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EFFICIENT ADDITIVATED GASOLINE LEAN ENGINE

GV-02-2016 – PROJECT 724084



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UNIVERSITÀ DEGLI STUDI DI NAPOLI
FEDERICO II



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

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ITSC, Yokohama ; Japan ; May 29th, 2019

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Funding ≈ 6M€

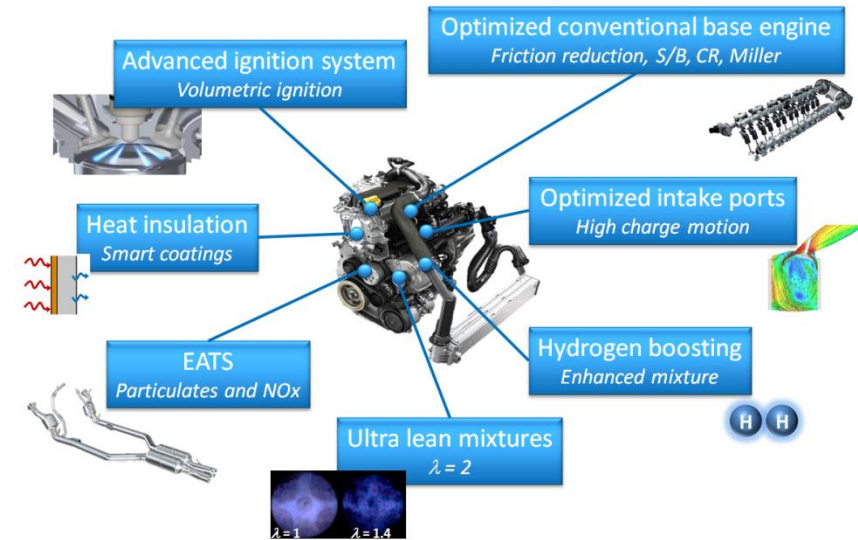
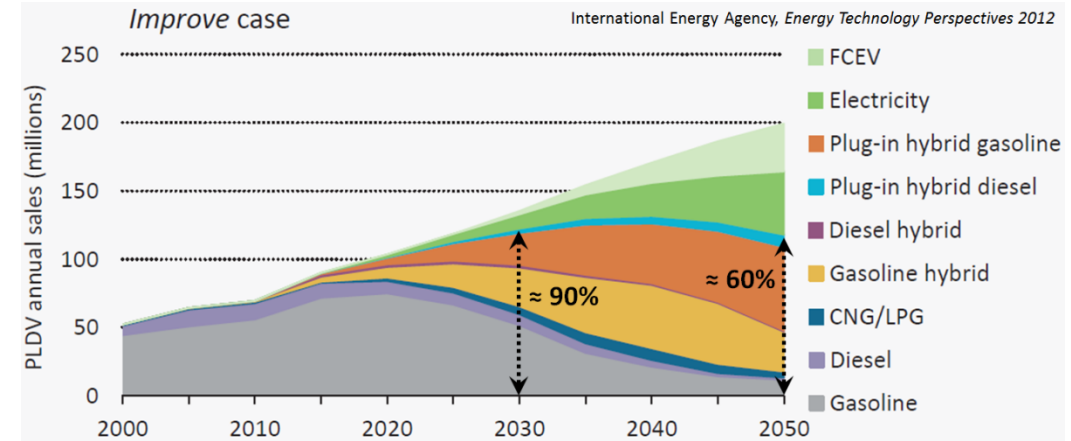
October 2016 - March 2020

EAGLE project objectives

- Long term fleet target of 50 gCO₂/km (WLTC)

- 50% peak thermal efficiency

- Ultra-lean mixtures (high air/fuel ratio)
- H₂ boosting
- Pre-chamber ignition system
- Optimized intake ports
- **Smart coatings**
- Optimized NOx after-treatment systems



