Combustion Characteristics of Hydrogen Direct Injection in a Helium-oxygen Compression Ignition Engine

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- Introduction
- Objectives
- Methodology
- Hydrogen Ignitability at Low Temperature and CR
- Effect of Intake Temperature on Combustion Characteristics
- Effect of Compression Ratio on Combustion Characteristics
- Heat Transfer Analysis
- Conclusion

INTRODUCTION

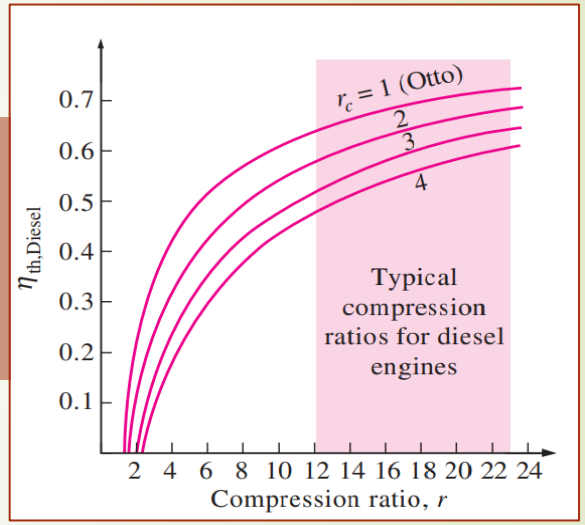
Hydrogen in ICE

- Hydrogen combustion has a larger energy efficiency due to its low density.
- Only water is produced when hydrogen is burned.
- Hydrogen has a high auto-ignition temperature of 858 K.

Working gas

- An ideal engine requires a good working gas with a high specific heat ratio to give the appropriate heat during compression to the engine,

$$\eta_{th,Diesel} = 1 - \frac{r^{1-k}(r_c^k - 1)}{k(r_c - 1)}$$



Helium as Working gas

- Helium is the lightest noble gases elements with a specific heat ratio of 1.66.
- The higher the specific heat ratio, the more heat can be released and the temperature may be raised to reach the hydrogen auto-ignition point.
- Previous study had only focused on argon-oxygen atmosphere.

Properties	N_2	Noble gases	
		He	Ar
Molecular weight (kg/mol)	28.014	4.00	39.95
Density (kg/m³)	1.165	0.1786	1.7818
Boiling point (K)	77.15	4.21	87.29
Melting point (K)	63.15	0.95	83.6
Specific heat capacity (J/kg.K)	1040	5190	519
Specific heat ratio, k	1.40	1.66	1.76
Price (USD/m³)	0.18	1.77	0.76

