



Combustion radiation in Ammonia-based fuels: Progress and challenges

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ABSTRACT

Ammonia is attracting increasing attention as a carbon-free fuel for high-temperature thermal systems, but its weak radiative heat-transfer capability remains a critical barrier to direct application in industrial furnaces, boilers, and combustors. Unlike hydrocarbon flames, pure ammonia flames contain no carbon dioxide or soot, leading to fundamentally different radiative characteristics that are mainly governed by H₂O, with possible minor contributions from residual NH₃, NO, and other nitrogen-containing species. This review critically synthesizes recent progress in combustion radiation from ammonia-based fuels, including pure NH₃, NH₃/H₂ blends, cracked NH₃, NH₃/hydrocarbon blends, COG–NH₃ flames, and ammonia co-combustion with solid fuels. Particular attention is given to the dominant radiation mechanisms, spectral features, radiative heat-flux trends, measurement reliability, radiation-model applicability, and furnace-scale engineering implications. The reviewed literature shows that pure NH₃ and NH₃/H₂ flames establish a low-radiation baseline because they lack CO₂, soot, and particle radiation; hydrocarbon and COG blending can partially recover radiative output through CO₂ and possible soot-related emission; and ammonia/solid-fuel co-combustion is strongly affected by particle radiation from char, ash, fly ash, and soot. Current measurement data remain difficult to compare because of differences in burner geometry, pressure, equivalence ratio, fuel composition, detector field of view, wavelength range, wall temperature, background subtraction, and optical path length. Radiation modelling also remains challenging because optically thin, WSGG, SNB, FSCk, and LBL approaches differ substantially in their assumptions, spectral accuracy, and computational cost. Key research gaps are identified in high-pressure and furnace-scale radiation data, standardized measurement protocols, high-temperature spectroscopic databases, radiation–combustion–NO_x coupling, and strategies for compensating weak ammonia flame radiation through both flame-side enhancement and furnace-side heat-transfer adaptation. This review provides a synthesis of current knowledge and practical guidance for the design and optimization of ammonia-based low-carbon combustion systems.

1. Introduction

Thermal radiation plays an important role in high-temperature combustion systems, including industrial furnaces, gas turbines, boilers, kilns, and process heaters. In these systems, radiation often accounts for a large proportion of the total heat transfer and can strongly influence flame temperature, wall heat flux, thermal efficiency, and pollutant formation [1–6]. Therefore, accurate characterization of combustion radiation is essential for predicting flame behaviour and for designing reliable high-temperature energy-conversion systems.

The increasing need to reduce CO₂ emissions has motivated the search for sustainable and carbon-free alternative fuels. Among the

available candidates, ammonia has attracted considerable attention because it contains no carbon, can be liquefied under moderate conditions, and is easier to store and transport than hydrogen using existing infrastructure [7]. These advantages make ammonia a promising fuel and hydrogen carrier for future low-carbon combustion systems. However, the direct use of ammonia in high-temperature applications remains challenging because of its low laminar burning velocity, narrow flammability range, high auto-ignition temperature, fuel–NO_x formation tendency, and, importantly, weak radiative heat transfer compared with hydrocarbon fuels [8–10].

In conventional hydrocarbon flames, thermal radiation is produced mainly by banded gas radiation from H₂O and CO₂, together with broadband continuum radiation from soot or particles under some