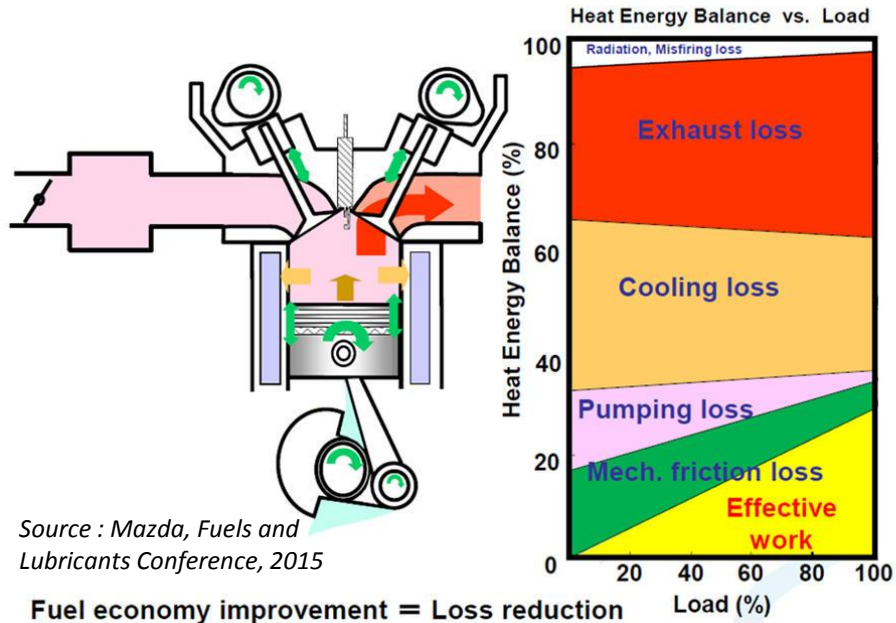
CONTENT

ITSC

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



Energy losses in internal combustion engine



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

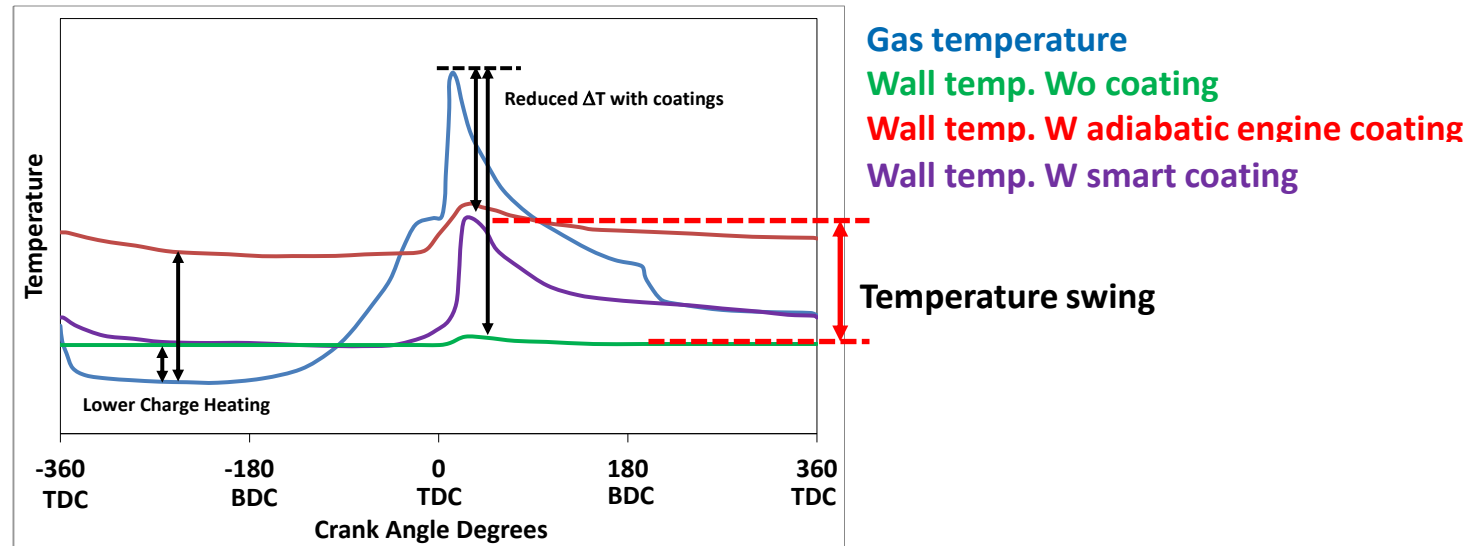
⇒ Heat transfer gas to wall

Heat

$$\Phi = \text{Area} \cdot \text{Convection Coefficient} \cdot (T_{\text{Gas}} - T_{\text{Wall}})$$

How can we reduce those cooling losses ?

- Adiabatic engine (tested in 80s~90s)
⇒ NOT THE SOLUTION : Too much downgrade of the combustion efficiency due to heat accumulation



