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Ammonia Sprays for Combustion: A Review

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Abstract

Ammonia is a globally transported chemical used for a variety of applications, most notably, the production of fertilizer. Over the past decade, attention has been afforded to the use of ammonia as an energy carrier, coupling global supply of renewable energy to demand regions. Ammonia's advantages as an energy carrier include its ease of liquefaction and established international transportation routes; overcoming its low reactivity, excessive production of nitrogen oxides, and its toxicity remain as challenges. For energy applications, fuel delivery is a critical aspect of effective combustion in boilers, burners and engines. Due to its adaptable phase change characteristics, ammonia fuel may be injected as a liquid or vapour, each with respective advantages or disadvantages. The focus of this review concerns the characterisation of liquid ammonia fuel injection for combustion, including recent research findings from experimental and simulation studies. Liquid ammonia injection can result in the highly dynamic so-called 'flashing' or 'flash boiling' phenomena.

Research findings have been drawn from other related applications such as accidental hazardous releases. Bespoke optical experimental rigs together with diagnostic techniques and two-phase CFD simulations have enabled studies of the flashing jets under various initial/final conditions, with recent work also examining ammonia spray combustion. The review concludes with an insight into future trends and requirements for liquid ammonia combustion. Reciprocating engines for marine propulsion are cited as potential early adopters of ammonia energy.

1. Introduction

Despite technological improvements providing efficiency gains, it is anticipated that global demand for energy will continue to grow for several decades. Demand is predicted to grow by 1.8% in 2024, driven largely by a continued strong demand from Asia. Over the past 40 years there has been increasing awareness of anthropogenic emissions, particularly carbon dioxide, resulting largely from the burning of fossil fuels. Currently, oil, gas and coal continue to meet around 82% of world energy needs, despite continued growth in renewables, which (including hydro) account for 14% of primary energy usage (1). This has led to increased CO₂ concentrations in the upper atmosphere, inducing the 'global warming' effect and consequent environmental hazards. This man-made risk has been cited as one of the most complex and critical challenges facing humanity (2, 3).

Wind, solar, hydro- and bio- energy are the primary contributors to a global sustainable energy supply. However, wind and solar are intermittent sources which vary based on weather and seasonal conditions, which provide a non-dispatchable supply. Moreover, there are vast quantities of these renewable energy resources

“stranded” in difficult-to-access or remote locations, which cannot be easily or economically recovered and transported to demand centres using direct connections to local power grids. Amongst the methods for energy storage that can be used to recover these resources, chemical energy storage has been relied upon for centuries. Fossil fuels have been a testimony of society’s dependence on chemical energy storage since the industrial revolution. Natural gas is currently the predominant source of dispatchable power in the UK, but unabated, releases CO₂ into the atmosphere. To complement intermittent renewable supply, additional sources of zero-carbon dispatchable energy are required. Hydrogen from renewables is one such candidate that has been proposed and continues to be developed, whilst biofuels provide another option. Non-fuels-based alternatives include battery storage or pumped hydro, both with their limitations.

Most recently, ammonia, a molecule that has been used widely for over a century (mainly as a fertilizer) has been presented as a potential platform for hydrogen storage and renewable power, offering ease of storage and a low cost of transportation compared to other options (4). Ammonia, which has the chemical formula NH₃, is the second most transported chemical in the world, and so its international shipping market is well established. The main procedure used for ammonia production is the well-established Haber-Bosch (H-B) process (5) via very large-scale plants capable of producing up to 3,000 t/day, a capacity that is expected to increase substantially. Ammonia from the H-B process can be produced utilising hydrogen from any source. Currently, the vast majority of hydrogen (approximately 79%) is derived from fossil fuels, most commonly by steam-methane reformation. Most of the remaining hydrogen

production is as a by-product of other industrial processes, with renewable sources estimated to contribute only 0.03% of total global production (6).

When zero-carbon renewable sources are used to produce hydrogen via electrolysis, the end product is categorised as “green ammonia”. Several projects seek to establish the foundations for the production, distribution, storage, and utilisation of green ammonia - with potential use cases including power generation and transport, as well as its continued use as a fertiliser for food production (see Fig. 1). RWE, who considers green ammonia as one of the most competitive hydrogen vectors due to its technological maturity, has recently announced the construction of an ammonia terminal in Brunsbüttel, Germany (7).

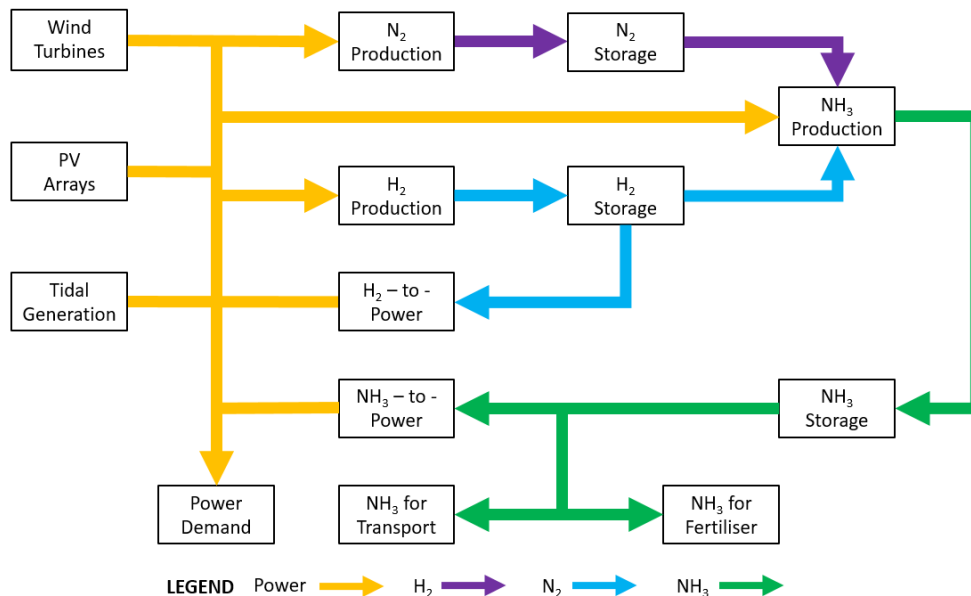


Fig. 1. Green ammonia from renewables, sector utilisation

Japan, a leading proponent for the use of ammonia, has ambitious plans for the chemical in both the process and energy industries. NEDO (New Energy and Industrial Technology Development Organization) has recently announced a ~\$500 million USD program dedicated to ammonia R&D. Mitsubishi Power announced the development of

100% ammonia fuelled boilers for industrial heat applications. A project to demonstrate the reliability of these systems is being conducted by JERA in their coal power stations, in parallel to their Hekinan demonstration project (8). The initiative comes in hand with the announcement of the development of the first commercial 40MW class gas turbine design fuelled by 100% ammonia (9). Similarly, GE Vernova and the Japan-based IHI Corporation have recently announced a collaborative agreement towards the development of a 100% ammonia capable gas turbine combustor for power generation by 2030 (10).

However, ammonia is not a drop-in fuel, and issues such as high NO_x emissions and low combustion efficiencies have been identified when ammonia is deployed in combustion systems optimised for conventional fossil fuels. The reaction chemistry of ammonia-air combustion is relatively slow compared to hydrocarbon fuels, with a low heat of combustion, a slower laminar burning velocity and reduced radiation heat transfer (11). Ammonia-air flames also display poor flammability/ignition characteristics with a narrow flammability range and high ignition temperature. Another significant challenge for ammonia handling and utilisation is its toxicity which needs to be managed safely and may limit its use in certain applications.

For simplicity, much of the early fundamental combustion research and successful experimentation by combustion demonstrators has involved the use of ammonia in its vapour form. However, there are inherent limits with the vapour delivery of ammonia for large scale and/or pressurised combustion systems. Early attempts to utilise liquid ammonia in gas turbines were unsuccessful owing to its high heat of vaporization leading to significant heat loss during phase change and aforementioned poor combustion characteristics (12). With appropriate control

however, modern injection systems have the potential to supply ammonia as an atomised liquid spray for transport, heat and power generation applications. There is currently limited research published in relation to liquid ammonia injection, although there has been a significant increase in interest and publications over the past 3 years as the potential of ammonia power has increased in credibility and popularity.

It is evident that ammonia has been gaining considerable acceptance from the industrial sector as a means for the production of power and heat, and propulsion. However, greater understanding is required towards solving the operational hurdles associated with its use as a liquid fuel. The focus of this paper is to review current research relating to the use of liquid ammonia in industrial scale combustion systems, where it is inconvenient to operate with ammonia in its vapour form. Here, a review of the literature relating to the characterisation and quantification of the liquid ammonia fuel injection process is presented, evaluating both the work of modelling and experimental research programmes. An overview of recent ammonia spray combustion studies completes the review.

2. Ammonia Spray Phenomena

When considering the use of liquid delivery and sprays for ammonia, it is important to understand the difference in how the fuel is prepared and delivered to the region in which combustion occurs. For industrial heat and large-scale power generation, burners which produce 'stationary' flames are ubiquitous. Fig. 2 shows an example of the coupling between liquid fuel spray development and combustion for a stationary flame. For these types of systems, it is the interaction between the fuel

spray and the combustion air which is key in determining the overall efficiency and emissions performance.

