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Review Article

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Ammonia as a Carbon-Free Fuel for Heavy-Duty Compression Ignition Engines

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Abstract

Ammonia contains no carbon, can be stored as a liquid at moderate pressure, and is already made and shipped in very large quantities, which has made it a serious candidate fuel for the long-haul trucks, ships, locomotives and off-road machines that are hard to electrify. Its combustion properties, however, are close to the opposite of what a compression ignition engine wants: it resists autoignition, burns slowly and absorbs a great deal of heat on evaporation. This narrative review examines what the published literature shows about using ammonia in heavy-duty compression ignition engines. It covers the fuel properties that govern engine behaviour, the early engine work of the 1960s, and the strategies studied since, including diesel-pilot dual fuelling, blending with dimethyl ether, hydrogen assistance and direct injection of liquid ammonia. Emissions receive particular attention, because an ammonia engine exchanges carbon dioxide for a nitrogen problem: nitrogen oxides, unburned ammonia and nitrous oxide, the last a powerful greenhouse gas. The review also considers aftertreatment, materials and safety, and it identifies the questions on which the practical case for ammonia as an engine fuel still depends.

Keywords: Ammonia, Compression ignition engine, Dual-fuel combustion, Nitrous oxide, Heavy-duty transport, Carbon-free fuels

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1. Introduction

Heavy-duty engines are the hardest part of road, rail and marine transport to decarbonise. Their duty cycles demand large amounts of stored energy, and the weight and charging time of batteries become limiting as range and payload grow. Attention has therefore turned to fuels that can be made from renewable electricity and burned in engines broadly similar to those in service. Hydrogen is the simplest such fuel, but it is costly to store and move. Ammonia, a compound of nitrogen and hydrogen, offers a way of carrying hydrogen in a form that liquefies under modest pressure or mild refrigeration (Zamfirescu and Dincer, 2008; Valera-Medina et al., 2018).

Ammonia also has an industrial history that hydrogen lacks. It has been synthesised by the

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Haber-Bosch process for more than a century, chiefly for fertiliser, and that industry has shaped world agriculture (Smil, 2001; Erisman *et al.*, 2008). Pipelines, tanks, ships and handling codes already exist. Production today relies largely on hydrogen from natural gas and is carbon intensive, so ammonia is a low-carbon fuel only if the hydrogen comes from electrolysis or if the carbon dioxide is captured, a transition whose technical routes are set out by MacFarlane *et al.* (2020).

Whether ammonia can then be burned efficiently and cleanly in a compression ignition engine is a separate question, and it is the subject of this review. The compression ignition engine is the natural target because it dominates heavy-duty service and because its efficiency is the benchmark any replacement must approach.

2. Scope and Approach

The article is a narrative review of published work: the technical papers from the first period of interest in the 1960s, the engine studies that followed renewed interest from about 2008, the combustion science reviews that summarise flame and kinetic data, and earlier reviews of ammonia engines (Dimitriou and Javaid, 2020; Chiong *et al.*, 2021; Kurien and Mittal, 2022). No formal search protocol was applied and no claim of completeness is made. Spark ignition studies are drawn on only where they clarify matters common to both engine types.

3. Fuel Properties and Their Consequences

At atmospheric pressure ammonia boils at about minus 33 °C, and at ordinary ambient temperatures it remains liquid under a pressure of roughly ten bar, conditions similar to those for liquefied petroleum gas. Its lower heating value is less than half that of diesel fuel per unit mass, so tanks must be larger and injected quantities greater. Because ammonia needs much less air per unit mass than a hydrocarbon, the energy content of a stoichiometric cylinder charge is nonetheless close to that of conventional fuels, and power density need not suffer greatly (Kobayashi *et al.*, 2019).