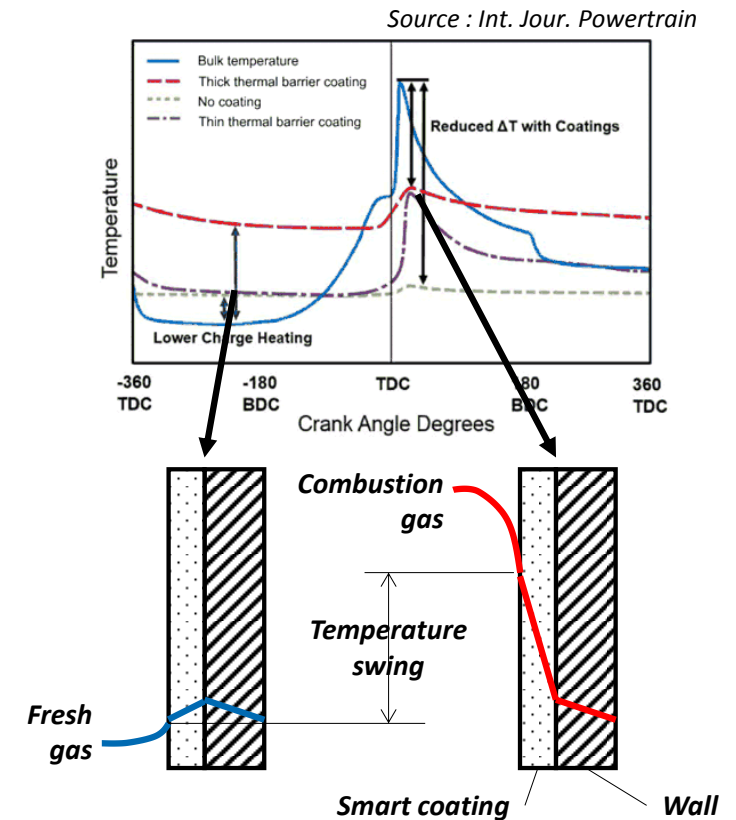
- Smart coating / thermo-swing coating
 - SOLUTION ? : Close match between wall and gas temperature during at every point of the combustion cycle

COATING DEFINITION

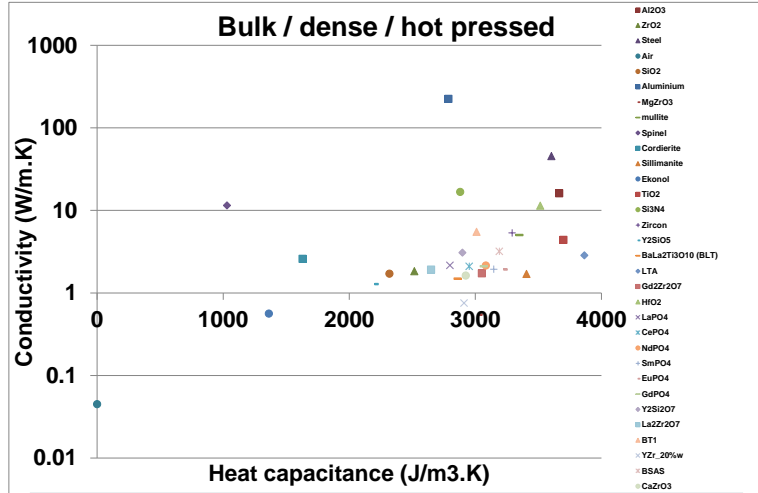
- Close match between wall and gas temperature during at every point of the combustion cycle

⇒ Insulation without heat accumulation

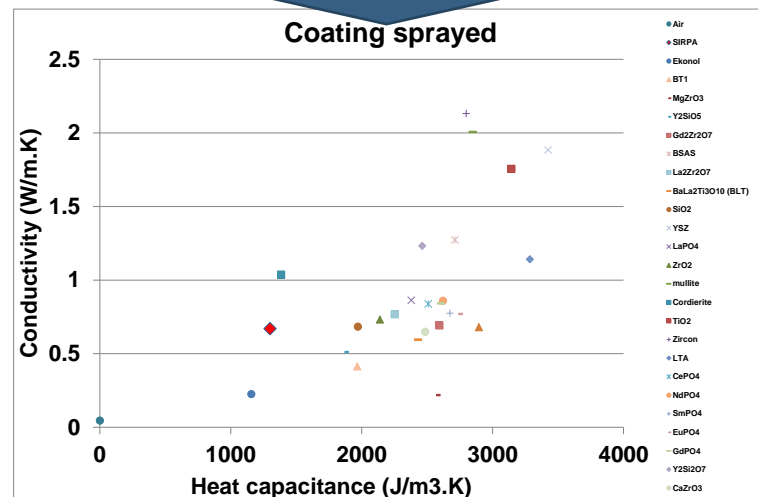
- Coating specifications
 - Low thermal conductivity
 - Low volumetric heat capacity
 - Density ; specific heat capacity ; porosity
 - Low volume => low thickness
 - Around 100 μ m
 - High mechanical strength at medium temperature
 - Thermal cycling = 10-40 Hz



