New Ceramic Thermal Barrier Coatings Development in a Spark-Ignition Engine – Experimental Investigation

Bernard Bouteiller, Alain Allimant, Jean-Marc Zaccardi, Jerome Cherel

EFFICIENT ADDITIVATED GASOLINE LEAN ENGINE

GV-02-2016 – PROJECT 724084

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IFP Energies nouvelles

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ITSC, Yokohama ; Japan ; May 29th, 2019

ITSC2019 New Waves of Thermal Spray Technology for Sustainable Growth
INTERNATIONAL THERMAL SPRAY CONFERENCE AND EXPOSITION
YOKOHAMA, JAPAN
MAY 26-29, 2019

EFFICIENT ADDITIVATED GASOLINE LEAN ENGINE

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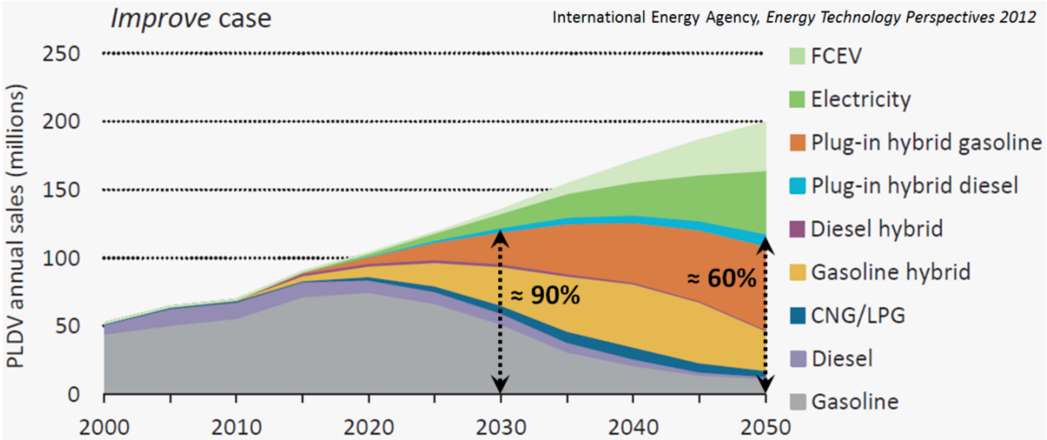
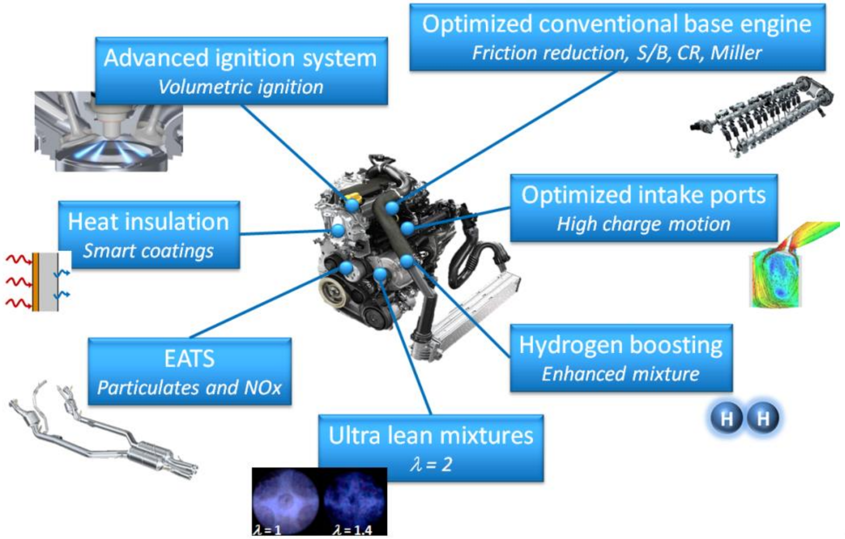
This project has received funding from the European Union's Horizon 2020 research and innovation programme

Funding ≈ 6M€

October 2016 - March 2020

- EAGLE project objectives
  - Long term fleet target of 50 gCO_2/km (WLTC)
  - 50% peak thermal efficiency
    - Ultra-lean mixtures (high air/fuel ratio)
    - H_2 boosting
    - Pre-chamber ignition system
    - Optimized intake ports
    - **Smart coatings**
    - Optimized NOx after-treatment systems





CONTENT

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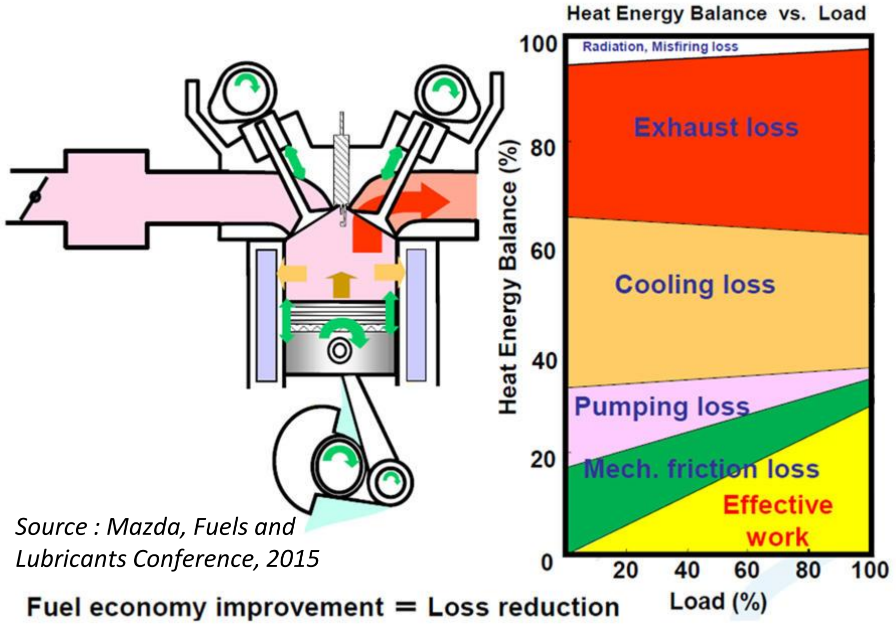
- Concept
- Specifications
- Material screening & selection
- Coating system
- Testing / improvement
  - Testing rig
  - Test results
- Test sum-up
- Perspective