The combustion properties are less accommodating. The autoignition temperature of ammonia is far above that of diesel fuel, its flammability range in air is narrow, and its laminar burning velocity is a small fraction of that of common hydrocarbons, as flame measurements over a range of pressures confirm (Hayakawa *et al.*, 2015). Its latent heat of vaporisation is several times that of diesel, which cools the charge strongly when liquid ammonia is injected and further delays ignition. An engine that relies on compression alone to ignite ammonia therefore faces a fuel that is hard to light and, once lit, slow to burn. Figure 1 traces how these properties constrain the choices made in combustion, emissions control and vehicle design.

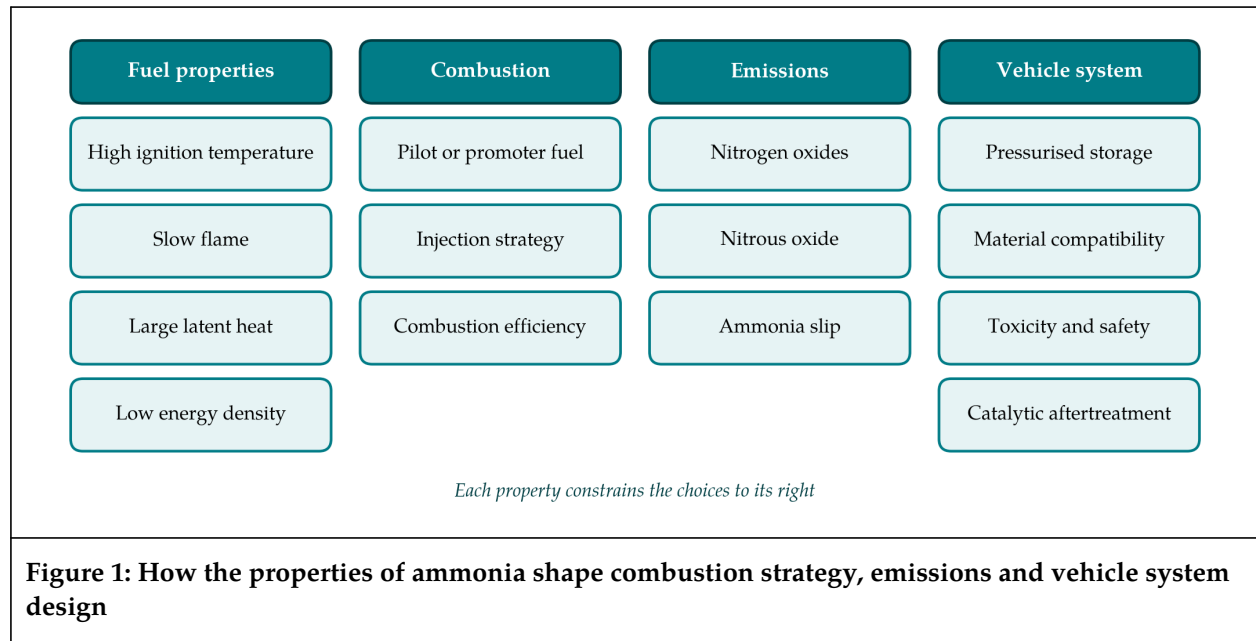
4. Early Engine Work

Ammonia has been burned in engines before. Kroch (1945) described motor buses operated in Belgium during the Second World War on ammonia with coal gas as a combustion promoter, when diesel fuel was unobtainable. Systematic research came in the 1960s, when the United States Army examined fuels that could be synthesised in the field. Starkman *et al.* (1966) analysed ammonia in spark ignition engines, and two studies addressed compression ignition directly.

Gray *et al.* (1966) found that neat ammonia could be made to ignite by compression only at compression ratios far beyond normal diesel practice, and that at ordinary ratios it needed a pilot injection of a more ignitable fuel or some other ignition aid. Pearsall and Garabedian (1967) reached the same conclusion and reported satisfactory running with a diesel pilot, as well as with spark ignition in a converted diesel engine. These papers established the framework that later work has refined: ammonia in a compression ignition engine is, in practice, a dual-fuel problem.