Material screening from literature



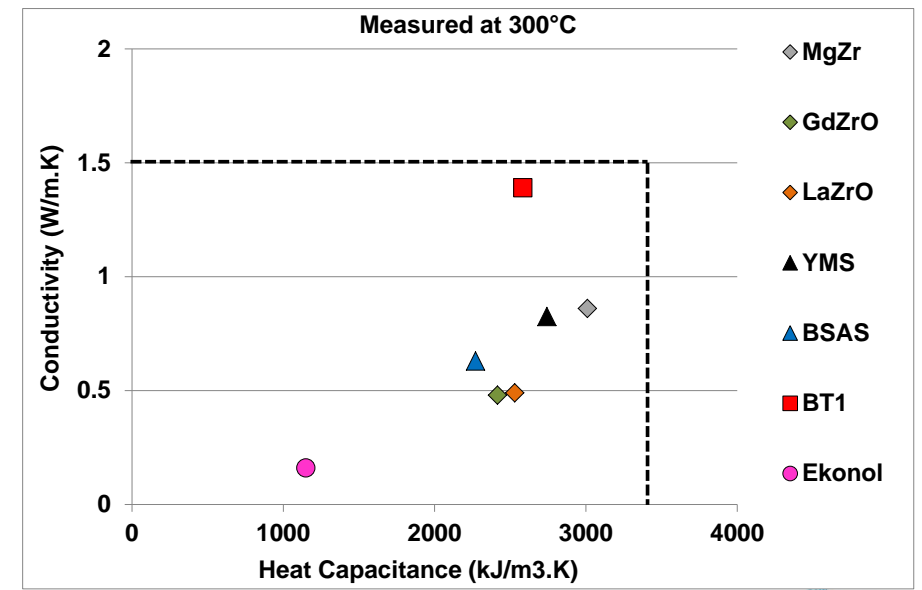
Use of Hashin-Shtrikman model to estimate properties as porous



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



- Selection:**
- ⇒ Ceramic oxide
 - ⇒ Zirconate (MgZr, LaZr, GdZr)
 - ⇒ Silicate (BSAS, YMS)
 - ⇒ Quasicrystal
 - ⇒ Cristome® BT1
 - ⇒ Polymer
 - ⇒ Ekonol®



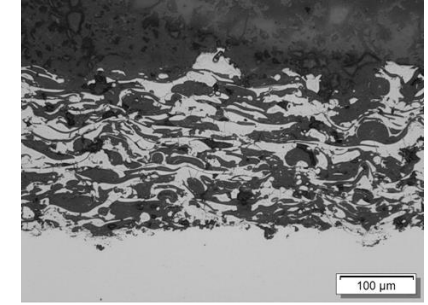
COATING SYSTEM

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

⇒ Composite of different nature of materials

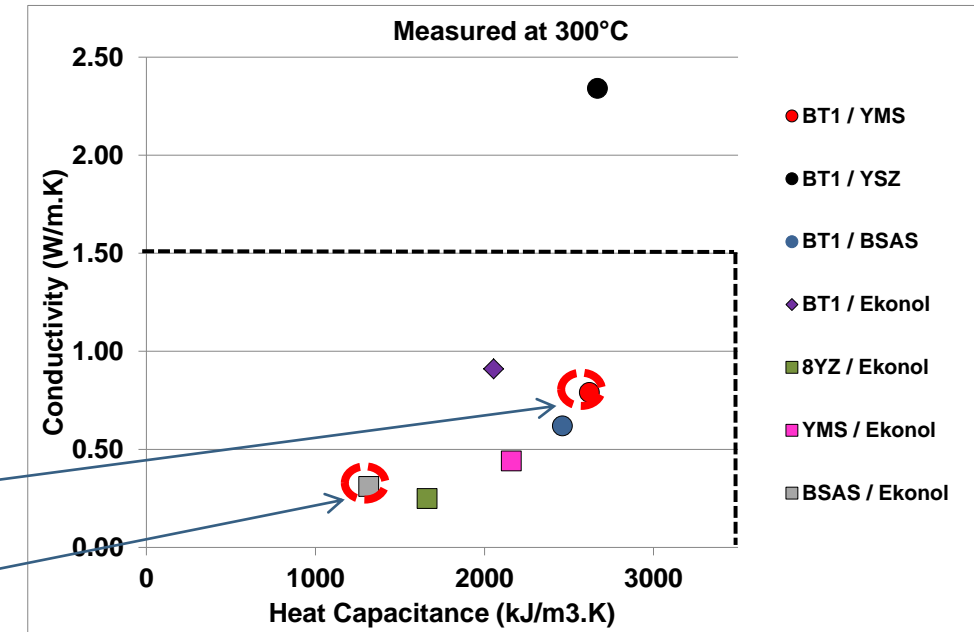
- Ceramic oxide / Polymer
- Quasicrystal / Ceramic oxide
- Polymer /Quasicrystal

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



Selection of two coating materials

- Ceramic oxide (YMS) + Quasicrystal (BT1®)
 - Assumption good matching with substrate
- Ceramic oxide (BSAS) + Polymer (EkonoI®)
 - Best tradeoff