CONCEPT

Energy losses in internal combustion engine



Source : Mazda, Fuels and Lubricants Conference, 2015

>30% of fuel energy is lost through heat energy transfer to cooling system

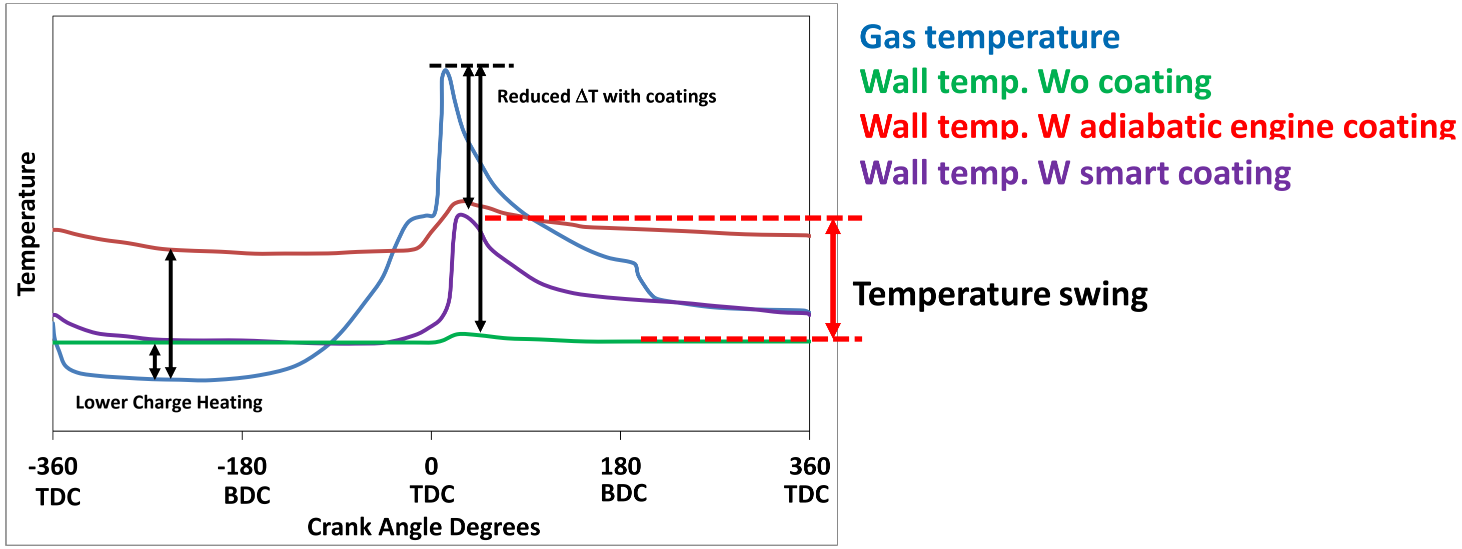
$\Rightarrow$ Heat transfer gas to wall

$$\Phi = \text{Area} \, . \, \underset{Coefficient}{\overset{Heat}{Convection}} \, . \, (T_{Gas} - T_{Wall})$$

How can we reduce those cooling losses ?

- Adiabatic engine (tested in 80s~90s)

  $\Rightarrow$NOT THE SOLUTION : Too much downgrade of the combustion efficiency due to heat accumulation



- Smart coating / thermo-swing coating
  - SOLUTION ? : Close match between wall and gas temperature during at every point of the combustion cycle

COATING DEFINITION

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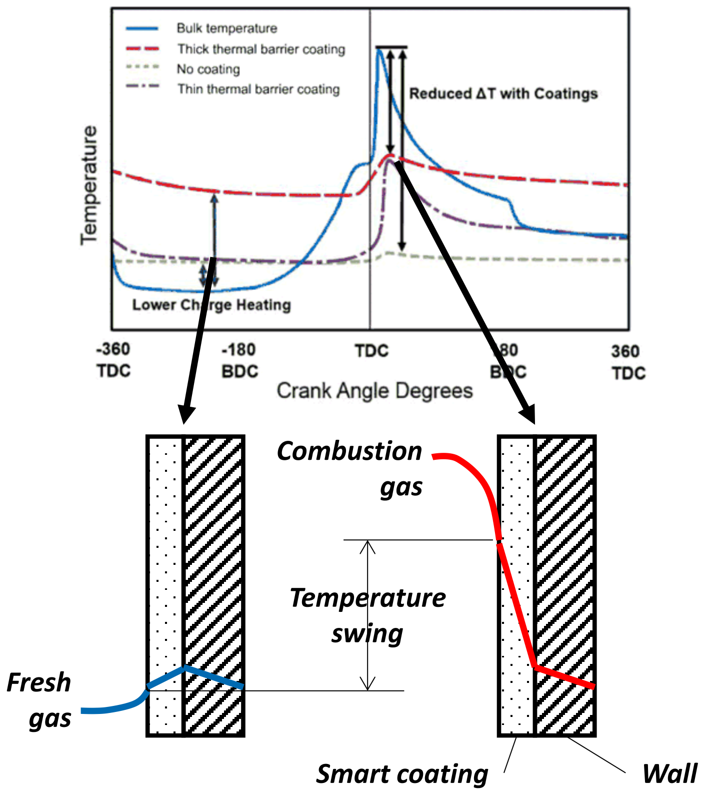
- Close match between wall and gas temperature during at every point of the combustion cycle