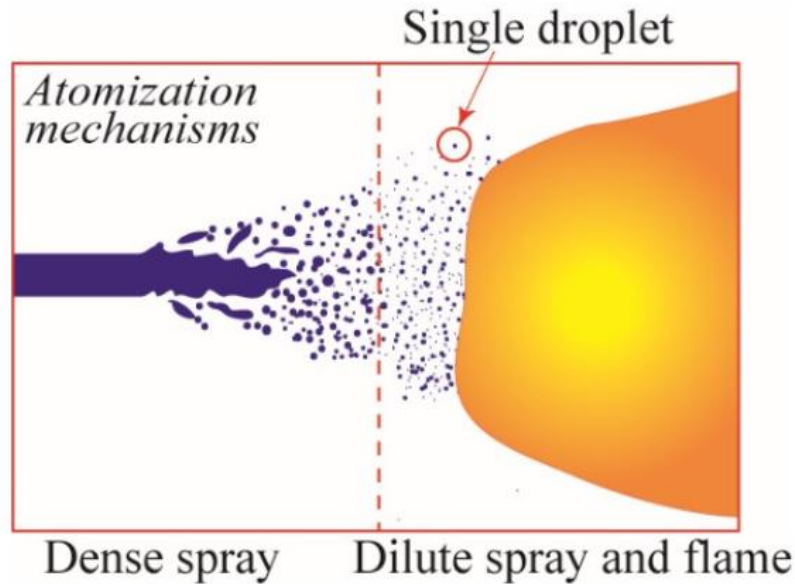


Fig. 2. Schematic Representation of Liquid Fuel Spray Combustion (Reproduced from Shinjo, 2018 (13))

Other applications, such as reciprocating engines, require the formation of a dispersed two-phase fuel mixture, through which the flame propagates; as shown in the numerical simulations of An et al. (14) in Fig. 3.

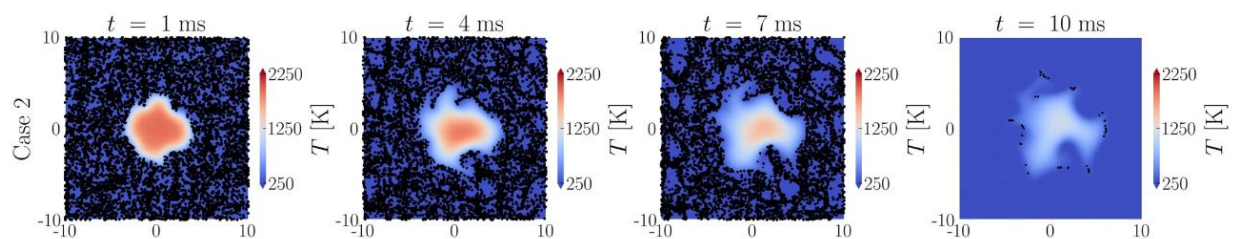


Fig. 3. Temporal evolution of gas temperature through a droplet suspension, where droplets are shown as black dots and sizes determined by their diameters (enlarged by around x40 for visual clarity) (14)

The use of an injector (or atomiser) to introduce liquid ammonia either immediately before, or directly into, the combustion system has the capacity to

simplify the fuel control system and facilitate combustion at increased pressures. The avoidance of the requirement for pre-vaporisation hardware can also potentially increase overall efficiency. Much like fossil fuels, the challenge of the concept is related to the requirement to limit the emission of NO_x , N_2O and unburned fuel. The technological developments that occurred in the automotive sector, first with the introduction of injection systems controlled by advanced Engine Control Units (ECU's) and later with the introduction of Gasoline Direct Injection (GDI) have provided a route for the advancement of this technology for ammonia utilisation.

Aside from combustion applications, large-scale hazardous releases of liquid ammonia have been studied to examine issues relating to atmospheric dispersion and toxicity. The safety aspects of storing and transporting ammonia in large quantities are very well known, though large-scale releases clearly provide additional complications both in terms of computational modelling as well as experimental validation (15, 16). Nevertheless, the underlying physical processes should be consistent between fuel injection for propulsion applications and accidental atmospheric dispersion, under comparable initial/boundary conditions.

The physical properties of ammonia are similar to propane, with both fuels easily stored as a pressurised liquid, and with a resultant high energy density when compared to their gaseous form. Both propane and ammonia are commonly used as the working fluid in refrigeration cycles due to their relatively high latent heats of vaporisation, of 428 kJ/kg and 1369 kJ/kg respectively. The physical properties of ammonia; boiling point of approximately 239.8K at 1.013 bara (1 atm) pressure and a vapour pressure of 10.0 bara at standard ambient temperature (298.15K), mean

that similar to propane, it is relatively straightforward to store and transport the chemical.

Compared to conventional liquid fuels, the vapour-pressure characteristics of ammonia result in additional complexities that need to be considered when evaluating the method by which atomisation occurs. The boundary conditions, i.e. the pressure and temperature of both the ammonia and the environment into which it is being introduced, need to be related to the liquid boiling properties to evaluate how the thermodynamic and 'mechanical breakup' processes interact. This contrasts significantly with the established understanding of the atomisation of more traditional fuels, which are primarily governed by 'mechanical breakup' in which the aerodynamic and surface tension forces within the jet compete. Different authors use different terminology to describe a thermodynamically unstable jet release (17, 18), but essentially the process involves a metastable liquid jet as it transitions between pure liquid and gaseous states.

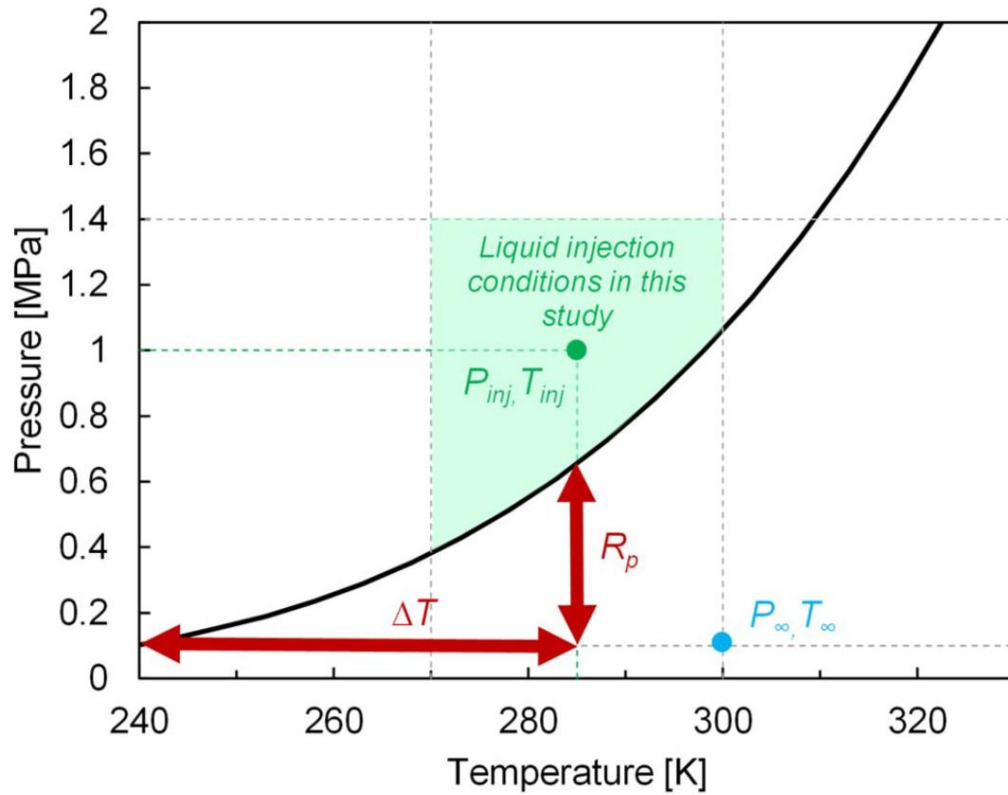


Fig. 4. Ammonia Liquid-Vapour Phase Change (19)

Generally, the most influential characteristic of a liquified jet release is the degree of superheat, which can be represented either in terms of the temperature or pressure conditions of the fluid at release (15, 18) i.e.:

$$\Delta T = T_{inj} - T_{sat}(P_{\infty}) \quad \text{or} \quad R_p = P_{sat}(T_{inj}) / P_{\infty}$$

When considered in terms of temperature, the degree of superheat, ΔT , is the difference between the liquid injection temperature, T_{inj} , and the saturation temperature of the liquid at the ambient pressure conditions, $T_{sat}(P_{\infty})$. If considered in terms of pressure, the degree of superheat, R_p , is the ratio between the saturation pressure of the liquid at the release temperature, $P_{sat}(T_{inj})$, and the ambient pressure condition, P_{∞} . For most of the controlled release scenarios of liquid ammonia, the

subsequent liquid jet rapidly boils producing a two-phase flow. The dynamics of two-phase releases have been extensively studied from a hazard viewpoint, in order to develop droplet-size correlations and validate dispersion models (20). More recently, more intricate models are being developed specifically to represent the changing forces and energies acting within superheated ammonia releases (21).

Depending on the ambient environment conditions, the introduction of a liquid phase can result in the 'flash boiling' or 'flashing jet' phenomena, as the jet converges towards thermodynamic equilibrium. This process is applicable for many liquid fuels and various injection technologies under suitable thermodynamic conditions, for example, the use of gasoline has been shown to 'flash' in a Direct-Injection Spark-Ignition (DISI) engine at certain load conditions (22). This phenomenon is prevalent for fluids with low boiling points. For fluids (in this case ammonia) releases may therefore be split in three main categories: (i) vapour release (ii) non-flashing liquid release, and (iii) flashing liquid release. Flashing jets, such as those associated with an ammonia release, have become better characterised since the pioneering characterisation study of Kitamura et al. (18).

Fig. 5 (a) and (b) respectively show photographic images and a graphical representation of particle SMD vs. superheat for the three main stages of jet breakup identified for a release from a simple orifice (15) following the methodology of Kitamura. For the first category (A), the jet breaks up with very little evidence of boiling processes. This occurs for releases with little or very low degrees of flashing, or superheat, with this category considered to be dominated by 'mechanical' jet breakup. Mechanical breakup occurs based primarily on the competition between aerodynamic forces, serving to separate liquid fuel into smaller geometries, with the

opposing surface tension forces binding the liquid together. Correlations representing this category of breakup are governed by the established non-dimensional parameters such as Weber, Ohnesorge and Reynolds numbers. For category A releases, the atomisation process involves ligaments and globules being stripped from the surface of the jet, which then in turn breakdown to finer droplet throughout the later stages of the atomisation process.

