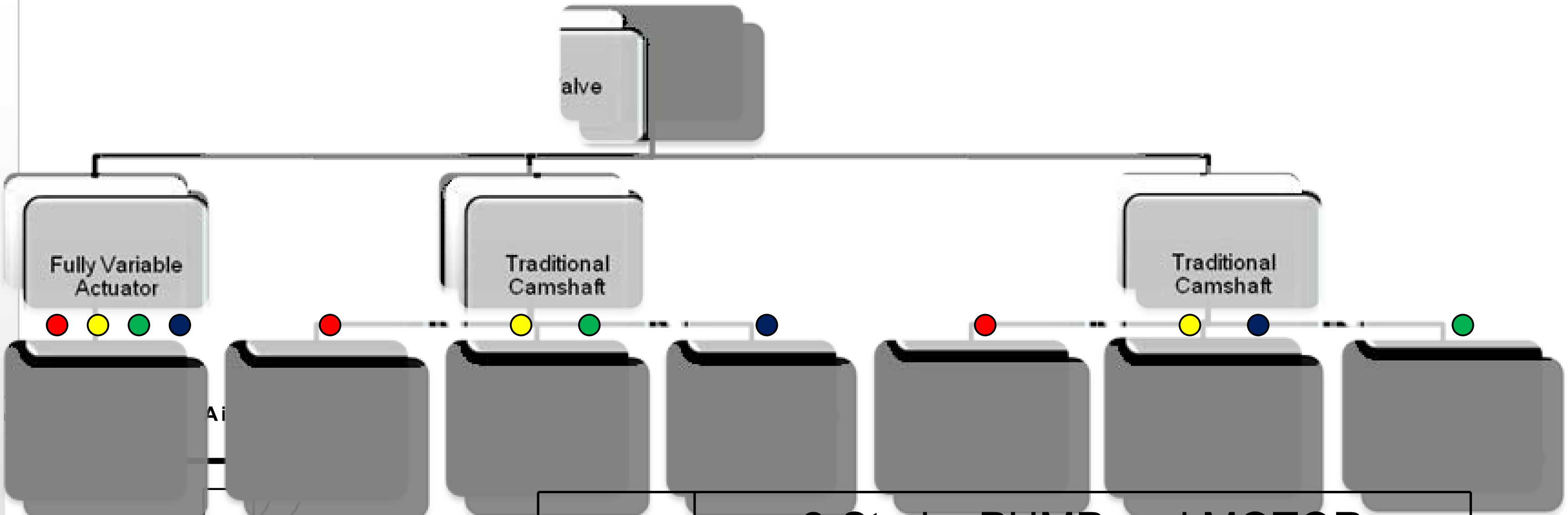
New thermodynamic cycles :

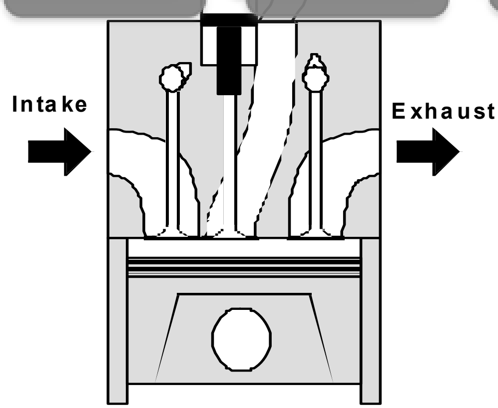
- PNEUMATIC **PUMP** MODE (*)
- PNEUMATIC **MOTOR** MODE (*)
- **UNDER-CHARGED** CONVENTIONAL MODE
- **SUPER-CHARGED** CONVENTIONAL MODE

Pneumatic Hybrid Concept



Valve train technologies

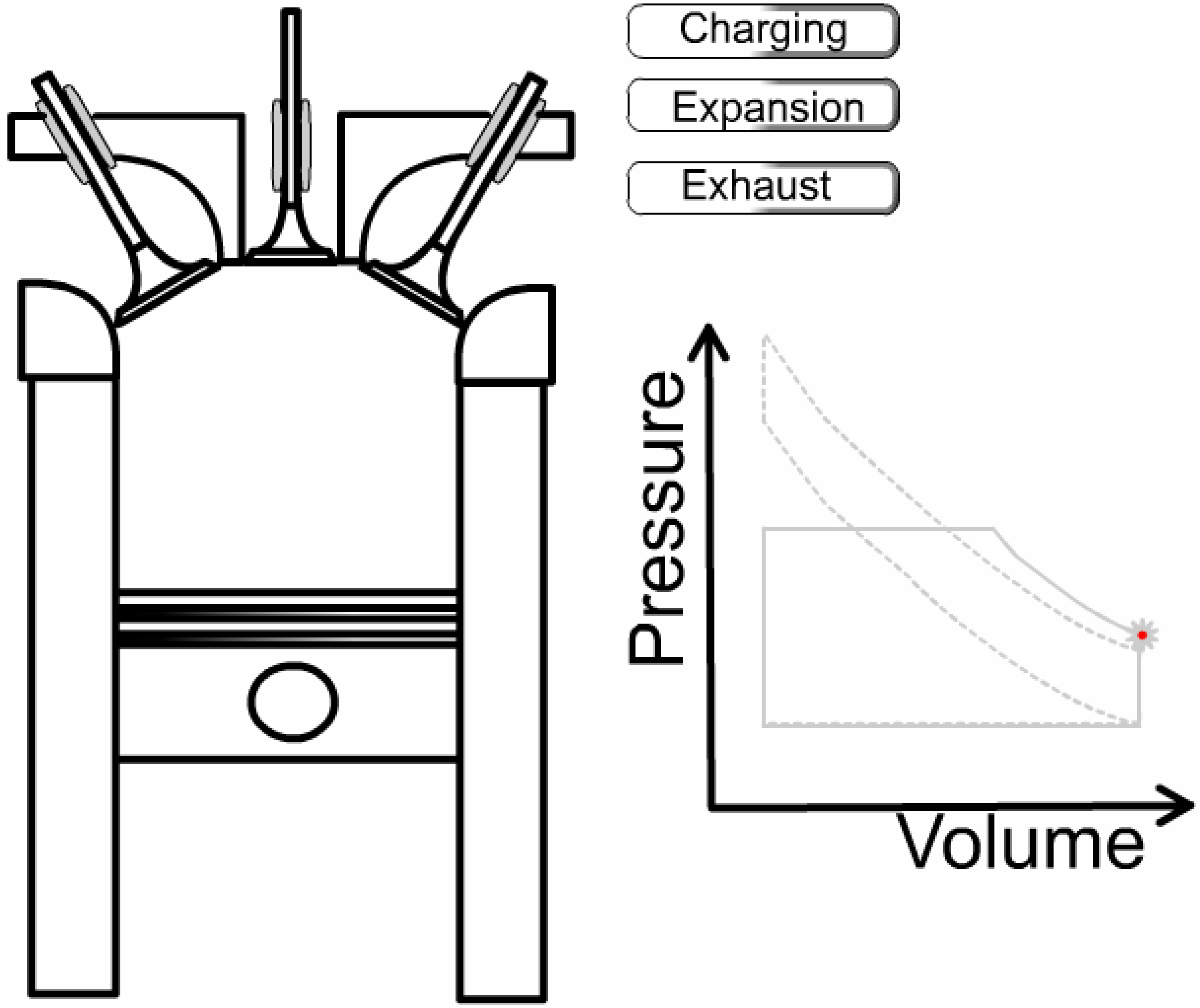




🔴	2-Stroke PUMP and MOTOR
🟡	4-Stroke PUMP and MOTOR
🟢	4-Stroke PUMP with Exhaust Off
🔵	4 –Stroke MOTOR with Inlet Off

