LE STUDIUM
Loire Valley
Institute for Advanced Studies

LE STUDIUM Multidisciplinary Journal
ISSN 2669-7807
www.lestudium-ias.com

FELLOWSHIP FINAL REPORT

Potential of low and zero-carbon fuels in high-efficiency clean combustion engines

Ganesh Duraisamy[1, 2*], Christine Mounaïm-Rousselle[2,3]

[1]Department of Mechanical Engineering, College of Engineering-Guindy Campus,
Anna University, Chennai, India
[2]PRISME Laboratory, University of Orléans, Orléans, France
[3]Institut Universitaire de France, IUF, France

REPORT INFO

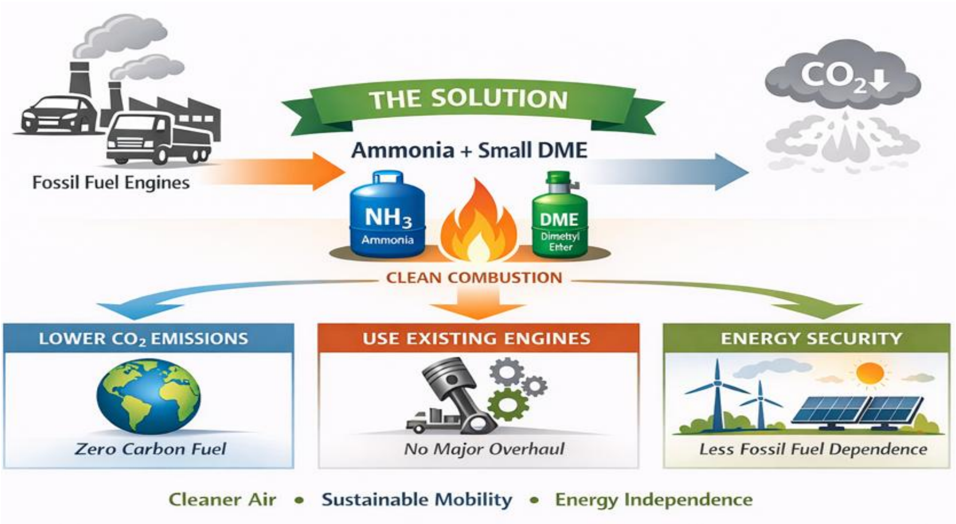
Fellow : **Dr. Ganesh Duraisamy**
From Anna University, India
Host laboratory in the region Centre-Val de Loire : ***PRISME Laboratory***
Host scientist :
Professor Christine Mounaïm-Rousselle
Period of residence in the region Centre-Val de Loire **:** March 2024 – March 2025

Keywords:
Ammonia, Dimethyl Ether, High efficiency, Carbon neutral fuels, SICI engines, clean combustion

ABSTRACT

Achieving the European Green Deal objectives and global net-zero targets requires rapid decarbonization of the transport sector, which remains a significant source of greenhouse gas emissions. While electrification is expanding, long vehicle lifecycles and infrastructure limitations necessitate complementary low-carbon solutions that can be integrated into existing engine platforms. Ammonia (NH_3) is emerging as a strategic zero-carbon energy carrier because it contains no carbon, can be produced from renewable electricity, and benefits from established global storage and distribution infrastructure. However, its slow ignition and poor combustion reactivity limit direct application in internal combustion engines. This research evaluates the use of small quantities of dimethyl ether (DME) as an ignition promoter to enable stable and efficient ammonia combustion under multiple operating modes. The results demonstrate that minimal DME addition significantly enhances ignition reliability, combustion stability, and efficiency while maintaining low carbon emissions. By enabling the use of ammonia in existing engine technologies, this work supports near-term emission reduction strategies, strengthens energy security by reducing fossil fuel dependence, and contributes to Indo-French scientific collaboration aligned with European climate and innovation policies.

Graphical Abstract



Ganesh Duraisamy, Christine Mounaïm-Rousselle. Potential of low and zero-carbon fuels in high-efficiency clean combustion engines, LE STUDIUM *Multidisciplinary Journal*, **2025**, 9, 101-110
https://doi.org/10.34846/le-studium.291.01.fr.03-25

1- Introduction

The global transport sector remains one of the largest contributors to greenhouse gas emissions. In the European Union, transportation accounts for nearly 23% of total CO_2 emissions [1], making it the second-largest emitting sector after energy production. India faces similar challenges as mobility demand continues to grow rapidly [2]. Both regions have committed to ambitious climate targets — carbon neutrality by 2050 in the EU and by 2070 in India [3]. However, achieving these goals requires not only electrification but also transitional solutions that can reduce emissions from existing internal combustion engines [4].