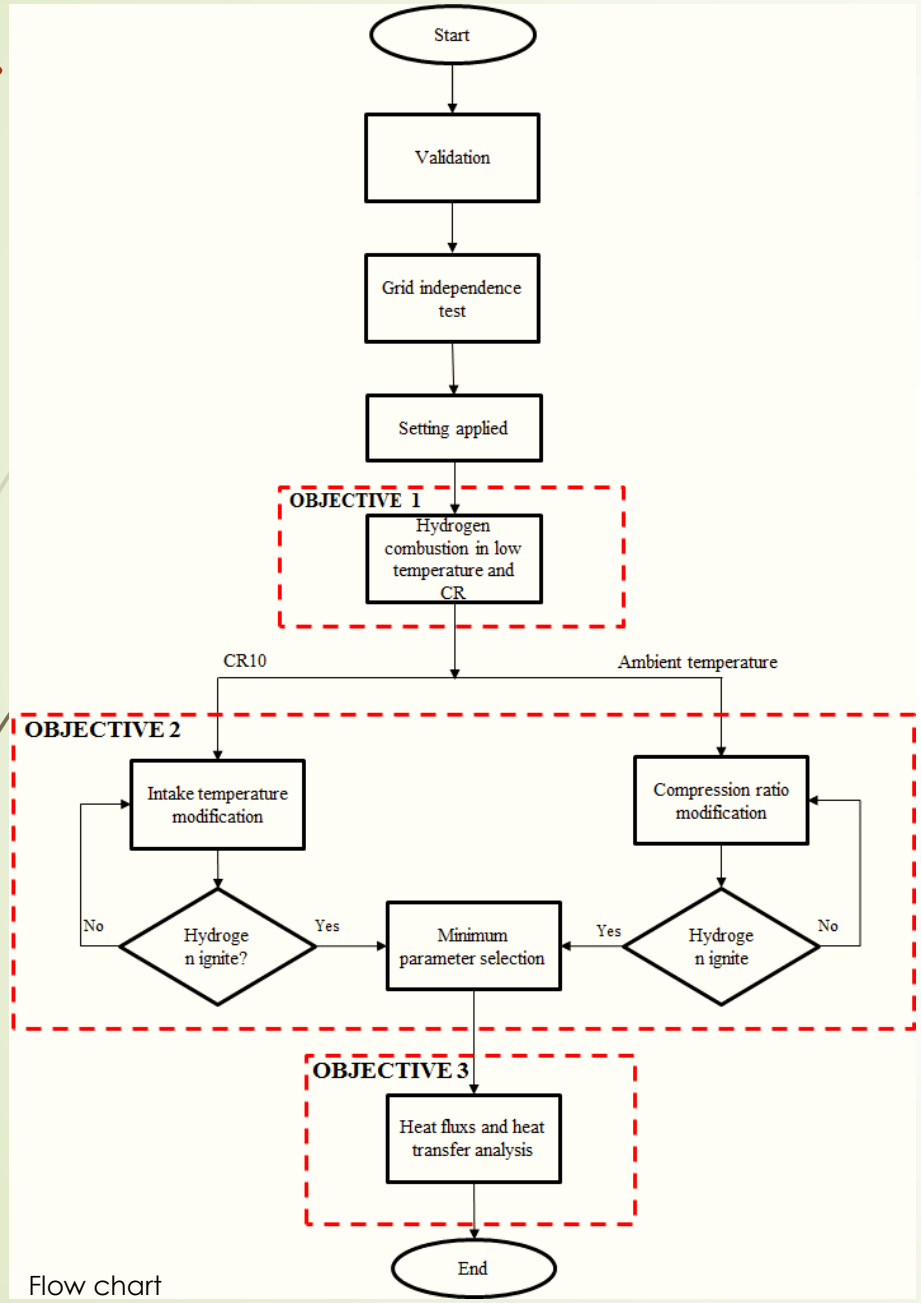
OBJECTIVES

To emphasizes the potential of helium-oxygen atmosphere for hydrogen combustion in CI engines at low temperature and compression ratio

To study the effect of high intake temperature and compression ratio on hydrogen combustion characteristics

To analyse the heat transfer during hydrogen combustion in helium-oxygen atmosphere