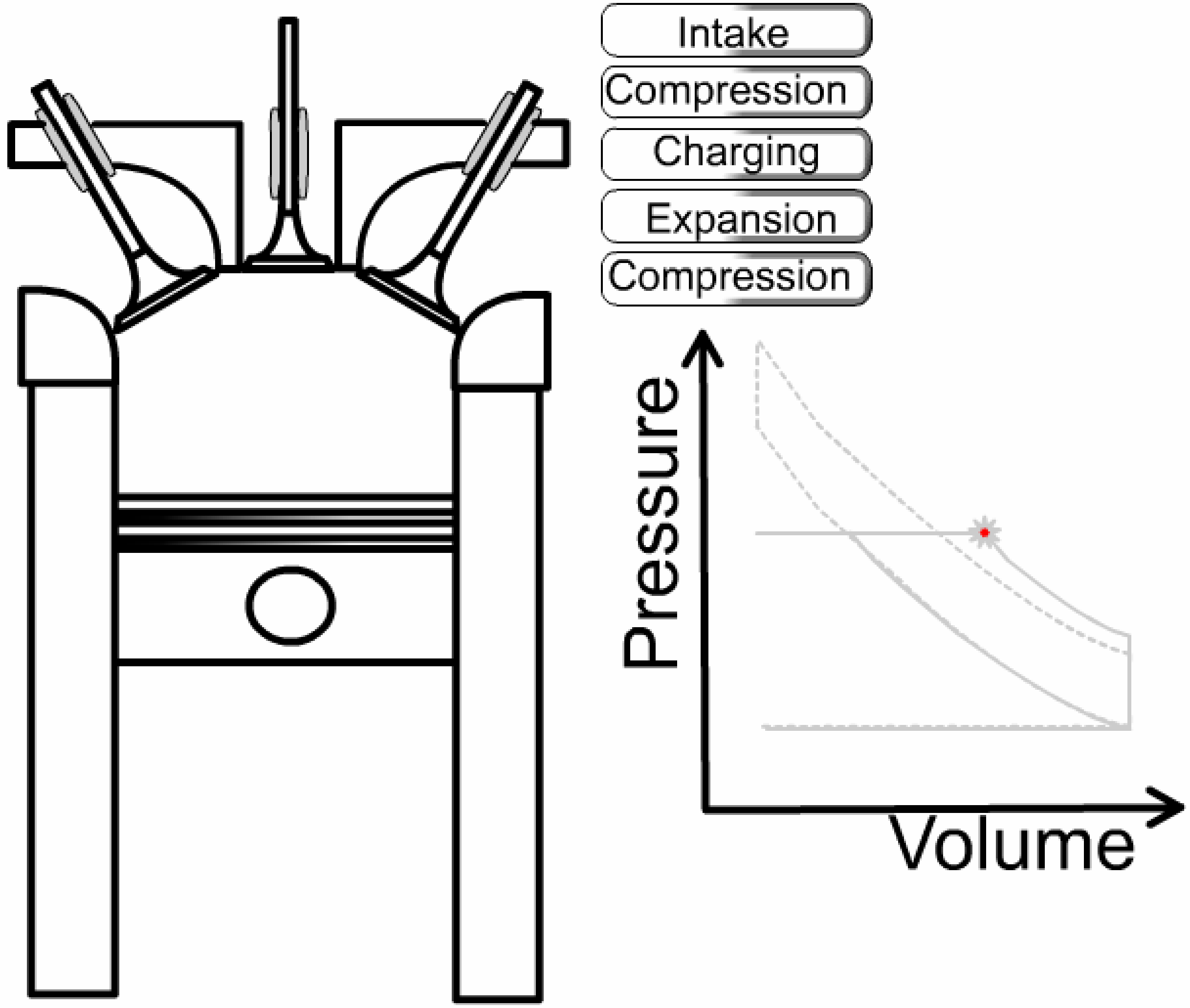
2 - IDEALIZED CYCLES

2-STROKE PNEUMATIC MOTOR



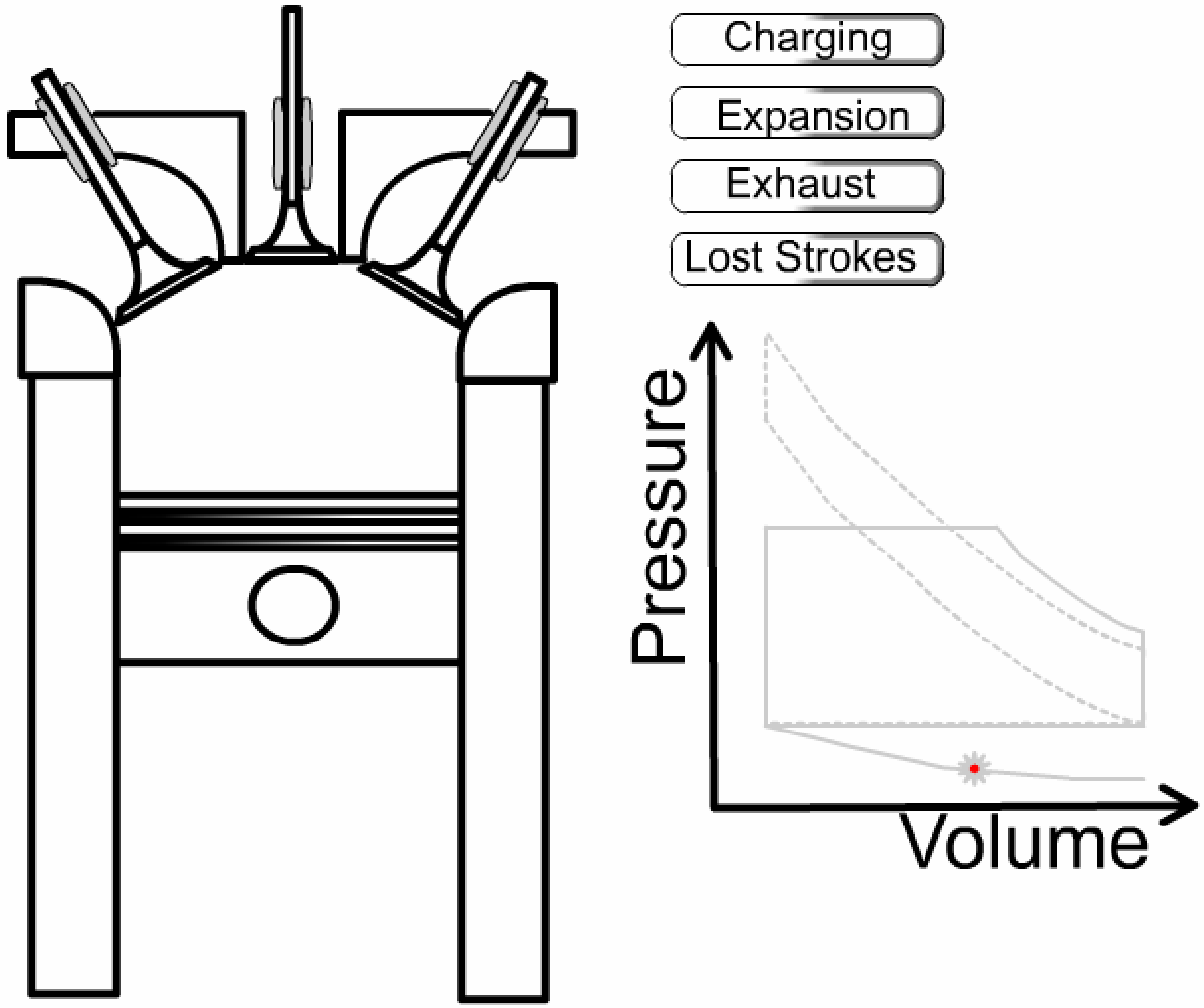
2 Stroke Pneumatic MOTOR

4-STROKE PNEUMATIC MOTOR



4 Stroke Pneumatic MOTOR Mode

