CIMAC Cascades in Kobe, on 12. Oct. 2018

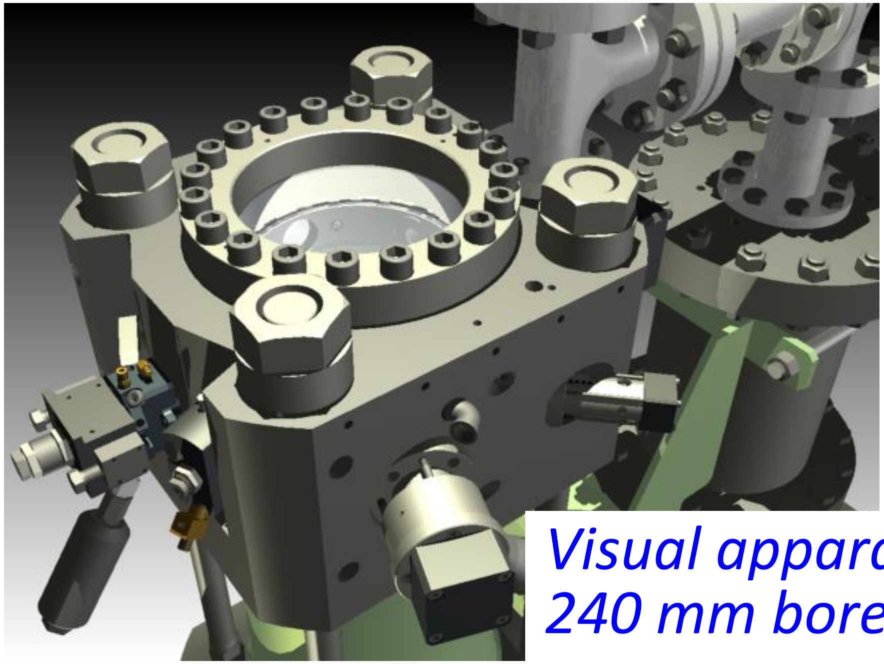
Keynote

Combustion of future marine fuels

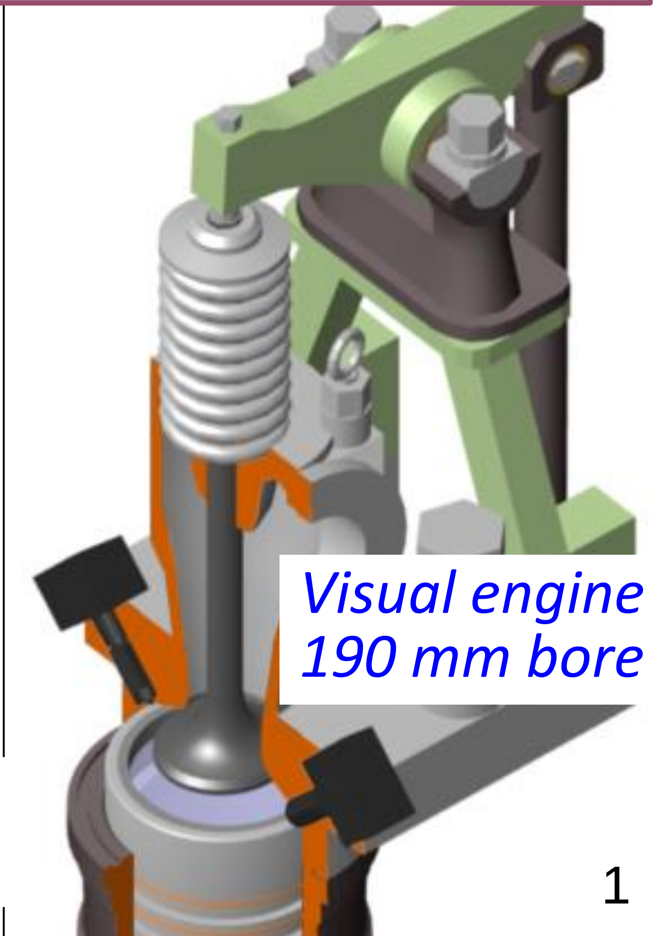
Prof. (Emeritus), Dr., ***Koji TAKASAKI****, Kyushu University, Japan*

Especially for young engineers and students

Visualization could help your study.



Visual apparatus 240 mm bore



Visual engine 190 mm bore

Contents

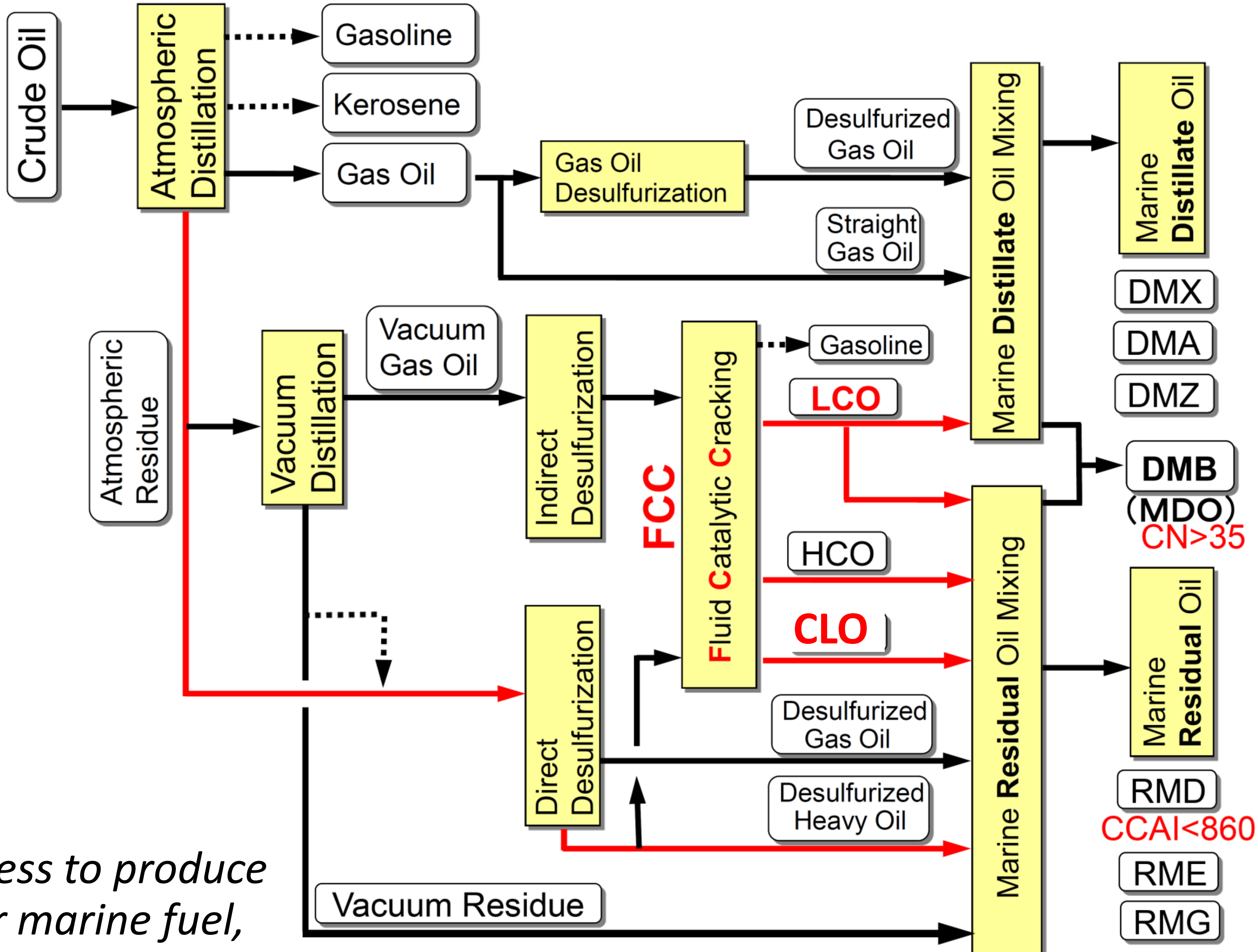
1. *What kind of marine fuel would appear after 2020 ?*
(0.5% Sulfur global cap from 2020)

- *Ignition and combustion of*
low-sulfur but high-aromatic Fuel

2. *Combustion of alternative sulfur-free liquid fuels*
    - ***Methanol***
    - ***Liquid Propane (LPG)***

3. ***Natural gas** (methane) combustion*
    - ***Lean-burn** (**Otto**-cycle) type*
    - ***GI** (high-pressure **G**as **I**njection) (**Diesel**-cycle) type*

Conventional Oil Refinery *(Red lines: realistic ways to reduce sulfur in fuel)*

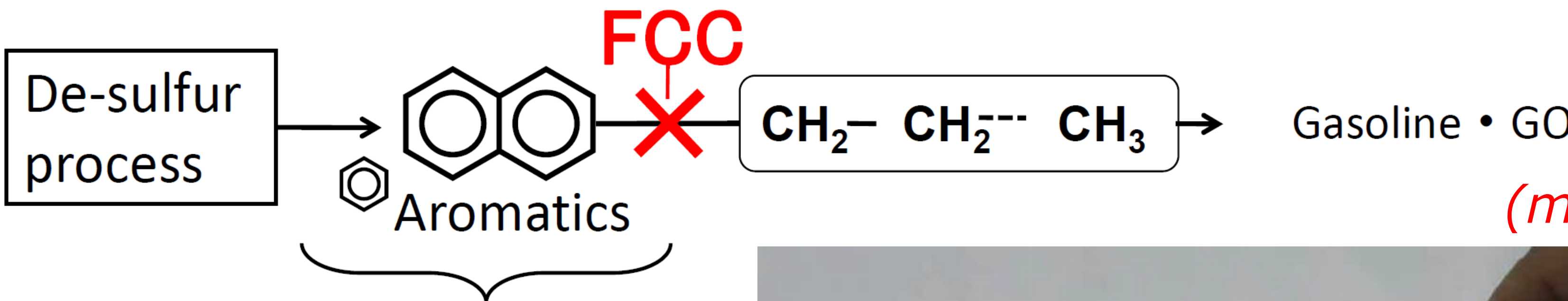


*At the process to produce a low sulfur marine fuel, as a great deal of low sulfur potion like LCO and HCO/**CLO**, the rest of FCC process would be mixed., the fuel becomes **higher aromatic.***

*It is **NOT** guaranteed that low-sulfur fuel always burns better than high sulfur one.*

*Difference of Ignition and combustion between paraffinic and **aromatic** fuel*

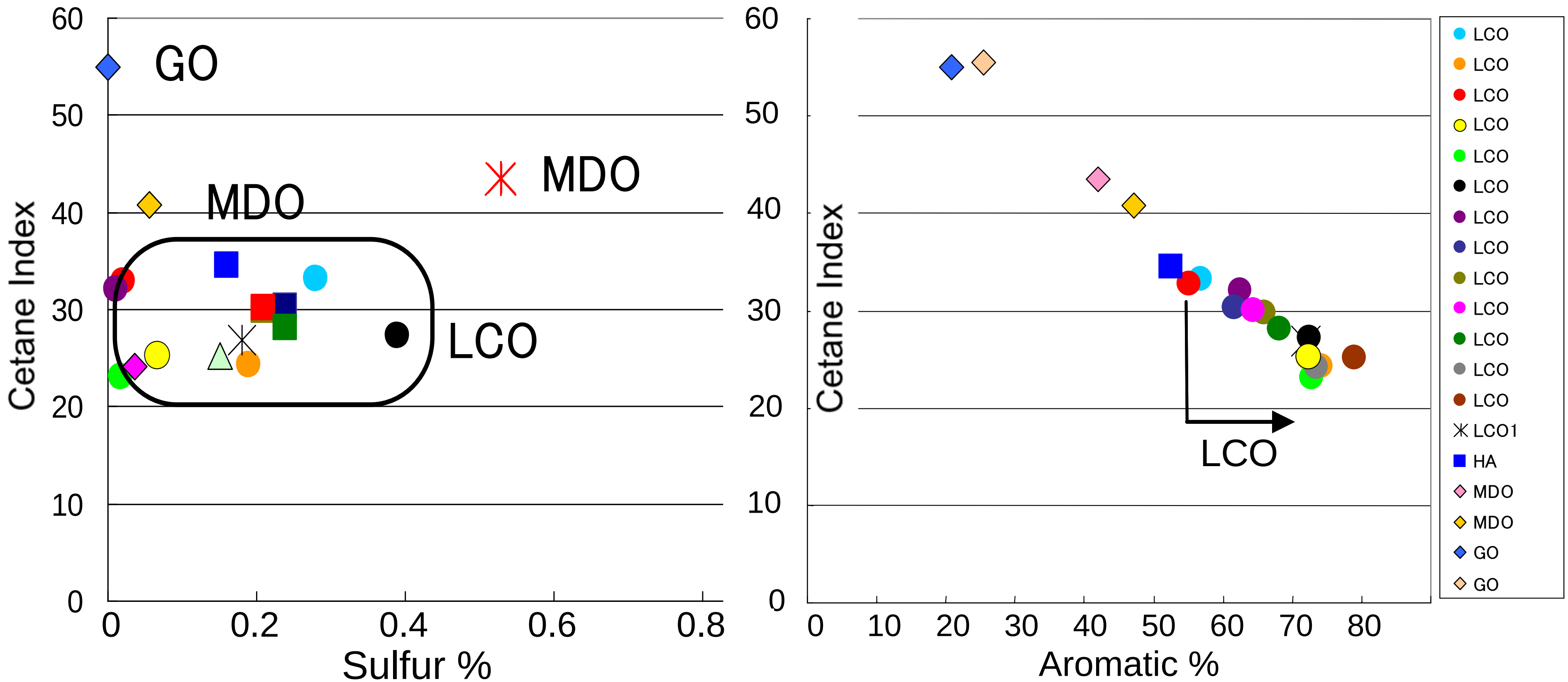
zero aroma *high-aroma*



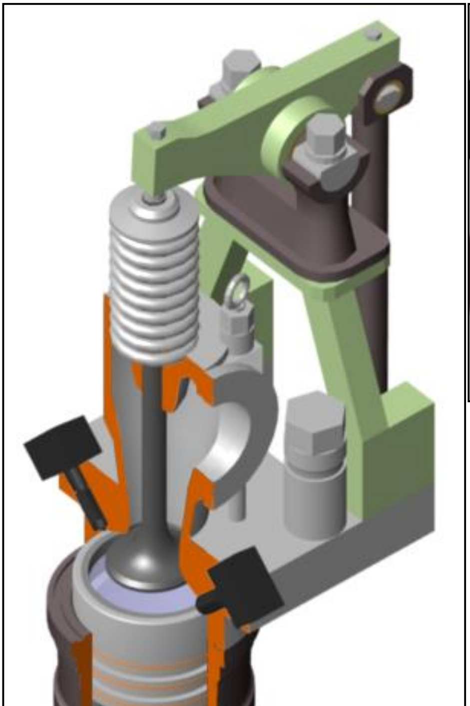
***LCO** (**L**ight **C**ycle **O**il)*

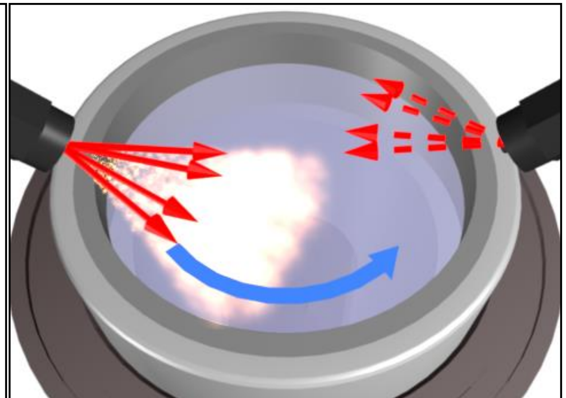
(movie)