Although electric vehicles are expanding, their large-scale adoption faces infrastructure, cost, and resource constraints. Millions of conventional vehicles and industrial engines will remain in operation for decades. Therefore, developing carbon-neutral fuels that can be used in current engine technologies represents a practical and immediate pathway toward reducing emissions without waiting for complete fleet replacement [5].

Ammonia (NH_3) has emerged as a promising zero-carbon energy carrier [6]. It contains no carbon, meaning it does not produce CO_2 during combustion. Additionally, ammonia is easier to store and transport than hydrogen, making it attractive for large-scale energy distribution. Ammonia can also be produced using renewable electricity, further enhancing its potential as a sustainable fuel.

However, ammonia has significant combustion limitations. It ignites poorly, burns slowly, and requires high energy input for stable engine operation. These characteristics make direct use of ammonia in conventional engines challenging. This research addresses a critical question of societal relevance: How can we enable clean, efficient, and stable ammonia combustion in existing engine technologies to accelerate the transition toward carbon-neutral mobility?

To overcome ammonia’s combustion limitations, this study proposes the use of dimethyl ether (DME), a low-carbon, highly reactive fuel, as a combustion enhancer. By adding small quantities of DME, the ignition and stability challenges of ammonia can be significantly improved.

The work conducted during this fellowship at PRISME Laboratory (France), in collaboration with Anna University (India), investigates ammonia–DME blends across multiple advanced combustion modes. The objective is to develop scientifically validated strategies that enable zero-carbon fuel operation in internal combustion engines while maintaining efficiency, stability, and industrial feasibility.

This research contributes directly to:

- European and Indian climate commitments
- Development of carbon-neutral fuels
- Energy security and reduced fossil fuel dependence
- Strengthened Indo-French scientific collaboration

By bridging advanced combustion science with practical decarbonization strategies, this study supports the global transition toward sustainable mobility.

2- Experimental Details

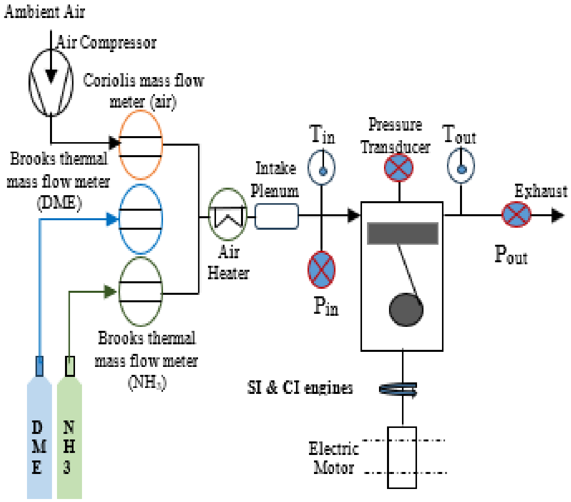


Fig.1 Experimental test setup

To evaluate the feasibility of ammonia-based combustion as a sustainable alternative to fossil fuels, experiments were conducted using two single-cylinder research engines representing spark-ignition (SI) [EP6 PSA], homogeneous charge compression ignition (HCCI), and dual-fuel combustion [PSA DW10] strategies [Table 1]. These configurations were selected to simulate different practical engine operating modes [Table 2] and to assess ammonia's adaptability across various combustion concepts.

Before testing, engine oil and coolant temperatures were stabilized at 80°C to ensure repeatable and realistic operating conditions. Ammonia (NH_3), dimethyl ether (DME) [Table 3], and air were supplied in controlled proportions using precision mass flow controllers, allowing accurate adjustment of the equivalence ratio (ϕ). This approach ensured reliable comparison of combustion behavior under lean and near-stoichiometric conditions.

In SI and HCCI modes, ammonia and DME were premixed with air in the intake system. In the dual-fuel configuration, ammonia was premixed with air, while small quantities of DME were directly injected into the cylinder at high pressure. This strategy allowed DME to act as an ignition promoter, triggering ammonia combustion without significantly increasing carbon content. Combustion performance was evaluated using high-resolution in-cylinder pressure measurements and crank-angle analysis. From these measurements, key indicators such as heat release rate, $\frac{\mathbf{dQ}}{\mathbf{d\alpha}} = \frac{\boldsymbol{\gamma}}{\boldsymbol{\gamma}-\mathbf{1}}\mathbf{P}\frac{\mathbf{dV}}{\mathbf{d\alpha}} + \frac{\mathbf{1}}{\boldsymbol{\gamma}-\mathbf{1}}\mathbf{V}\frac{\mathbf{dP}}{\mathbf{d\alpha}} + \frac{\mathbf{dQ_w}}{\mathbf{d\alpha}}$ (where P – cylinder pressure, α – crank angle, and V-cylinder volume), ignition delay, combustion duration, indicated mean effective pressure (IMEP), and cycle-to-cycle variation were determined. These parameters were selected because they directly reflect engine stability, efficiency, and operational feasibility — critical factors for real-world application.