Category B releases occur when there is a significant degree of flashing, or superheat, with external jet breakup through bubble expansion clearly evident, occurring a short distance from the orifice. Category C releases occur at the highest degree of flashing, or superheat, and produce a fully broken-up spray dominated by bubble-nucleation and micro-explosions. Nucleation invariably commences upstream of the orifice exit, sometimes causing issues concerning stability of upstream flow through vapour locking or injector deterioration. Transition between the different modes of flashing jet breakup is governed by thermodynamic processes, represented by dimensionless groups such as the Jakob number, Weber number and liquid/vapour density ratio. Fully flashing jets are highly dynamic atomisation processes, accompanied by significant turbulence generation and air-entrainment, which are of great relevance to producing readily combustible mixtures.

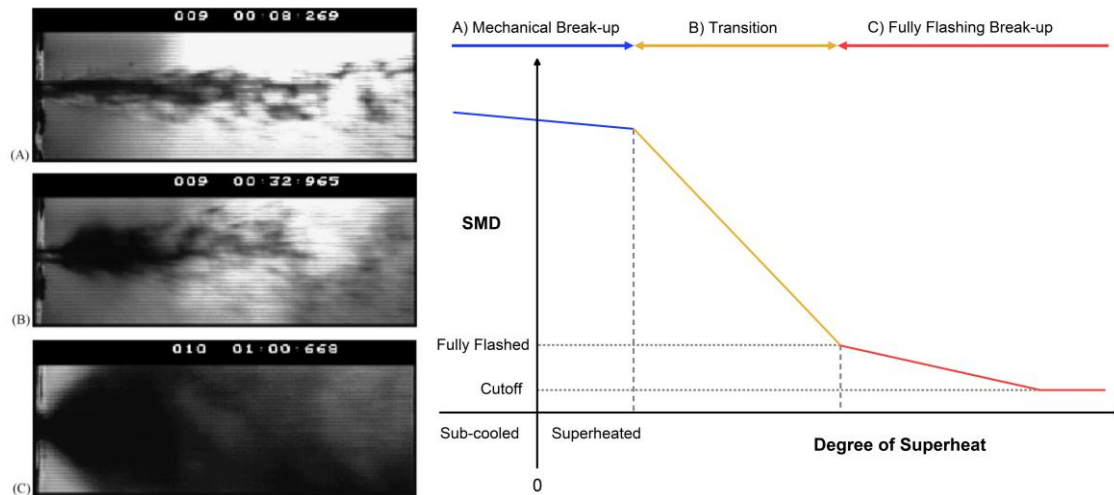


Fig. 5. (a) High-Speed imaging of Jet Breakup Modes with increasing Superheat (15),
 (b) Correlating Kitamura Jet-Breakup to Spray Quality through Tri-Linear Model
 (Recreated from (20))

More recently, Li et al. (23) re-appraised the phenomenology of flashing ammonia jets in the context of reciprocating engines. Near-field bubble explosion characteristics were correlated with the measured far field tip penetration. Similar to the atmospheric dispersion studies, they concluded that flashing (or superheated) ammonia sprays can be divided into an initial flashing region ($1.0 < R_p < 2.0$), a transitional flashing region ($2.0 < R_p < 5.0$), and what they termed 'flare flashing' for $R_p > 5.0$. A non-dimensional analysis was established to correlate critical features. The observed bubble explosion intensity in the near field was dominated by the degree of superheat and fuel viscosity over the entire flashing region, whilst the Ohnesorge number was more influential in the transitional-flare regions. The tip penetration presented similar characteristics to conventional liquid fuels under critical/initial flashing conditions, whereas jet bubble behaviour dominates penetration under transitional/flare flashing conditions.

Colson et al. (19) developed the phenomenology of flashing (ammonia) sprays, building upon the earlier phenomenological models of Kitamura et al. (18) and Cleary et al. (15). Liquid ammonia sprays were observed using high speed backlit imaging for a range of superheat values between 3.5-8.5 for single-hole injectors with diameters between 0.1-0.21 mm, and additional parameter of injector aspect ratio (L/d) between 2.5-10. Consistent with previous studies, it was found that superheat dominated the transition to flashing, which was also highly dependent upon the injector L/D ratio. Previous transition criteria were not found to correlate well with for the ammonia case for the diameters and aspect ratios investigated. The upstream internal flows of the injector were visualised (Fig. 6) with results suggesting that increasing the orifice section towards the outlet of the injector could enhance the flashing of the liquid ammonia spray.

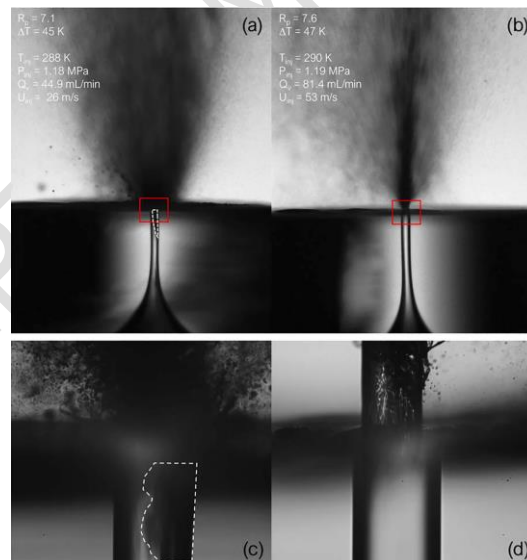


Fig. 6. Effect of small change in the orifice geometry and inner flashing for $L/D = 11$ reproduced from (19).

3. Characterisation of Ammonia Sprays

3.1. Spray Characterisation

Non-intrusive methods for studying spray diagnostics have developed significantly over the past 40 years. The 1970/80s saw the introduction of high-speed imaging to interrogate global spray parameters such as jet penetration, spray cone-angle and spray morphology. Fig. 7a) below shows the basic traditional parameterisation of a non-flashing spray via its release orifice dimension, cone angle and overall penetration. Fig. 7b) shows a recent utilisation of high-speed 'Schlieren' imaging to reveal a three-stage propagation behaviour associated with tip penetration for an ammonia jet of 2 ms injection duration, relevant to IC engine applications. Clearly there are application design uses for such diagnostics and simplified correlations.

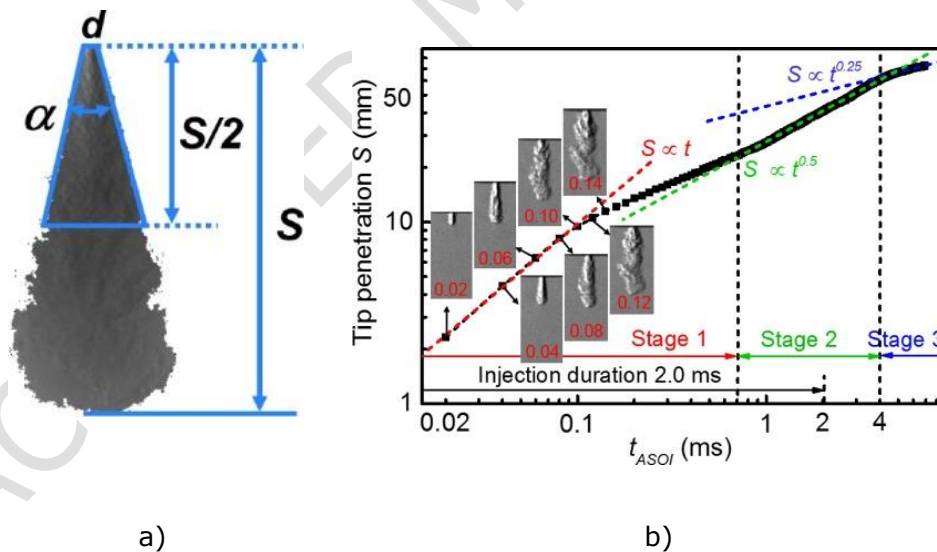


Fig. 7. Three-stage behaviour of the tip penetration of ammonia jets. ($P_{inj} = 8.0$ bar, $P_a = 2.0$ bar, $T_a = 298$ K, $\tau = 2.0$ ms) (24)

Pelé et al. (25) presented high speed images of liquid and superheated ammonia jets, enabling a comparison of jet penetration for liquid or two-phase ammonia releases into elevated ambient conditions. The Schlieren imaging technique together with dedicated image post-processing enabled identification of the vapour phase relative to the spray boundary. Fig. 8 demonstrates the penetration for liquid and liquid/vapour (25).

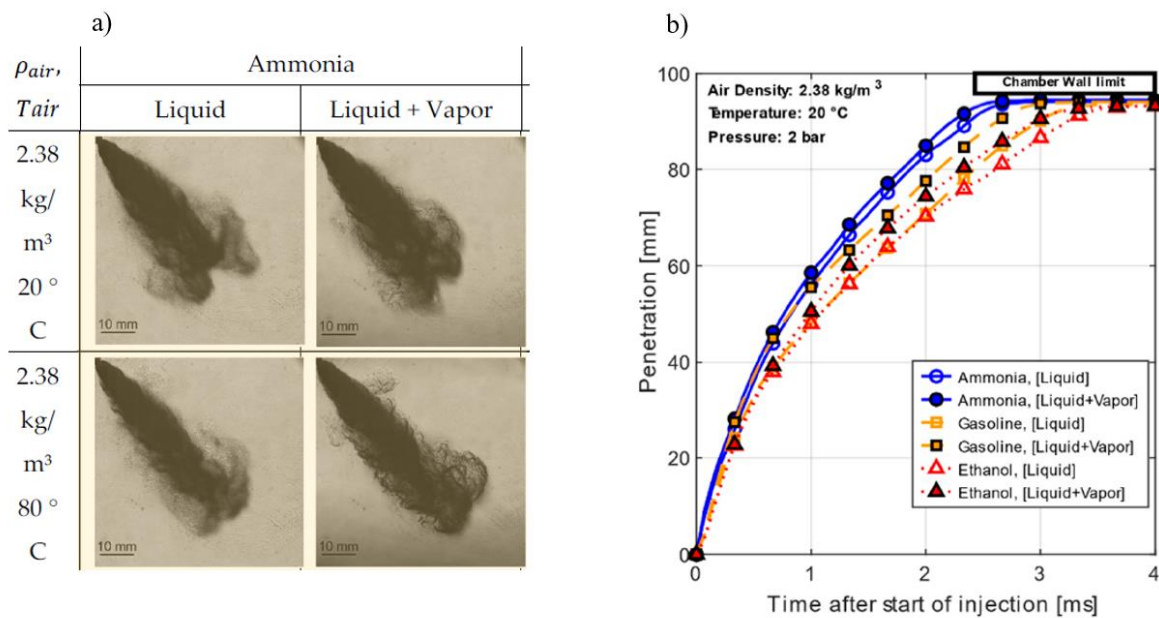


Fig. 8. Comparison of spray penetration for ammonia (continuous line), gasoline (dashed line), and ethanol (dotted line), a) $T_{air} = 293$ K and $P_{air} = 2$ bar, b) $T_{air} = 293$ K and $P_{air} = 7$ bar, c) $T_{air} = 393$ K and $P_{air} = 2.69$ bar, and d) $T_{air} = 393$ K and $P_{air} = 9.39$ bar (25)