Sulfur %, Aromatic % and Ignition Quality (Cetane Index) of Japanese LCO Samples



*Difference of Ignition and combustion between paraffinic and **aromatic** fuel* *（Ignition delay, soot formation and after-burning by high aromatic LCO）*





Fuel injection conditions are just the same for both fuels

*Inj. Press. ：**70** MPa*

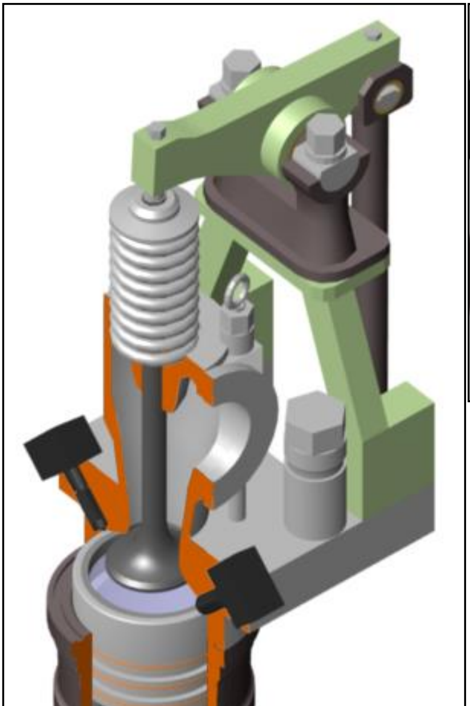
<u>Visual test engine</u>

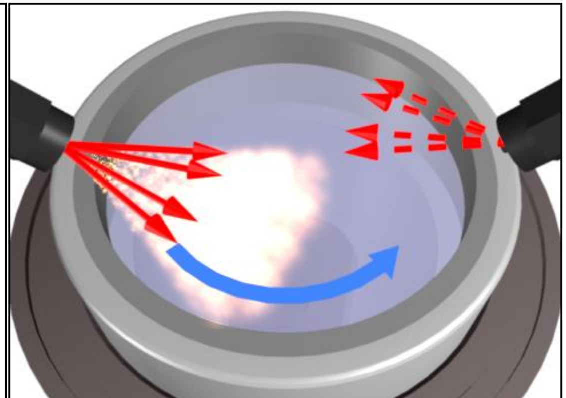
Bore/Stroke :
190 mm/ 350 mm
Two-stroke,
Super-charged
Engine speed：
400 rpm

Automobile GO ***LCO***

MOVIE

*Difference of Ignition and combustion between paraffinic and **aromatic** fuel （Ignition delay, soot formation and after-burning by high aromatic LCO）*





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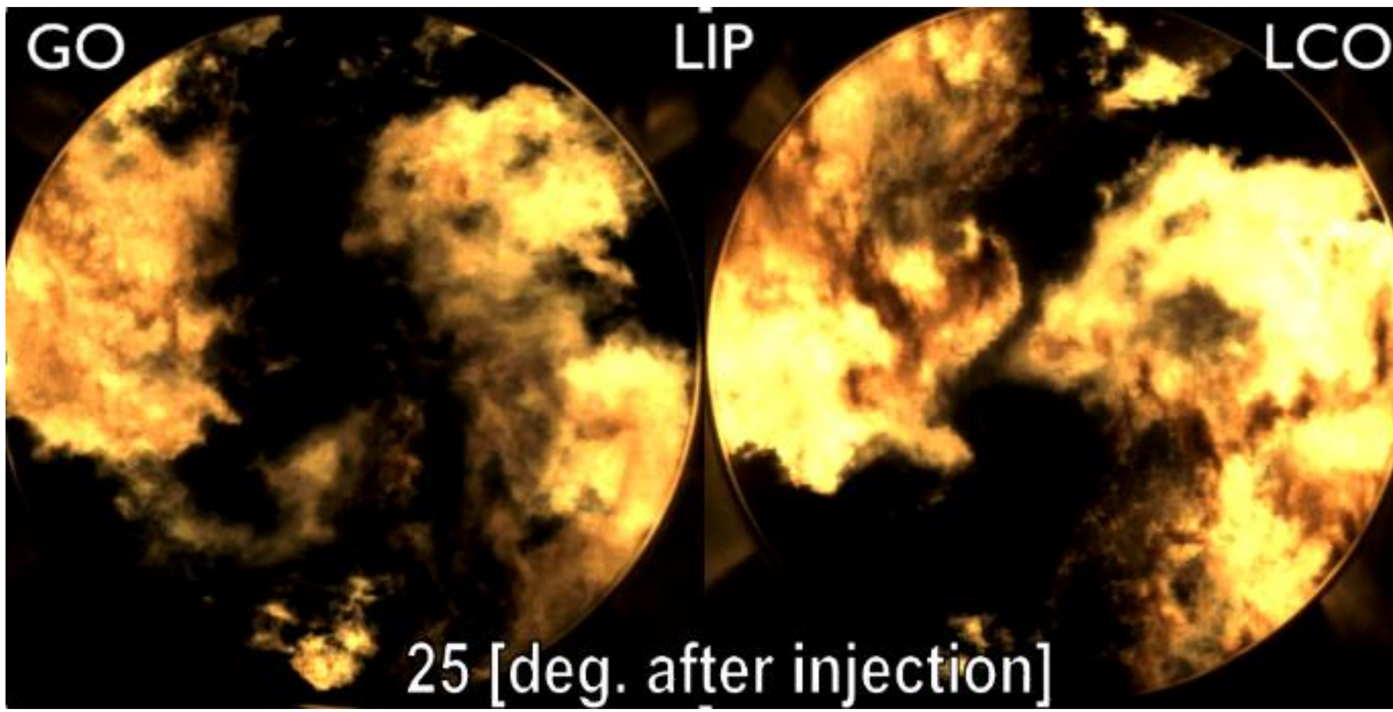

Automobile GO ***LCO***

<u>Visual test engine</u>

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- ***Lean-burn** (**Otto**-cycle) type*
- ***GI** (high-pressure **G**as **I**njection) (**Diesel**-cycle) type*

Reduction of EEDI by changing the fuel

- ***EEDI*** *(Energy Efficiency Design Index) **:** CO_2 g／ton ·mile*

$$= \frac{\text{Engine Power (kW)} \times \text{SFC (g/kWh)} \times C_F}{\text{DWT (ton) x Speed (mile/h)}}$$

- *• 2020～-20%, 2025～-30% for newly built ships*

EEDI reduction by natural gas, LPG and methanol

***MGO** base・・*	***HFO** base・・*
***MGO** 100%*	***HFO** 100%*
Natural gas 76% (-24%)	*Natural gas 74% (-26%)*
LPG 86% (-14%)	*LPG 84% (-16%)*
Methanol 92% (-8%)	*Methanol 89% (-11%)*

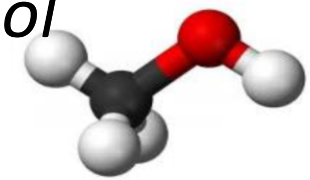
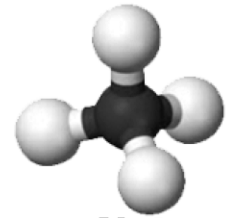
Calculated EEDI ratio with Lower calorific value and C_F

As a common sense for the conventional fuels, poor ignition quality represents the poor combustion quality like LCO case.

But・・

- *the following future fuels, Methanol, LPG and natural gas have poor self-ignitability and pilot-injection of diesel fuel is necessary.*
- *However, once ignited, they show a good combustion state after that.*

Characteristics of Diesel fuel, natural gas and methanol


Fuel	Methanol	Natural Gas	Diesel
Density (kg/l)*	0.79	0,44 (as LNG	0,85
Boiling point (°C)	65	-162	150-370
Flash point (°C)	11	-188	min. 60
Auto ignition (°C)	464*	540*	240
Viscosity cSt at 20°C	~ 0,6	na	~ 13,5
Octane RON/MON	109/89	120/120	-
Cetane No.	3*	- *	45-55
LHV (MJ/kg)	20	50**	42
Flammability Limits, Vol%	7-36	5-15	1-6
Flame Speed (cm/s)	52	37	37
Heat of Evaporation (kJ/kg)	1178	na	233
Stoichiometric Air-Fuel Ratio	6,45	17,2	14,7
Adiabatic flame temp. (°C)	1910	1950	2100

*** High auto-ignition point (low CN) needs a diesel fuel pilot injection.**

Natural Gas (CH4)

Methanol CH3OH *LNG*

Renewable Methanol possible

Bio material

Power to liquid

(CO2 zero count)

Methanol spray combustion compared to GO and methane (gas)

<u>Distinguish between ignition and combustion quality.</u>

<u>Less luminous flame represents clean combustion with less soot formation.</u>

Direct photo

Gas Oil **（F16)**

Inj. Hole Dia. **0.5** [mm]

Inj. Press. **89.1** [MPa]

Methanol CH3OH **（F2.8）**

Inj. Hole Dia. **<u>0.8</u>** [mm]

Inj. Press. **56.9** [MPa]

Reference

Methane CH4 **（F16）**

Inj. Hole Dia. 1.0 [mm]

Inj. Press. **30.1** [MPa]

Pc= 15 MPa

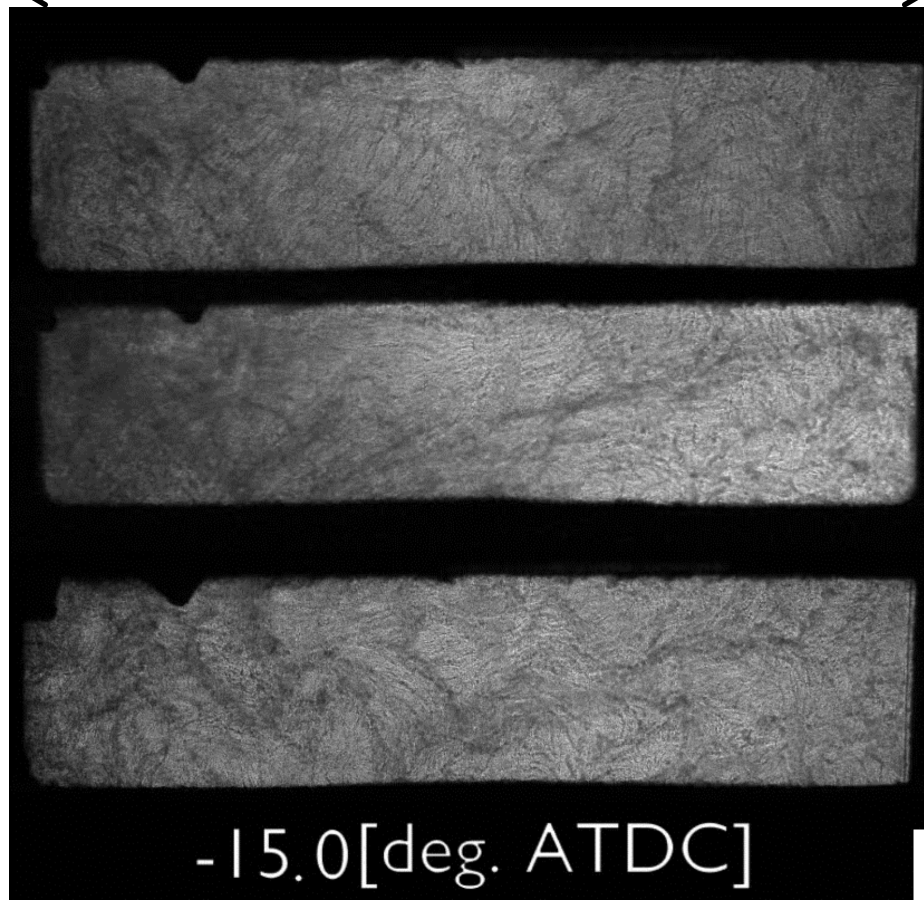
200 mm

Methanol spray combustion compared with GO and methane (gas)

by Shadowgraph technique

(Movie)

200 mm



Pc= 15 MPa

Gas Oil
Inj. Hole Dia. ***0.5*** *[mm]*
Inj. Press. ***89*** *[MPa]*

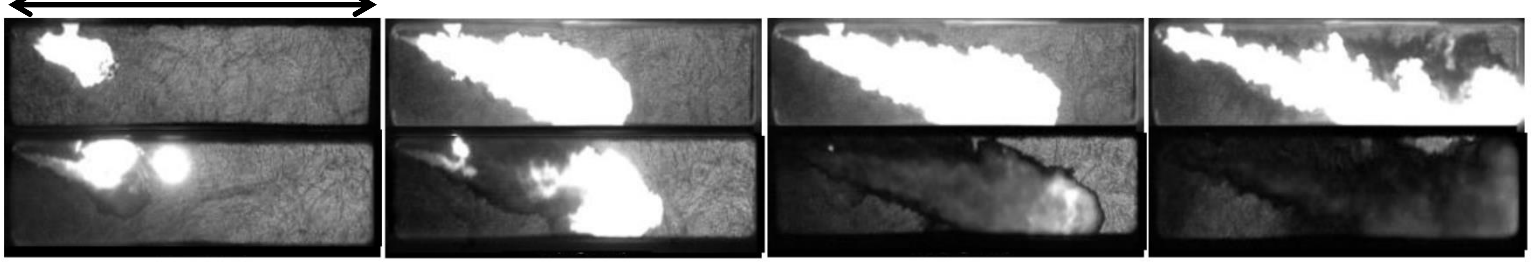
Methanol CH3OH + Pilot
Inj. Hole Dia. ***0.8*** *[mm]*
Inj. Press. ***57*** *[MPa]*