APPLICATION TEST / OUTCOMES

- Test of insulation coatings on single cylinder engines

Metal single cylinder engine

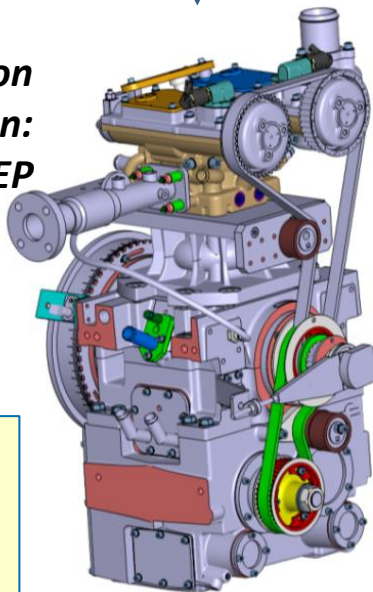


Optical single cylinder engine

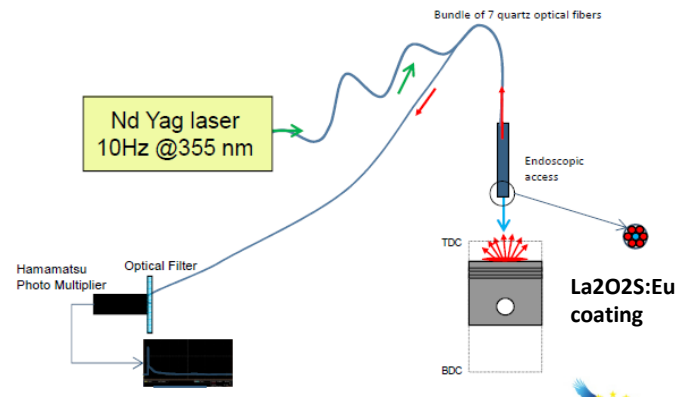
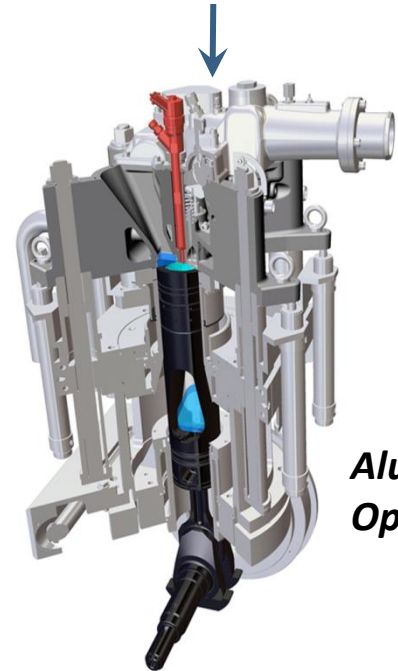
Thermodynamic performance

Temperature swing measurements using LIP
(Laser Induced Phosphorescence)

Aluminum piston
Operating condition:
3000rpm-7bar IMEP



Similar properties
Stroke, bore, CR, ...



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

⇒ Piston surface temperature

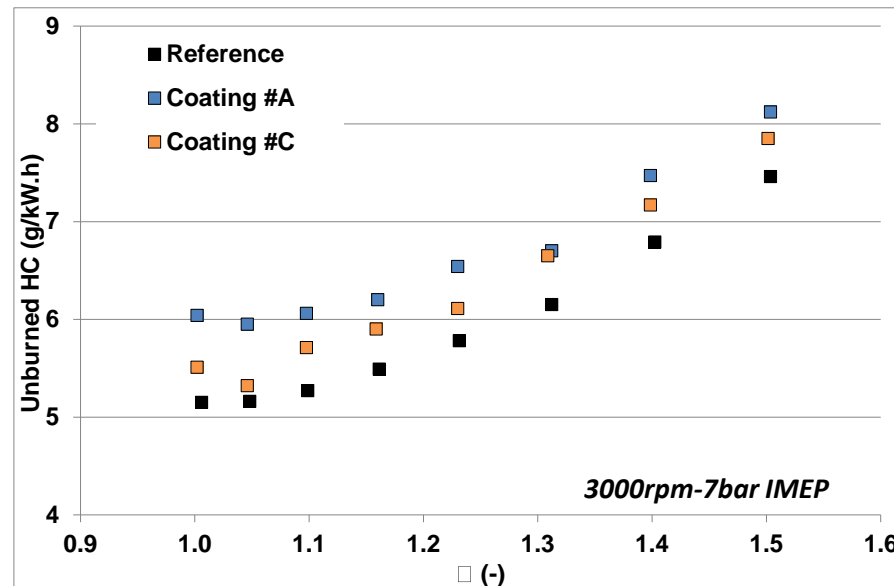
Lean gasoline engine
 λ = ratio between the actual air-fuel ratio and the stoichiometric air-fuel ratio