⇒ Insulation without heat accumulation

- Coating specifications
  - Low thermal conductivity
  - Low volumetric heat capacity
    - Density ; specific heat capacity ; porosity
  - Low volume => low thickness
    - Around 100µm
  - High mechanical strength at medium temperature
    - Thermal cycling = 10-40 Hz

Source : Int. Jour. Powertrain



MATERIALS: SCREENING / SELECTION

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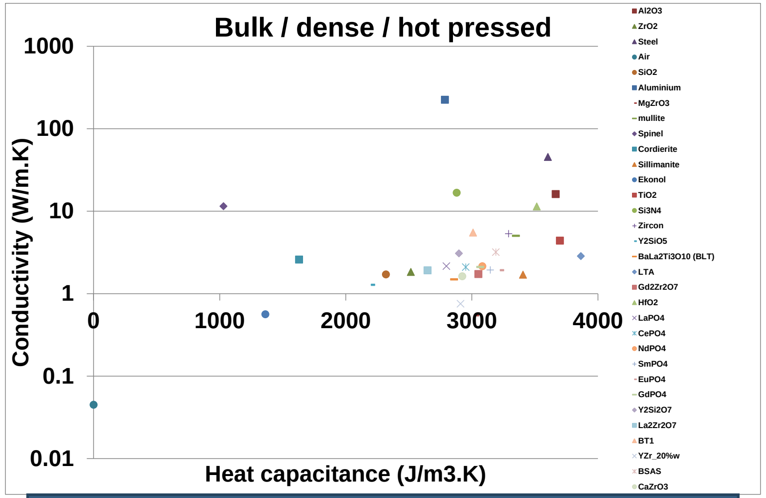
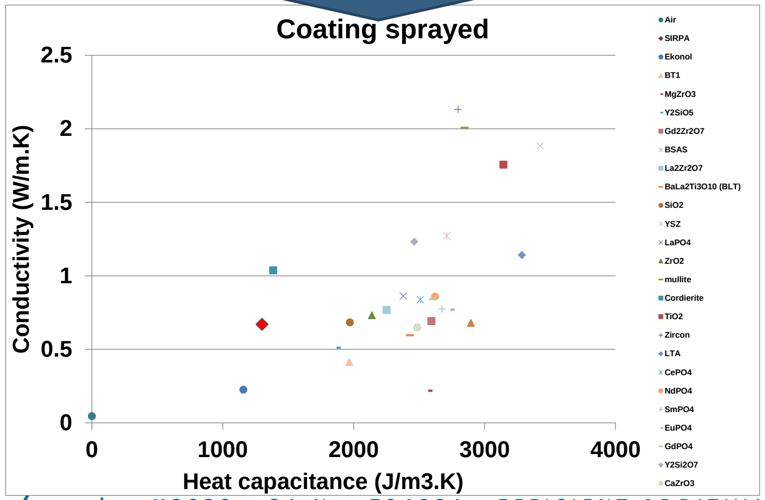
Material screening from literature



Use of Hashin–Shtrikman model to estimate properties as porous



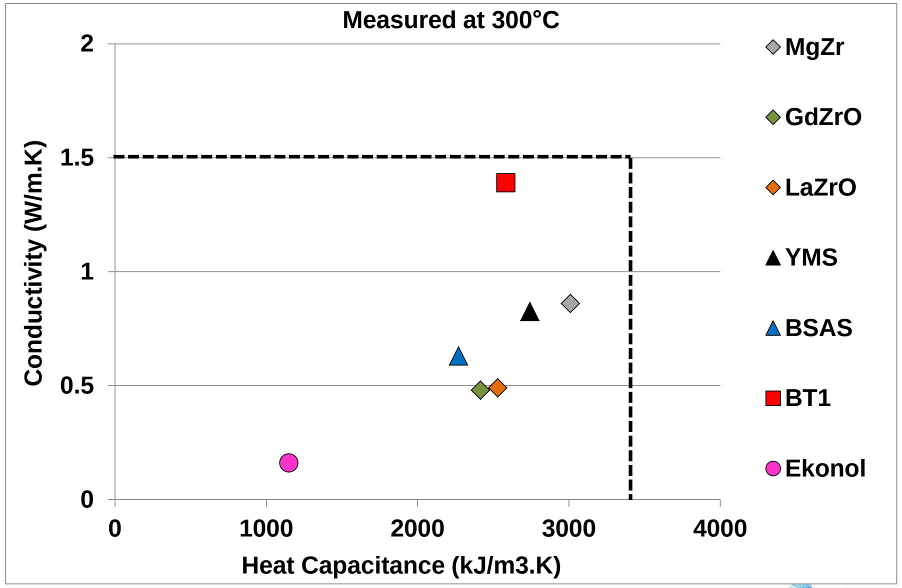
Material selection criteria : better than materials which show positive impact in literature ($<1.5\ W.m^{-1}.K^{-1}$; $<3500\ kJ.m^{-3}.K^{-1}$)

Selection:

⇒ **Ceramic oxide**
  ⇒ **Zirconate (MgZr, LaZr, GdZr)**
  ⇒ **Silicate (BSAS, YMS)**