Reference
Methane CH4 + Pilot
Inj. Hole Dia. ***1.0*** *[mm]*
Inj. Press. ***30*** *[MPa]*

200 mm

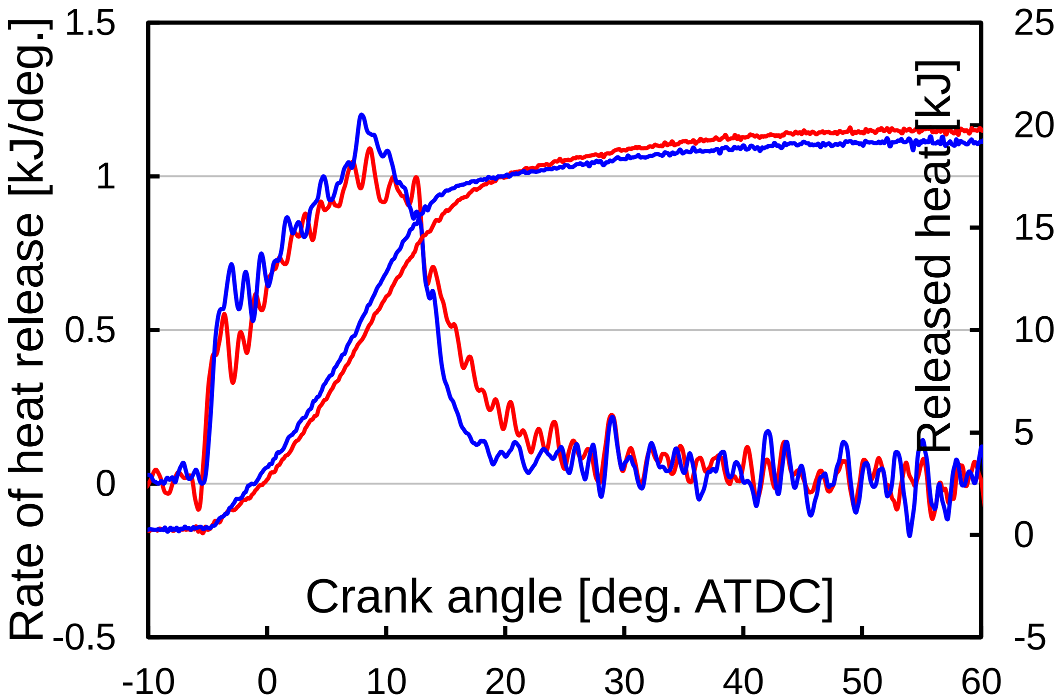
Gas Oil
Inj. hole dia. 0.5 [mm]
Inj. press. 90 [MPa]

Methanol
Inj. hole dia. **0.8** [mm]
Inj. press. **57** [MPa]



3.6 deg. 9 deg. 12 deg. 22 deg. (after inj. start)

Combustion rate of Methanol in the visual apparatus compared with GO case



Gas Oil

Inj. Hole Dia. **0.5** [mm]

Inj. Press. **91** [MPa]

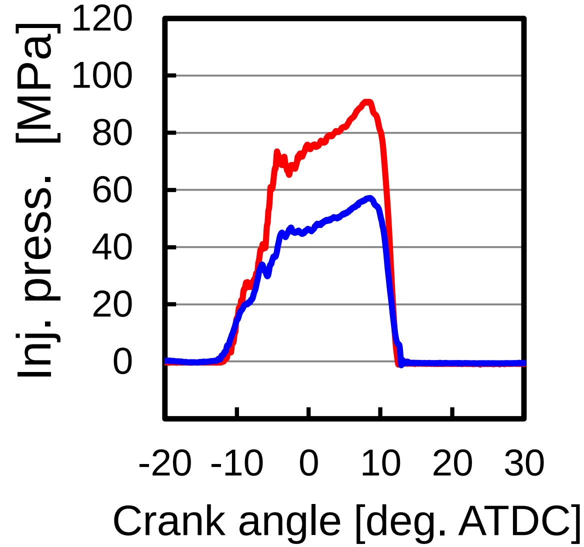
Methanol（CH3OH）

Inj. Hole Dia. **0.8** [mm]

Inj. Press. **57** [MPa]

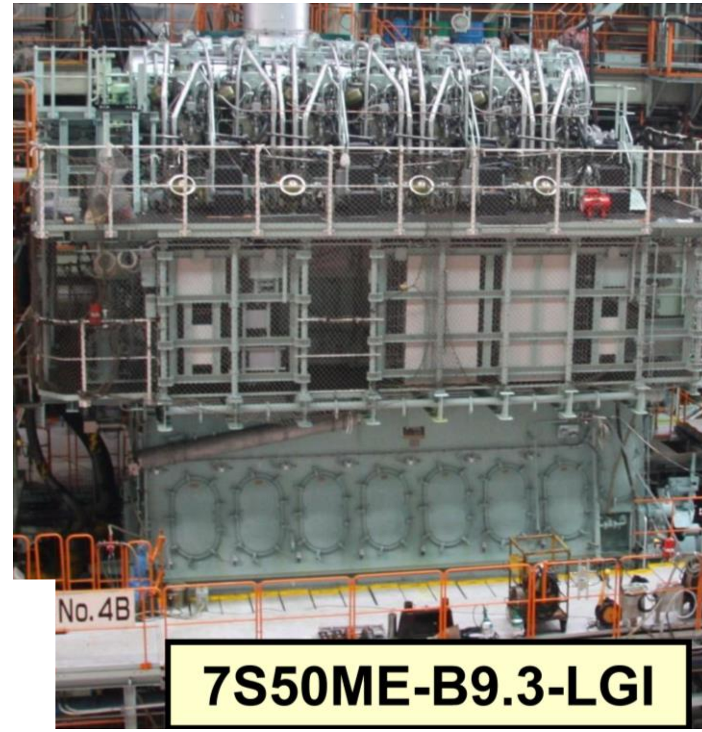
Two times more mass of methanol than Gas Oil is injected from a larger hole, because of difference in LHV.

Methanol shows rather shorter after-burning, in spite of the lower injection pressure.

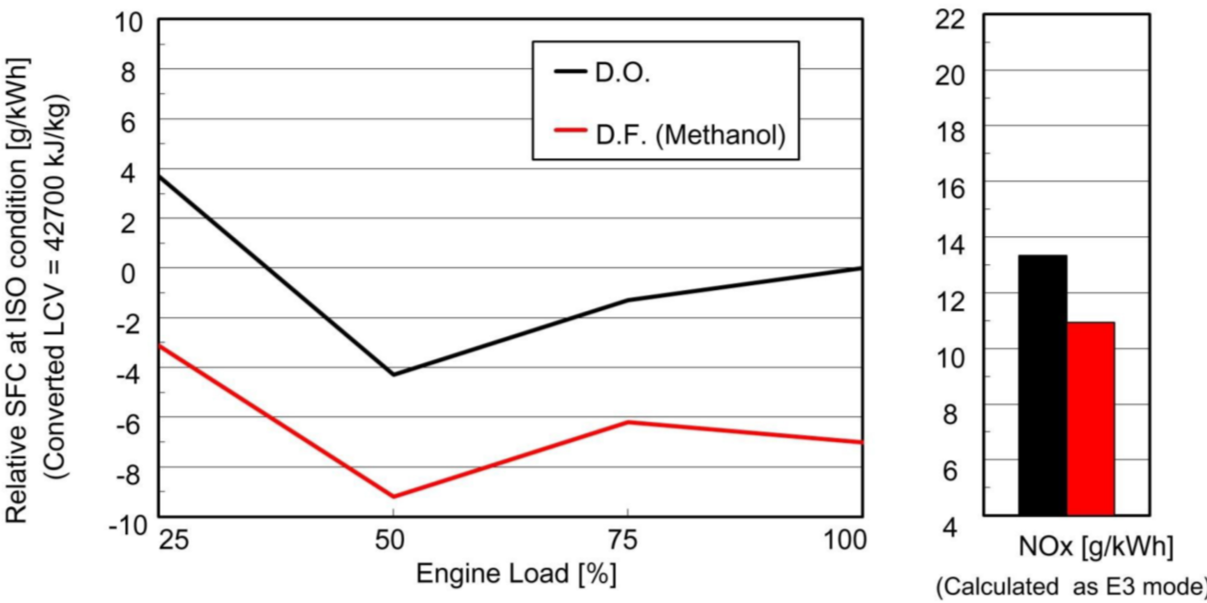


Methanol fueled methanol tankers are already in service.

Methanol
(Zero sulfur)
(Zero aroma)



Cylinders	7
Bore	0.5 m
Connection rod	2.214 m
Stroke	2.214 m
Compression volume	16 l/cyl
Power	8,470 kW
MEP	16.9 bar
Speed	99 rpm
Max. pressure	185 bar

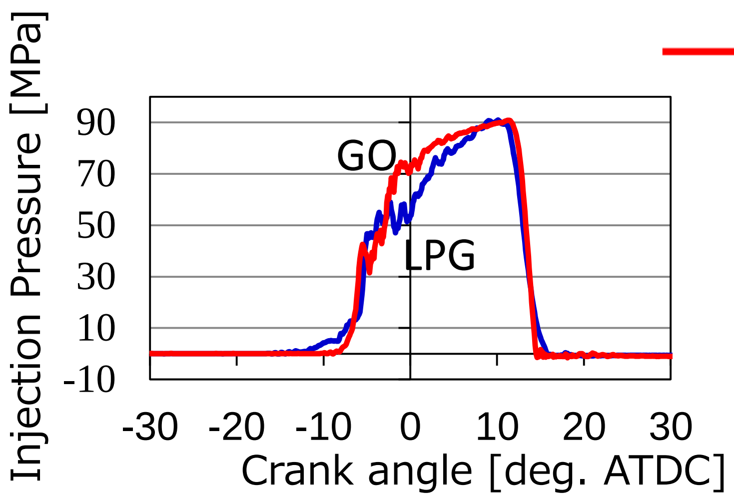


Improvement of thermal efficiency and NOx

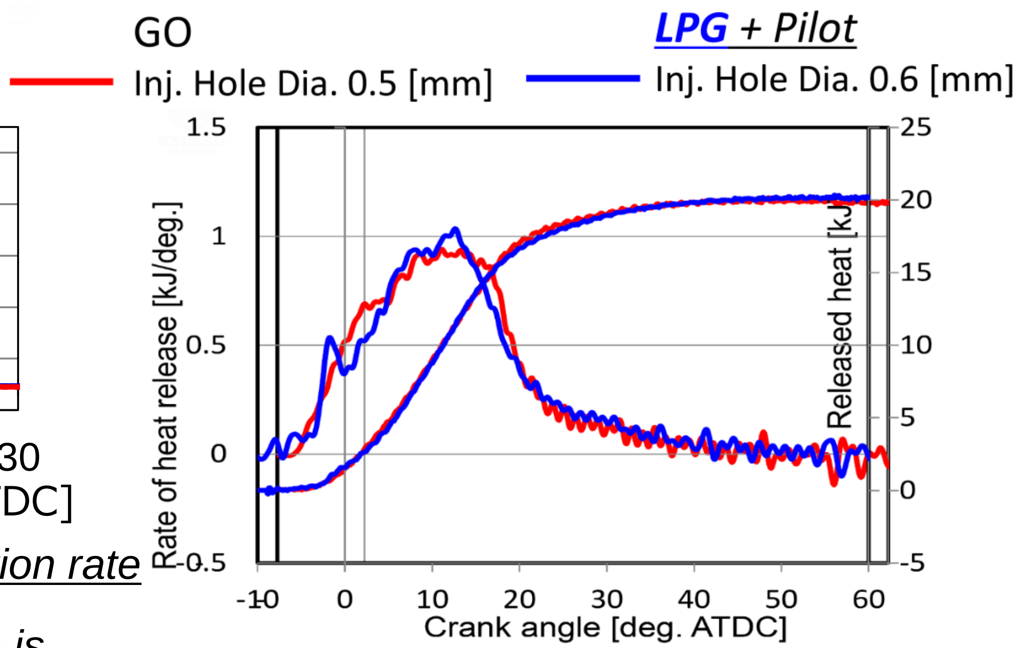
A design of LPG career propelled by a ***LPG*** fueled low-speed two-stroke engine
(LPG for fuel is stored at 18 bar (not cooled) on the deck and is sent to the engine as liquid.)

LPG combustion ・Table : Properties of propane compared with Gas Oil

Fuel	Gas Oil	Propane (C3H8)
Density @288K [kg/m^3]	835	508
Boiling point [℃]	287	-42
Ignition Point / Flash point [℃]	250 / 40～70	432 / -104



Example of injection press. and combustion rate



- Unlike the natural gas case, propane is convenient as it can be injected as liquid phase (LPG) at a high injection pressure similarly to diesel fuel.
- Some reduction of emissions could be obtained compared with gas oil (GO) by the experiment (right).