The average size of droplets in an established spray is generally described as the spray 'quality' – via some defined average diameter, such as the Sauter Mean Diameter (SMD) for combustion applications (26). The SMD has been identified as generally having a strong influence upon subsequent processes, whether that be the ignition or turbulent flame propagation in the context of internal or external

combustion engines, or for non-combustion applications such as the rainout and subsequent pool boiling and re-evaporation for stratified atmospheric releases. Spray quality may also be represented as a distribution of droplet sizes through volume (or number) distributions. The so-called 'Rosin-Rammler' distribution function has been often deployed to represent the distribution of droplet sizes in sprays. A range of correlations for droplet distributions and mean droplet sizes have been developed and utilised by researchers for different applications, and as such it is important to ensure the correct parameter is used when comparing and evaluating results.

The laser-diffraction technique – primarily a line-of-sight technique – was one of the first non-intrusive laser-based particle sizing techniques developed to measure droplet sizes and is still used extensively today. Subsequently, more complex non-intrusive laser techniques have been developed enabling considerably more detailed spatial and temporal characteristics to be unveiled, which in turn has led to the development of more intricate modelling subroutines which are then validated against experimental data. Two techniques have prevailed in terms of spray flow-field kinematics - Laser Doppler Anemometry (LDA) and Particle Imaging Velocimetry (PIV). The former (LDA) is an absolute method which relies on measuring the frequency of Doppler bursts produced when droplets pass through an optical fringe control volume to evaluate the components of the velocity at a point in space, whereas the latter (PIV) relies on the visual interrogation of sequential imaging with dedicated post processing to track particle velocity components that have been illuminated within the flow-field.

Depending on the application, different techniques have been developed to enhance the basic spray diagnostic techniques outlined above. For example, transient multi-dimensional diagnostics are desirable for engine applications. This has resulted

in the development and widespread utilisation of full flow-field temporal development of sprays, such as phase-resolved Phase Doppler Anemometry (PDA). This has proven robust and highly valuable for the development of non-flashing direct injection (e.g., GDI) sprays for example. The other diagnostic, which is one of the more challenging, is that of quantifying the vapour phase or both liquid/vapour phases independently (27). Various permutations of the laser-induced fluorescence (LIF) principles have been deployed for spatial and temporal phase resolution, with varying degrees of success.

3.2. Influence of Operational Ammonia Spray Parameters

The boundary conditions that are to be used for the characterisation of ammonia sprays depend upon the particular application. Reciprocating engine applications rely on dedicated, well-established industry-specific fuel injector technology and detailed proprietary atomiser designs, whereas hazardous atmospheric releases are a function of the operational control conditions and variable release orifice shape. Hence, whilst a fuel injector and its operational control parameters (mass flowrate, release pressure, etc.) can be carefully designed and engineered, atmospheric releases are generally idealised from a potential sharp-edged, non-geometric shaped orifice which is characteristic of a containment rupture or leak.

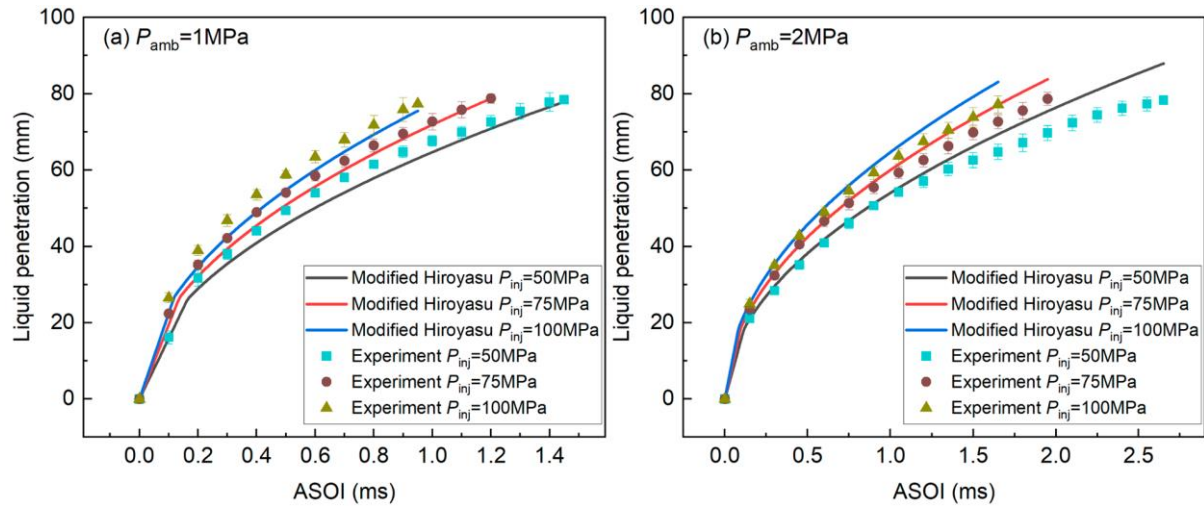


Fig. 9. Influence of P_{inj} upon Liquid Penetration (28)

Concerning the ‘ambient’ boundary conditions, reciprocating engine applications need to consider injection into potentially elevated pressure and/or temperature environments, depending upon the particular fuelling strategy being deployed. Additionally, reciprocating engine applications can utilise a range of injector durations, injector pressures (e.g., Fig. 9) and even multiple injection strategies, which can have variable times of injection during the engine stroke, changing the ‘ambient’ boundary condition. Hence, a number of dedicated optical rigs for spray characterisation have evolved over the past 30 years (designed by various research groups (20, 25)), which through careful design have included suitably specified optical access for the variety of non-intrusive analytical techniques previously described.

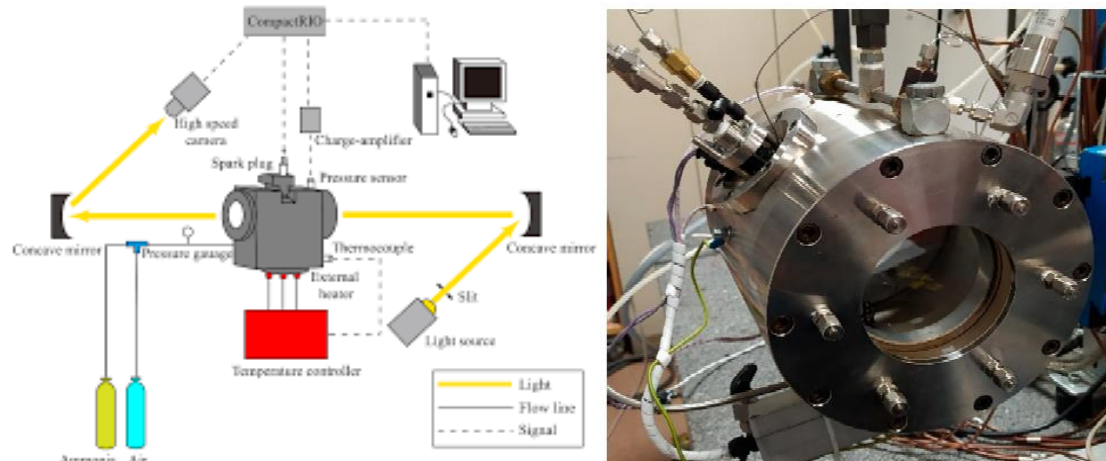


Fig. 10. Experimental apparatus used by various authors to study ammonia spray characteristics for a GDI engine injector (25, 29)

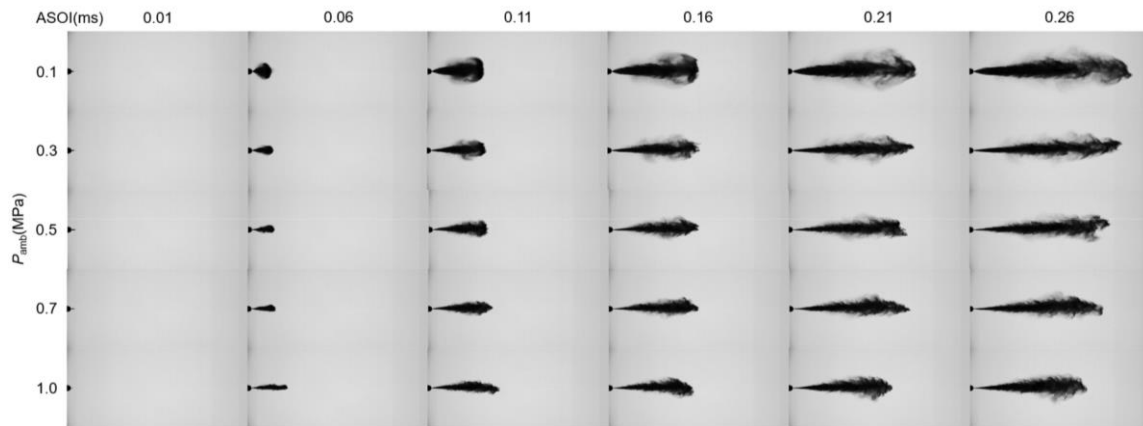


Fig. 11. Influence of Ambient Pressure on Transient Flashing Ammonia Jet Morphology (28)

The work of Fang et al. (28) included an investigation of high-pressure liquid ammonia injections at pressures up to 1000 bar under both non-flash and flash boiling conditions. Results from this work, an example of which is shown in Fig. 11, compares the penetration rates observed in their high-pressure vessel against established empirical models (e.g. Hiroyasu et al. (30), Naber and Siebers (31)). The flash boiling condition identified a suppression of spray penetration during the early stages and was named the 'spray resistance phenomenon', which was observed when P_{amb} was less

than 7 bar and was found to be highly correlated to the degree of superheat. The reason attributed to the spray resistance is the injector needle lift leading to cavitation upstream of the exit orifice (18, 20) which results in an undesirable injector blockage due to vapour generation. The requirement to eliminate or suppress a strong vapour generation within the nozzle is emphasised, such that the design of an ammonia fuel delivery system is more challenging as it is not simply a case of generating fully flashing sprays.