METHODOLOGY



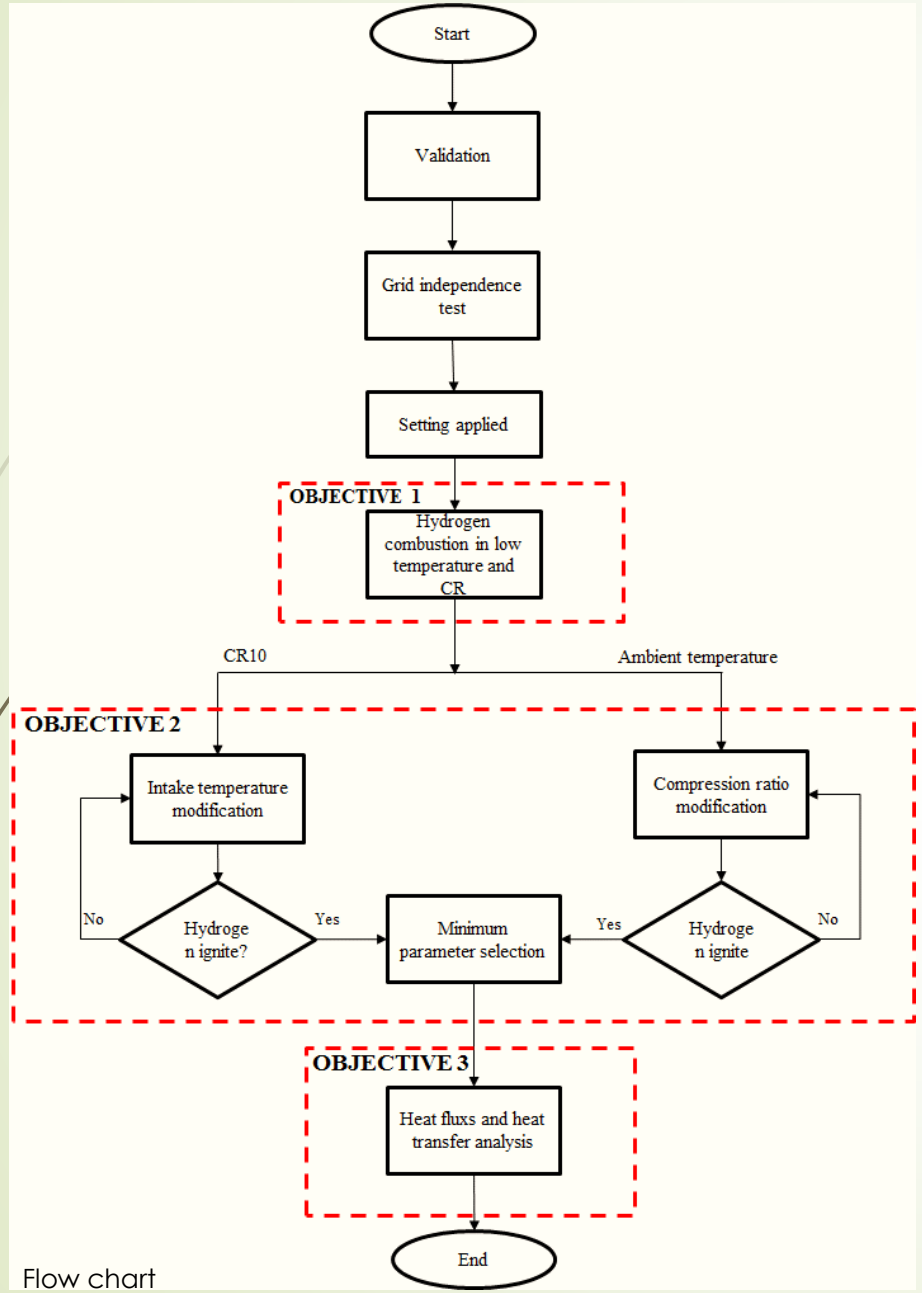
Flow chart

- This study are carried out numerically through simulation by using a Converge CFD software based on **Yanmar NF19SK direct injection compression ignition** engine parameters.
- The simulation was validated from the experiment using the same engine model conducted by Rey (2014) with a **9.89%** error percentage.
- The **grid independence test** determines that **0.005 m** is the best grid size.

Engine model specification and initial conditions

Engine specifications		**Injection and initial conditions**	
Engine type	CI	Working gas	79% (N_2, Ar, He) + 21% O_2
Engine model	NF19SK	Intake pressure	0.114 MPa
Engine speed	600 RPM	Injector location	Center of cylinder head
Bore x stroke	(110 x 106) mm^2	Injection timing	-3 °CA BTDC
Compression ratio	10, 12	Injection duration	5 CA
Intake valve open	179 °CA BTDC	Injection pressure	8 MPa
Exhaust valve closed	179 °CA ATDC	Intake temperature	300 K, 340 K, 380 K, 400K

METHODOLOGY



Flow chart

Objective 1

- At CR10 and ambient temperature, hydrogen ignitability and combustion characteristics of hydrogen combustion in helium-oxygen atmosphere was analyse.

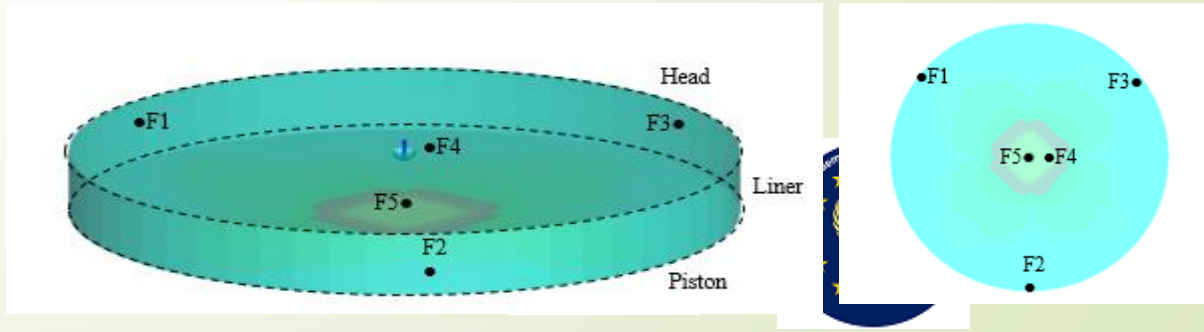
Objective 2

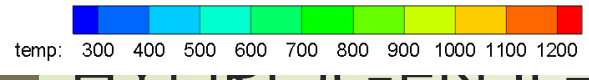
- In CR10, the intake temperature are varied; at 300K, 340K, 380K, and 400K
- At 300K, the compression ratio are varied; in CR10, CR12, CR14 and CR16.