Emissions from GO and LPG combustion

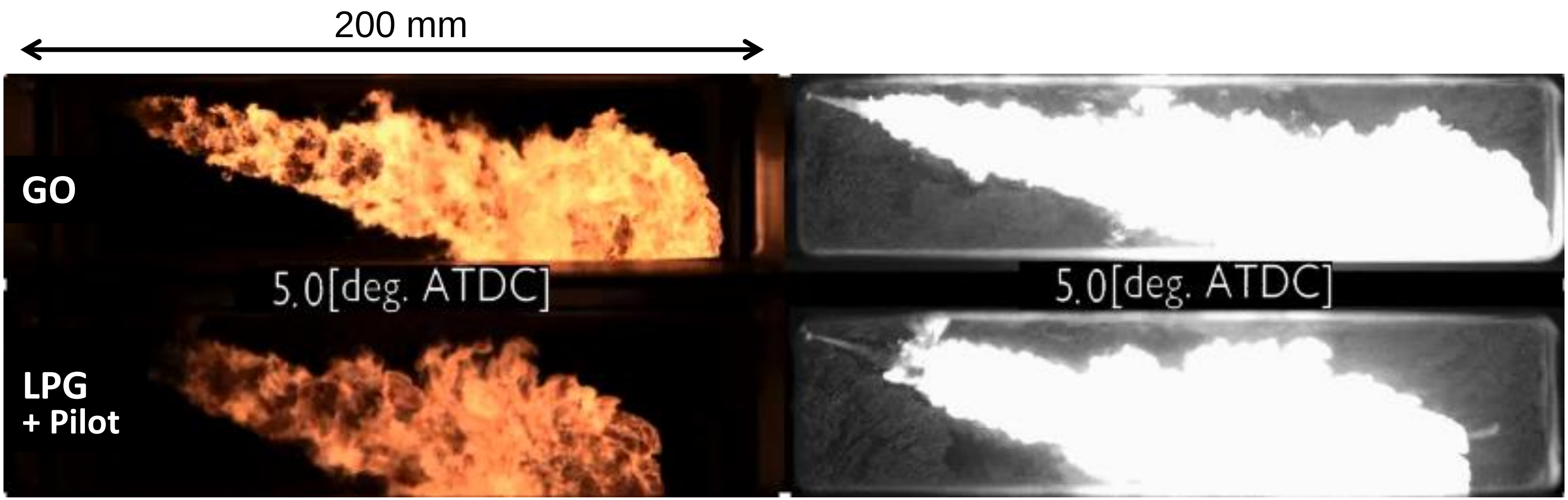
	GO	Liquid propane
CO (ppm)	38	16
HC (ppm)	84	72
NOx (ppm)	320	268 (-16%)

LPG (Liquid Propane) injection + pilot

LPG (+ pilot) spray combustion compared with Gas Oil

GO	
Inj. Hole Dia.	*0.5 [mm]*
Inj. Press.	*110 [MPa]*
Total Q	*19.9 [kJ]*

LPG + Pilot	
Inj. Hole Dia.	*0.6 [mm]*
Inj. Press.	*100 [MPa]*
Total Q	*19.9 [kJ]*



Direct Photos *Shadowgraph*

- *After ignition, propane flame quickly expands and burns rather fast similarly to Gas Oil spray.*

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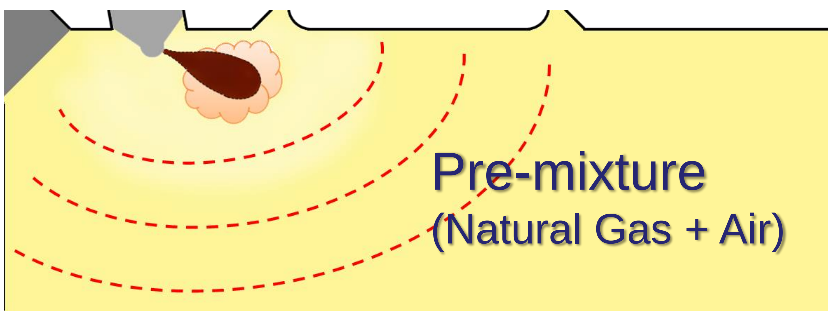
Table 1: Categorization	*Lean-burn (pre-mixed) (low-pressure gas supply)*	***GI** (**G**as **I**njection) (high press. gas injection)*
Medium-speed 4-st.	*Currently all*	*Possible but not yet applied*
Low-speed 2-st.	*Existing*	*Existing*

Otto-cycle type gas engine



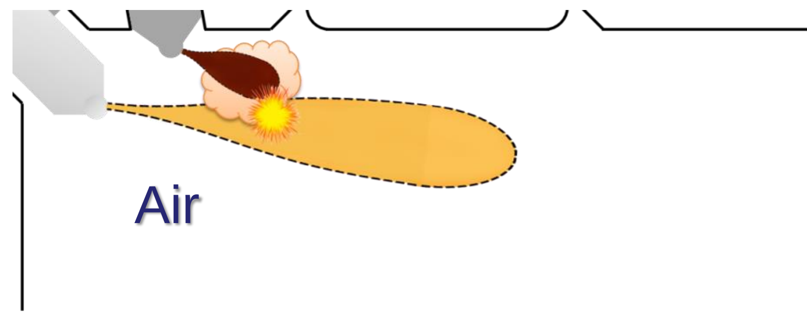
Pro's:

- *Low pressure gas supply*
- ***Low NOx***

Con's:

- *Output limited by **knocking***
  - *･･Sensitive to Methane Number*

Diesel-cycle type gas engine



Pro's:

- ***Knocking-free,** pre-ignition-free, any Methane Number is OK.*
- *Less methane slip*

Con's:

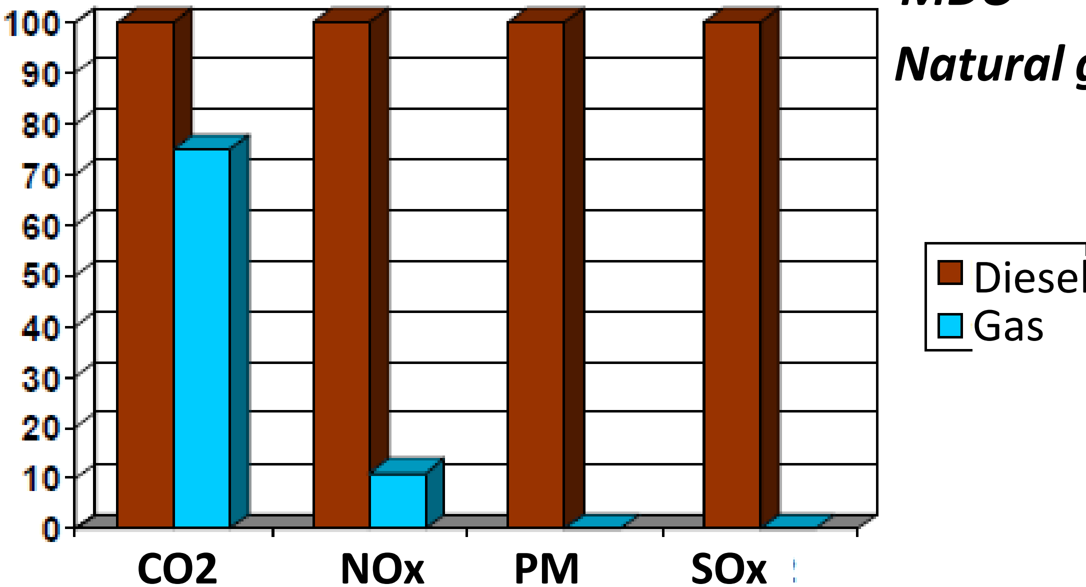
- *Higher gas pressure system*
- *Higher NOx*

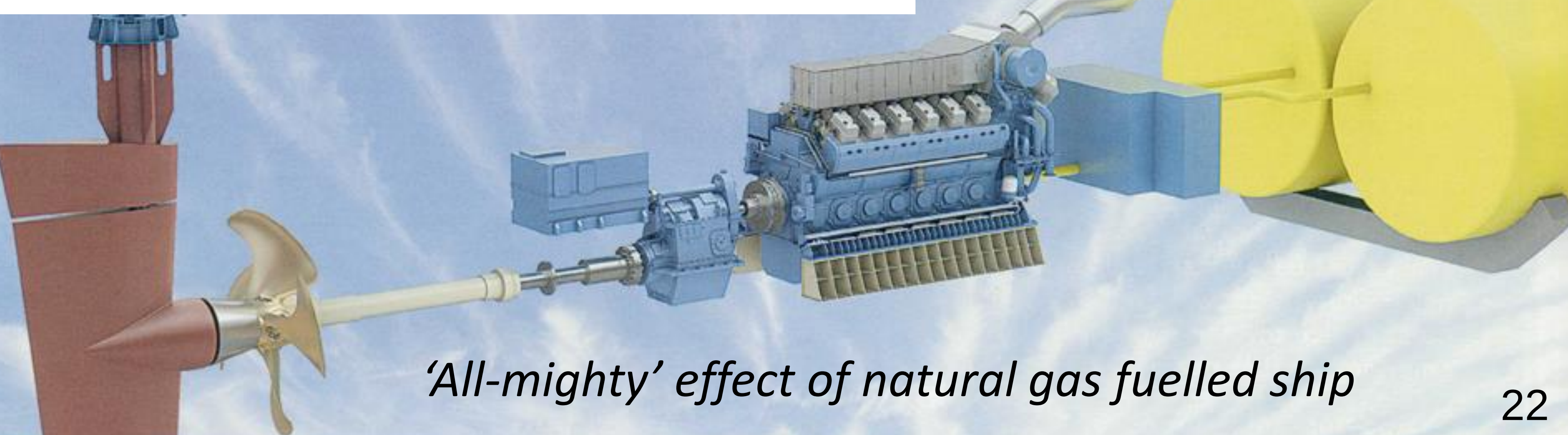
3.1 Natural gas (methane) combustion

- *Lean-burn (Otto-cycle) type*

MDO $C_{16}H_{34}$ · · $\underline{16\ CO_2}$ + 17 H_2O + Q

Natural gas 12 CH_4 · · $\underline{12\ CO_2}$ + 24 H_2O + Q





'All-mighty' effect of natural gas fuelled ship

Natural gas fueled ships in service

(Ferry, off-shore supply vessel, etc., mainly in North Europe).

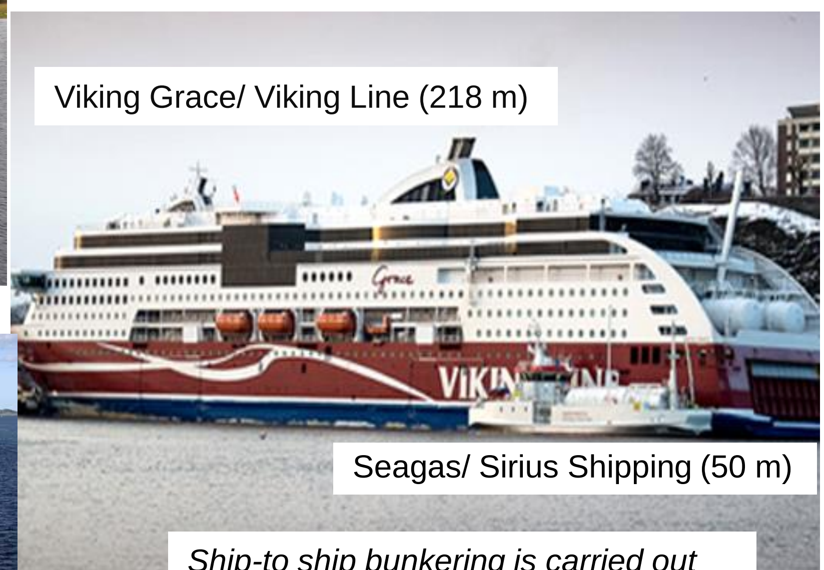

Bergensfjord/ Fjord 1 (130 m)


Viking Energy/ Eidesvik (95 m)


Bit Viking/ Tarbit Shipping (177 m)


Argonon/ Deen Shipping (110 m)


Høydal/ Nordnorsk Shipping (70 m)


Viking Grace/ Viking Line (218 m)

Seagas/ Sirius Shipping (50 m)

Ship-to ship bunkering is carried out from Seagas (LNG supply vessel) to Viking Grace (Natural gas fueled ferry).


EcoNuri/ Incheon Port Authority (36 m)

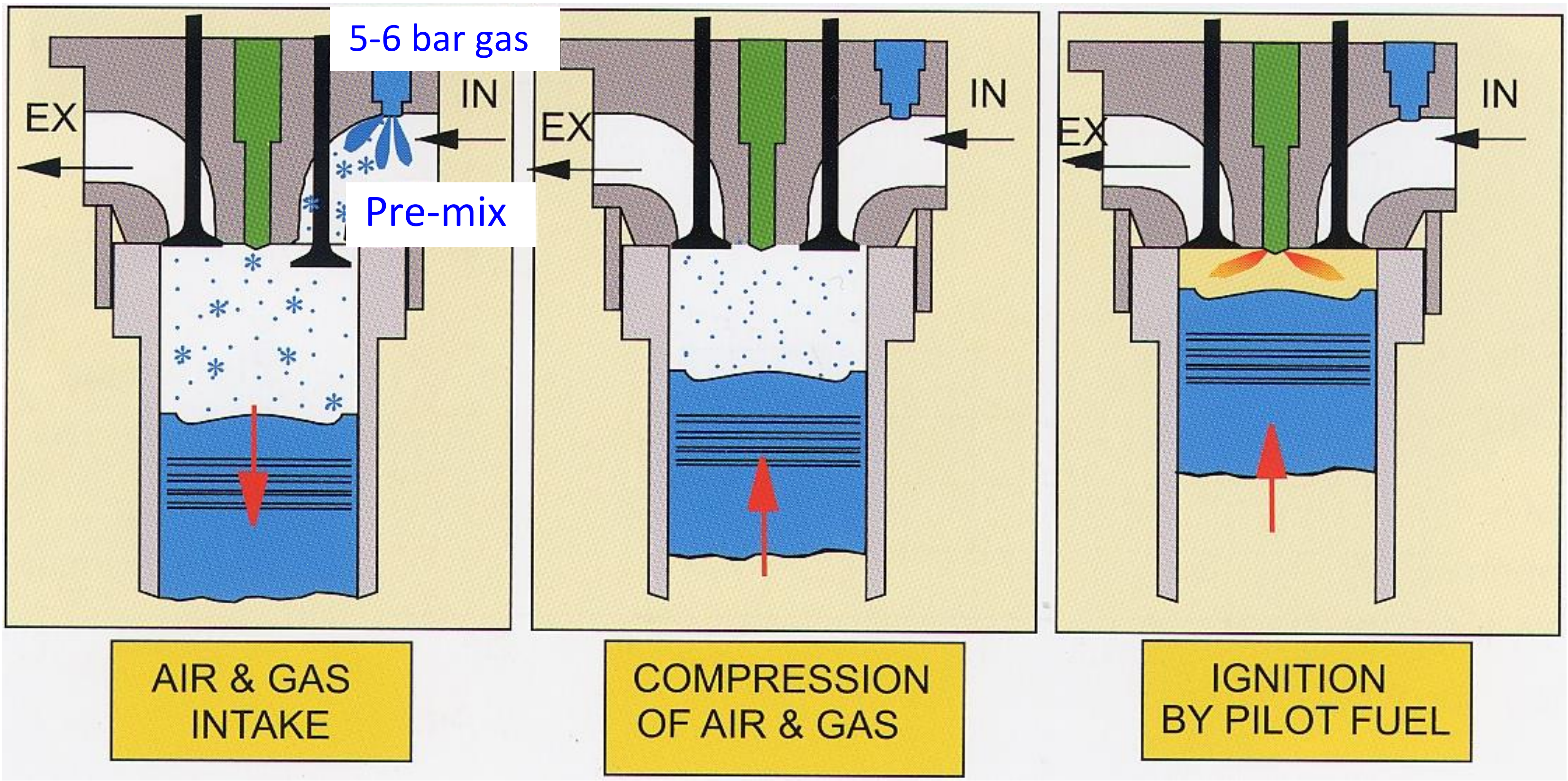

Barentshav/ Norwegian Coast Guard (93 m)


Francisco/ Buquebus (99 m)

Key word :

*<u>Methane number</u> (**MN**) : Anti-knocking number for natural gas*

To keep safe operation at high load, MN higher than 80 is desirable.