⇒ **Quasicrystal**
  ⇒ **Cristome® BT1**

⇒ **Polymer**
  ⇒ **Ekonol®**



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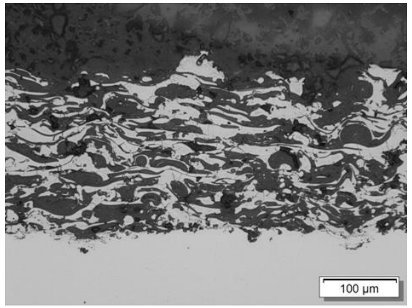
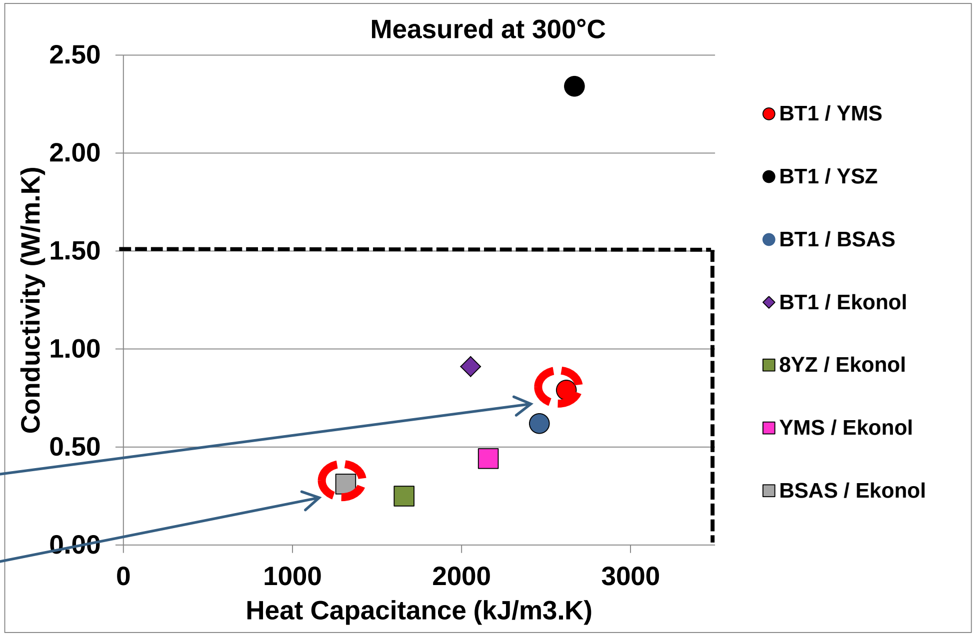
COATING SYSTEM

- High mechanical strength at medium temperature
  - Avoid brittle behavior
  - Avoid CTE mismatch

⇒ Composite of different nature of materials
  - Ceramic oxide / Polymer
  - Quasicrystal / Ceramic oxide
  - Polymer /Quasicrystal

- Thermal properties
  - Inside our target <1.5 $W.m^{-1}.K^{-1}$; <3500 $kJ.m^{-3}.K^{-1}$





Selection of two coating materials
- **Ceramic oxide (YMS) + Quasicrystal (BT1®)**
  - **Assumption good matching with substrate**
- **Ceramic oxide (BSAS) + Polymer (Ekonol®)**
  - **Best tradeoff**

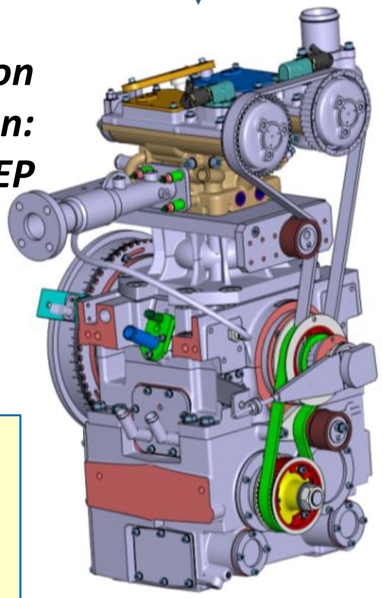
APPLICATION TEST / OUTCOMES

- Test of insulation coatings on single cylinder engines

Metal single cylinder engine

Thermodynamic performance

Aluminum piston
Operating condition:
3000rpm-7bar IMEP

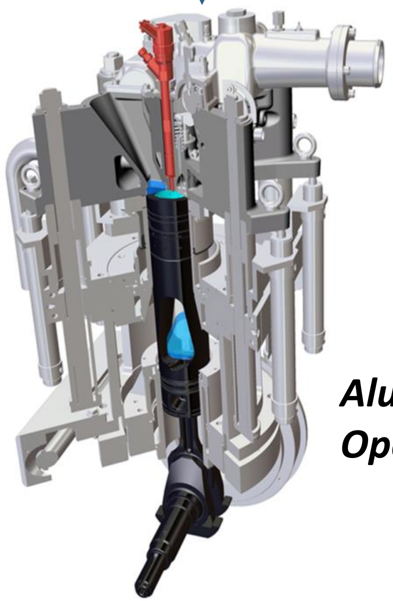


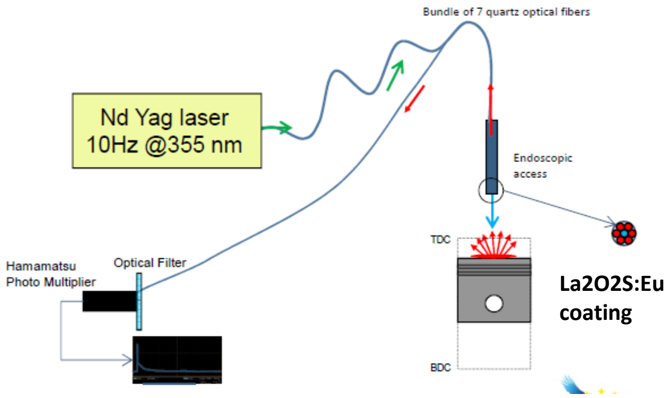
⇒ Fuel consumption
⇒ Combustion behavior
⇒ Gas emissions