Overall, the experimental framework was designed not only to study combustion chemistry, but to assess whether ammonia–DME blends can provide stable, efficient, and scalable solutions compatible with existing engine technologies.

Table 1. Engine specifications

Description	EP6 PSA SI	PSA DW10 CI
Displaced volume	535 cm^3	500 cm^3
Stroke	115 mm	88 mm
Bore	77 mm	85 mm
Connecting rod length	177 mm	145 mm
Compression ratio	12.1	16.4
Number of valves	4	4
Coolant and Oil temperatures	80°C	80°C

Table 2. Operating conditions

Descriptions (Units)	Combustion modes		
	SI	HCCI	DF
Equivalence ratio (ϕ)	0.65-1	0.3-0.5	0.65-1.25
Intake pressure (bar)	0.8,0.85,1	1-1.9	1
Intake temperature (°C)	40-46	Vary	80-86
Engine speed (rpm)	1000, 1500, 2000	1000	1000
NH_3 (vol. %)	90-100	90-100	99
DME (vol. %)	0-10	0-10	~1
Spark ignition timing (CAD aTDC)	-24 to -48	-	-
Spark duration (µs)	2000	-	-
Direct injection timing (CAD aTDC)	-	-	-24 to -38
Injection pressure (bar)	-	-	130.135

Table 3. Test fuel properties [7]

Parameters	Ammonia	DME
Molecular formula	NH_3	CH_3OCH_3
Molecular weight, g/mol	35.046	46.07
Carbon content, wt. %	0	52
Hydrogen content, wt. %	17.6	13
Nitrogen content, wt. %	82.4	0
Oxygen content, wt. %	0	35
Density at 15°C and 1 bar, kg/m^3	0.73	0.668
Research Octane Number	130	-
Cetane number	-	55-66
Lower heating value, MJ/kg	18.64	27.6
Volumetric energy density, MJ/m^3	13.7	19
Autoignition temperature, °C	651	235
Stoichiometric air-fuel ratio, kJ/kg	6.04	9
Laminar flame speed, m/s	0.015	0.45
Heat of evaporation, kJ/kg	1370	467
Flammability limits in air, vol.%	15-28	3.4-27
Ignition energy in air, mJ	8	0.29

3. Results and discussion

Ammonia alone typically exhibits slow combustion characteristics and ignition challenges. However, when small amounts of DME were introduced, ignition stability improved significantly. This confirms that DME can function as an effective ignition promoter, enabling ammonia combustion without substantially increasing carbon emissions.

Ammonia combustion is kinetically limited due to slow radical formation, resulting in long ignition delay and low laminar flame speed [8]. These characteristics restricts its application in both SI and HCCI modes. Chemical Kinetics studies reveal that the introduction of small quantities of DME significantly enhances combustion reactivity by promoting early radical formation [9], thereby reducing ignition delay as shown in Fig.1 and increasing flame propagation speed (refer Fig.2.) This demonstrates that DME is an effective combustion promoter for ammonia-fueled engines.

This finding is important because it shows that carbon-free ammonia can be integrated into existing engine platforms with minimal modification, reducing reliance on fossil fuels while maintaining engine operability.