Function of medium-speed lean-burn gas engine

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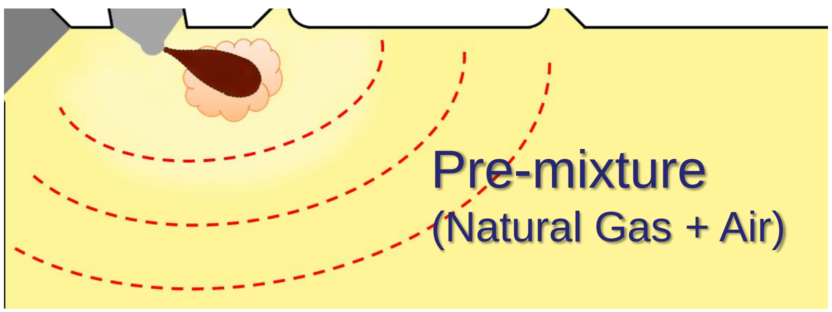
Otto-cycle type gas engine



Pro's:

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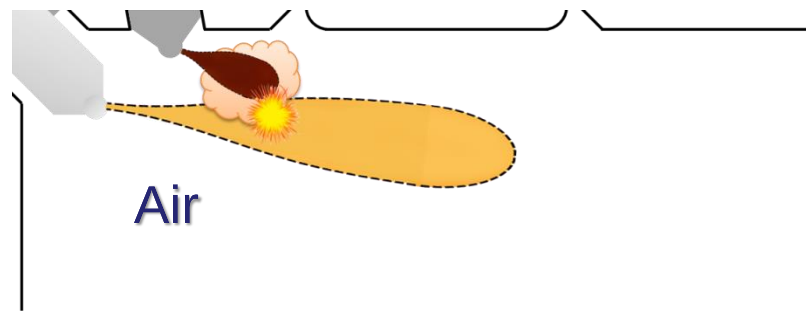
Diesel-cycle type gas engine



Pro's:

- ***Knocking-free,** pre-ignition-free, any Methane Number is OK.*
- *Less methane slip*

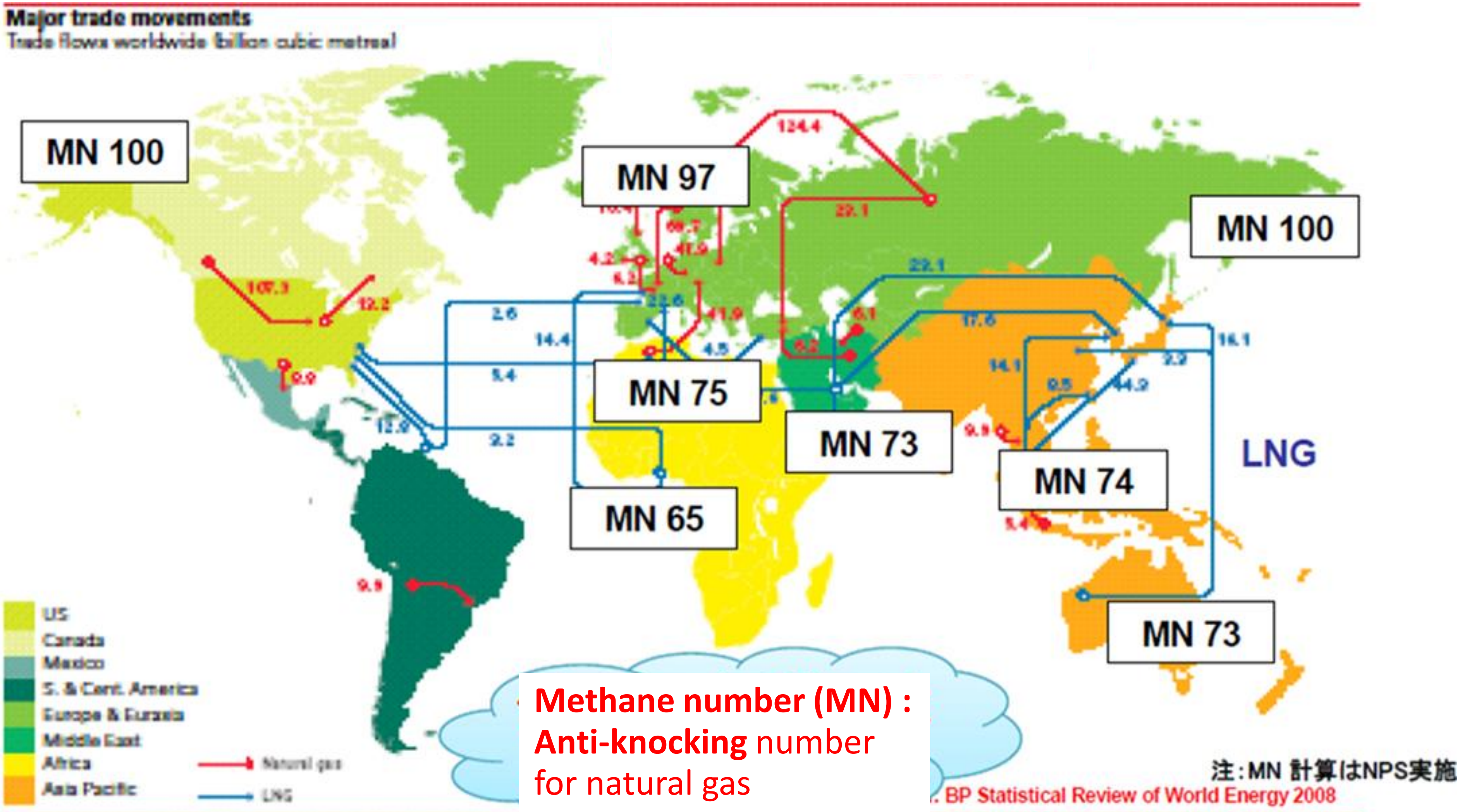
Con's:

- *Higher gas pressure system*
- *Higher NOx*

At first, let's see a movie on knocking phenomena in automobile gasoline engine as a reference.

(Gasoline with high 'Octane Number' allows high compression ratio.)

Current Methane Number of natural gas in each area



Methane number (MN) :
Anti-knocking number
for natural gas

Merit of DF ('Dual Fuel') engine

(An example of platform supply vessel in rough sea condition in the North Sea）

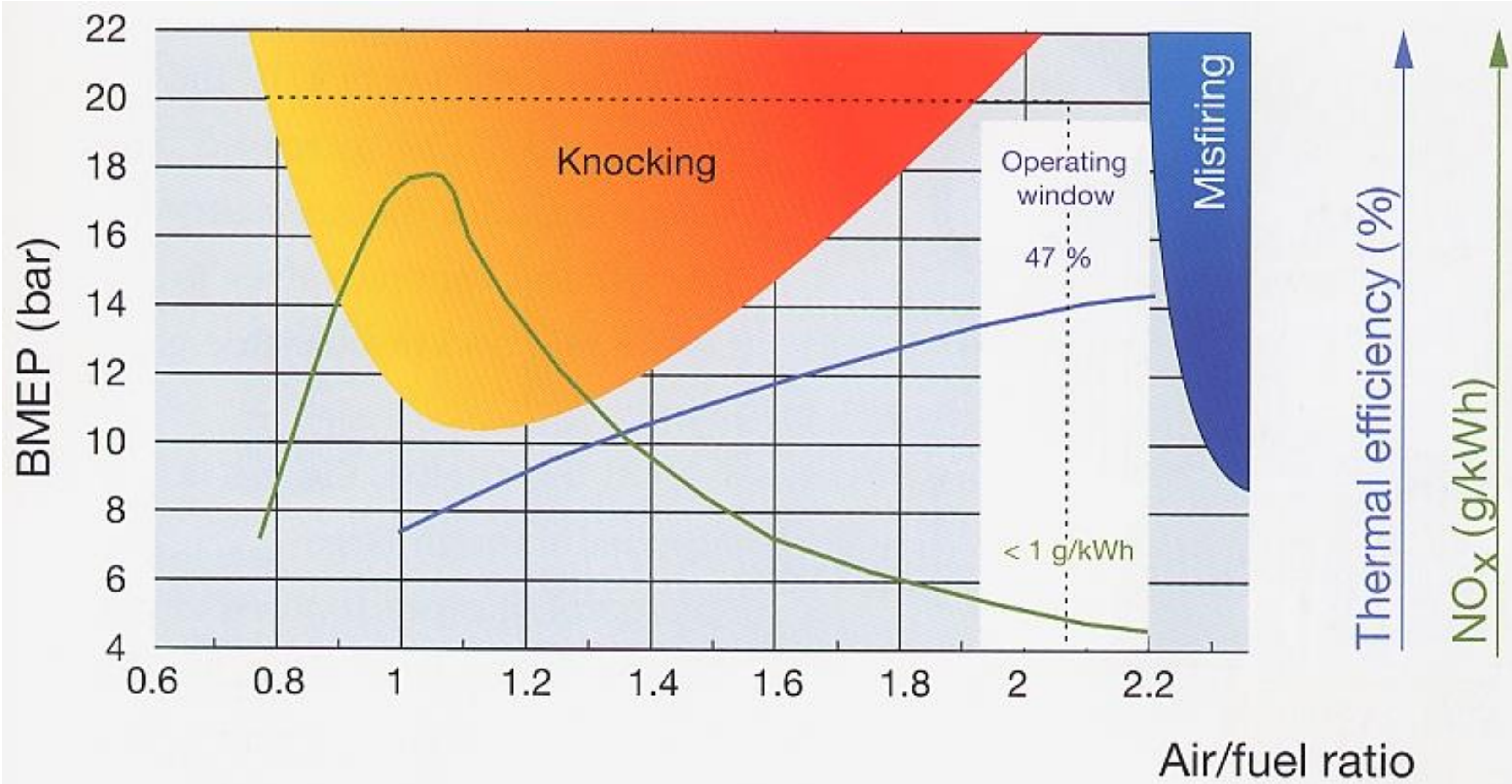
・・Wartsila 32DF + Electric propulsion

- Escape from knocking caused by load fluctuation by availing DF system (Switching to diesel fuel from gas mode)

Function of liquid fuel injector for DF engine

(for Wartsila DF engines・・Wartsila社資料）

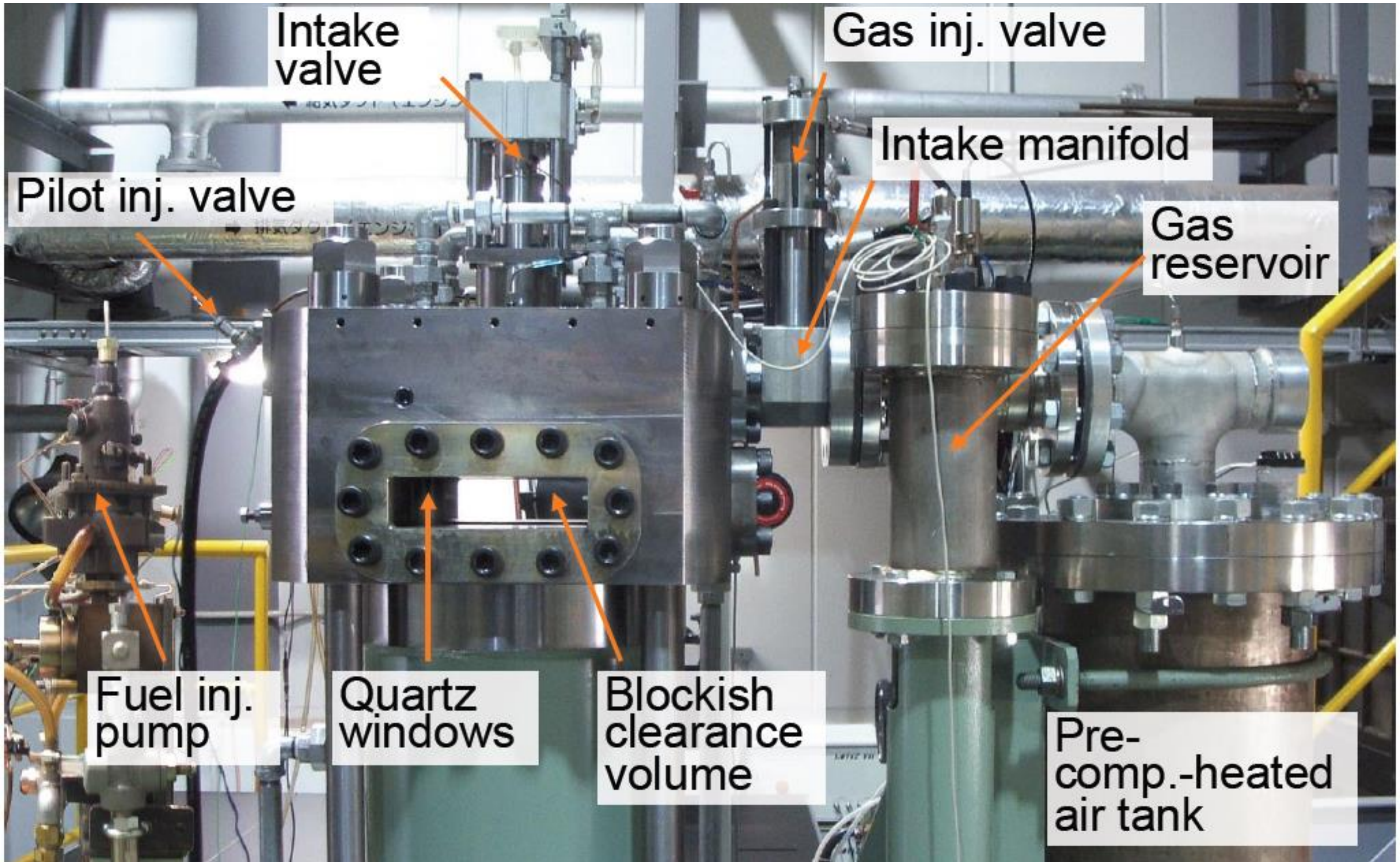
The smaller holes are used for pilot injection at gas mode.
When emergency has occurred at gas mode, fuel gas is stopped and full amount of heavy fuel injection starts from the larger holes.