Similar properties
Stroke, bore, CR, …

Optical single cylinder engine

Temperature swing measurements using LIP (Laser Induced Phosphorescence)





Aluminum & steel piston
Operating condition: 2000rpm-4bar IMEP

⇒ Piston surface temperature

Lean gasoline engine
λ= ratio between the actual air-fuel ratio and the stoichiometric air-fuel ratio

BASE LINE : SINGLE LAYER

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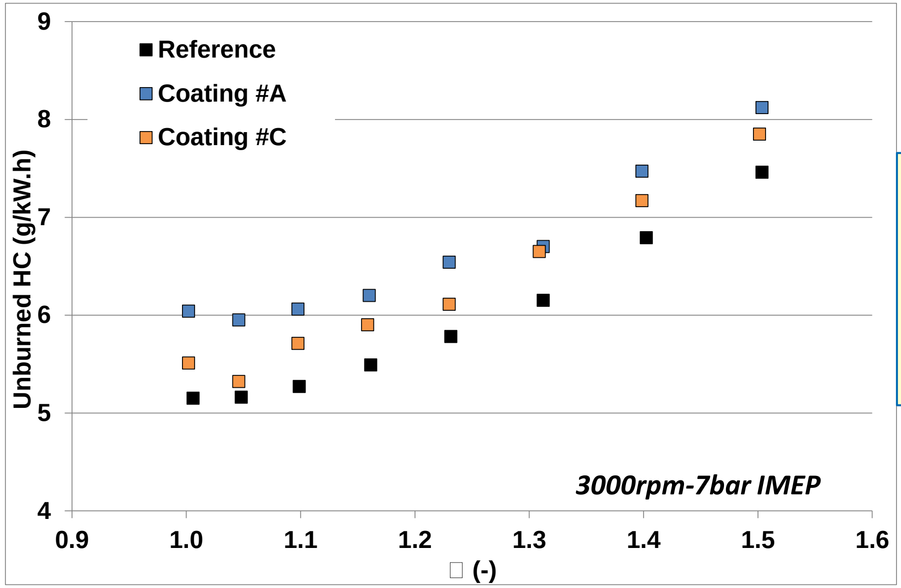
- 2 first coatings tested : Coating #A & #C
- Main drawback measured
  - Unburned hydrocarbon emissions increase by 15~20%
- Assumption impact of roughness and/or open porosity

Name	Coating #A	Coating #C
Nature	Single layer - Quasi crystal / ceramic oxide composite	Single layer - Polymer / ceramic oxide composite
Thickness [µm]	Piston: 126 +/- 7	Piston: 104 +/- 7
Porosity [%]	10	26
Roughness - Ra [µm]	8	10



Unburned hydrocarbon emissions to be reduced
⇒ Fuel trapped in
⇒ Roughness ?
⇒ Open porosity ?

IMPROVE COATING SYSTEM : TOP LAYER

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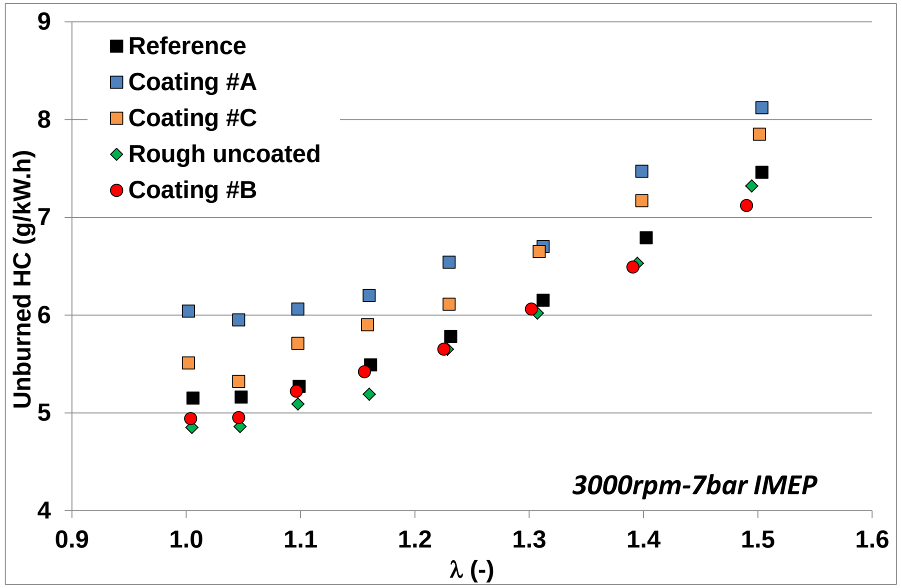
- Discriminate effect of porosity and roughness
  - Uncoated piston with equivalent roughness as coating designed and tested
  - Double layer with dense top layer :
    - Polymer / Ceramic oxide + dense Ceramic oxide layer (results not shown)
    - Quasicrystal /Ceramic oxide + sealing layer

Name	Coating #A	Coating #B	Coating #C	Rough piston
Nature	Single layer - Quasi crystal / ceramic oxide composite	Double layer - Quasi crystal / ceramic oxide composite - Sealing layer on top	Single layer - Polymer / ceramic oxide composite	Un-coated
Thickness [µm]	Piston: 126	Piston: 160	Piston: 104	-
Porosity [%]	10	10 (bottom layer) 0 (top layer)	26	“0”
Roughness – Ra [µm]	8	1	10	9