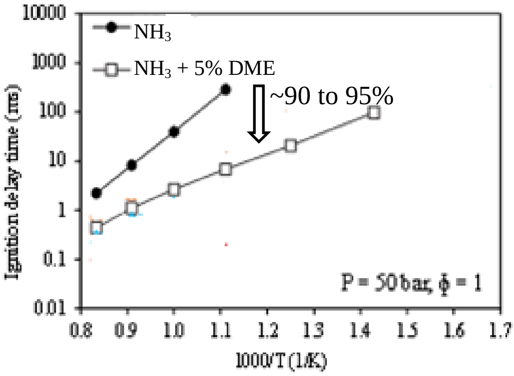


Fig.1 Combustion limitations of neat ammonia

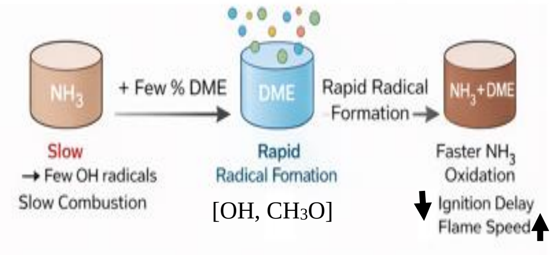


Fig.2 DME promotes ammonia combustion

3.1 NH_3-DME Fuelled Engine Performance and Combustion Stability in SI, HCCI, and DF modes

The experimental results demonstrate that ammonia can be successfully utilized in internal combustion engines when assisted by small quantities of DME. Across spark-ignition (SI), HCCI, and dual-fuel modes, stable combustion was achieved within controlled operating ranges presented in Table 2.

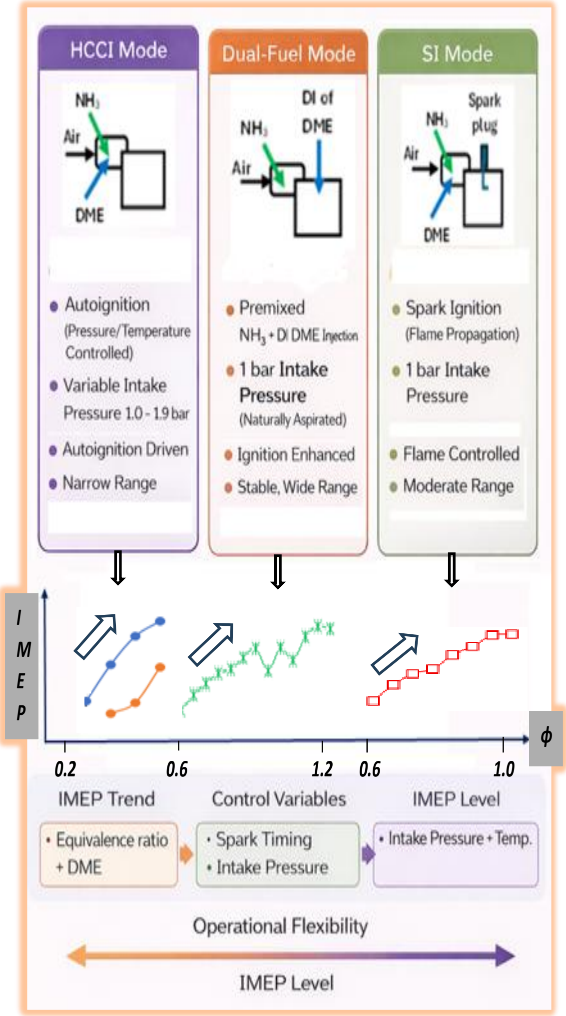
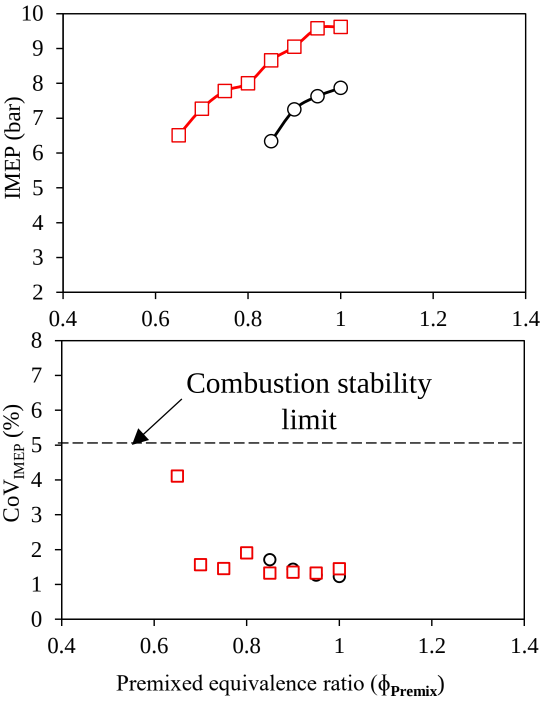
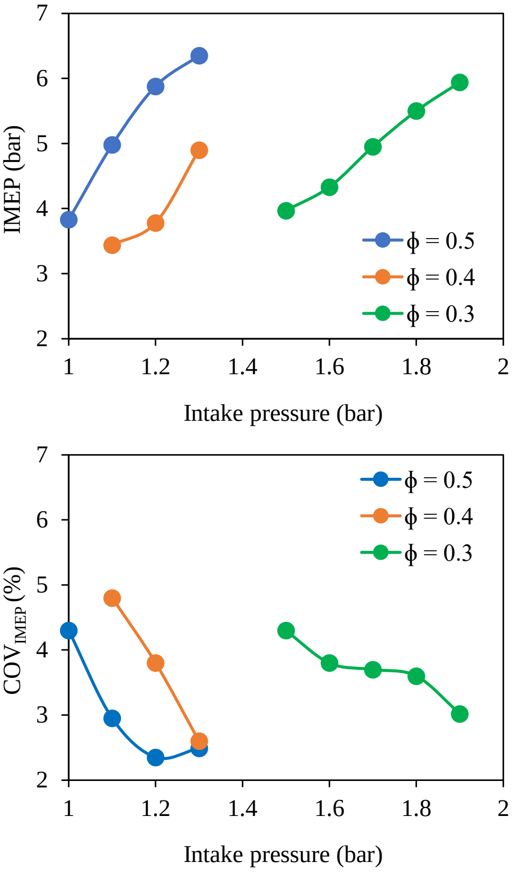