4-STROKE PNEUMATIC MOTOR INLET OFF



4 Stroke MOTOR Inlet Off

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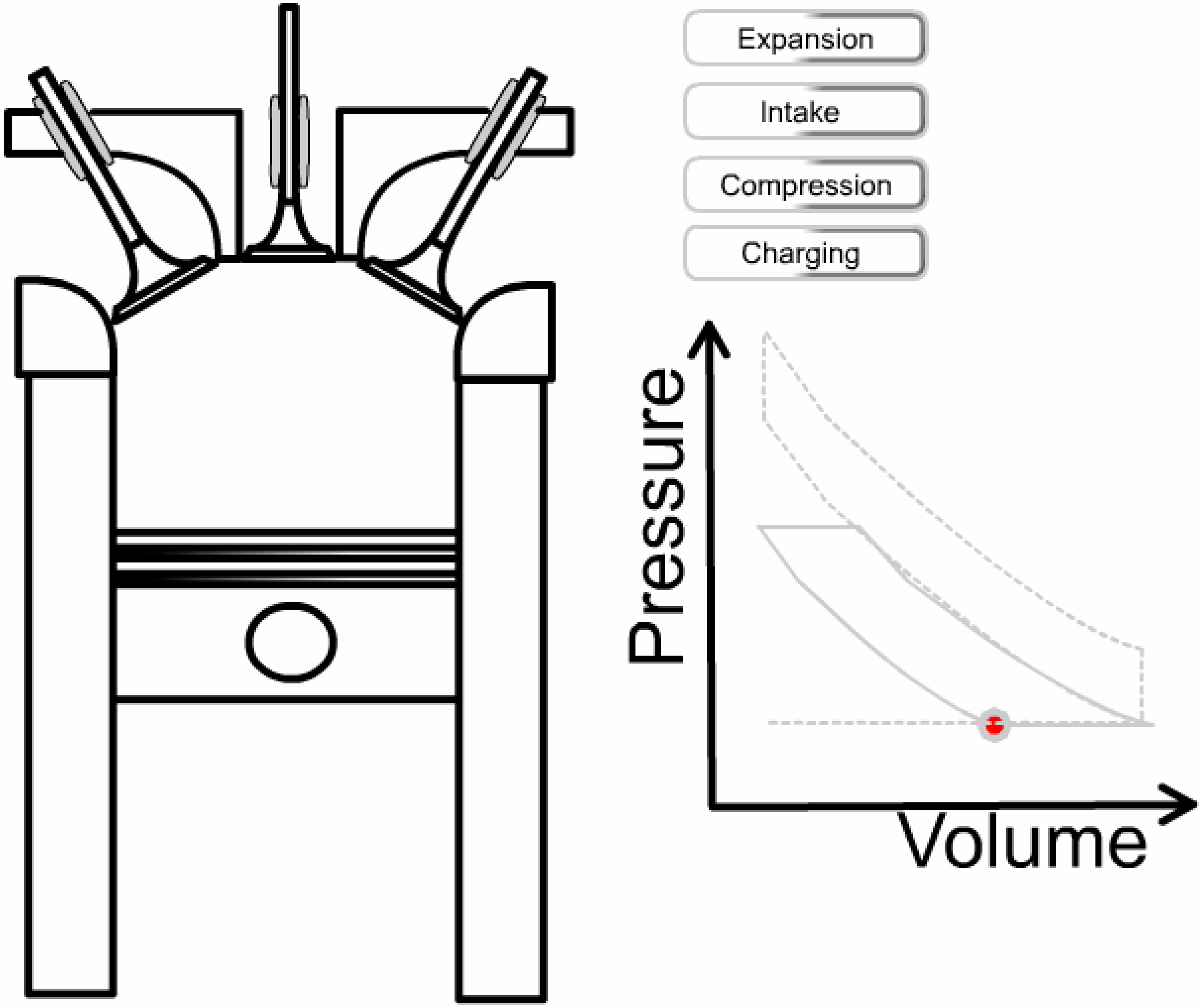
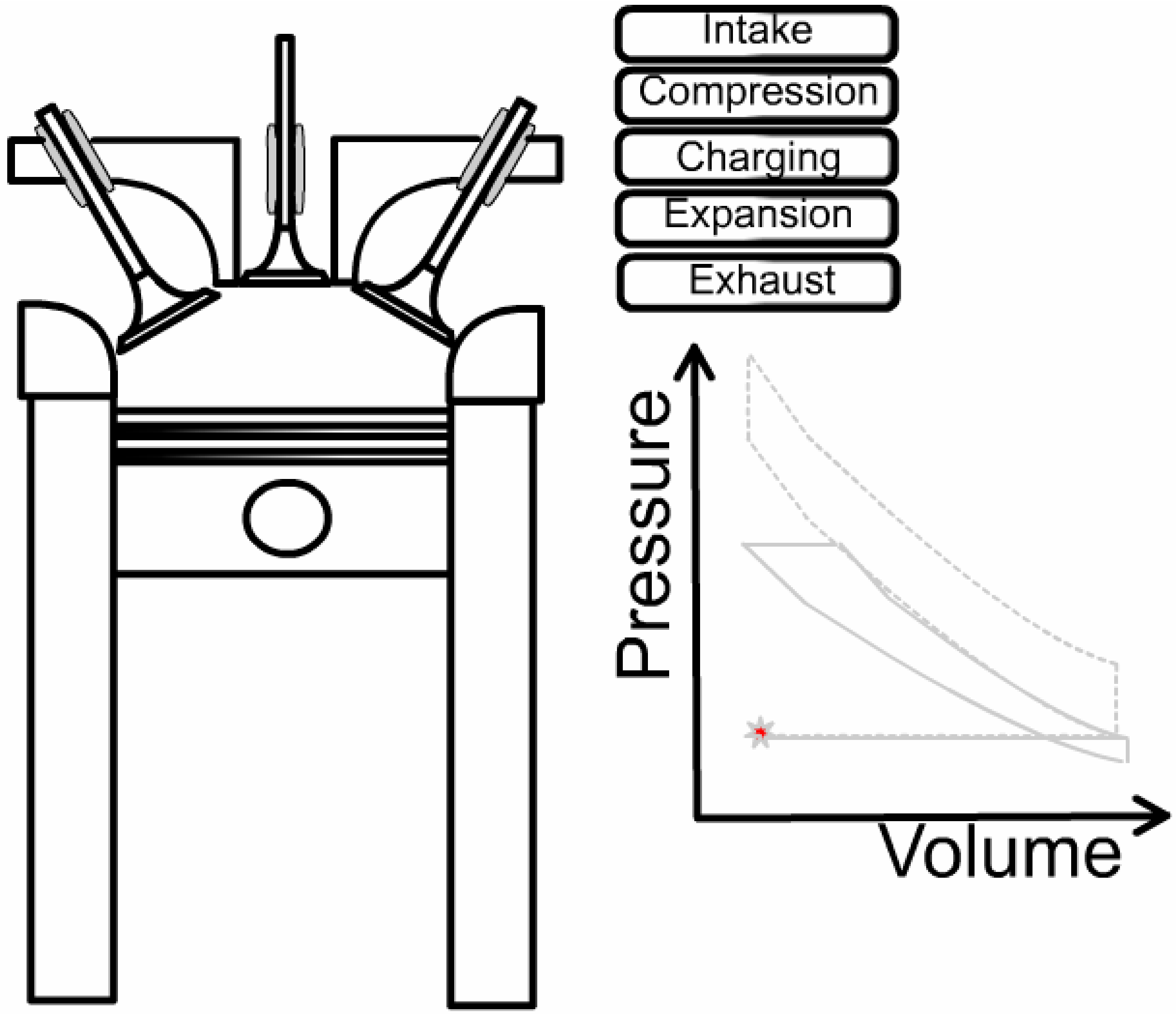
2-STROKE PUMP CYCLE