- ⇒ Fuel consumption
- ⇒ Combustion behavior
- ⇒ Gas emissions

BASE LINE : SINGLE LAYER

- 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

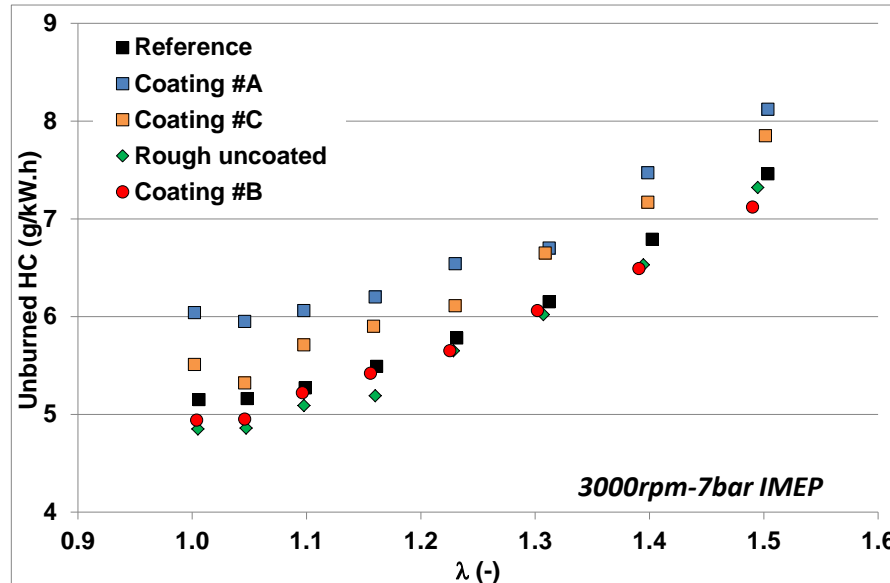
⇒ Roughness ?

⇒ Open porosity ?