Objective 3

- Heat flux values are measured at 5 different positions; F1, F2, F3, F4 and F5.
- The heat flux readings from the hydrogen combustion at different intake temperature and compression ratio are compared.

Heat flux measurement locations





HYDROGEN IGNITABILITY AT LOW TEMPERATURE AND CR

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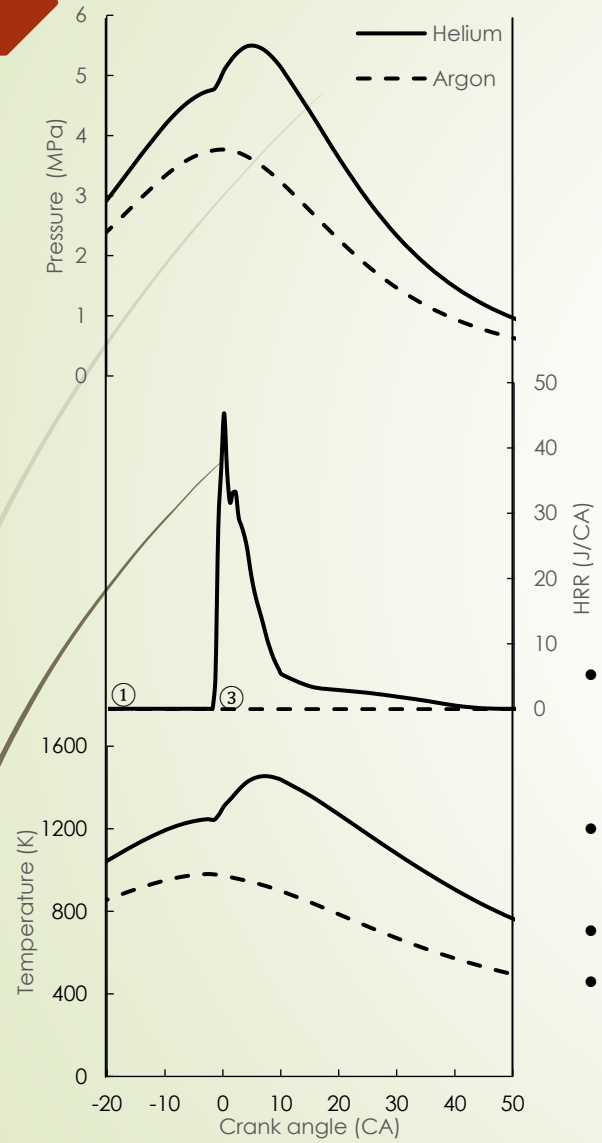
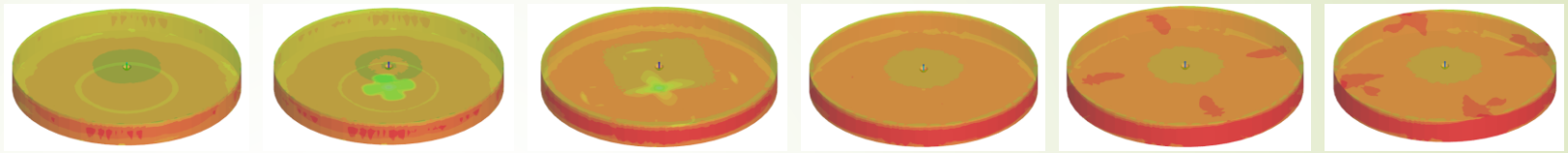
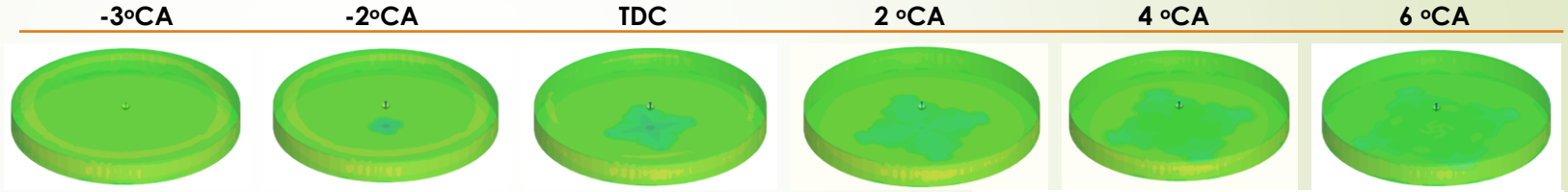