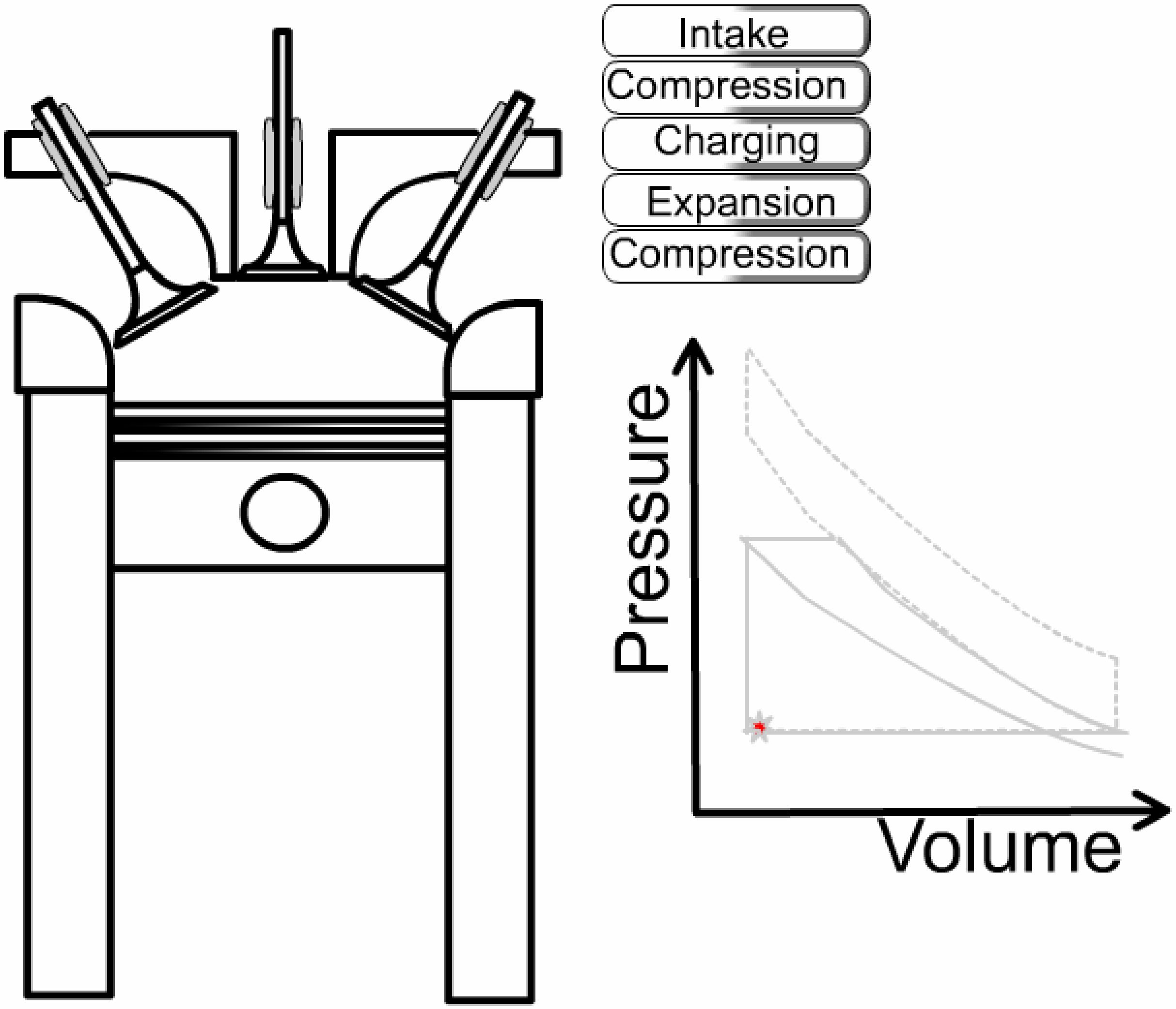


4-STROKE PUMP CYCLE



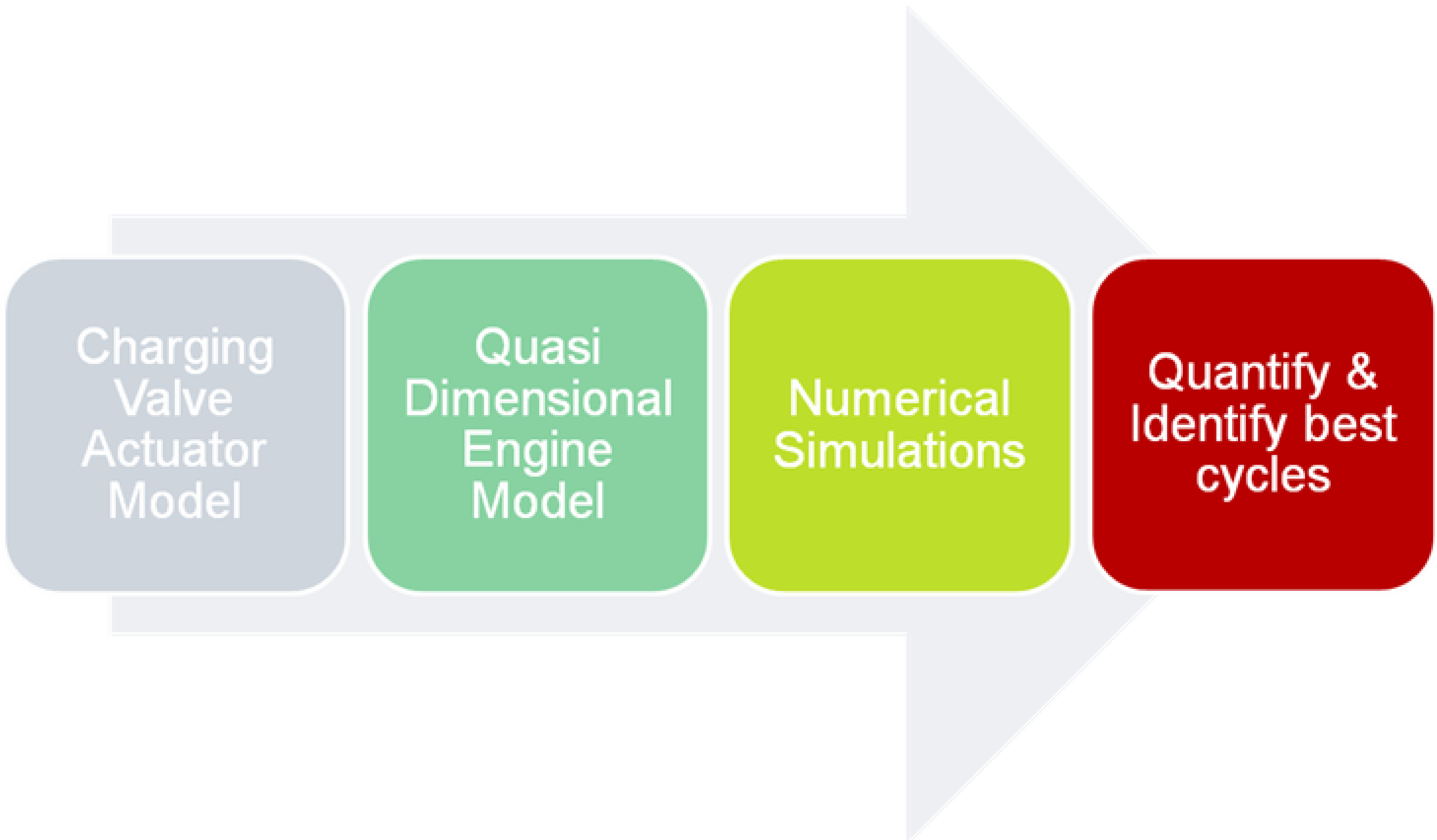
4 Stroke Pneumatic PUMP Mode

4-STROKE PUMP CYCLE EXHAUST OFF