4. Modelling Ammonia Sprays

Numerical computational methods have been utilised and developed for the modelling of the formation of NH_3 jets or sprays and the propagation of a flame throughout dispersed droplet fields. Recently Zemi et al. (29) developed and 'tuned' a commercial CFD numerical model, incorporating the RNG- $k\epsilon$ turbulence model, to provide a detailed simulation of both a flashing and non-flashing spray, validated against accompanying experimental data. Schlieren imaging was utilised to identify the spray and vapour boundaries for validation, whilst laser diffraction was utilised to generate line of sight SMD. The fuel injector utilised was a contemporary Bosch GDi unit comprising 7 holes of 150 μm diameter. The authors found that validated global spray characteristics were readily obtained for the flashing spray, whereas more detailed temporal/spatial resolution for diagnostics such as droplet sizes and vapour mass fraction proved more challenging. An example of their findings is shown in Fig. 12. Previous work has drawn similar conclusions using a pressure-swirl G-Di injector (32).

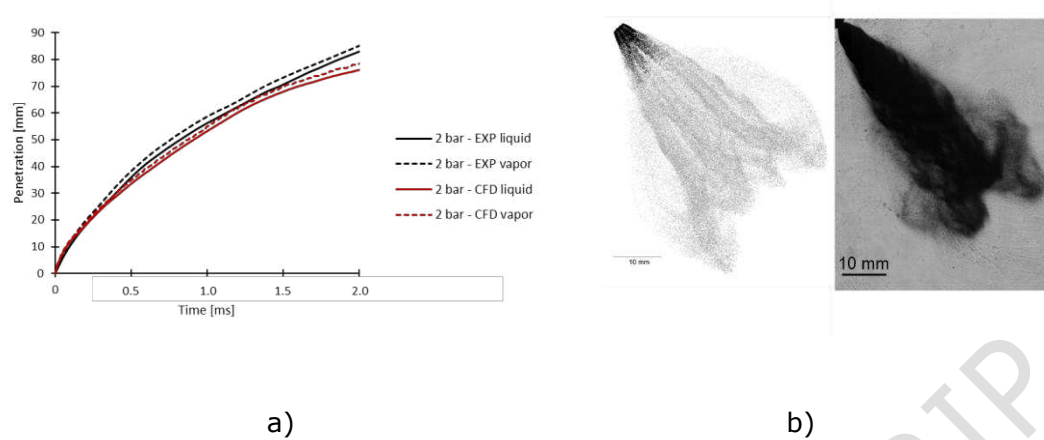


Fig. 12. Comparison between experiments and simulation in terms of penetration a) and spray morphology b) for flashing ammonia spray (29).

Fig. 13 shows the significant variation in the predicted vapour mass fraction between the flashing and non-flashing sprays using the tuned simulation. Validation of such quantified temporal/spatial diagnostics remain a challenge. Fig. 14 shows the difference in SMD for flashing jets, predicting a reduction in SMD from 30-40 μm for the non-flashing case, to below 10 μm for flashing. In terms of combustion, this difference in droplet size distribution would be very influential, as the 'mode' of spray combustion changes from diffusion-based droplet-droplet propagation to premixed spray propagation traversing the so-called droplet combustion 'transition range' (33). These processes will vary, and may be diminished, within the high-pressure/high temperature engine injection environments, but the modes should still appear and depend primarily on spray quality.

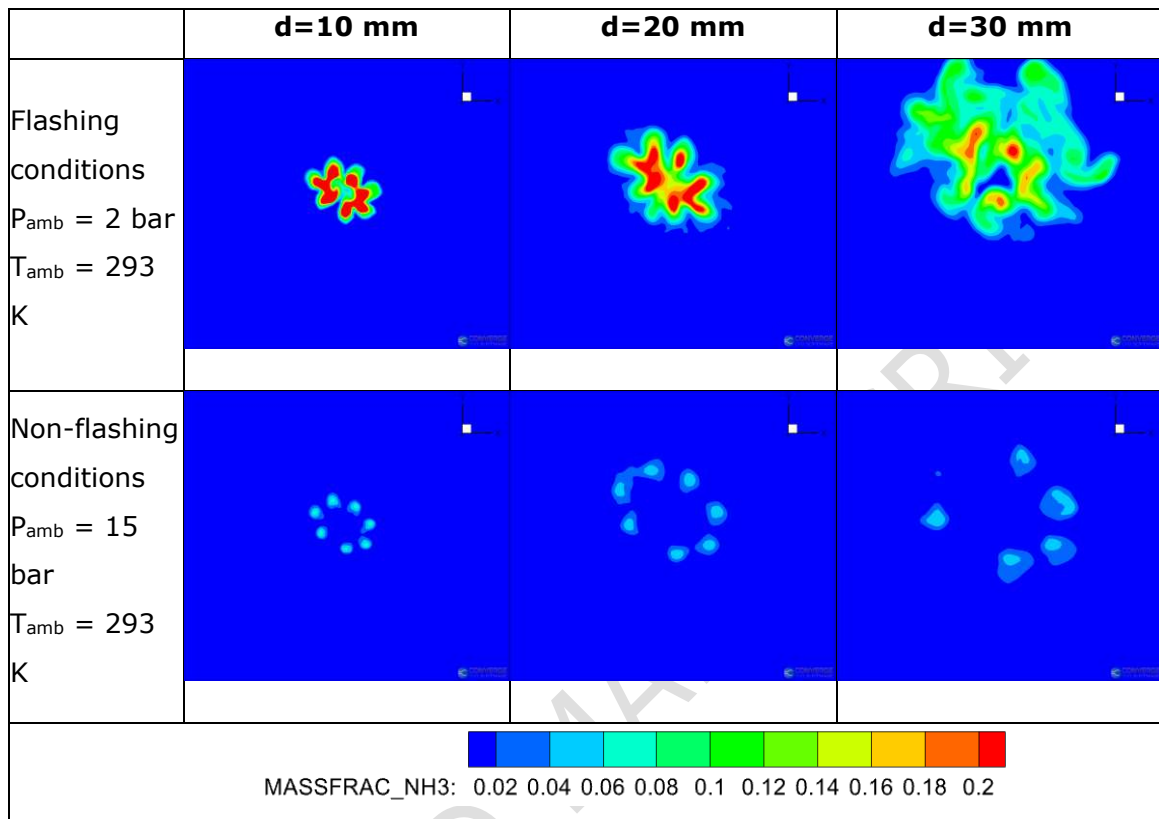


Fig. 13. Ammonia Vapour Mass Fractions for Flashing and non-flashing jets (simulated) (29)

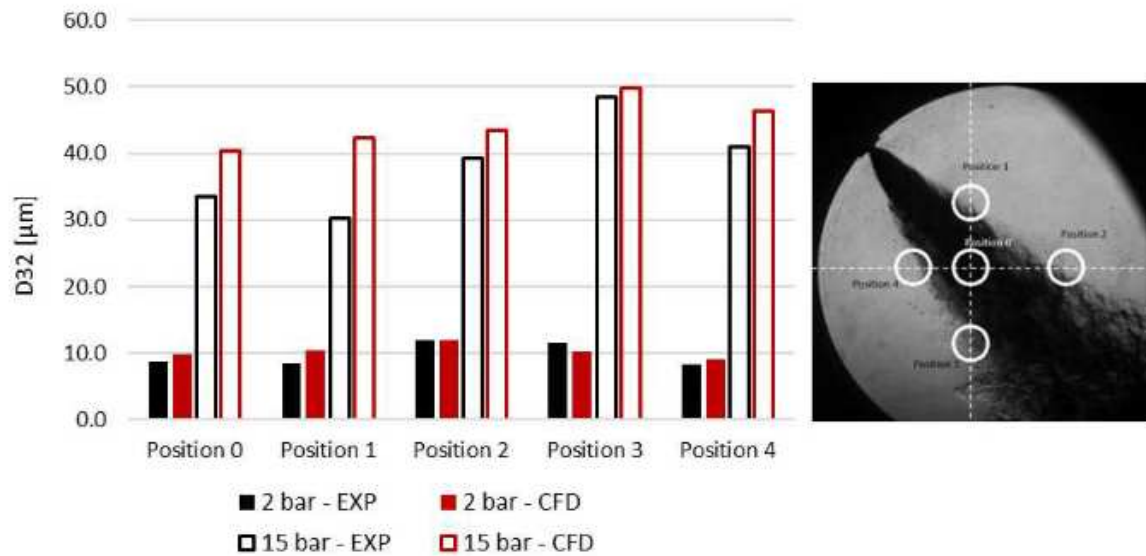


Fig. 14. Comparison between experiments and simulation in terms of local SMD - flashing (2 bar) vs. non-flashing (15 bar) (29).