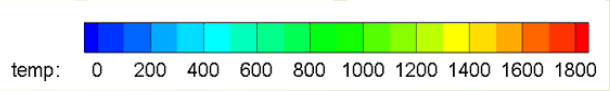
Hydrogen combustion in helium and argon-oxygen atmosphere at ambient intake temperature and in low compression ratio engine

Helium-oxygen atmosphere



Argon-oxygen atmosphere





- Helium-oxygen atmospheres reach hydrogen **ignition stability faster** than argon-oxygen atmospheres at ambient temperature and low compression ratio (CR10).
- As a result, without any engine modifications, helium-oxygen is **recommended** as the best working gas.
- The quick shift in pressure or heat release is indicative of ignition.
- The **ignition delay** of hydrogen in helium-oxygen atmosphere also very short, around **0.28 ms**.

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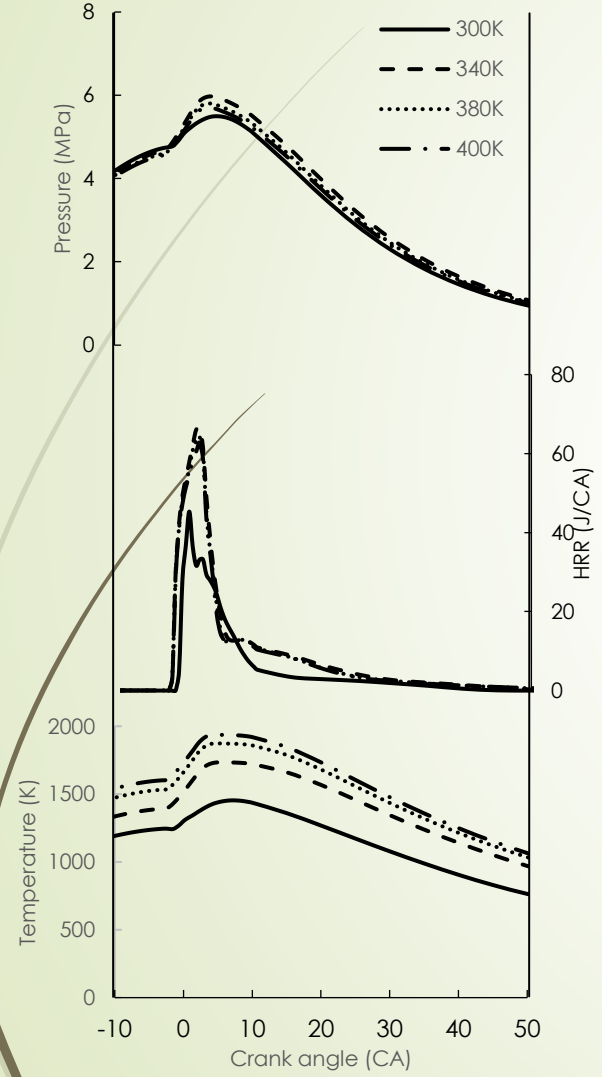
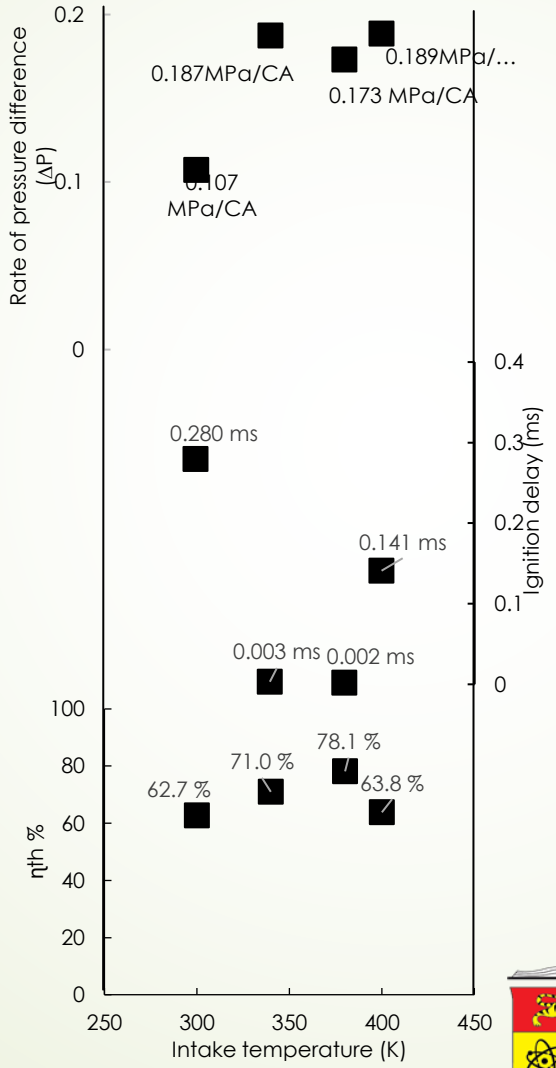
EFFECT OF INTAKE TEMPERATURE ON COMBUSTION CHARACTERISTICS