No increase of Unburned HC with dense layer and rough uncoated piston
⇒ Open porosity to be reduced

THERMODYNAMIC PERFORMANCE AND TEMPERATURE SWING

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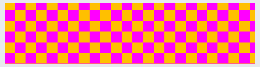
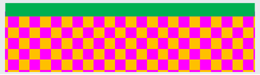
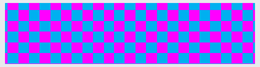
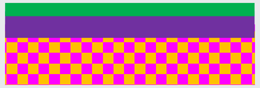
- Properties of coating tested on single cylinder engines

Name	Coating #A	Coating #B	Coating #C	Coating #D	Coating #E
Nature	Single layer - Quasi crystal / ceramic oxide composite	Double layer - Quasi crystal / ceramic oxide composite - Sealing layer on top	Single layer - Polymer / ceramic oxide composite	Double layer - Polymer / ceramic oxide composite - Dense ceramic oxide on top	Triple layer - Quasi crystal / ceramic oxide composite - Dense ceramic oxide layer - Sealing layer on top
Schematic					
Thickness on parts for metal engine [µm]	Piston: 126+/- 7	Piston: 160+/- N.A.	Piston: 104+/- 7	-	Piston: 207+/- 20 Cyl. head: 154+/- 20
Thickness on parts for optical engine [µm]	Piston: 158 +/- 8	-	Piston: 126 +/- 10	Piston: 130 +/- N.A.	Piston: 133 +/- 8
Porosity [%]	10	10 (bottom layer) 0 (top layer)	26	26 (bottom layer) 4 (top layer)	10 (bottom layer) 4 (middle layer) 0 (top layer)
Roughness – Ra [µm]	8	1	10	5	2
Conductivity [W.m-1.K-1]	0.79	0.88	0.38	0.46	0.85
Heat capacitance [kJ.m-3.K-1]	1600	2500	1200	1700	2600
Density	4.2	4.1	1.8	2.3	4.2

Several compositions (QC, CO, P) and structures (# layer and composite)

From 100 to 200µm

w/ & w/o open porosity on top layer

Low conductivity
Low heat capacitance

TEMPERATURE SWING

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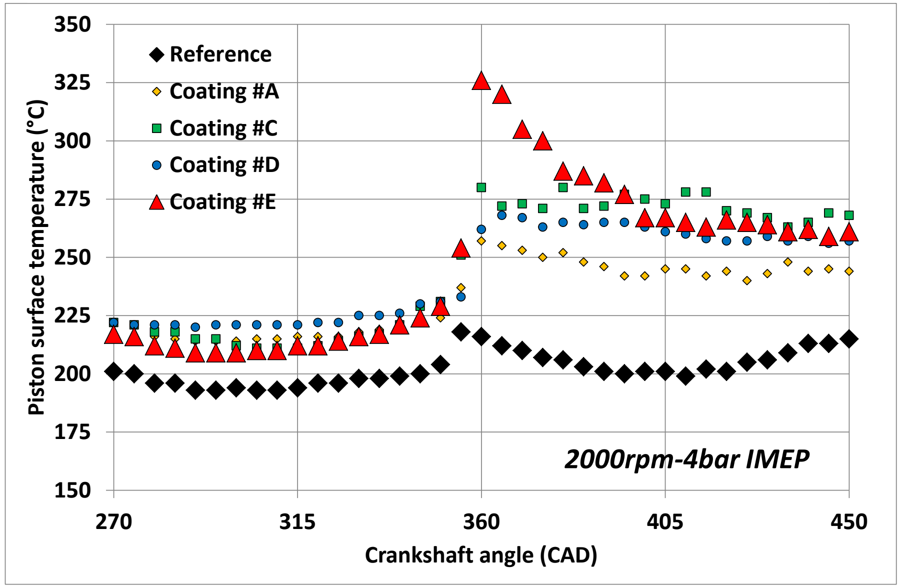
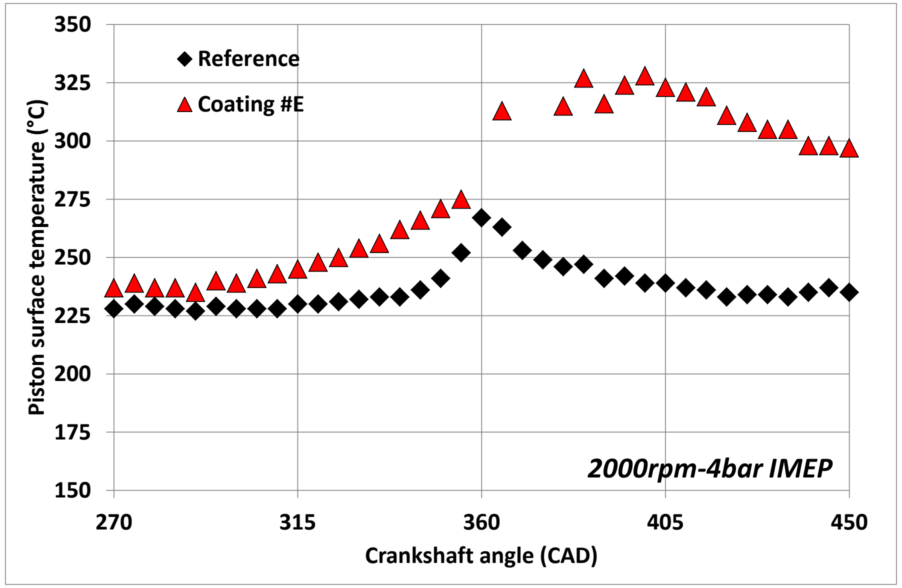
- Temperature swing (LIP) on Aluminum and Steel piston