Fig.3 Comparison of SI, HCCI and DF combustion regimes

The comparative combustion regime analysis clearly demonstrates that DME addition significantly enhances the operational flexibility of the ammonia-fueled engine, both in premixed (SI and HCCI) and dual-fuel modes.

Though, experiments were conducted at different operating conditions as mentioned in Table 2, the discussion is restricted to an intake pressure of 1 bar and engine speed of 1000 rpm with 10% DME addition in premixed SI and HCCI modes and 1% DME addition in dual fuel mode to demonstrate the potential of DME in supporting operational flexibility with stable and clean combustion in SI, HCCI and DF modes.





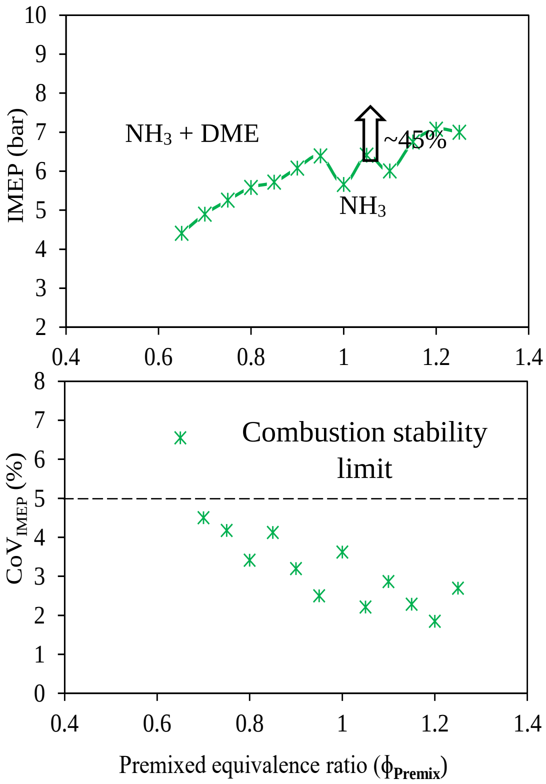


Fig.4 Performance and stability of NH_3-DME combustion in SI mode

Fig.5 Performance and stability comparison of NH_3-DME combustion in HCCI mode

Fig.6 Performance and stability of NH_3-DME combustion in Dual Fuel mode

In SI operation with pure NH_3 (Fig.4) Stable combustion is observed only in the near-stoichiometric region (ϕ ≈ 0.85–1.0). IMEP remains moderate (~6–8 bar). Lean operability is limited due to Low laminar flame speed, High ignition energy requirement, Narrow flammability limits, and Poor flame propagation of NH_3 under lean conditions (refer Table 3). Thus, pure ammonia shows restricted load range and limited lean-burn flexibility.

With 10% DME (by volume) premixed with NH_3–air, IMEP increases across the entire investigated ϕ (0.65 to 1.05) range. Stable operation extends further into lean conditions (ϕ ≈ 0.65). Higher peak IMEP of ~9–10 bar compared to pure NH_3. DME enhances combustion of ammonia by promoting rapid chemical reactivity and improving flame propagation through its oxygenated molecular structure and higher cetane number. DME addition widened lean operating window, increased IMEP (load) at the same intake pressure and reduced cyclic variability to lèss than 5%. More stable combustion in transitional equivalence ratios.