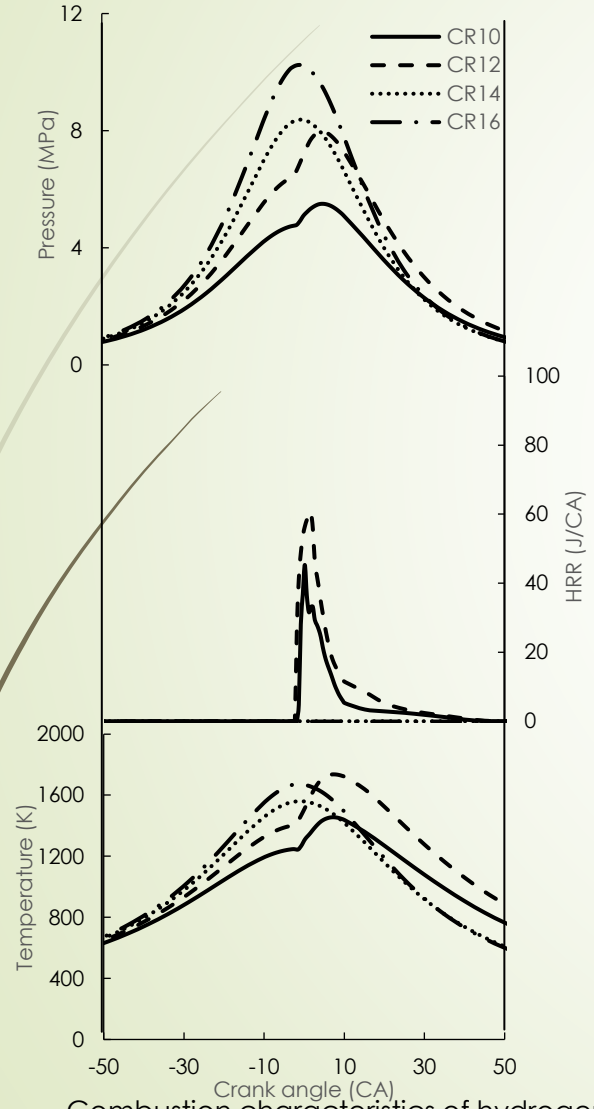




- Higher intake temperature results in good combustion progress.
- Increased intake temperature above ambient results in increased pressure and temperature, as well as smoother combustion with minimal knock or detonation issues.
- **340K and 380K** are the most suitable intake temperature for an optimum combustion progress, with an ignition delay around 0.002 ms.
- Short ignition delay indicates that the combustion progress took part in the engine is longer.
- Helium-oxygen atmosphere promotes an efficient hydrogen combustion progress at all intake temperatures.

Combustion characteristics of hydrogen combustion in low CR engine, at various intake temperature.

EFFECT OF COMPRESSION RATIO ON COMBUSTION CHARACTERISTICS



Combustion characteristics of hydrogen at ambient intake temperature in various compression ratio

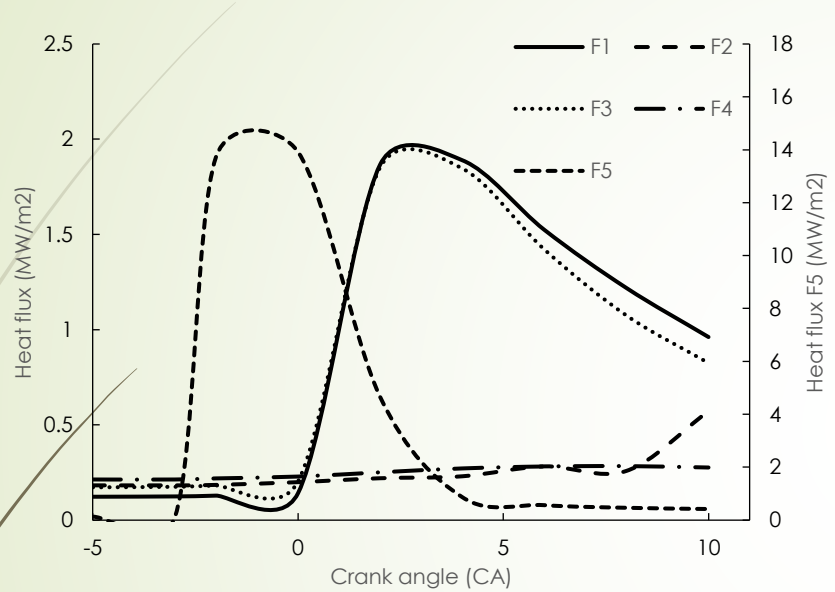
Ignition delay, rate of pressure difference and thermal efficiency of hydrogen combustion in helium-oxygen atmosphere in different CR engine