Aluminum piston



Steel piston



	2000 rpm – 4 bar IMEP	
	Aluminum	Steel
Reference: uncoated piston	20-30°C	35-40°C
Reference + coating #A	40-55°C	Not measured
Reference + coating #C	55-65°C	Not measured
Reference + coating #D	60-65°C	Not measured
Reference + coating #E	100-120°C	70-100°C

⇒ **Temperature swing measured**

⇒ **Similar temperature swing with Steel and Aluminum piston**

THERMODYNAMIC PERFORMANCE

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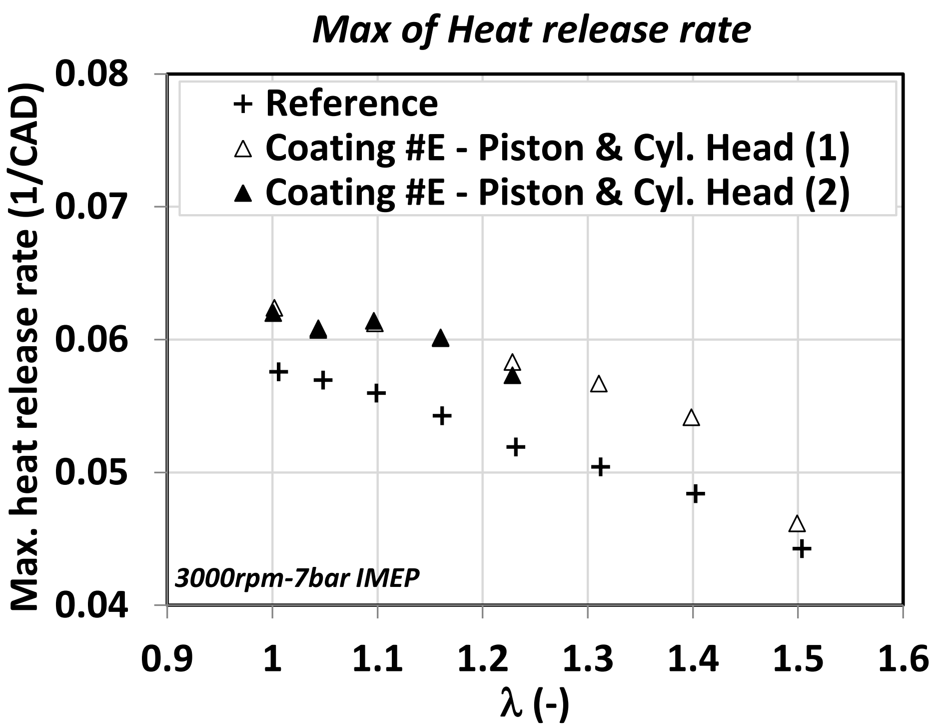
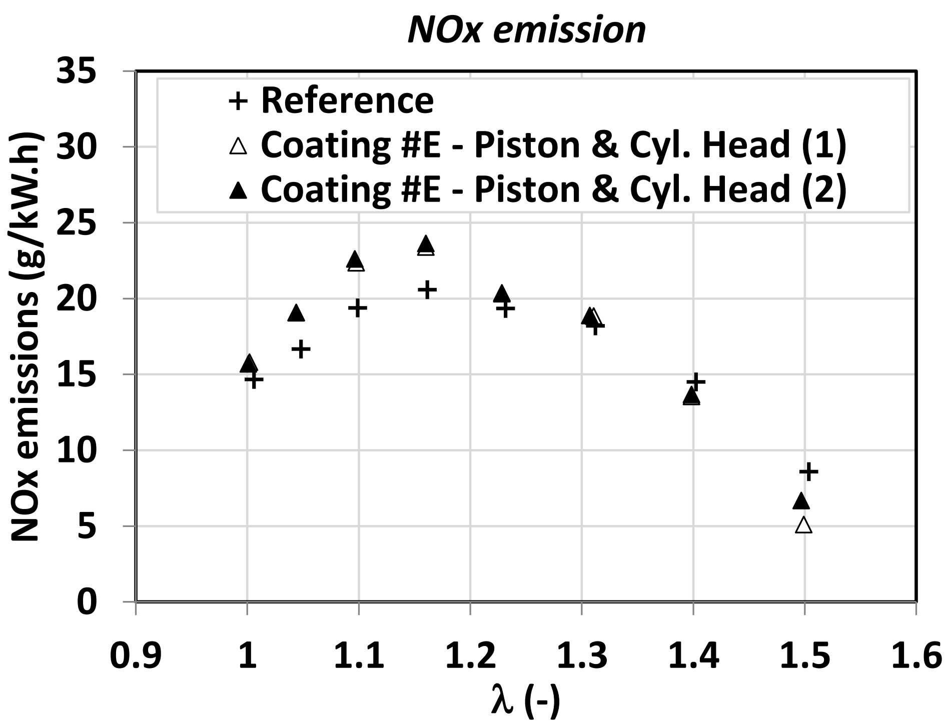
- Combustion behavior : 2 criteria





⇒ **Higher combustion temperature**

- **RoHR shows the combustion (burning rate) speed**
- **NOx thermal formation process**