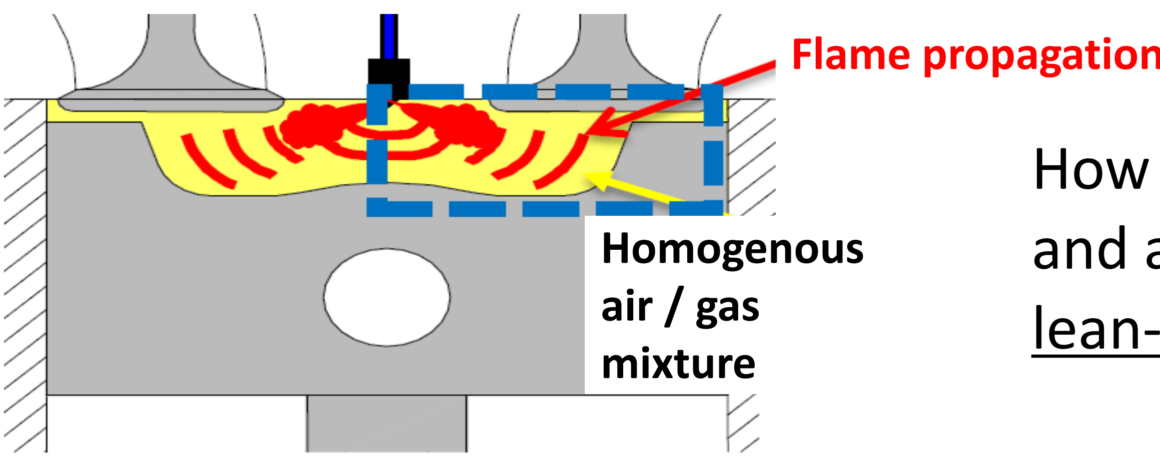


（Excess Air Ratio）

Possibility of abnormal combustion for lean burn gas engine

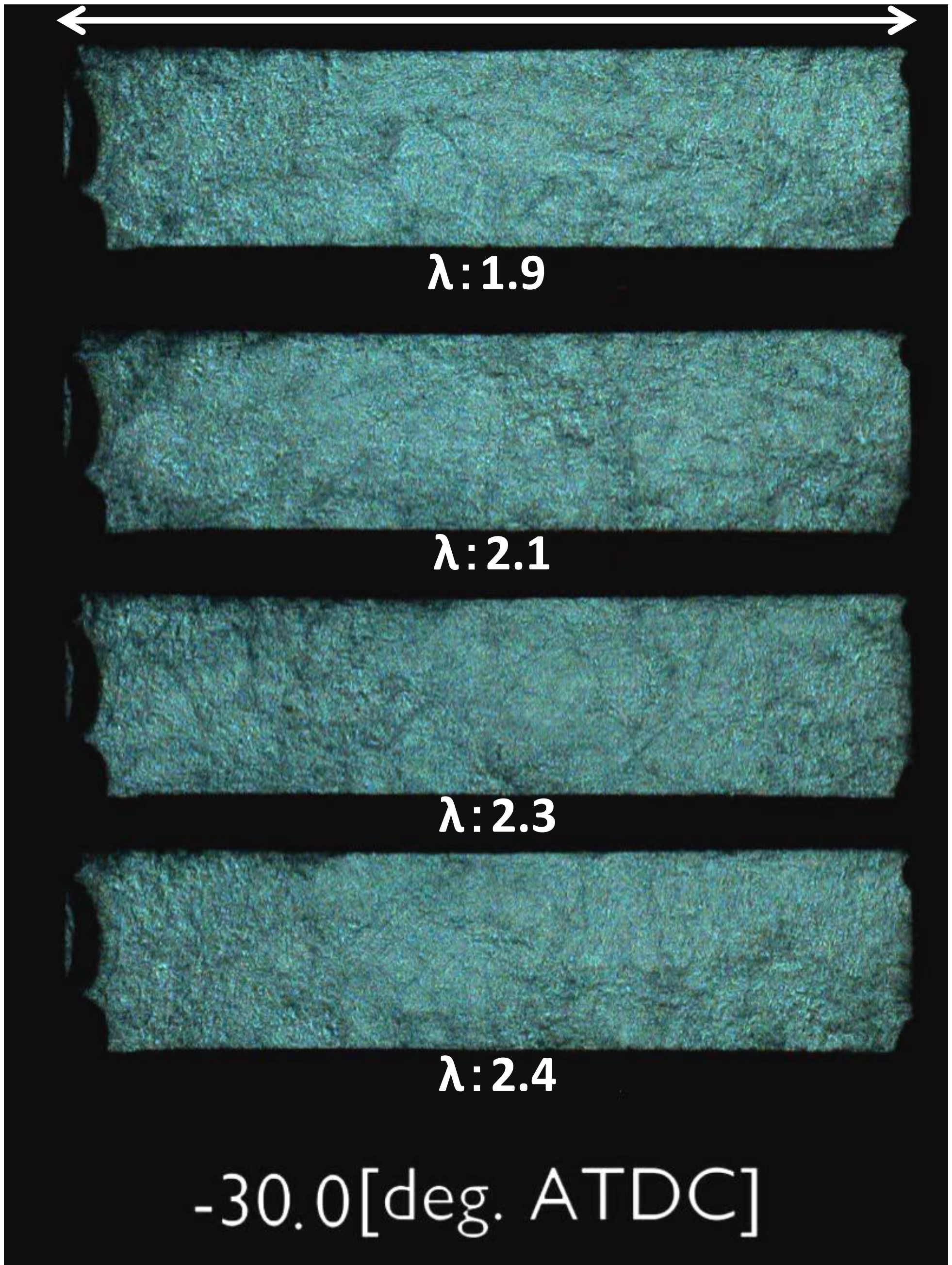
Wartsila company’s data

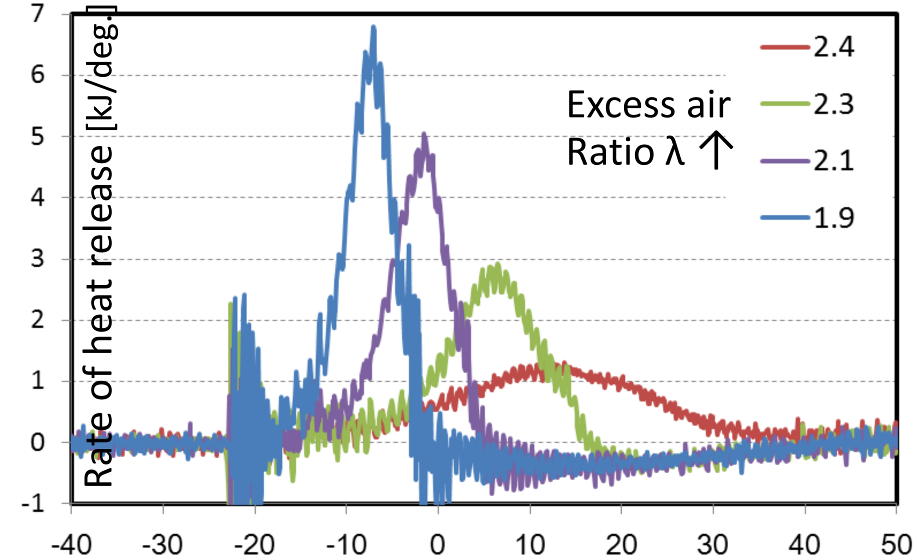


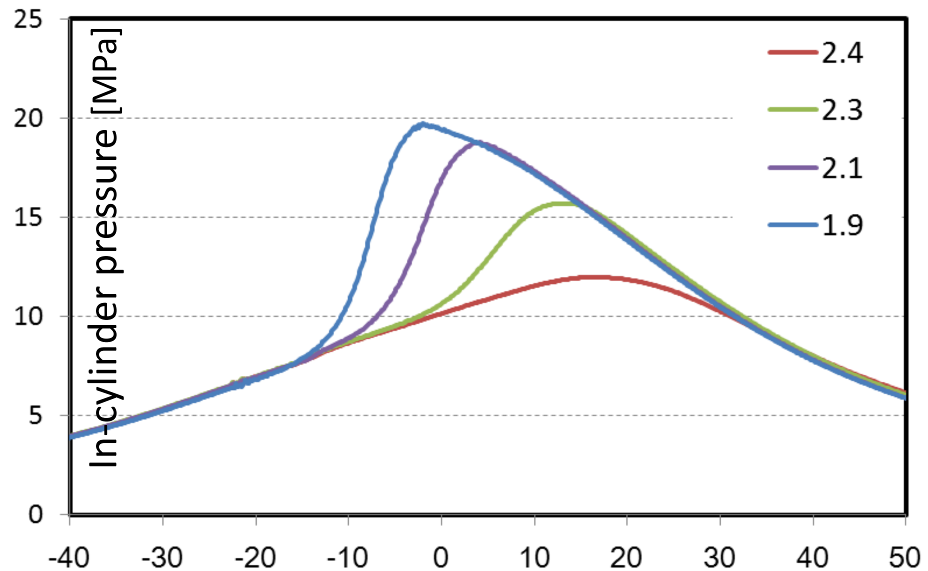


How is the flame propagation and abnormal combustion in <u>lean-burn type gas engine</u>?

Lean mixture burns with non-luminous flame. (Burning area looks black by applying Shadowgraph.)





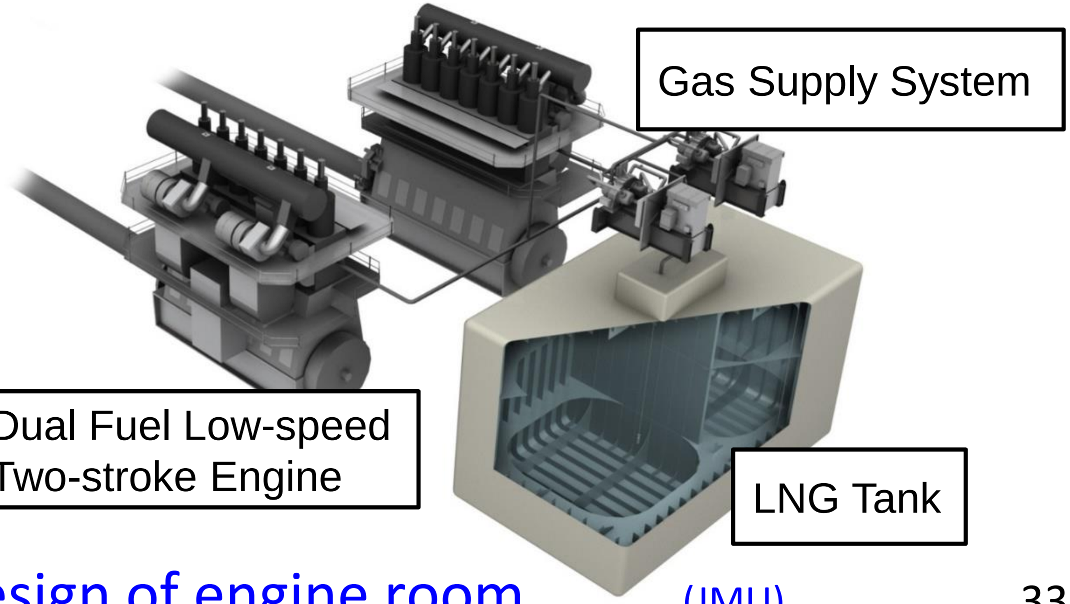


Fuel Gas : Japanese natural gas, Pilot: GO

Natural gas fueled large-sized ships in service
(Car career and container vessel)

- United European Car Carriers (UECC) jointly owned by NYK and Wallenius Lines has ordered KHI two PCCs propelled by MAN low-speed ME-GI gas (DF) engine. (for voyage in European ECA)

- TOTE Line has ordered 3,100TEU container ships propelled by MAN low-speed ME-GI gas (DF) engine. (Route: Florida⇔ Puerto Rico)



A design of engine room (JMU)

Low-speed 2-stroke
Lean-burn type test engine
(IHI DU)

6 cylinders X-DF
- Bore x Stroke: 720 x 3086 mm
- MCR: 19350 kW @89 rpm
- BMEP: <u>17.3 bar</u>

CIMAC Helsinki 2016 | Paper No.136
Combustion Behavior in Largest 2-Stroke Gas Engine
Takayuki Hirose, IHI Corporation