5. Combustion Strategies

The strategies studied since differ in how the ammonia is introduced and in what ignites it. Table 1 summarises the main approaches, which are discussed below.



5.1. Diesel-pilot dual fuelling

The approach with the largest body of evidence admits gaseous ammonia to the intake air and ignites the premixed charge with a diesel injection. [Reiter and Kong \(2008\)](#) demonstrated it on a multi-cylinder agricultural diesel engine and showed that ammonia could supply the majority of the fuel energy while engine torque was maintained, with carbon dioxide emissions falling in step with the diesel displaced. Their later study mapped combustion and emissions across substitution ratios and found the most favourable fuel economy at intermediate ammonia shares: with little ammonia the premixed charge is too lean to burn completely, and with a great deal the small pilot struggles to ignite it ([Reiter and Kong, 2011](#)).

The weakness of the method is incomplete combustion. Ammonia that enters with the intake air fills crevices and the cool boundary layers near the walls, where the slow flame cannot reach it, and some passes straight through during valve overlap. The result is unburned ammonia in the exhaust at concentrations that would be unacceptable without aftertreatment, a finding common to the dual-fuel studies reviewed by [Dimitriou and Javaid \(2020\)](#).

Table 1: Strategies studied for burning ammonia in compression ignition engines			
Strategy	Principle	Main attraction	Main difficulty
Neat ammonia, compression alone	Very high compression ratio ignites ammonia unaided	No second fuel	Impractical ratios; narrow operating range
Diesel-pilot dual fuel	Ammonia vapour in intake air; diesel injection ignites charge	Uses existing engines with few changes	Ammonia slip; pilot carbon remains
Ammonia-DME blends	Miscible liquid blend injected directly	Single injection system	Ignition delay grows with ammonia share
Hydrogen assistance	Hydrogen, possibly cracked on board, promotes combustion	Carbon-free promoter	Cracker heat demand and control
Liquid ammonia direct injection with pilot	High-pressure ammonia spray burns in pilot flame	Less ammonia in crevices and exhaust	Charge cooling; injector durability

Table 1: Strategies studied for burning ammonia in compression ignition engines

Strategy	Principle	Main attraction	Main difficulty
Conversion to spark ignition	Premixed ammonia ignited by spark, often with hydrogen	Reliable ignition timing	Loss of diesel-cycle efficiency

5.2. Blends with dimethyl ether

Dimethyl ether ignites readily, liquefies at similar pressures to ammonia and mixes with it, which allows a single liquid fuel to be injected directly. [Gross and Kong \(2013\)](#) and [Ryu *et al.* \(2014\)](#) tested such blends in a small direct-injection engine. They found that ignition delay lengthened and cycle-to-cycle variation grew as the ammonia share increased, and that high ammonia fractions required very early injection, giving combustion closer to a premixed, low-temperature mode than to a conventional diesel flame. Dimethyl ether can itself be made from renewable feedstock, but it is not carbon free, so the blend reduces carbon emissions without eliminating them.

5.3. Hydrogen assistance and direct injection

Hydrogen is the one promoter that keeps the fuel system free of carbon, and it can in principle be made on the vehicle by decomposing part of the ammonia over a heated catalyst. Most of the evidence comes from spark ignition engines, where [Morch *et al.* \(2011\)](#) and [Lhuillier *et al.* \(2020\)](#) showed that a small hydrogen addition stabilises ammonia combustion and that a larger one raises nitrogen oxides, and where [Mounaim-Rousselle and Brequigny \(2020\)](#) argue the general case for the spark-ignited ammonia engine. For compression ignition, hydrogen shortens the burn but does not by itself solve ignition, so a pilot or an ignition source is still needed.

More recent interest centres on injecting liquid ammonia at high pressure into a flame already established by a pilot, so that the ammonia burns in a diffusion mode as diesel does. This keeps ammonia out of the crevices and promises lower slip, at the cost of strong spray cooling and of injectors that must tolerate a fuel with little lubricity. The recent reviews describe this work as promising but still at an early stage ([Chiong *et al.*, 2021](#); [Kurien and Mittal, 2022](#)).