IMPROVE COATING SYSTEM : TOP LAYER

- 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

● 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

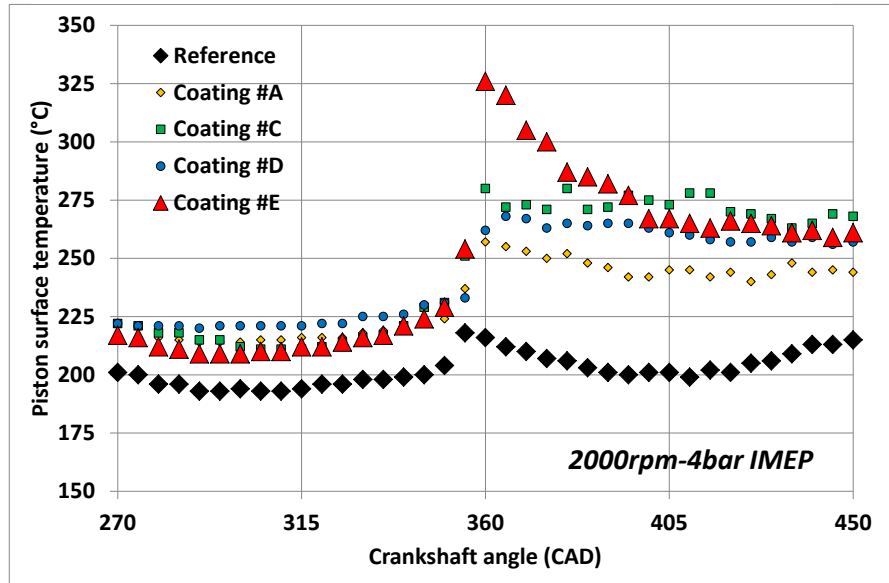
Low conductivity
Low heat capacitance



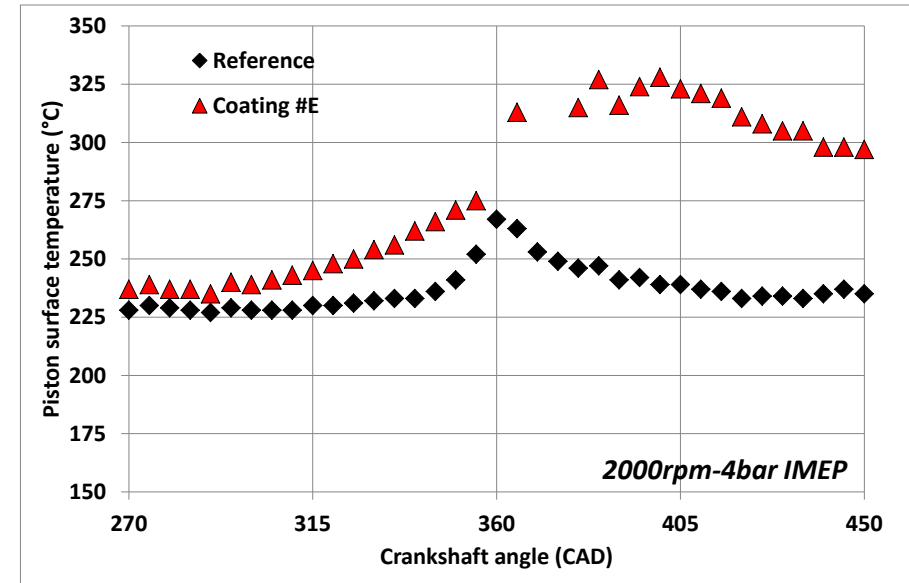
TEMPERATURE SWING

- Temperature swing (LIP) on Aluminum and Steel piston

Aluminum piston



Steel piston

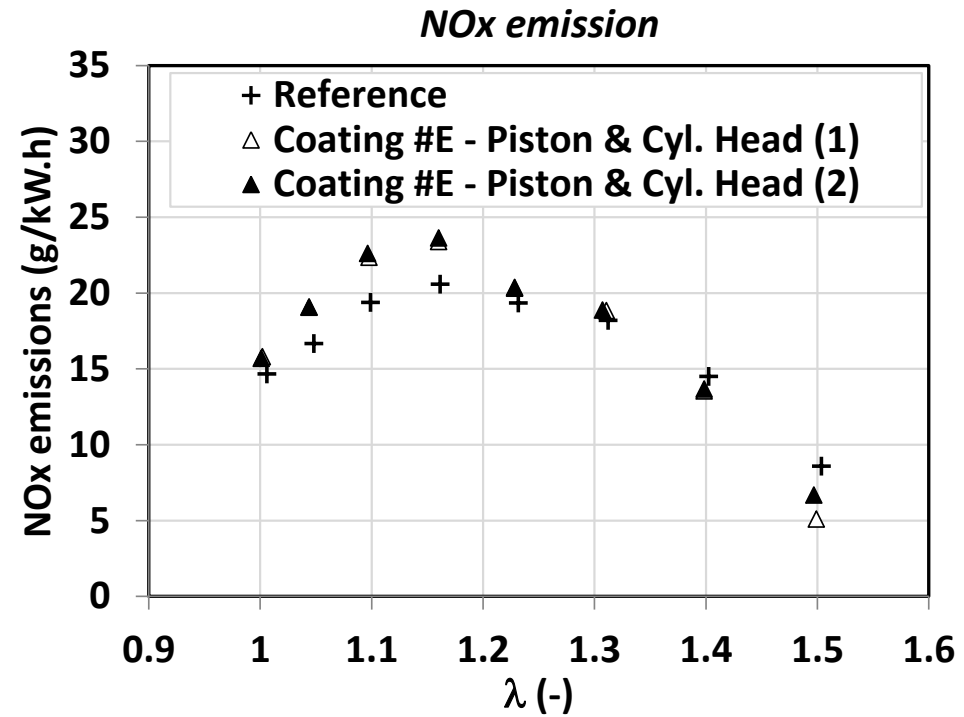
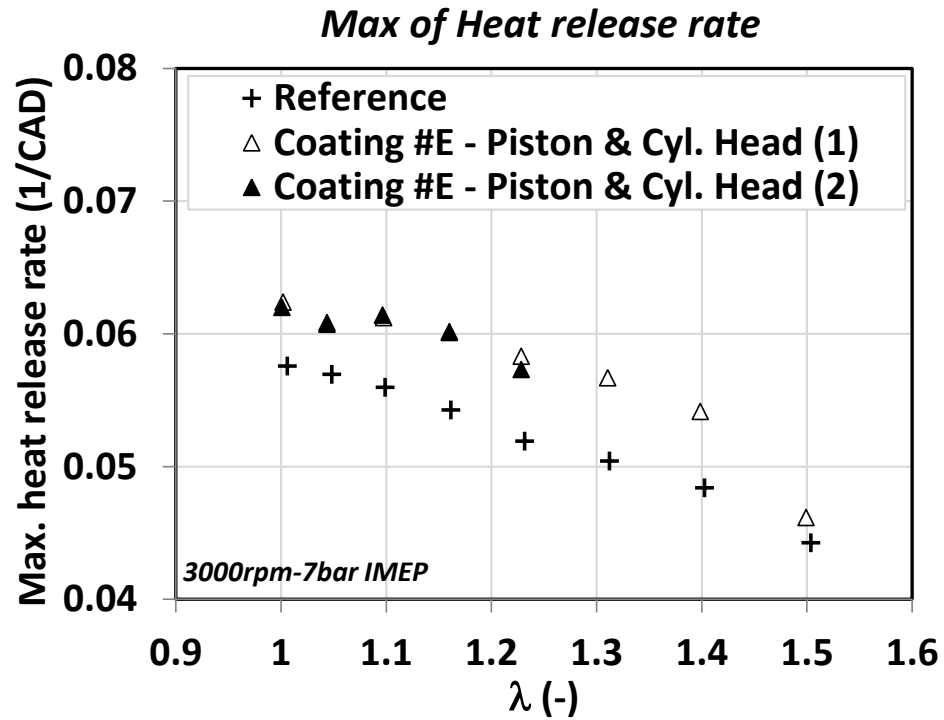


	2000 rpm – 4 bar IMEP	
	Aluminum	Steel
Reference: uncoated piston	20-30°C	35-40°C
Reference + coating #A	40-55°C	Not measured
Reference + coating #C	55-65°C	Not measured
Reference + coating #D	60-65°C	Not measured
Reference + coating #E	100-120°C	70-100°C