In HCCI mode, ammonia, DME, and air is premixed at an equivalence ratios 0.3,0.4, and 0.5 and autoignited by varying the intake temperature and pressure. With 10% by volume of DME in HCCI mode resulted in stable combustion at $\phi = 0.3$, 0.4, and 0.5 as show in Fig.5. It is observed that DME addition reduced the intake temperature required to autoignite the premixed air-fuel mixture at all ϕ. Further intake temperature also decreases with increase in intake pressure (example : at $\phi = 0.5$, with 10% DME, intake temperature required at 1 bar, 1.1 bar, 1.2 bar and 1.3 bar are 114^0C, 70^0C, 53^0C, and 39^0C respectively). The decrease in ϕ, at constant intake pressure increases the intake temperature. IMEP in HCCI mode increases with increase in ϕ. Low ϕ HCCI operation requires increased intake pressure and temperature for stable combustion and improved IMEP. DME act as an ignition promoter enabling controlled autoignition at lower ϕ and extension of ultra-lean operability compared to pure NH_3. However, Load capability remains limited and combustion phasing sensitivity restricts further expansion. The CoV_{IMEP} analysis reveals that stable operation (CoV < 5%) is achieved at relatively low intake pressure levels for $\Phi = 0.5$, while ultra-lean operation demands intake pressures above 1.7 bar. This indicates that intake pressure plays a dominant role in extending the lean operating limit of ammonia-based HCCI combustion.

Fig.6 illustrates the performance and combustion stability behavior of ammonia-DME combustion in dual fuel operation mode. The intake pressure and engine speed remains same (1 bar and 1000 rpm). Ammonia and air remains premixed and DME of 1% by volume is injected directly into the cylinder at 38 CAD bTDC and 135 bar pressure for assisting ammonia auto-ignition. Stable combustion was observed from equivalence ratio $\phi = 0.65$ to 1.25 with gradual increase in IMEP across wide equivalence ratio range. In dual fuel operation operability extends into richer mixture beyond SI range ($\phi_{DF} = 0.65$ to 1.25 vs $\phi_{SI} = 0.65$ to 1.05). In this case, direct-injected DME acts as a localized high-reactivity ignition source, a stratified combustion initiator and a controllable ignition trigger independent of global mixture strength. Unlike premixed DME (10% by volume), the DI strategy does not significantly alter global mixture composition [10], allows control over ignition timing via injection timing, and enables combustion stabilization even with minimal DME fraction. Overall, Dual fuel operation provides stable combustion at both lean and rich limits, improved high load capability with lower DME requirement compared to SI and HCCI modes. This indicates that reactivity stratification is more effective than uniform premixed enhancement for expanding operational range.

Table 4 Comparative Summary on operational flexibility

Mode	**DME strategy**	**Lean Limit**	**Rich Limit**	**Load Limit**	**Flexibility Level**
SI NH_3	None	Narrow	Moderate	Moderate	Limited
SI + 10% DME	Pre mixed	Extended	Near stoich.	High	Improved
HCCI + 10% DME	Pre mixed	Very lean	Restricted	Low	Low load flexibility
Dual Fuel (1% DI of DME)	Direct injection	Extended	Extended	Moderate to High	Highest

3.2 Combustion Characteristics

Detailed in-cylinder pressure analysis revealed that combustion timing and duration are highly sensitive to mixture strength and DME injection strategy.

Key observations include:

- Advancing DME injection (38 CAD bTDC) improves ignition reliability.
- Lean operation reduces pressure rise rates, improving mechanical durability.

- Excessively rich ammonia mixtures increase combustion variability.

These findings highlight the importance of precise fuel control strategies for ammonia-based systems. Importantly, the experiments demonstrate that combustion behavior can be engineered and optimized using modern electronic control systems.

This confirms that ammonia combustion is not a theoretical concept but a controllable and tunable process.

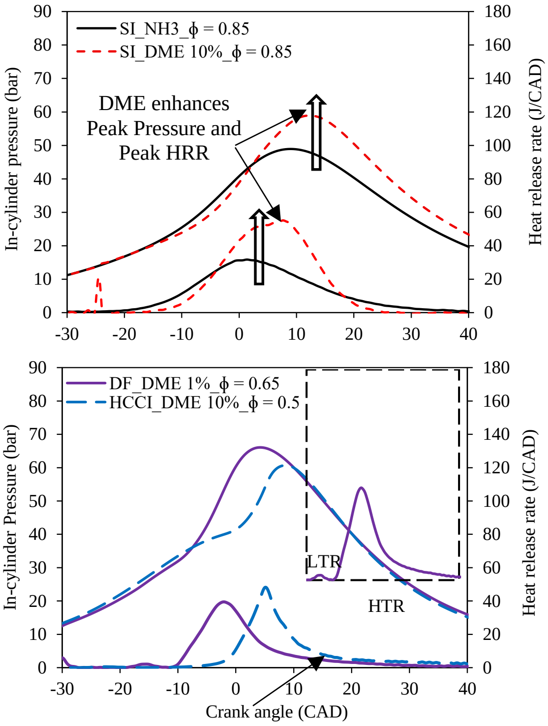


Fig.7. Combustion characteristics of DME assisted NH_3 combustion in SI, HCCI, and DF modes

Fig.7 provide clear insight into how DME addition modifies combustion phasing, intensity, and heat release characteristics in ammonia-fueled operation under SI, HCCI, and dual-fuel modes.