6. Emissions

An ammonia engine emits no carbon dioxide from the ammonia itself, but the nitrogen in the fuel opens reaction paths that a hydrocarbon engine lacks. Nitrogen oxides form not only by the thermal route from atmospheric nitrogen but also from the oxidation of ammonia and its fragments, through chemistry described in the classic account of [Miller and Bowman \(1989\)](#) and updated by [Glarborg *et al.* \(2018\)](#). The same chemistry works in reverse: ammonia and its radicals reduce nitric oxide to nitrogen within a certain temperature window, which is the basis of selective non-catalytic reduction. Engine-out nitrogen oxides from ammonia combustion therefore depend on mixture strength and temperature history in a less straightforward way than in diesel combustion.

Nitrous oxide deserves separate mention. It is an intermediate of fuel-nitrogen chemistry that survives where the gases cool before it can decompose, as happens in lean, low-temperature regions and near walls. It is a greenhouse gas far more potent than carbon dioxide per unit mass and is now the most important ozone-depleting emission from human activity ([Ravishankara *et al.*, 2009](#)). Even small exhaust concentrations can therefore cancel a meaningful part of the climate benefit of removing carbon from the fuel. Studies that report carbon dioxide alone give an incomplete account, and nitrous oxide should be measured as a matter of routine.

7. Aftertreatment, Materials and Safety

Heavy-duty diesel engines already carry selective catalytic reduction systems that use ammonia, released from urea solution, to convert nitrogen oxides to nitrogen and water ([Koebel *et al.*, 2000](#)). An

ammonia-fuelled engine has the reductant on board and often in the exhaust already, so the same catalyst technology is the obvious means of dealing with nitrogen oxides and, with an oxidation stage downstream, with slip. The balance between ammonia and nitrogen oxides in the exhaust varies with load, however, and catalysts that remove nitrous oxide at exhaust temperatures are less mature.

Ammonia attacks copper, brass and zinc and some elastomers, which rules out materials common in diesel fuel systems, and its interaction with lubricating oil over long service is not well documented. It is toxic and has a sharp odour detectable at low concentrations, which gives warning but does not remove the hazard of a large release in an enclosed space. Industrial handling practice is well developed (Valera-Medina et al., 2018). Carrying that practice over to vehicles serviced in ordinary workshops, or to ships with crew quarters near the machinery, is a task for regulation as much as for engineering.

8. Gaps and Future Work

Three gaps stand out. The first is the absence of durability evidence: published engine tests are short, and little is known about injector wear, deposit formation, oil degradation or catalyst ageing over the service life expected of a heavy-duty engine. The second is transient behaviour. Dual-fuel and direct-injection results come almost entirely from steady operating points, whereas slip and nitrous oxide are likely to be worst during cold starts and load changes. The third is the pilot fuel. Diesel pilots leave a residual carbon emission, and how small a pilot of renewable origin can be made while still giving reliable ignition across the operating range has not been settled.

A broader question concerns the comparison with alternatives. Ammonia competes with hydrogen, methanol and batteries, each with its own losses between renewable electricity and the wheels or propeller. The engine literature can inform that comparison only if efficiency and all nitrogen-containing emissions are reported on a common basis.

9. Conclusion

The literature shows that ammonia can be burned in compression ignition engines and that it cannot yet be burned alone under practical conditions. A pilot or promoter fuel is required, and the choice among diesel, dimethyl ether and hydrogen, together with the choice between premixing and direct injection of the ammonia, determines efficiency, slip and nitrogen oxide formation. The carbon benefit is real but must be weighed against nitrous oxide and unburned ammonia, both of which demand aftertreatment designed for the purpose. Durability, transient emissions and safe handling outside industrial settings are the areas in which evidence is thinnest, and progress there will decide how far ammonia moves from the test bed into heavy-duty service.

Conflict of interest

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