Zembi et al. (29) also modelled another influential effect of flashing jets, namely the temperature reduction of the environment due to flash boiling (Fig. 15), a result of the large heat of vaporisation of ammonia. These are very significant reductions which in reciprocating engines can be utilised to enhance charge cooling, which has the potential for allowing for an increase in the physical compression ratio of the engine and/or a reduction in the peak cylinder temperatures, possibly resulting in an increase in overall efficiency or providing a mechanism for reducing NO_x formation.

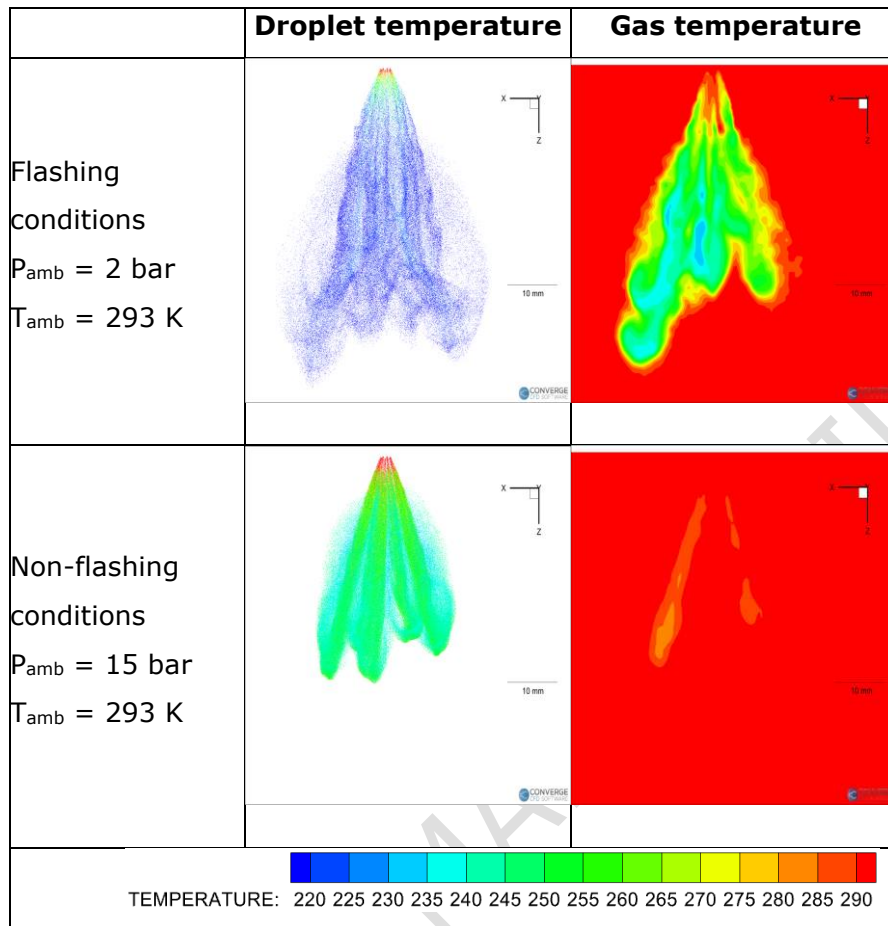


Fig. 15. Simulations of Droplet and Gas Temperatures flashing and non-flashing sprays 1 ms ASOI (29)

An et al. (14) studied, via numerical means, the combustion and spherically expanding flame propagation characteristics in a dispersed droplet field. The primary goal of this work was to compare liquid ammonia spray flames to the gaseous equivalent. Simulations of the spherically expanding flames were performed using the Eulerian-Lagrangian framework, where the Lagrangian method is used to capture droplet dynamics. Liquid ammonia spray simulations have been extended to reacting flows, where two-way coupling enables gas and droplet interactions (34). It was concluded that the presence of ammonia droplets significantly reduces the flame propagation speed and heat release due to the local heat loss caused by the flash

boiling. Preheating was found to be highly influential when it comes to ignition, whilst the liquid ammonia droplet suspension could not be ignited at normal (in this case 300 K) temperatures without preheating. Competition between the heat generated by the chemical reaction and the heat absorbed by the phase change was found to be the dominant factor when it comes to liquid droplet ammonia ignition. Smaller droplets were found to evaporate quickly, significantly reducing the temperature and increasing local mixture fraction, whereas flame-droplet interaction was more dominant for cases of large droplet diameter, with local heat loss near the larger droplets causing local extinction. Regarding equivalence ratios and heat fractions, the flame propagation characteristics were found to be dependent on the proportion of liquid ammonia and therefore the local evaporation rate, resulting in different levels of heat loss. Stoichiometric conditions were no longer predicted to be the most suitable for ignition.

5. Ammonia Sprays for Combustion Applications

Early work undertaken by Verkamp et al. (12) supplied NH_3 in both liquid and gaseous phases to a gas turbine combustor. The work summarised that ammonia could only be accommodated in conventional gas turbines when supplied in the gaseous phase to ensure flame stability, and that the diameter of the combustor liner would consequently need to be increased by a factor of ~ 2 . However, in later work by Okafor et al. (35) an improved understanding together with technical developments meant that a 230 kW gas turbine combustor could be successfully operated with a staged liquid NH_3 flame. Rich-lean staged liquid combustion was stated to be advantageous, since it can allow for significant reduction in NO_x , N_2O and unburned NH_3 emissions

over single staged combustors and mitigates the need for larger combustor geometries.

The work studied the effects of co-firing CH_4 , alongside changes in wall temperature, on flame stability. The authors suggest that sufficient compensation for heat extracted from droplet vaporisation is necessary to improve efficiency in the primary combustion zone, and thereby reduce the quantity of unburned NH_3 that is oxidized in the secondary zone – something that is also important for the control of N_2O emissions from the liquid spray flame. The conventional application of wall cooling in gas turbines was shown to contribute to flame extinction via blow-off together with higher NO , N_2O and unburned fuel emissions, and operating the system without wall cooling enabled an increase in wall temperature up to 1273 K, facilitating the stabilisation of the liquid NH_3 spray (Fig. 16).

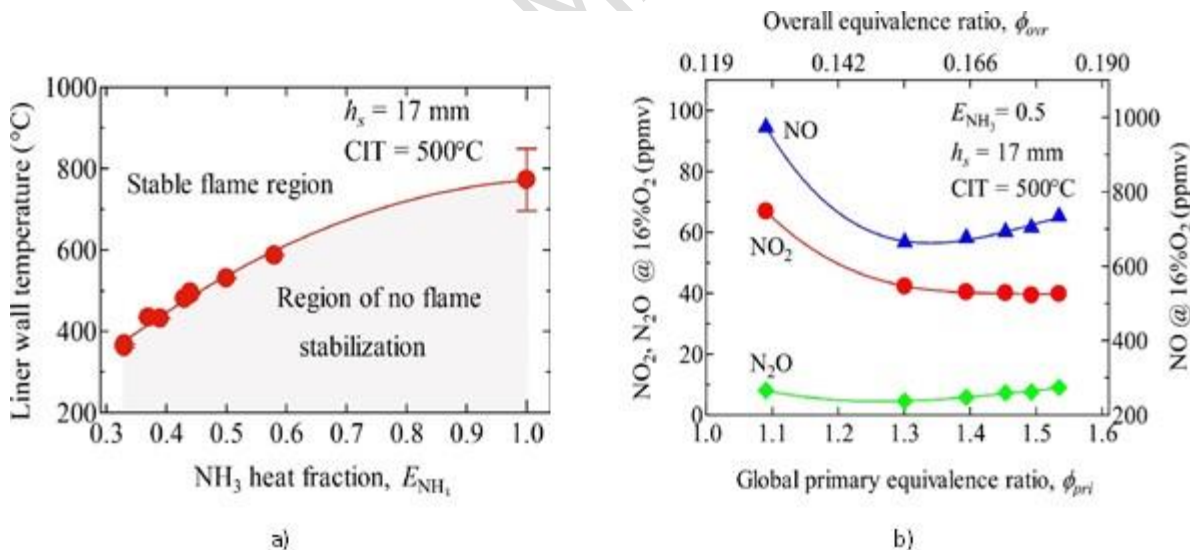


Fig. 16. a) Blow-off limits based on NH_3 heat fraction and liner wall temperature, showing the extension of the stable flame regions to pure liquid ammonia combustions b) Variation of NO , NO_2 and N_2O emissions with equivalence ratio at 50% NH_3 heat input (35).

Okafor et al. (36) also conducted liquid NH_3 trials in a novel swirl combustor co-fired with CH_4 . Particle Image Velocimetry (PIV) was used to measure the non-reacting air flow-field and the NH_3 spray was visualised by Mie scattering. The work concluded that stable combustion of liquid NH_3 was ensured by cooling the liquid ammonia to avoid evaporation in the supply line, and also reduce cavitation in the spray nozzle. The addition of CH_4 further improved flame stability and the overall combustion efficiency. However, the system still produced excessive emissions of NO , CO , HCN , H_2 and NH_3 , depending on the employed equivalence ratio.

Recent reciprocating engine studies, focussed on marine engine applications, have considered dual fuelling of ammonia with a diesel pilot, using numerical and experimental analysis. Scharl and Sattelmeyer (37) utilised a rapid compression-expansion machine (RCEM) to examine single ammonia sprays interacting with small diesel pilots at engine relevant conditions. The spatial/temporal interaction of the two sprays was enabled by a controlled variation of the interaction angle and the relative injection timing. It was found that the reliable ignition of ammonia was possible using a pilot with a LHV fraction as low as 3.2%, with the ignition delay increasing for smaller (diesel) pilot quantities. Shorter, high mass flux, pilot injection durations were found to reduce ignition delay and accelerate the onset of ammonia combustion. The paper concludes that HPDF combustion of ammonia is feasible in real engines and that development of multi-jet engine injectors is advocated. Also, due to the absence of real engine design features within the RCEM, real engines could perform significantly better than expected on the basis of the results presented.