Pure ammonia SI combustion shows slower pressure rise, lower peak pressure and broader pressure curve. Whereas 10% DME addition shows higher peak pressure, earlier pressure rise, and steeper pressure gradient. This is mainly due to enhanced reactivity and flame stabilization effect of DME. Increased peak pressure directly correlates with higher IMEP observed earlier in Fig.4. With regard to heat release rate (HRR) profile, DME case shows higher peak HRR, sharper and narrow HRR curve compared to broader, slower and lower peak HRR in pure ammonia case. As presented in Fig.7 at the same ϕ of 0.85, intake pressure and engine speed, 10% DME addition significantly advances combustion phasing, increases combustion intensity, improves pressure development, and enhances work extraction potential. This confirms that premixed DME improves high-load SI performance by accelerating NH_3 oxidation kinetics [9].

In the case of HCCI (i.e. premixed NH_3-DME 10%, ϕ = 0.5), sharp HRR spike is observed with single dominant combustion event and concentrated in a short crank angle duration. HCCI provide lean operation but has limited controllability. Dual fuel operation (i.e. NH_3 premixed + 1% DME DI at 38° bTDC, 135 bar injection pressure) results in two-stage heat release behavior, a small early premixed ignition spike known as low temperature reaction (LTR) followed by controlled main combustion phase known as high temperature reaction (HTR) [11]. Dual fuel operation also presents a smoother pressure rise, broader HRR curve, and high peak pressure comparable to HCCI. In Dual fuel operation direct injected DME creates localized high-reactivity zones and initiates ignition near spray region. Unlike HCCI, combustion does not occur simultaneously throughout the combustion chamber and results in moderated pressure rise rate. Advanced injection of DME and reactivity stratification facilitates improved combustion phasing control and more tunable combustion process than HCCI.

Combustion analysis clearly demonstrates that DME act as a combustion accelerator in SI mode, an autoignition promoter in HCCI mode, and as ignition trigger in dual fuel mode.

Although peak performance remains lower than conventional gasoline or diesel engines, the system demonstrates practical feasibility under moderate load conditions. This suggests that ammonia–DME blends can be suitable for stationary engines, generators, or transitional heavy-duty applications.

The broader implication is that decarbonized fuels can be implemented without entirely redesigning engine architectures. One of the major motivations of this study was environmental sustainability. Since ammonia contains no carbon, its combustion does not inherently produce CO_2. The small quantity of DME used contributes only minimal carbon emissions compared to fossil fuels.

The experimental results confirm that stable combustion can be achieved while significantly reducing carbon intensity relative to traditional fuels. This positions ammonia–DME combustion as a promising pathway toward low-carbon mobility and decentralized power generation.

While challenges remain in controlling nitrogen-based emissions and optimizing efficiency, the results clearly demonstrate progress toward practical decarbonized combustion systems.

3.5 Practical Significance

From an engineering perspective, the most important outcome of this work is the demonstration that:

- Existing engine platforms can operate with ammonia-DME based fuel blends.
- Only limited hardware modification is required.
- Combustion can be electronically controlled and optimized.
- Clean combustion strategies can be implemented using current infrastructure.

This strengthens the case for ammonia as a transitional energy carrier in sectors where electrification remains challenging, such as heavy-duty transport, maritime engines, and distributed power systems. Overall, the findings demonstrate that ammonia–DME dual-fuel combustion represents a technically feasible and scalable pathway toward low-carbon engine operation, bridging the gap between fossil-fuel dependency and fully renewable energy systems

4. Conclusion

This research demonstrates that dimethyl ether (DME) is a powerful enabler for practical ammonia combustion across multiple engine technologies, including spark ignition (SI), homogeneous charge compression ignition (HCCI), and dual-fuel compression ignition modes.