	CR10	CR12
Ignition delay (ms)	0.28	0.14
Rate of pressure difference (MPa/CA)	0.107	0.223
Thermal efficiency, η_{th} (%)	62.7	72.5

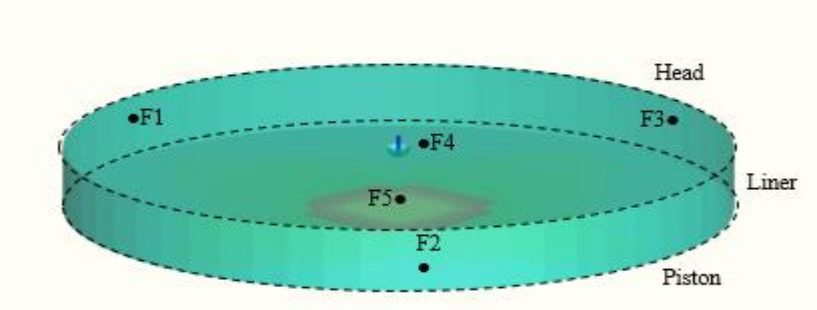
- At ambient intake temperature, the **compression ratio limit** for hydrogen combustion in helium-oxygen atmosphere is between **10 and12**.
- When the compression ratio exceeds 12, the in-cylinder pressure during compression stroke exceed the minimum pressure of injection **($P > P_{inj}$)**, resulting in poor ignitability.
- Hydrogen combustion **in CR12** shows a good combustion progress with the shortest ignition delay of 0.14 ms with thermal efficiency around 72.5%.

HEAT FLUX ANALYSIS

Heat flux at different locations



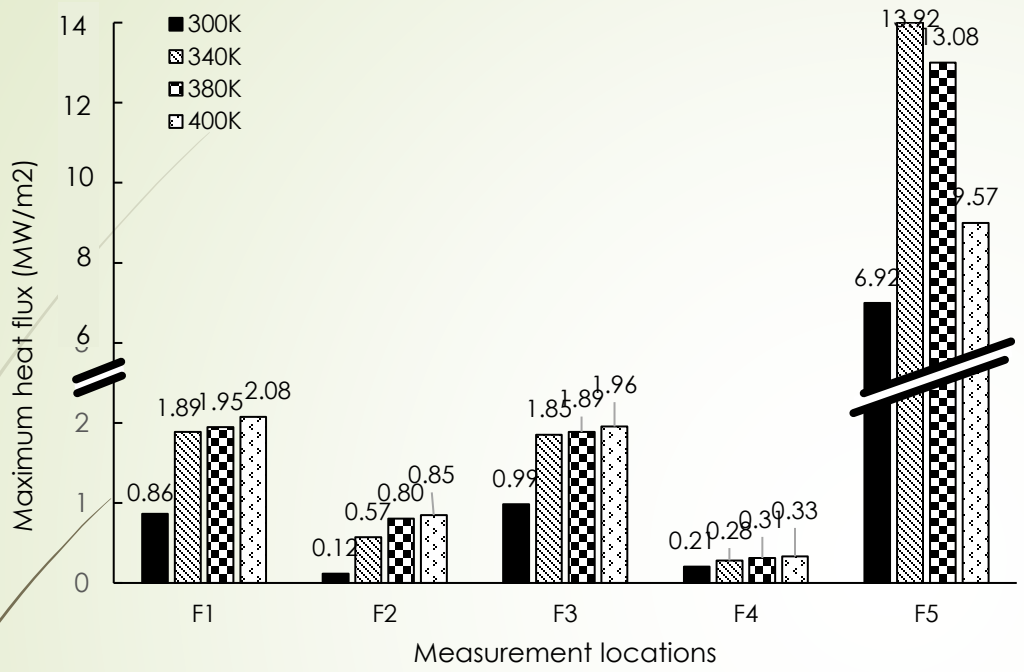
Heat flux measured during combustion at ambient temperature low CR