Zhou et al. (38) undertook CFD simulations of low speed, dual fuel, pilot diesel-ignited ammonia marine engines, to compare ammonia premixed and high-pressure

spray combustion modes. The Euler-Lagrangian numerical model predictions for both modes of operation were verified against experimental data of spray mixture formation, ignition delay, etc. The engine performance and emissions of both modes are optimised, leading to the conclusion that indicated thermal efficiencies of over 50% can be achieved for both modes. The optimised ammonia high-pressure spray combustion point can achieve a similar Indicated Thermal Efficiency (ITE) whilst exhibiting a reduction in the NO_x emissions of around 47% when compared with the diesel-only mode. For both the optimum points, the equivalent total greenhouse gas emissions (i.e., CO₂ + 300 × N₂O) were predicted to be reduced by around 97%, while the unburned NH₃ emissions are calculated to be negligibly small.

Very recently, An et al. (39) performed numerical simulations using flamelet-based models for turbulent liquid ammonia combustion under flashing conditions. A Three-dimensional Point-Particle Direct Numerical Simulation (PP-DNS) with detailed chemistry was first performed for a liquid ammonia/methane cofired flame, revealing three distinct regions in the combustion: 1) a mixing stage, 2) methane-dominated combustion stage and 3) fully reacting combustion stage. Heat release from methane-dominated combustion served to counter heat loss by the simultaneously flashing liquid ammonia droplets, effectively acting as a “pilot” flame before ignition of the vaporised ammonia. Using the DNS results as a baseline, subsequent comparison of three flamelet-based models was performed; the extended flamelet/progress variable (E-FPV), extended flamelet-generated manifolds (E-FGM), and extended hybrid (E-Hybrid). It was found that the E-FGM model provided the best agreement with DNS results, as it was able to better capture the to the rapid flash evaporation and sufficient

mixing of the liquid ammonia, and was therefore the best suited for future simulation of liquid ammonia combustion and liquid ammonia/methane co-fired flames.

6. Future Trends

Future trends concerning ammonia lifecycle analysis will include a steady adoption of near-zero emission technologies, with an increase in both the use of Carbon Capture and Storage as well as electrolysis at the production stage. By 2050, green ammonia production is predicted by the International Energy Agency (IEA) to make up more than 40% of the worldwide demand (40). Due to its convenient thermodynamic properties, it is anticipated that the use of ammonia in diverse sectors of industry, transportation, and power generation will develop quickly whilst the optimum systems for implementing ammonia-based fuels will rapidly mature.

The marine sector seems likely to be an early adopter of ammonia for propulsion, as evidenced by the joint efforts of Yara Clean Ammonia, North Sea Container Line, and Yara International towards development of an ammonia powered container ship by 2030 (41). Separately a Japanese consortium comprising Nippon Yusen Kabushiki Kaisha (NYK), Japan Engine Corporation, IHI Power Systems Co., and Nihon Shipyard Co. Ltd., has been formed with the aim of constructing the world's first ammonia-fuelled medium gas carrier (AFMGC), due for completion at the end of 2026 (42). As increasingly large quantities of liquefied ammonia will be transported to global markets by sea, using the product as a fuel in parallel seems an obvious corollary. Shipping is currently the most efficient means of transportation for limiting CO₂ emissions per metric ton-kilometre, being 25 times more efficient than air freight, and 2-3 times more efficient than rail freight (43). However, there are currently no

commercial ammonia fuelled engines for shipping, and there remain challenges for power-plant designers before fully optimised ammonia-fuelled engines can be deployed. One important aspect concerns the optimisation of ammonia fuel-injection systems in relation to efficiency improvements and pollutant, particularly NO_x, reduction.

Parametric optimisation of fuel injection initial and boundary conditions will be enhanced by new empirical correlations suitable for engine/system relevant conditions. This will be underpinned by fundamental experimental data, of which there is currently a lack of with regards to ammonia specific energy conversion systems. The University of Oxford's AmmoSpray project aims to address this by providing step-by-step fundamental data on the characteristics of ammonia sprays at combustion-relevant conditions (including liquid breakup), towards better understanding of the link between ammonia sprays and combustion behaviour (44). Also, multi-fuel injection is likely to become more prevalent, to overcome ammonia reactivity issues. Research into ammonia fuel injection will require further experimental temporal and spatial resolution, to enable appraisal and enhancement of contemporary simulations. Contemporary optical diagnostic techniques, for the large part, are capable of providing such data, though new techniques to quantify mixedness, for example, will be pursued. Numerical techniques will be developed and deployed to provide more efficient and accurate simulation of free surface problems such as ammonia sprays. Engine research design centres, fuel spray combustion fundamentalists, and manufacturers will work more closely together to ensure timely ammonia power-plant development, leading to significant contribution to the global net-zero carbon goals

and aspirations, and this is a key aim of the recently started MariNH₃ research programme (45).

A variety of concepts and ideas have been put together over the previous sections, each of which have important paths towards further development and progression. This has significance for the practical application of NH₃ mixtures, with a specific requirement for investigations at engine/system relevant conditions. There will also be enhanced work in the field of improving NH₃ flame stability, with scope to increase the maximum achievable fraction of NH₃ in fuel sprays. This may require enhancements to both reactant and combustor ambient temperature, and under such conditions, NO_x formation presents a significant barrier to the wider implementation of pure NH₃ as a future zero-carbon fuel. It is a crucial challenge for researchers to develop and employ advanced combustor concepts with NH₃, whilst ensuring the NO_x emissions meet relevant standards.

7. Conclusions

Ammonia is a zero carbon, combustible and internationally transported chemical, which liquifies at modest thermodynamic conditions enabling ease of transportation. However, ammonia combustion kinetics are generally slow, giving rise to a comparatively high ignition energy and low burning rates. Excessive NO_x production is another major inhibitor and challenge moving forward. Liquid fuel injection has the potential to enhance ammonia combustion performance across a range of heat, power and propulsion applications, including burners, boilers and engines.

Over the past 5 years, literature concerning releases of ammonia jets for combustion applications has developed rapidly, alongside global world-wide interest in utilising ammonia as an energy vector, led by countries including Japan, UK, France, China, Saudi-Arabia and Australia.

Due to ammonia's thermophysical properties, liquid fuel injection systems must be carefully designed to achieve the desired liquid, vapour or mixed liquid/vapour injection conditions. There are significant thermodynamic differences associated with high volatility fuels with phase-change potential such as ammonia, butane and propane, compared with stable traditional hydrocarbon liquid or vapour fuels.

Liquid ammonia injection can result in the so-called 'flash boiling' or 'flashing jet' phenomenon. This has been studied and analysed in the context of combustion applications as well as accidental releases of superheated toxic materials.

To date, engine researchers have mainly utilised previously designed bespoke optical rigs, together with established advanced optical diagnostics and multi-phase numerical models. This has resulted in ammonia-specific trends for global spray characterisation being produced and contrasted with those previously designed and utilised for fuel injection of a thermodynamically stable hydrocarbon fuel.

Non-flashing jets may be characterised via the established phenomenological model representation of primary and secondary atomisation, coupled with oxidant entrainment, prior to combustion. For 'flashing' or 'flash boiling' jets, the degree of superheat, together with the injector design dimensions are highly influential in characterising these sensitive jets. Critical transitional conditions have previously been correlated empirically by utilising non-dimensional thermofluid analysis groups, including Reynolds, Weber, Ohnesorge and Jakob numbers. For ammonia applications,

correlations concerning spray quality have been proposed, though validation is currently limited.

Several studies have employed numerical schemes for studying ammonia liquid sprays, with frameworks developed from characterising sub-cooled liquid hydrocarbon sprays. Spray/jet characterisations have mainly concentrated on global, yet influential, diagnostics parameters such as penetration and spray angle. Few studies have explored spray quality (mean particle sizes or distributions), and none in a detailed spatial-temporal sense, which would enable parallel CFD validation or enhancement for reciprocated engine simulation.

Original characteristics and empirical correlations in terms of tip penetration and spray angle have been proposed. Similarities have been reported for penetration (e.g., three stage tip penetration), cone angle and fuel mole fraction of ammonia compared with methane on the spray central axis, and tip penetration correlations have been generated for several initial/boundary conditions. A so-called 'spray resistance phenomena' has been identified for internally flashing jets, decreasing the mass flowrate and tip penetration velocity accordingly with implications for practical devices. The strong cooling effect anticipated due to the large heat of vaporisation, has been observed in numerical studies, which potentially provides a significant practical advantage in engines through charge cooling. The influence fuel injection and ambient pressure and temperatures.

Though there has been an accelerating interest measured in research outputs of ammonia spray combustion over the past five years, for both power generation and transport applications, there are still considerable gaps in the literature, which require addressing to enable optimised utilisation of ammonia as a fuel. Whilst a full review of

the application of ammonia sprays to internal combustion engines is not in the scope of this study, it is noted that the research presents positive signals for the future of ammonia fuelled systems within the marine sector in particular.