Ammonia alone, while carbon-free, suffers from poor ignition characteristics and limited combustion stability. The addition of small amounts of DME significantly improves ignition delay, flame propagation, combustion phasing, and overall engine performance. In several operating conditions, stable combustion was achieved with minimal DME supplementation, preserving the zero-carbon advantage of ammonia while ensuring technical feasibility.

From a broader societal perspective, these findings are highly significant. The results show that carbon-neutral fuels can be integrated into existing engine platforms without requiring complete technological replacement. This provides a realistic transition pathway that complements electrification rather than competing with it.

The study supports:

- Reduction of CO_2 emissions from transport and power generation
- Utilization of renewable ammonia as a sustainable fuel
- Improved energy security through alternative fuel development
- Industrial continuity by adapting current engine infrastructure
- Strengthened international collaboration between France and India

By combining chemical kinetics modeling, advanced engine experimentation, and cross-institutional collaboration, this fellowship has contributed to both scientific knowledge and climate-oriented innovation.

Ultimately, this work supports the development of high-efficiency, zero-carbon internal combustion technologies that can accelerate global decarbonization while preserving technological diversity and economic stability.

5. Perspectives of future collaborations with the host laboratory

Ammonia has the potential to become a major carbon-neutral fuel of the future. However, its combustion limitations have hindered practical application.

This fellowship demonstrates that small additions of dimethyl ether can overcome these limitations, enabling stable, efficient, and controlled combustion across multiple engine technologies.

Rather than replacing internal combustion engines immediately, this approach offers a realistic transitional pathway toward decarbonization — combining scientific innovation with industrial feasibility.

The outcomes of this research contribute not only to combustion science but also to global climate mitigation strategies, energy independence, and sustainable mobility development. The collaboration between Anna University (India) and PRISME Laboratory (France) establishes a strong foundation for:

- Joint PhD supervision
- Advanced combustion diagnostics
- CFD and chemical kinetics modeling
- EU–India funded projects
- Horizon Europe and CEFIPRA programs

This research positions France and India at the forefront of zero-carbon combustion innovation.

6. Articles published in the framework of the fellowship

International Journals :

1.Ganesh Duraisamy, Christine Mounaim Rousselle. "*Ammonia – DME Blends in Homogeneous Charge Compression Ignition Engine"*. Fuel Volume 405, Part A, 1 February 2026, 136463. **Impact Factor : 7.5**

International Conferences :

1. **Ganesh Duraisamy, Christine Mounaïm Rousselle.** Experimental Investigation of NH_3/DME HCCI Combustion. 3rd Symposium on Ammonia Energy, September 23-26, 2024, Shanghai, China.
2. **Ganesh Duraisamy, Christine Mounaïm Rousselle.** Comparative Analysis of Different Combustion Modes of Ammonia Engines with DME Supplementation. 4th Symposium on Ammonia Energy, September 27th – 1st October 2025, Minnesota, USA.
3. **D. Ganesh and C. Mounaïm Rousselle.** Enhancing Ammonia Combustion in SI Engine by DME Addition. Corfu, Greece, June 1-5, 2025.
4. **Ganesh Duraisamy, Christine Mounaïm Rousselle.** Extending Lean Operating Limit of Ammonia Combustion in Spark Ignition Engine by Dimethyl Ether Addition. Proceedings of the ASME 2025, ICE Forward Conference, ICEF 2025. October 19-21, 2025, Milwaukee, Wisconsin, USA ICEF2025-165351.
5. **Christine Mounaïm Rousselle and Ganesh Duraisamy.** DME Combustion Enhancer for Ammonia Engines. ICFD Japan 2025.

Plenary Lectures/ Invited Lectures Delivered

1. Low and Zero Carbon Fuels Policy in India and their Application in Engines – **Prof. Ganesh Duraisamy.** 1st July 2024, Seminar PRISME, 01-02, July 2024.
2. **Ganesh Duraisamy**, Improvement of Ammonia Ignition by DME addition. Core-to-Core Workshop 2024, International workshop on science and technology supporting energy conversion towards carbon neutrality. 3-4th July 2024, University of Orleans, France.

3. **Ganesh Duraisamy.** Low and Zero Carbon Fuels : Transforming Combustion Engines for a Sustainable Future. Le-Studium Thursday Seminar, 8th February 2025. Dunlop Hotel, Orleans France.

Acknowledgements

We thank ***Le-Studium, Institute for Advanced Studies – France*** for funding this research collaboration with PRISME laboratory, University of Orleans, France. We thank ***Bruno Moreau and Yahia Haidous*** for their technical and instrumentation support in carrying out the investigation. Also, we acknowledge ***University of Orleans, France, and Anna University, India*** for granting research facilities and support to undertake this research work.

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