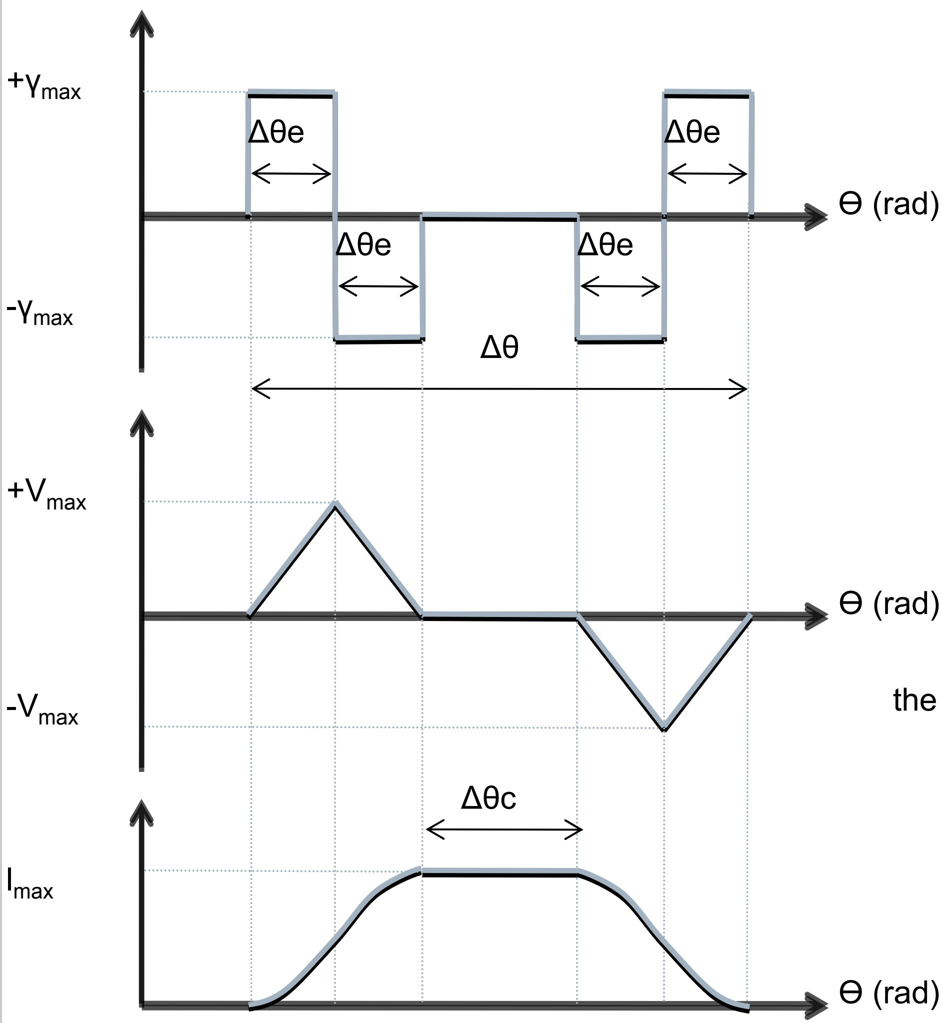
4 stroke PUMP Exhaust OFF

All idealized cycles presented suppose an instantaneous opening and closure of the valves, thus an Infinite acceleration