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9. References

1. Energy Institute (EI), 'Statistical Review of World Energy 72nd Edition', , 2023
2. United Nations (UN), 'Climate Change', UN : <https://www.un.org/en/global-issues/climate-change> (Accessed on 27 November 2023)
3. World Health Organization (WHO), 'Climate Change', WHO : <https://www.who.int/health-topics/climate-change> (Accessed on 27 November 2023)
4. A. Valera-Medina, F. Amer-Hatem, A. K. Azad, I. C. Dedoussi, M. de Joannon, R. X. Fernandes, P. Glarborg, H. Hashemi, X. He, S. Mashruk, J. McGowan, C. Mounaim-Rouselle, A. Ortiz-Prado, A. Ortiz-Valera, I. Rossetti, B. Shu, M. Yehia, H. Xiao and M. Costa, *Energy Fuels*, 2021, **35**, (9), 6964 LINK <https://doi.org/10.1021/acs.energyfuels.0c03685>

5. T. Kandemir, M. E. Schuster, A. Senyshyn, M. Behrens and R. Schlögl, *Angew. Chem. Int. Ed.*, 2013, **52**, (48), 12723 LINK
<https://doi.org/10.1002/anie.201305812>
6. International Energy Agency (IEA), 'Global Hydrogen Review 2021 – Analysis', IEA : <https://www.iea.org/reports/global-hydrogen-review-2021> (Accessed on 29 November 2023)
7. RWE, 'Import of Green Energy: RWE Builds Ammonia Terminal in Brunsbüttel', RWE 2022 : <https://www.rwe.com/en/press/rwe-ag/2022-03-18-import-of-green-energy-rwe-builds-ammonia-terminal-in-brunsbuettel/> (Accessed on 15 November 2023)
8. Julian Atchison, 'JERA Targets 50% Ammonia-Coal Co-Firing by 2030 – Ammonia Energy Association', Ammonia Energy Association : <https://www.ammoniaenergy.org/articles/jera-targets-50-ammonia-coal-co-firing-by-2030/> (Accessed on 15 November 2023)
9. Mitsubishi, 'Mitsubishi Power Commences Development of World's First Ammonia-Fired 40MW Class Gas Turbine System - Targets to Expand Lineup of Carbon-Free Power Generation Options, with Commercialization around 2025', Mitsubishi Power 2021 : <https://power.mhi.com/news/20210301.html> (Accessed on 27 November 2023)
10. General Electric (GE), 'GE Vernova and IHI Announce next Phase of the Technology Roadmap Aiming to Develop a 100% Ammonia Capable Gas Turbine Combustion System by 2030 | GE News' 2024 : <https://www.ge.com/news/press-releases/ge-vernova-and-ih-announce-next-phase-of-the-technology-roadmap-aiming-to-develop-a> (Accessed on 31 January 2024)
11. H. Kobayashi, A. Hayakawa, K. D. K. A. Somarathne and E. C. Okafor, *Proceedings of the Combustion Institute*, 2019, **37**, (1), 109 LINK
<https://doi.org/10.1016/J.PROCI.2018.09.029>
12. F. J. Verkamp, M. C. Hardin and J. R. Williams, *Symposium (International) on Combustion*, 1967, **11**, (1), 985 LINK [https://doi.org/10.1016/S0082-0784\(67\)80225-X](https://doi.org/10.1016/S0082-0784(67)80225-X)

13. J. Shinjo, *Energies*, 2018, **11**, (11), 2971 LINK
<https://doi.org/10.3390/en11112971>
14. Z. An, J. Xing, A. L. Pillai and R. Kurose, *Fuel*, 2024, **357**, 129660 LINK
<https://doi.org/10.1016/j.fuel.2023.129660>
15. V. Cleary, P. Bowen and H. Witlox, *Journal of Hazardous Materials*, Papers Presented at the 2005 Symposium of the Mary Kay O'Connor Process Safety Center 2007, **142**, (3), 786 LINK <https://doi.org/10.1016/j.jhazmat.2006.06.125>
16. S. Hanna, R. Britter, E. Argenta and J. Chang, *Journal of Hazardous Materials*, 2012, **213–214**, 406 LINK <https://doi.org/10.1016/j.jhazmat.2012.02.013>
17. M. Xu, Y. Zhang, W. Zeng, G. Zhang and M. Zhang, *SAE Int. J. Fuels Lubr.*, 2013, **6**, (1), 137 LINK <https://doi.org/10.4271/2013-01-1614>
18. Y. Kitamura, H. Morimitsu and T. Takahashi, *Ind. Eng. Chem. Fund.*, 1986, **25**, (2), 206 LINK <https://doi.org/10.1021/i100022a005>
19. S. Colson, H. Yamashita, K. Oku, K. D. K. A. Somarathne, T. Kudo, A. Hayakawa and H. Kobayashi, *Fuel*, 2023, **348**, 128612 LINK
<https://doi.org/10.1016/j.fuel.2023.128612>
20. H. W. M. Witlox, M. Harper, A. Oke, P. J. Bowen and P. Kay, *Journal of Loss Prevention in the Process Industries*, Papers Presented at the 2009 International Symposium of the Mary Kay O'Connor Process Safety Center 2010, **23**, (6), 831 LINK <https://doi.org/10.1016/j.jlp.2010.07.004>
21. J. Shin and S. Park, *Fuel*, 2023, **342**, 127841 LINK
<https://doi.org/10.1016/j.fuel.2023.127841>
22. M. H. Davy and P. A. Williams, 'The Effects of Flash Boiling on Mixture Formation in a Firing Direct-Injection Spark-Ignition (DISI) Engine', in 'Direkteinspritzung Im Ottomotor II', Expert-Verlag, 2000
23. S. Li, T. Li, N. Wang, X. Zhou, R. Chen and P. Yi, *Fuel*, 2022, **324**, 124683 LINK
<https://doi.org/10.1016/j.fuel.2022.124683>

24. Z. Zhang, T. Li, R. Chen, N. Wang, Y. Wei and D. Wu, *Fuel*, 2021, **304**, 121408
LINK <https://doi.org/10.1016/j.fuel.2021.121408>
25. R. Pelé, C. Mounaïm-Rousselle, P. Bréquigny, C. Hespel and J. Bellettre, *Fuels*, 2021, **2**, (3), 253 LINK <https://doi.org/10.3390/fuels2030015>
26. A. H. Lefebvre and D. R. Ballal, 'Gas Turbine Combustion: Alternative Fuels and Emissions', 3rd Ed., CRC Press, Boca Raton, 2010 LINK <https://doi.org/10.1201/9781420086058>
27. M. A. Alonso Rincon, 'Novel PLIF Techniques for Analysis of G-DI Spray Dynamics', phd, Cardiff University, 2009 Retrieved from <https://orca.cardiff.ac.uk/id/eprint/54816/>
28. Y. Fang, X. Ma, Y. Zhang, Y. Li, K. Zhang, C. Jiang, Z. Wang and S. Shuai, *Energies*, 2023, **16**, (6), 2843 LINK <https://doi.org/10.3390/en16062843>
29. J. Zembi, M. Battistoni, A. Pandal, C. Mounaïm-Rousselle, R. Pelé, P. Brequigny and C. Hespel, *Journal of Ammonia Energy*, 2023, **1**, (1), LINK <https://doi.org/10.18573/jae.13>
30. H. Hiroyasu, T. Kadota and M. Arai, 'Supplementary Comments: Fuel Spray Characterization in Diesel Engines', in eds. J. N. Mattavi and C. A. Amann, Springer US, Boston, MA, 1980 LINK https://doi.org/10.1007/978-1-4899-5298-1_12
31. J. D. Naber and D. L. Siebers, *SAE Transactions*, 1996, **105**, 82
32. M. A. Comer, P. J. Bowen, S. M. Sapsford and S. I. Kwon, *International journal of automotive technology*, 2004, **5**, (3), 145
33. P. J. Bowen and L. R. J. Cameron, *Process Safety and Environmental Protection*, 1999, **77**, (1), 22 LINK <https://doi.org/10.1205/095758299529749>
34. Z. An, J. Xing and R. Kurose, *Fuel*, 2023, **345**, 128229 LINK <https://doi.org/10.1016/j.fuel.2023.128229>
35. E. C. Okafor, O. Kurata, H. Yamashita, T. Inoue, T. Tsujimura, N. Iki, A. Hayakawa, S. Ito, M. Uchida and H. Kobayashi, *Applications in Energy and*

Combustion Science, 2021, **7**, 100038 LINK

<https://doi.org/10.1016/j.jaecs.2021.100038>

36. E. C. Okafor, H. Yamashita, A. Hayakawa, K. D. K. A. Somarathne, T. Kudo, T. Tsujimura, M. Uchida, S. Ito and H. Kobayashi, *Fuel*, 2021, **287**, 119433 LINK

<https://doi.org/10.1016/j.fuel.2020.119433>

37. V. Scharl and T. Sattelmayer, *Fuel*, 2024, **358**, 130201 LINK

<https://doi.org/10.1016/j.fuel.2023.130201>

38. X. Zhou, T. Li, N. Wang, X. Wang, R. Chen and S. Li, *Renewable and Sustainable Energy Reviews*, 2023, **173**, 113108 LINK

<https://doi.org/10.1016/j.rser.2022.113108>

39. Z. An, J. Xing, A. L. Pillai and R. Kurose, 'Evaluation of Flamelet-Based Models for Liquid Ammonia Combustion in a Temporally Evolving Mixing Layer' arXiv, 2023 LINK

<https://doi.org/10.48550/arXiv.2312.01665>

40. International Energy Agency (IEA), 'Ammonia Technology Roadmap – Analysis', IEA : <https://www.iea.org/reports/ammonia-technology-roadmap> (Accessed on 29 November 2023)

41. Yara International, 'The World's First Clean Ammonia-Powered Container Ship | Yara International', Yara 2023 : <https://www.yara.com/corporate-releases/the-worlds-first-clean-ammonia-powered-container-ship/> (Accessed on 29 January 2024)

42. T. Barlow-Brown, 'Japanese Consortium Signs Contracts for Construction of Ammonia-Fuelled Gas Carrier', The Royal Institute of Naval Architects (RINA) 2024 : <https://rina.org.uk/publications/the-naval-architect/japanese-consortium-signs-contracts-for-construction-of-ammonia-fuelled-gas-carrier/> (Accessed on 31 January 2024)

43. Bureau Veritas, 'Alternative Fuels Outlook for Shipping: An Overview of Alternative Fuels from a Well-to-Wake Perspective', White Paper, LINK
<https://marine-offshore.bureauveritas.com/newsroom/alternative-fuels-outlook-shipping>

44. University of Oxford, 'Green Ammonia Propulsion' :
<https://eng.ox.ac.uk/tpsrg/research/green-ammonia-propulsion/> (Accessed on 29 January 2024)
45. 'Home - MariNH₃' : <https://marinh3.ac.uk/> (Accessed on 29 January 2024)