THERMODYNAMIC PERFORMANCE

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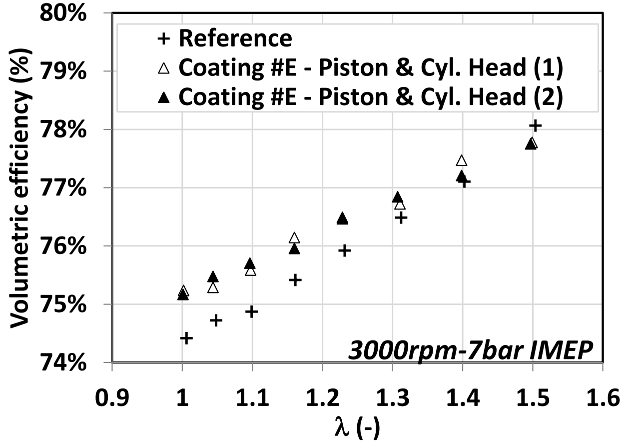
Volumetric efficiency



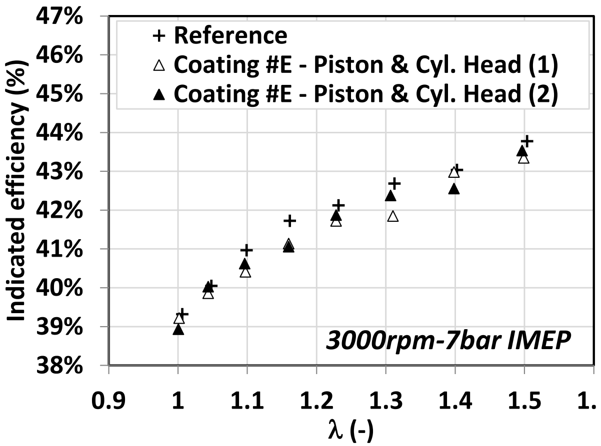
$$Vol.Eff. = \frac{Density\ of\ actual\ air\ fuel\ mixture}{Density\ of\ air\ fuel\ mixture\ at\ manifold\ condition}$$

⇒ Slightly better intake efficiency : No increase of the fresh air temperature during the intake

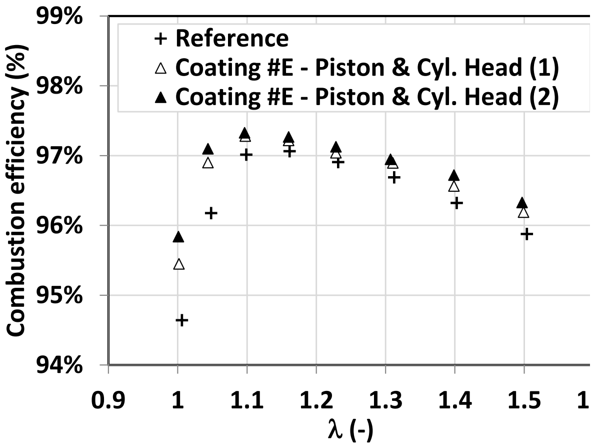
- Consistent with surface temperature measurement
- Drawback of the adiabatic solve with smart coating

Global efficiency

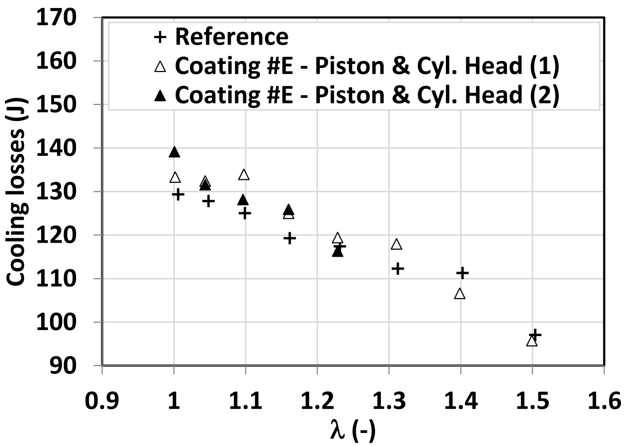
Indicated efficiency



Combustion efficiency



Cooling losses



⇒ No gain using coating on efficiency / fuel consumption

⇒ Small increase (<1% increase) of cooling losses

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EXPERIMENTAL TEST RESULTS SUM-UP

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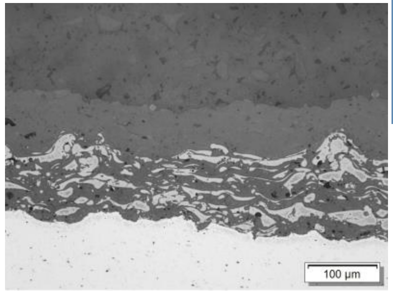

- Porosity
  - Open porosity lead to unburned HC
- Roughness
  - Piston surface roughness has no impact on unburned hydrocarbon emissions and on efficiency without any temperature swing (uncoated piston)
- Coating
  - Highest temperature swing (center piston) measured with coating #E
    - Measured on aluminum and results also obtained on steel piston
  - Higher combustion temperature with coating #E
    - Combustion speed increase and NOx emissions increase
  - No decrease of fuel consumption
  - Cooling losses inside the combustion chamber increased with coating #E
  - No increase of the fresh air temperature during the intake

Coating qualitatively reach the temperature swing objective
⇒ Positive impact on combustion behavior seems showing insulation effect during combustion
⇒ Drawback seems to counterbalance this positive effect => still to be identified

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PERSPECTIVE

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- Coating properties adjustment
  - Better understanding of the heat transfer physics
    - Thermal boundary layer investigation
    - Roughness
    - Radiative properties
  - Thermo-mechanical improvement

- Combination of the EAGLE breakthrough elements in the same engine
  - Combustion chamber design & Coating integration using alternative combustion systems
    - Refine coating location to avoid potential coating negative impact
      - Diffusion-like versus propagation flames
  - Combustion strategy

- End project Q1-2020

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Thank you for your attention