3 - KINEMATIC MODEL OF THE CHARGING VALVE

Kinematic Model Of The Charging Valve



$$\gamma = \gamma_\theta . \omega^2$$

$$v_{max} = \gamma_{max} . \frac{\Delta\theta e}{\omega}$$

$$l_{max} = \gamma_{max} . \left(\frac{\Delta\theta e}{\omega}\right)^2$$

$\Delta\theta \geq 4.\omega\sqrt{\frac{l_{max}}{\gamma_{max}}}$	$\Delta\theta < 4.\omega\sqrt{\frac{l_{max}}{\gamma_{max}}}$
$\Delta\theta_c \geq 0$	$\Delta\theta_c = 0$
the valve reaches the desired lift l_{max}	the valve does NOT reach the desired lift l_{max}
$\Delta\theta e = \omega\sqrt{\frac{l_{max}}{\gamma_{max}}}$	$\Delta\theta e = \frac{\Delta\theta}{4}$ $l_{effective} = \gamma_{max} . \left(\frac{\Delta\theta}{4.\omega}\right)^2$

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Kinematic Model Of The Charging Valve

- Desired max lift is l = 5mm
- Δθ= 20 ° with Δθe=5° (max duration available)
- ω=3000 RPM

=> **γ = 64 800 m/s².**

Today's actuator cannot produce such a high acceleration **(γ =3 000 m/s²)**

Comparison : a traditional camshaft for N=7000 RPM produces :

γ =10 000 m/s²

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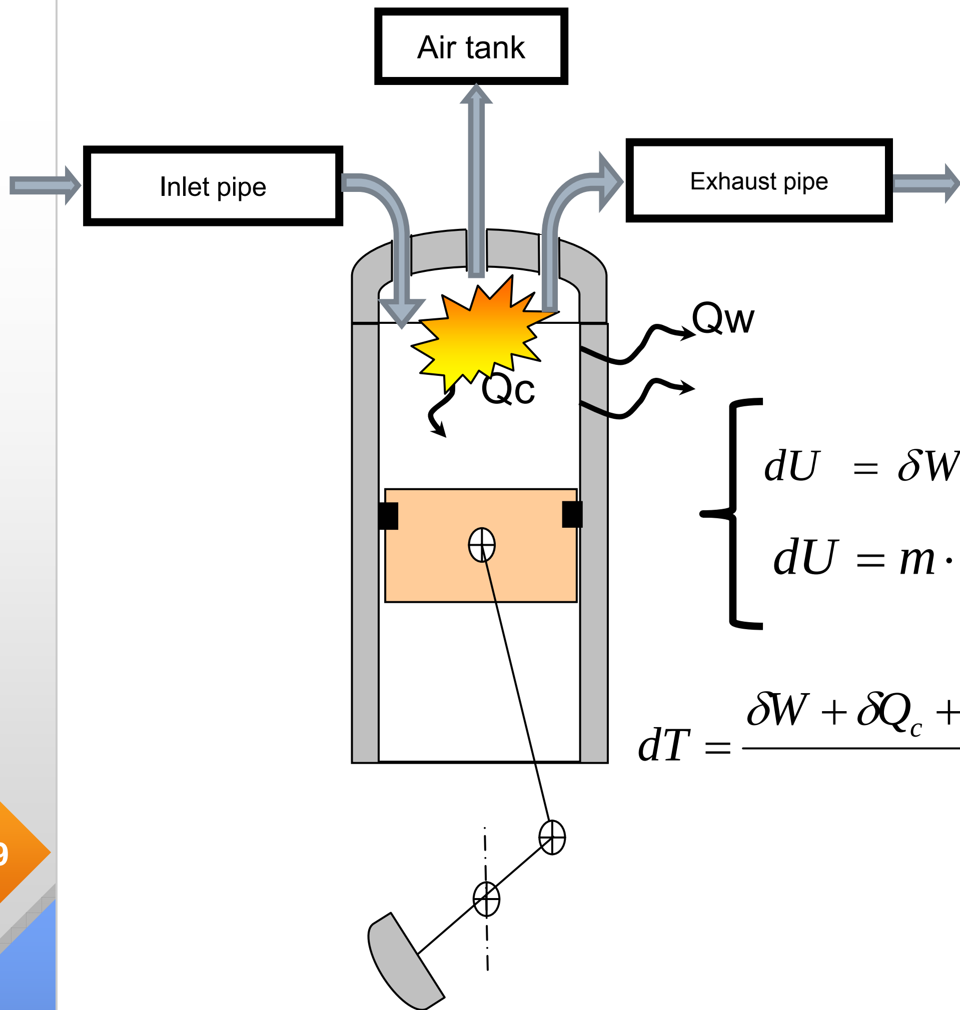
4 - QUASI DIMENSIONAL ENGINE MODEL.

Quasi Dimensional Engine Model



Barré Saint Venant Equation

⇩

$$dm_i , dm_o$$

(5 majors chemical species : O_2 N_2 C_xH_y CO_2 H_2O)

⇩

δQw : Standard WOSCHNI model

δQc : Standard WIEBE model

⇩

$$\begin{cases} dU = \delta W + \delta Q_c + \delta Q_w + \sum h_i \cdot dm_i + \sum h_o \cdot dm_o \\ dU = m \cdot c_v \cdot dT + c_v \cdot T \cdot dm \end{cases}$$

⇩

$$dT = \frac{\delta W + \delta Q_c + \delta Q_w + \sum h_i . dm_i + \sum h_o . dm_o - c_v \cdot T \cdot dm}{m \cdot c_v}$$

⇩

$$T = \int dT$$

⇩

$$P = \frac{m \cdot r \cdot T}{V}$$

5 – SIMULATIONS RESULTS

Simulated Engine

Single Cylinder

Cylinder volume around 400 cm3

5 valves including one Charging valve

Charging valve diameter is around 15 mm

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Pneumatic PUMP Mode

Air Tank Pressure : 5 bar

Engine speed : 1500 RPM

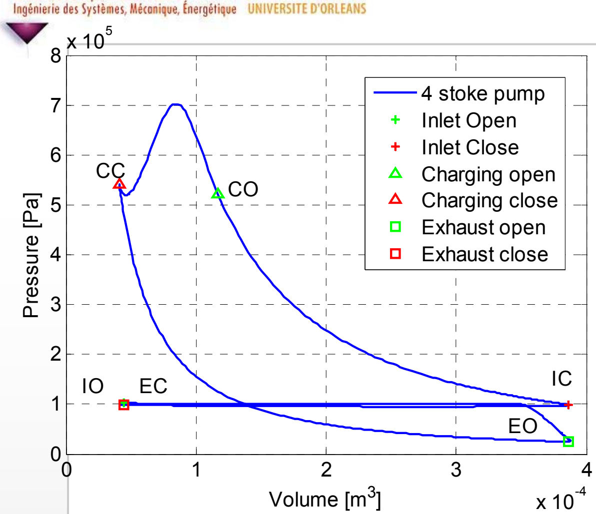
Valve acceleration : 3 000 m/s²

For each mode, the opening and closure timings of the **charging valve** have been **optimized.**

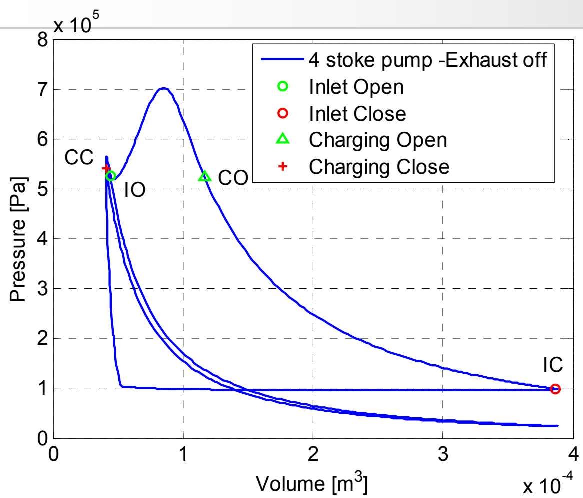
CRITERION : Maximize the air sent to the tank.