Mixture formation in the case of 2-stroke + lean-burn

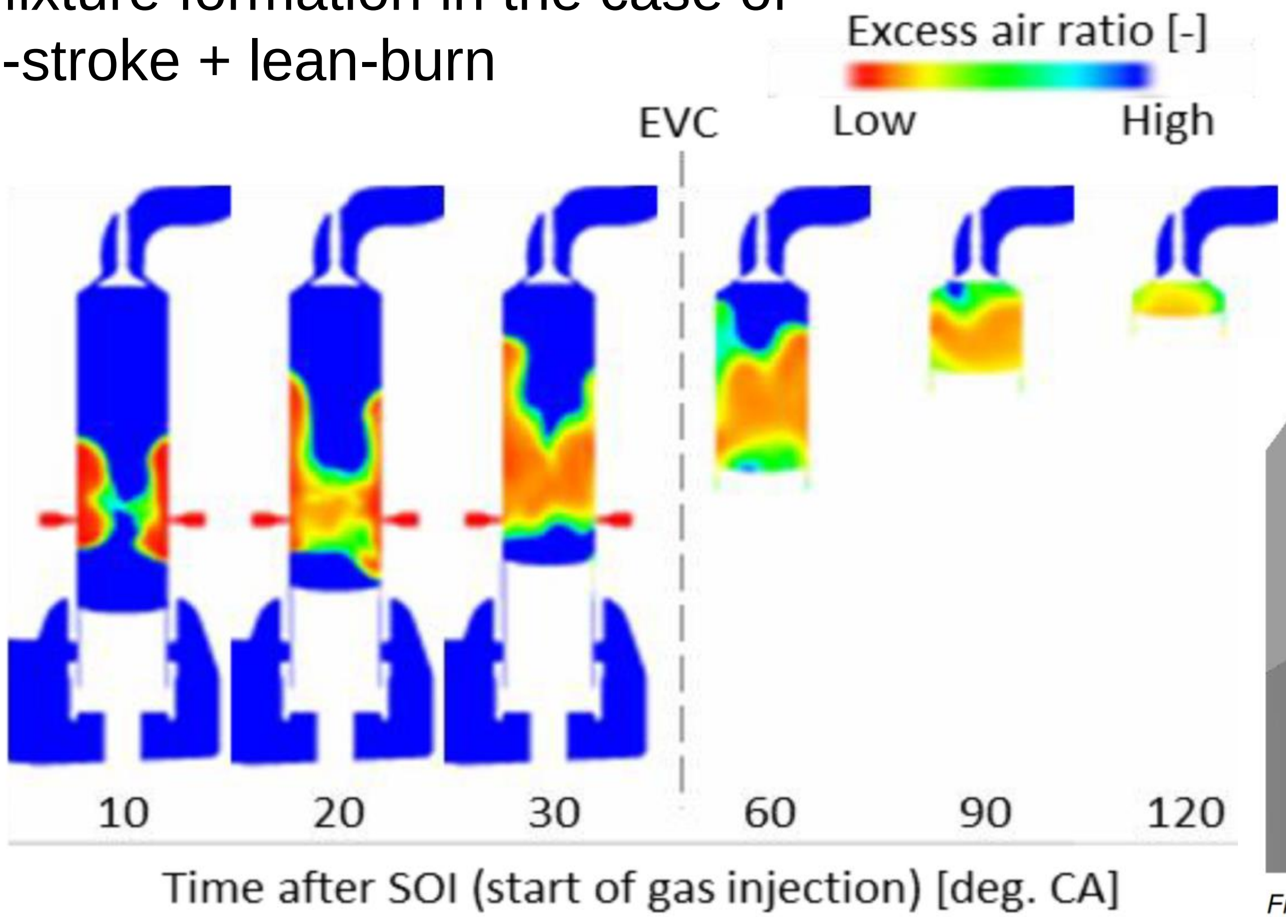


Figure 11 λ distribution of fuel gas injected from the liner

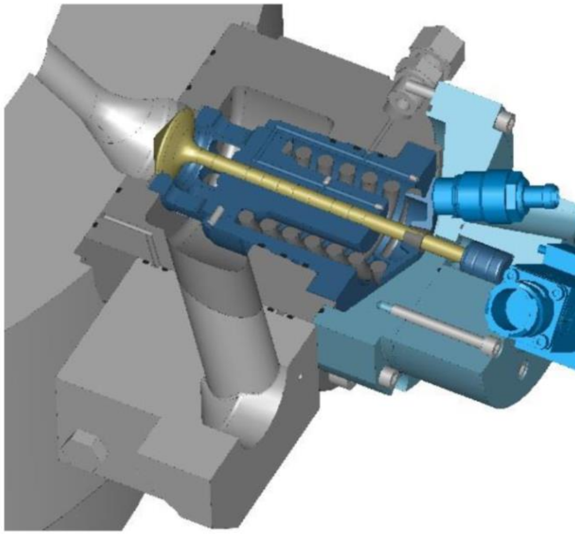


Figure 4: Gas admission valve section

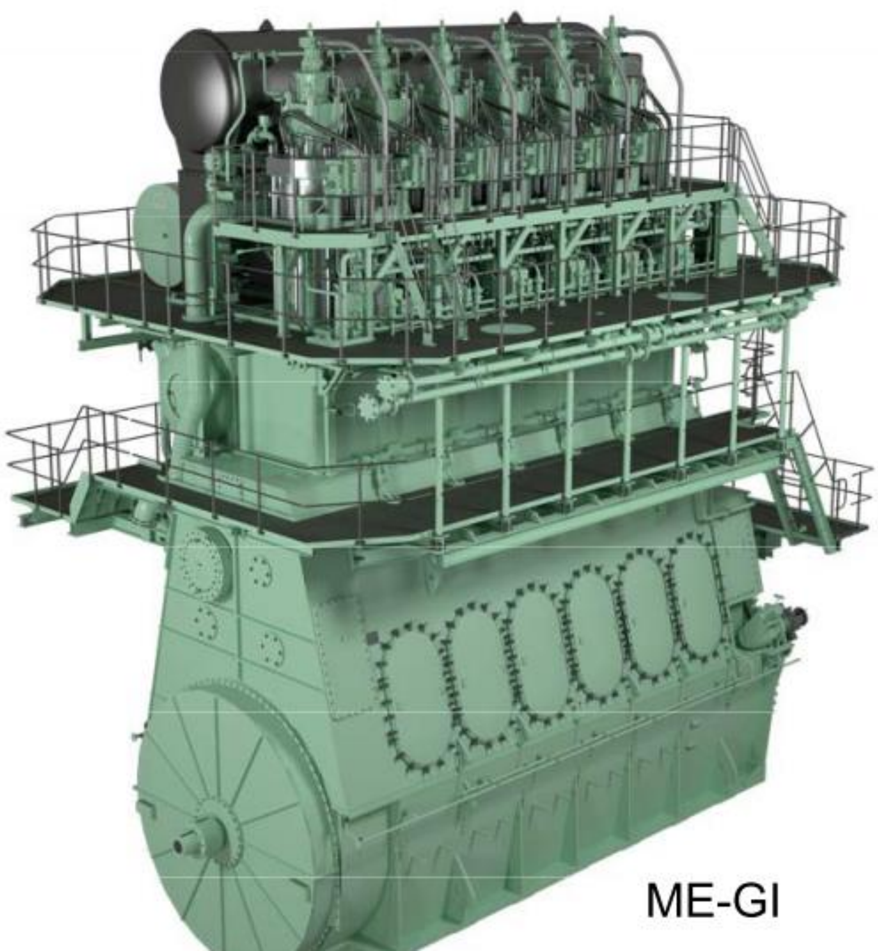
2-stroke gas concepts – Low pressure DF (16 bar max.)

CIMAC 2016 • Paper No.207
"Study on Mixture Formation Process in Two Stroke Low Speed Premixed Gas Fueled Engine"
Takahiro Kuge (IHI Corporation, Japan)

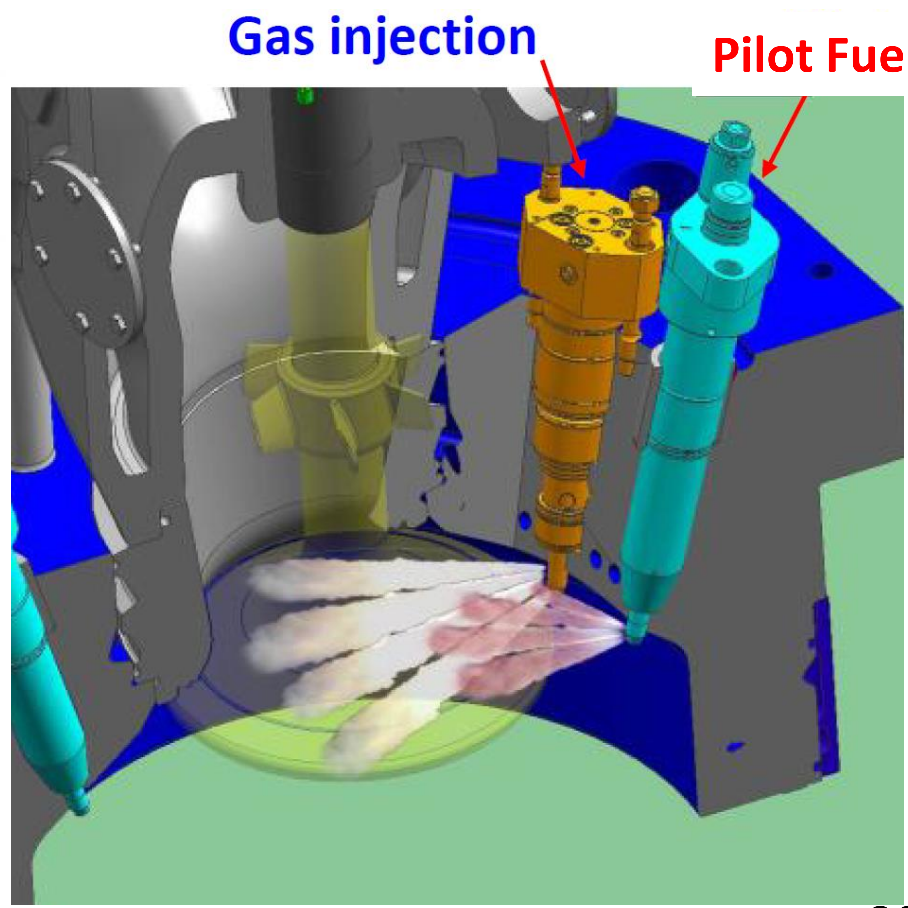
3.2 **Natural Gas** *(Methane) high pressure injection + pilot*

*For **GI** (**G**as **I**njection) type ・・named 'Diesel cycle gas engine'*

Merits : Free from knocking & abnormal combustion (Any MN is allowable.)
Lower methane slip

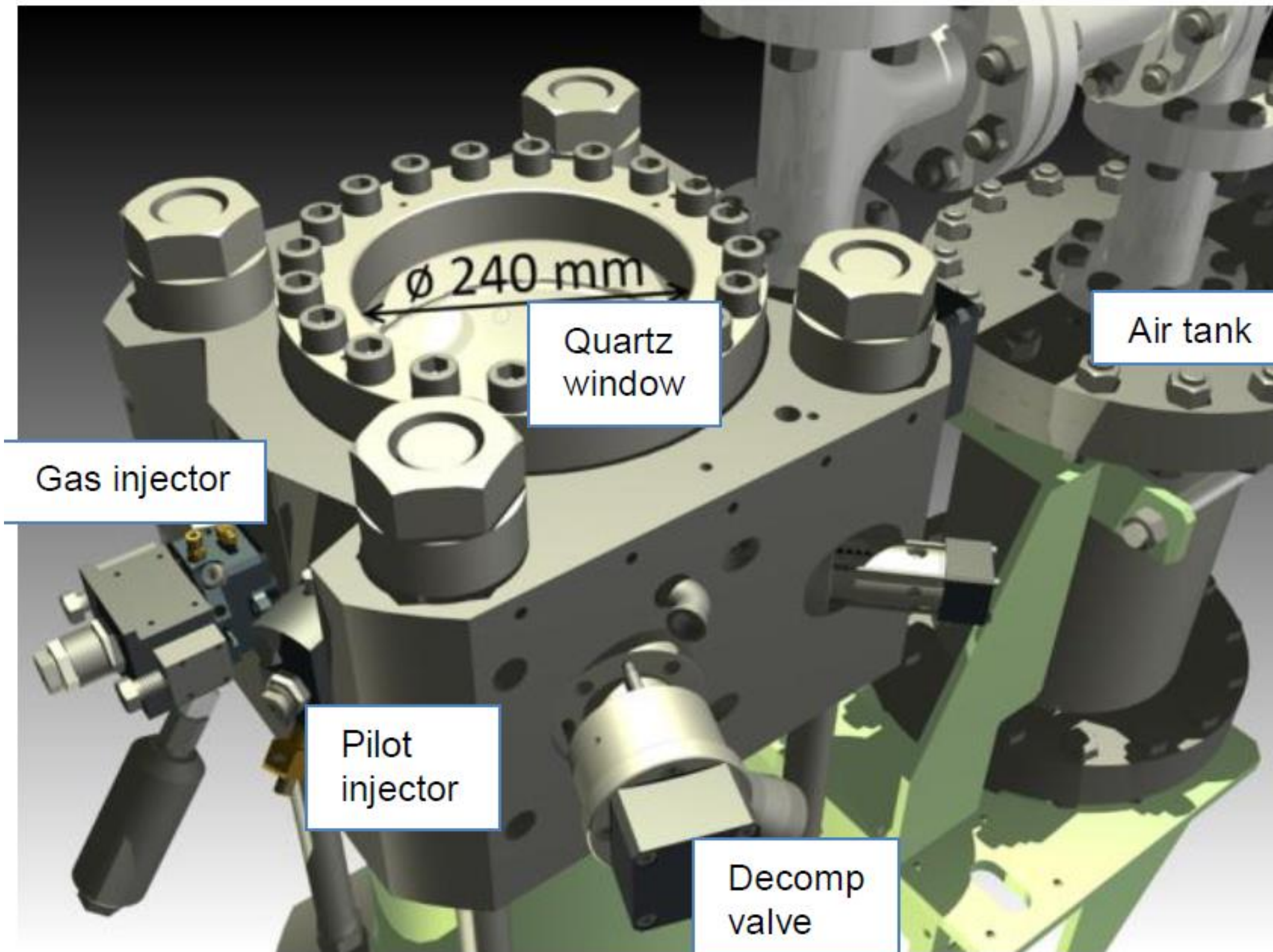


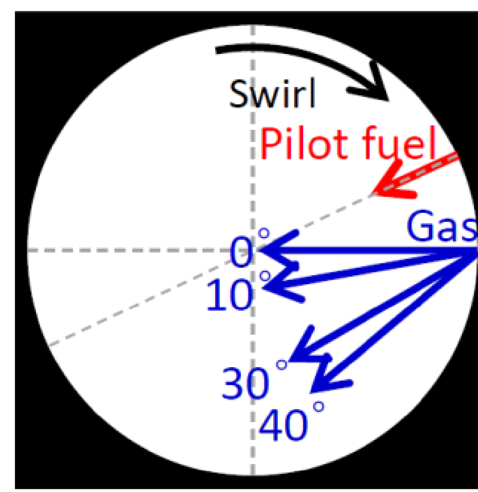
ME-GI



Observation of <u>Methane</u> GI multi flames in air swirl

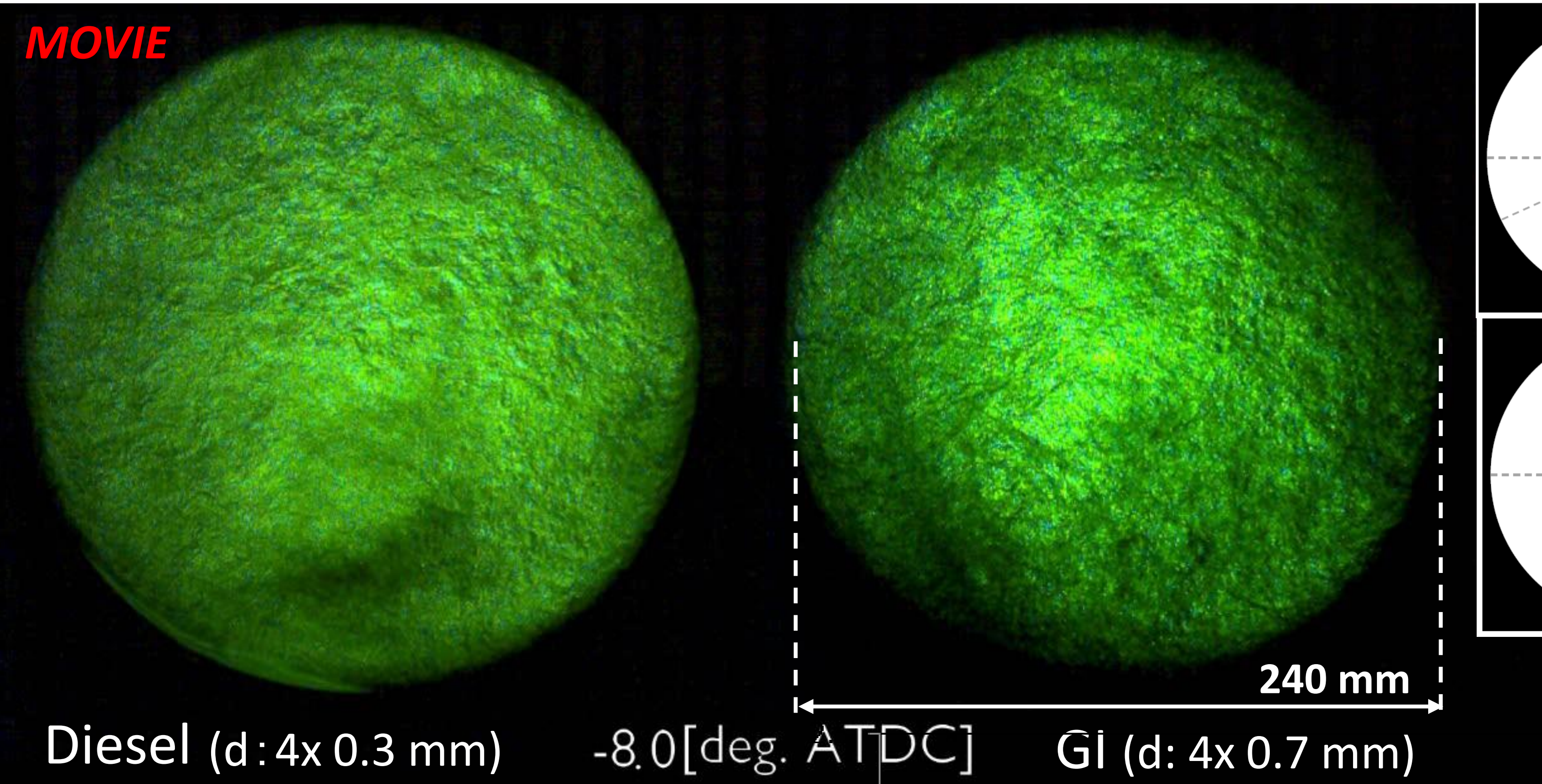
- *GI flame compared to diesel flame*
- *GI flame under the lower oxygen air simulating EGR to reduce NOx*