⇒ Temperature swing measured
 ⇒ Similar temperature swing with Steel and Aluminum piston

THERMODYNAMIC PERFORMANCE

- Combustion behavior : 2 criteria

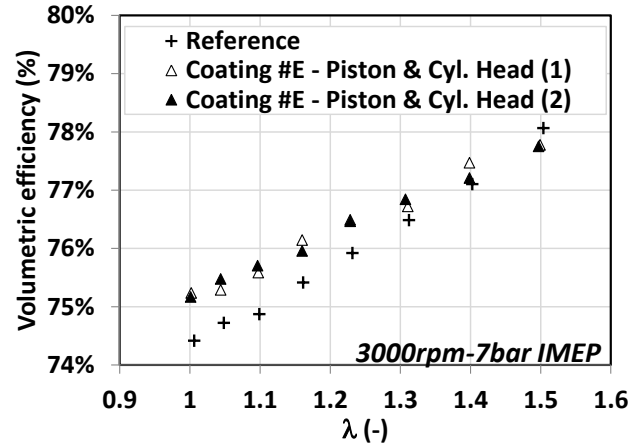


⇒ Higher combustion temperature

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

Volumetric efficiency

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

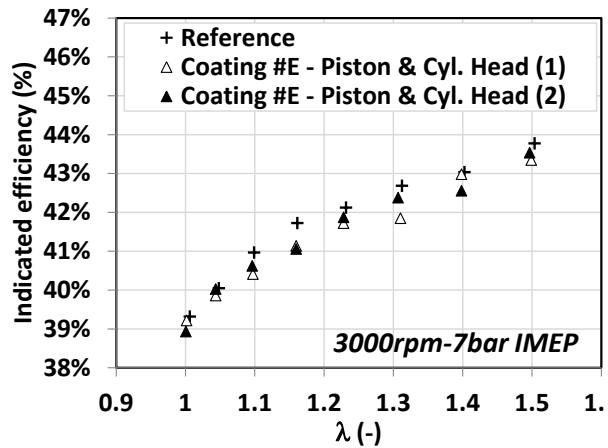


⇒ Slightly better intake efficiency : No increase of the fresh air temperature during the intake

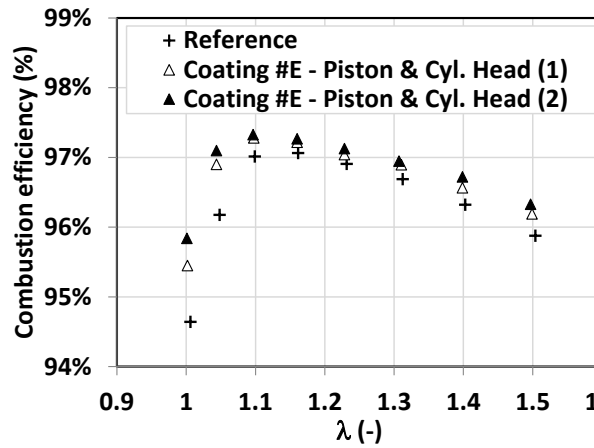
- Consistent with surface temperature measurement
- Drawback of the adiabatic solve with smart coating

Global efficiency

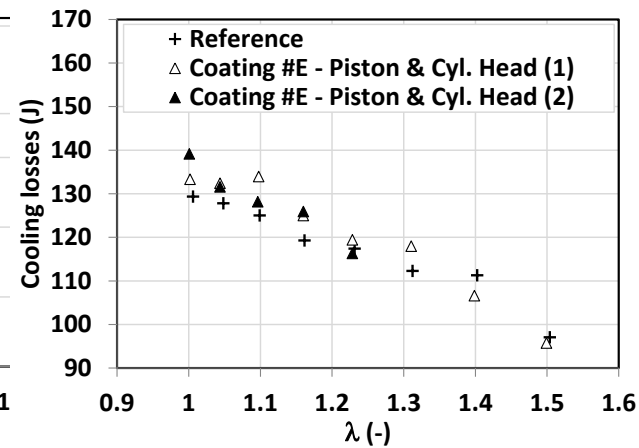
Indicated efficiency



Combustion efficiency



Cooling losses

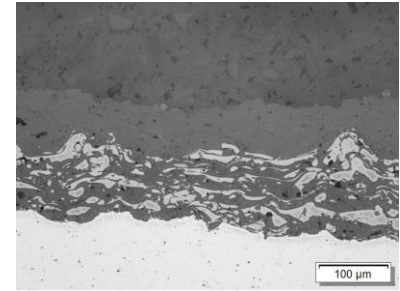


⇒ No gain using coating on efficiency / fuel consumption

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

EXPERIMENTAL TEST RESULTS SUM-UP

ITSC



- 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**

- 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

Efficient Additivated Gasoline Lean Engine



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Thank you for your attention