	4-Stroke	4-Stroke Exhaust Off	2-Stroke full variable (*)
Inlet Open	-10°	710°	35°
Inlet Close	190°	190°	190°
Charging Open	310°	310°	310°
Charging Close	360°	360°	360°
Exhaust Open	530°	x	x
Exhaust Close	10°	x	x

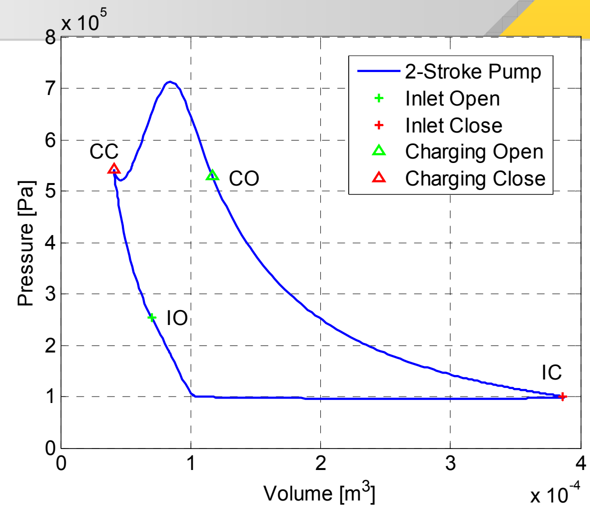
Pneumatic Pump Mode



4 Stroke Pump



4 Stroke Pump
Exhaust Off

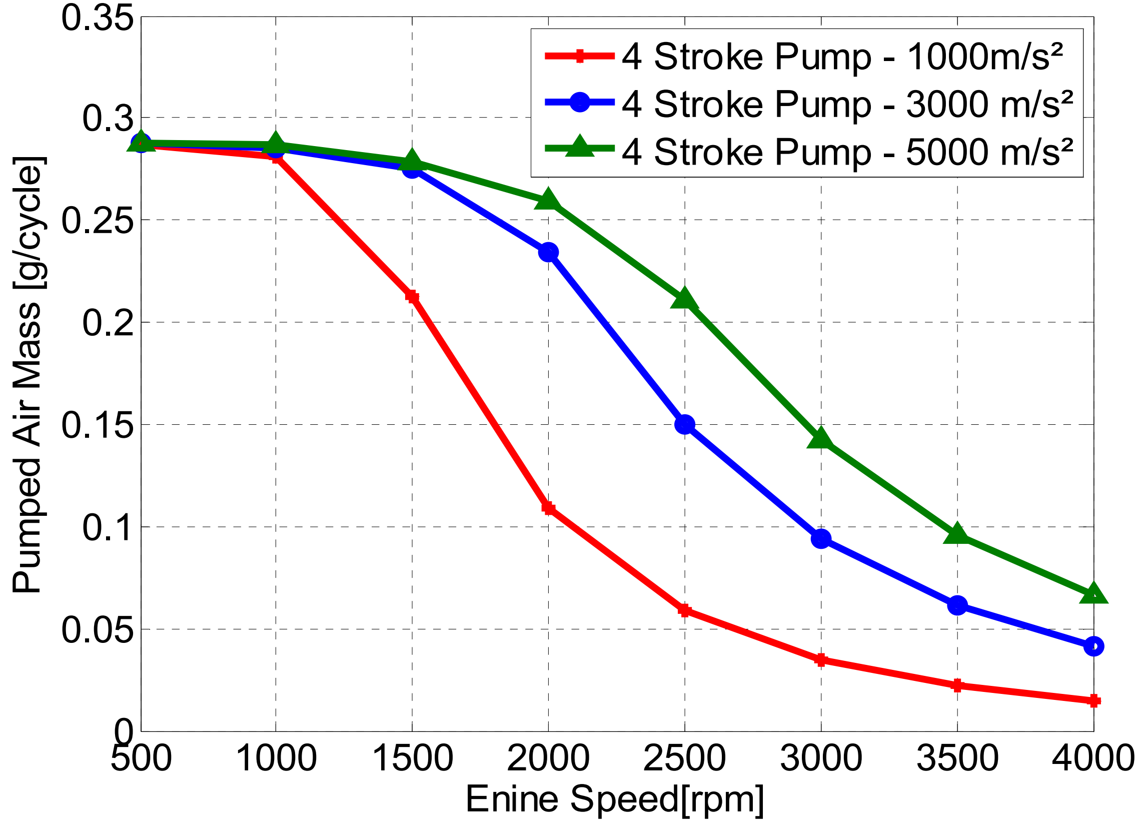


2 Stroke Full Variable

$$SPC\left(\frac{J}{g}\right) = \frac{Wi\left(\frac{J}{cycle}\right)}{m_{air.tank}\left(\frac{g}{cycle}\right)}$$

	4-stroke	4-stroke Exhaust Off	2-stroke full variable
Indicated Work (J/cycle)	73.1	74.1	62.9
Pumped Air mass (g/cycle)	0.275	0.275	0.280
S.P.C. (J/g)	265.9	269.6	224.6

Impact of the Valve-train sophistication on the performance of the pneumatic PUMP mode