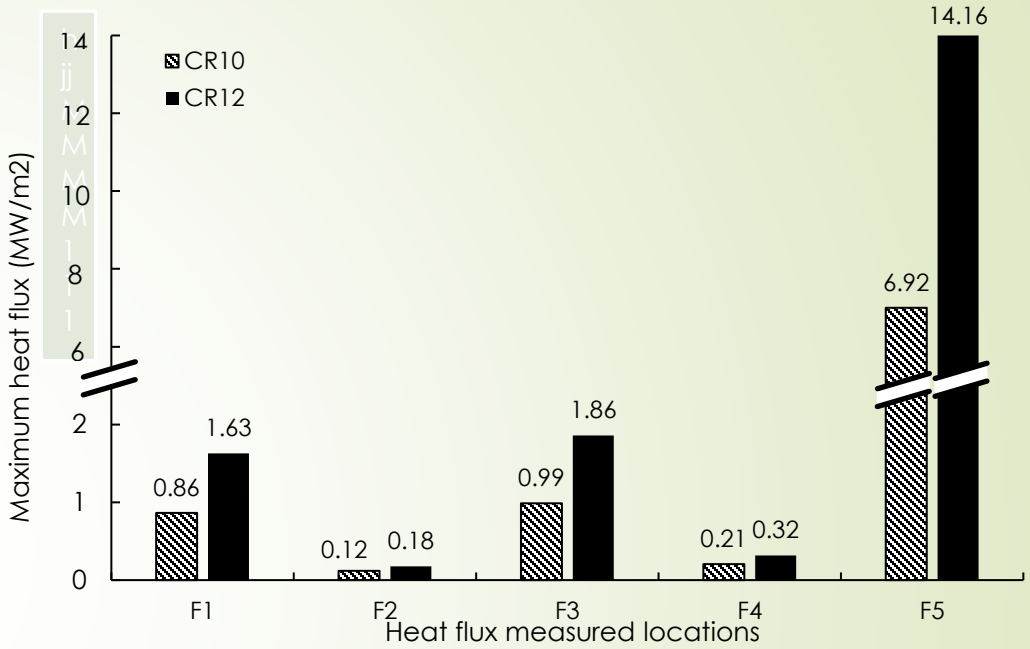
Locations of heat flux measurement

- Heat flux was measured at 5 different locations
- Heat flux measured at F1,F2 and F3 indicates the heat formed at the wall of the engine.
- F4 and F3 are measured on the head of the cylinder and piston.
- At low temperature and compression ratio, heat flux measured at the wall is increase during hydrogen ignition.
- Heat flux at the **piston** is the highest as soon as the flame reached the surface upon hydrogen ignition.

HEAT FLUX ANALYSIS



Maximum heat flux at different intake temperature



Maximum heat flux in different compression ratio engine

- The heat flux at the wall increases as the **flame dominates the wall** at the **higher intake temperature** for longer than the lower intake temperature.
- During the hydrogen combustion at **340K and 380K**, heat flux measured at the piston recorded the **highest value** due to the immediate heat release from the hydrogen combustion.
- The heat flux recorded during the combustion in high compression ratio released **more heat at F1** compared to F3. At F3, the heat flux for combustion in high compression ratio is reduced.
- In a **high compression ratio**, the heat flux measured **at piston, F5**, for hydrogen combustion in high compression ratio is **two times higher** than in low compression ratio.

CONCLUSIONS

- Hydrogen combustion in **helium-oxygen atmosphere produces higher pressure, HRR and temperature** than in argon-oxygen atmosphere.
- In low compression engine, the **minimum intake temperature** for the hydrogen ignition in helium-oxygen atmosphere is **300K**, however, intake temperature **340K results in greater engine thermal efficiency** and better combustion progress.
- At **ambient intake temperature**, the maximum compression ratio allowed for hydrogen ignition in helium-oxygen atmosphere is **CR12**, while greater CR causes ignition failure. CR12 is the most appropriate compression ratio.
- High intake temperature and compression ratio causes the higher heat flux at the cylinder wall. **Intake temperatures of 340K at low compression ratio engine** and **CR12 at ambient intake temperature** are **recommended** based on the heat fluxes and performance.

THANK YOU

Any enquiries or suggestion, feel free to contact

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