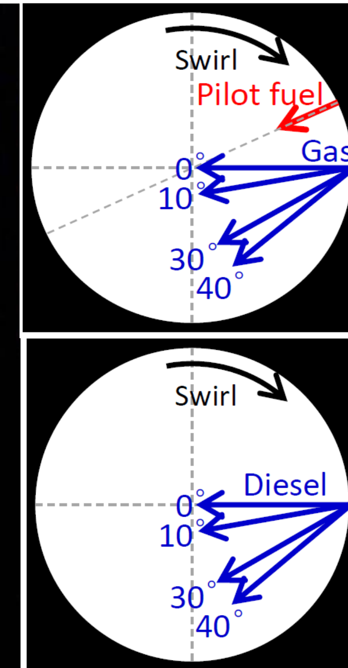


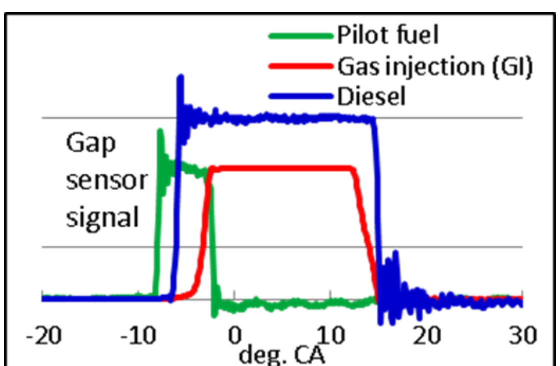


(Air: Pc 9.5 MPa, Tc 500 ℃)

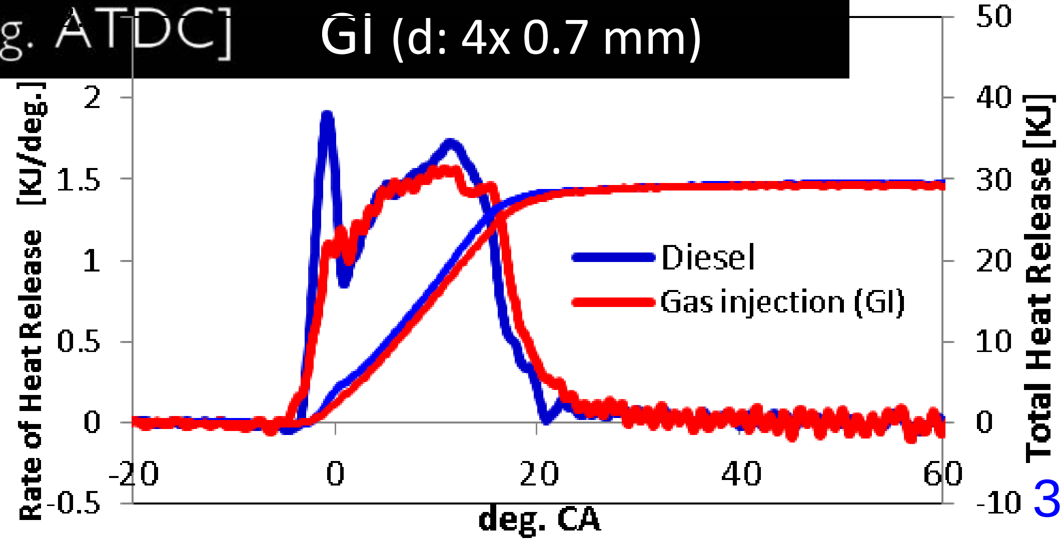
Diesel (Gas Oil : Pinj. :135 MPa) **GI** (Methane • • 31.5 MPa)

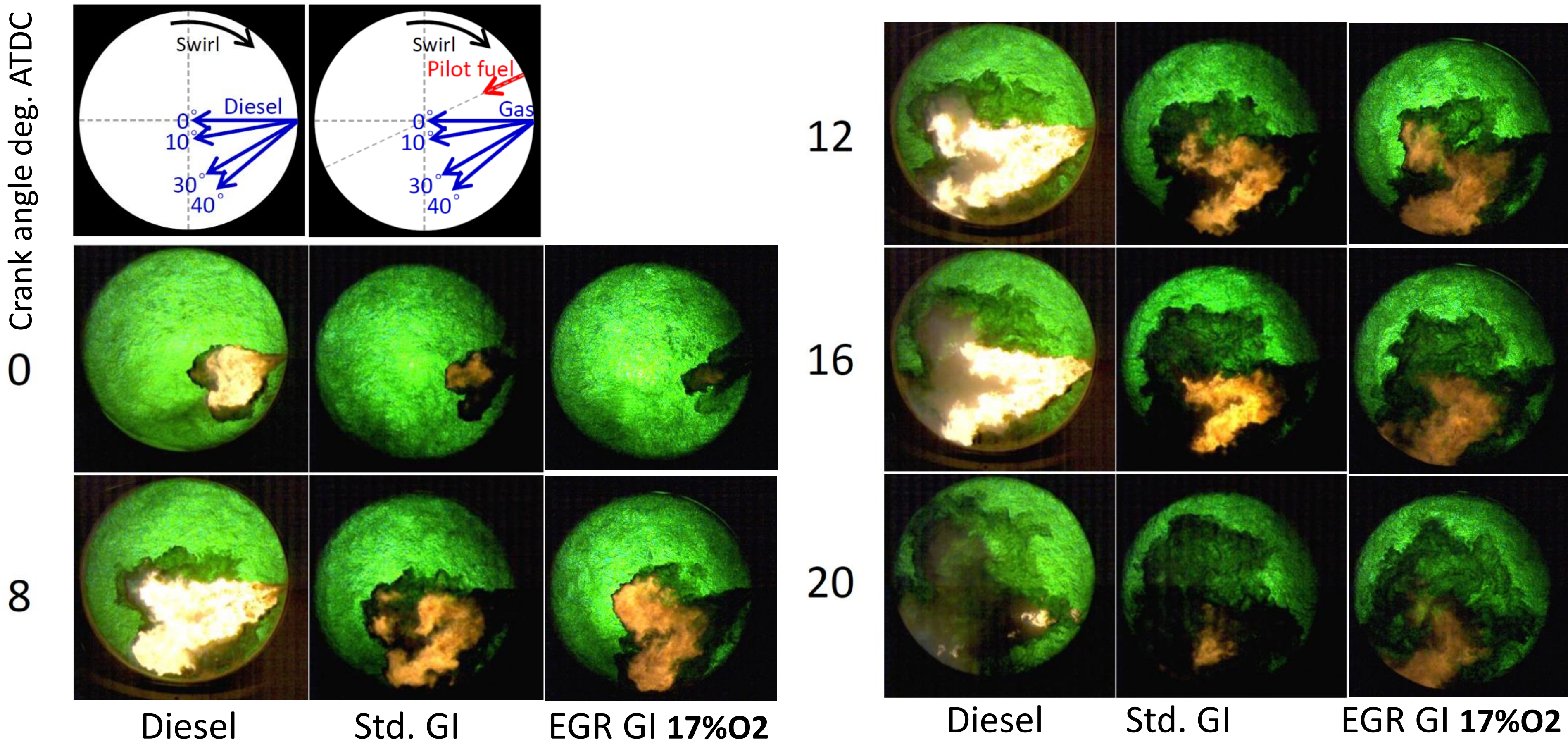




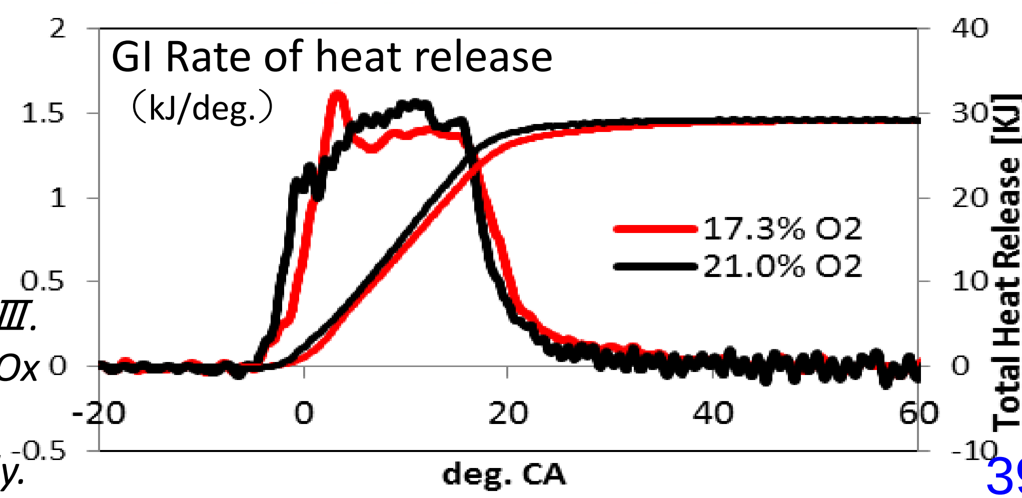


Diesel, GI and pilot injection duration





Emissions	Diesel	Std. GI	EGR GI
CO[ppm]	17	30	45
NOx[ppm]	499	300	44



EGR or SCR is necessary for GI to clear NOx Tier Ⅲ. EGR condition is simulated by 17% O2 air and NOx is reduced to 10% of diesel mode with minimum sacrifice of combustion in this fundamental study.

Thank you for your kind attention.

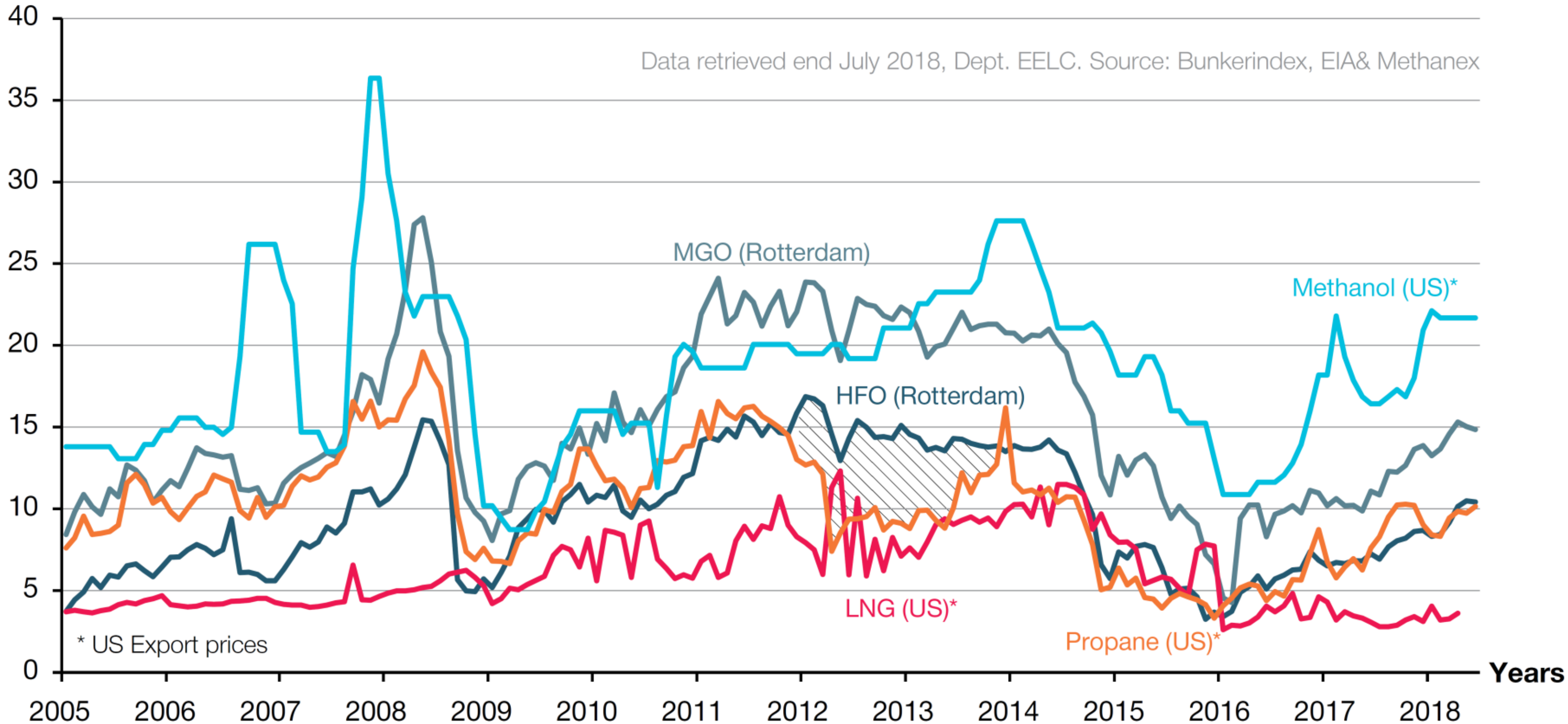


Fig. 11: Fuel price fluctuations for some gaseous fuels and conventional fuel during the last 13 years.