N < 1000 RPM => No significant effect

N > 1000 RPM => Serious impact of the acceleration on performance

Pneumatic MOTOR Mode

Air Tank Pressure : 10 bar

Engine speed : 1500 RPM

Valve acceleration : 3 000 m/s²

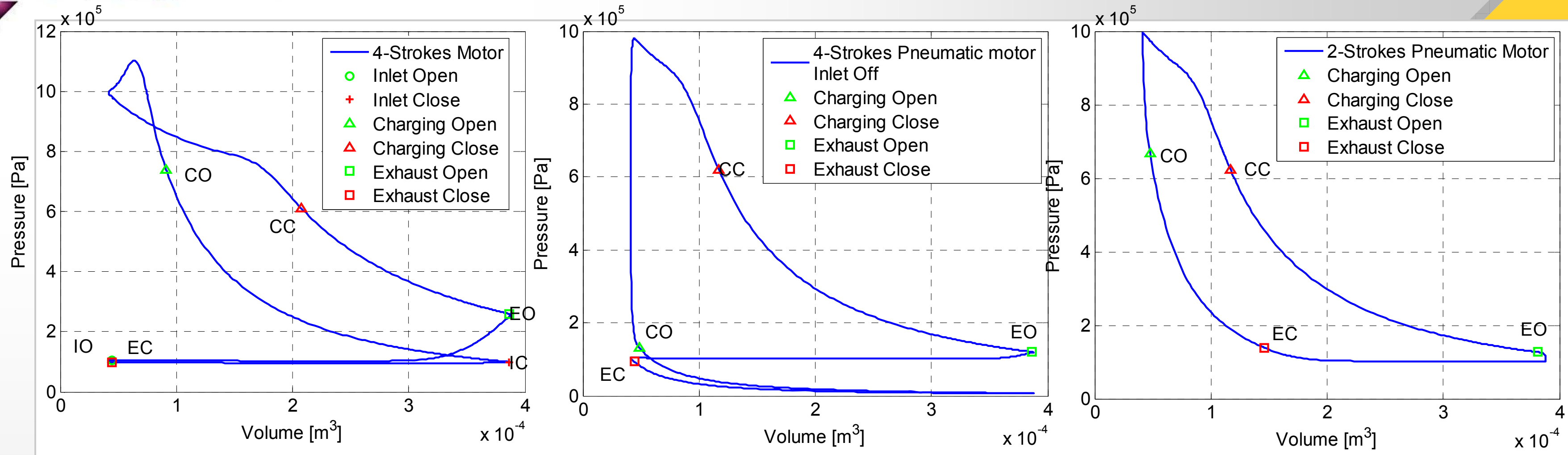
For each mode, the opening and closure timings of the **charging valve** have been **optimized.**

CRITERION : Maximize the Pneumatic Motor Efficiency

$$PME\left(\frac{J}{g}\right) = \frac{Wi\left(\frac{J}{cycle}\right)}{m_{air.\tan k}\left(\frac{g}{cycle}\right)}$$

	4-stroke	4-stroke Inlet Off	2-stroke full variable
Inlet Open	-10°	x	x
Inlet Close	190°	x	x
Charging Open	320°	345°	-15°
Charging Close	440°	410°	50°
Exhaust Open	530°	530°	160°
Exhaust Close	10°	10°	-60°

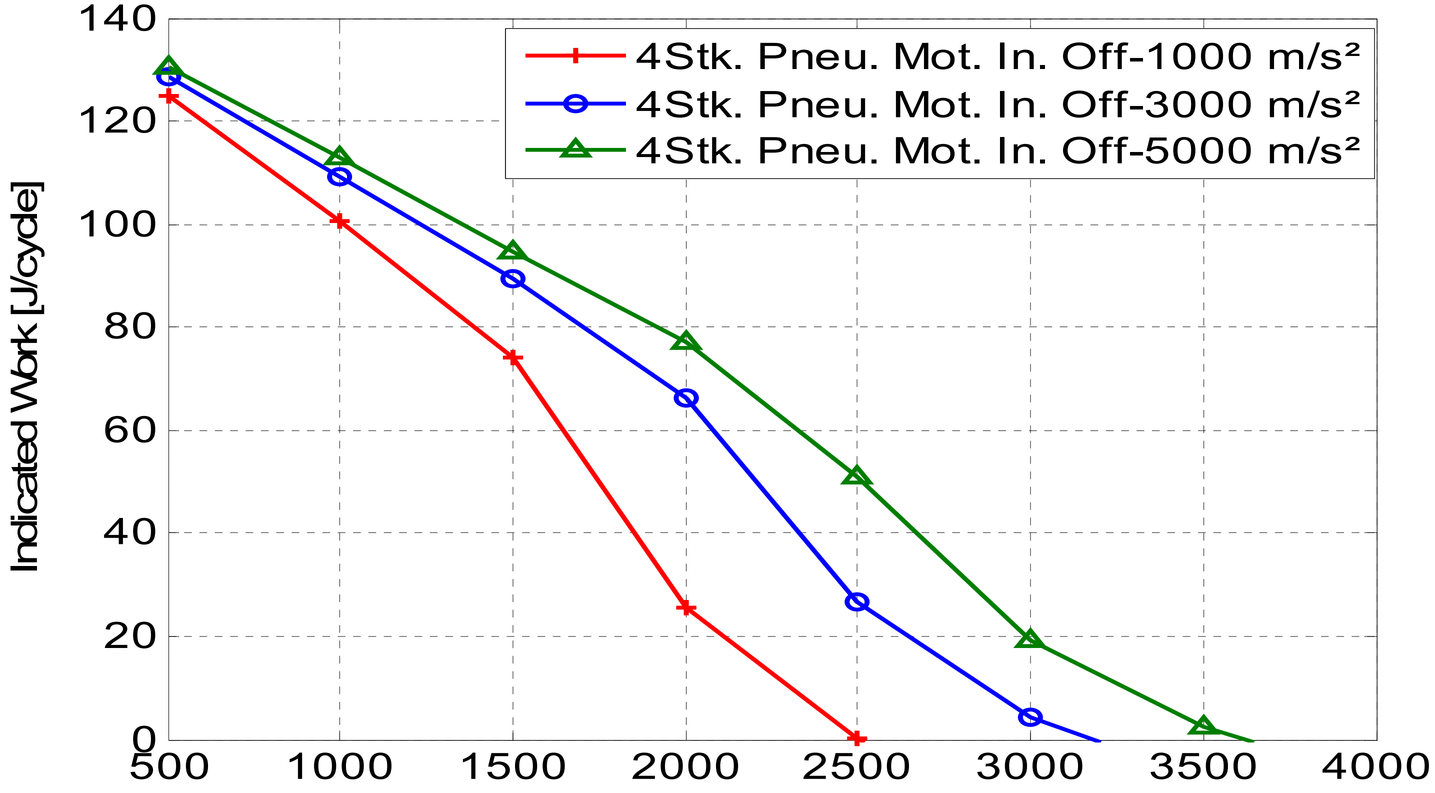
Pneumatic MOTOR Mode



$$PME\left(\tfrac{J}{g}\right) = \frac{Wi\left(\frac{J}{cycle}\right)}{m_{air.\tan k}\left(\frac{g}{cycle}\right)}$$

	4-stroke	4-stroke Inlet Off	2-stroke full variable
Indicated Work (J/cycle)	74.6	94.80	76.26
Consumed Air mass (g/cycle)	0.983	0.767	0.547
P.M.E. (J/g)	75.9	123.4	**139.3**

Impact of the Valve-train sophistication on the performance of the pneumatic MOTOR mode



Important loss of Indicated Work for any value of acceleration, as soon as N = 1500 RPM

=> Pneumatic motor should be used to start and drive the vehicle at low speed.

6 – CONCLUSION

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CONCLUSION

1. The valve train acceleration is the key to best performance for pneumatic cycles, especially for the pump mode. For higher maximum valve accelerations, the range where pneumatic modes can be used with high efficiency is extended.

2. In the case of 4-Stroke modes (motor and pump), it has been showed, that a benefit exists in using a disengagable inlet camshaft. Conversely, no benefit has been founded with a disengagable Exhaust camshaft

3. In the case of 2-Stroke fully variable modes, simulations have shown a slight benefit of using them. But the technical complications and the cost generated leave the question of the viability of these solutions open.