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Nomenclature			
c	Speed of light	θ	Angle between radiation direction and surface normal
E	Emitted radiative power per unit area	CH_4	(Methane)
h	Planck's constant	CH^*	Excited methylidyne radical
I_λ	Spectral radiation intensity	COG	Coke oven gas
$I_{b,\lambda}$	Blackbody spectral intensity	CO	Carbon monoxide
k_B	Boltzmann's constant	CO_2	Carbon dioxide
L	Optical path length	DOM	Discrete ordinates method
p	(Pressure)	FSCk	Full-spectrum correlated-k model
p_i	Partial pressure of species i	H_2	(Hydrogen)
q_{rad}	Radiative heat flux	H_2O	Water vapour
s	Radiation path length	HRR	Heat release rate
T	Gas temperature	IR	(Infrared)
T_∞	Surrounding temperature	LBL	Line-by-line model
T_w	Wall temperature	LES	Large-eddy simulation
ε	Surface emissivity	LHV	Lower heating value
κ_λ	Spectral absorption coefficient	MILD	Moderate or intense low-oxygen dilution
$\kappa_{\lambda,i}$	Species-specific spectral absorption coefficient	NH_3	(Ammonia)
κ_p	Planck mean absorption coefficient	NH_2	Amidogen radical
λ	(Wavelength)	NO	Nitric oxide.
Ω	Radiation direction or solid angle	NO_x	Nitrogen oxides
Ω'	Incident radiation direction	OH^*	Excited hydroxyl radical
Φ	Equivalence ratio	OTA	Optically thin approximation
σ	Stefan–Boltzmann constant	OTM	Optically thin model
$\sigma_{s,\lambda}$	Spectral scattering coefficient	RANS	Reynolds-averaged Navier–Stokes
τ_λ	Spectral optical thickness	RTE	Radiative transfer equation
		SNB	Statistical narrow-band model
		WSGG	Weighted-sum-of-grey-gases model

combustion conditions. CO_2 has strong infrared bands around 2.7, 4.3, and 15 μm , while H_2O radiates strongly around 2.7, 6.3, and 20 μm [9]. These radiating species and particles are central to heat transfer in hydrocarbon-fuelled furnaces. In contrast, pure ammonia combustion produces no CO_2 and no soot because the fuel contains no carbon. Its radiation is therefore mainly associated with H_2O , with possible minor contributions from residual NH_3 , NO, and other nitrogen-containing species [11,12]. Therefore, ammonia flames generally exhibit lower radiative heat flux and more selective non-grey spectral behaviour than hydrocarbon flames.

This difference creates an important challenge for ammonia-fired heating applications. In radiation-dominated systems, replacing methane, coal, or other conventional fuels with ammonia may reduce the radiative heat flux received by walls, heating surfaces, and processed materials. This can alter the temperature distribution, reduce wall-heating capability, increase the relative importance of convective heat transfer, and require changes in burner design, furnace geometry, wall properties, or heat-transfer surface arrangement. Therefore, ammonia flame radiation is not only a fundamental combustion issue, but also a practical design problem for the deployment of ammonia in industrial furnaces and other high-temperature systems.

It is necessary to systematically review the current research on radiation in ammonia and ammonia-based fuel combustion from the perspective of ammonia combustion. The discussion focuses on radiating species, spectral characteristics, radiative heat-flux trends, measurement reliability, radiation modelling approaches, and engineering implications for furnace applications. The aim is not only to summarize existing studies, but also to identify the main physical trends, methodological limitations, and research gaps that must be addressed before ammonia can be confidently applied in radiation-dominated combustion systems.

2. Fundamentals of flame radiation relevant to Ammonia-based combustion

2.1. Radiative transfer in participating media

Flame radiation is mainly governed by the emission and absorption of thermal radiation by participating media, as well as scattering in particle-laden systems. In combustion environments, the participating media mainly include H_2O , CO_2 , NH_3 , soot, and other radiatively active species or particles. The spectral radiative transfer equation for radiation travelling along path s in direction Ω can be written as [13,14]:

$$\frac{dI_\lambda(\mathbf{s}, \Omega)}{ds} = \kappa_\lambda I_{b,\lambda}(T) - \kappa_\lambda I_\lambda(\mathbf{s}, \Omega) - \sigma_{s,\lambda} I_\lambda(\mathbf{s}, \Omega) + \frac{\sigma_{s,\lambda}}{4\pi} \int_{4\pi} I_\lambda(\mathbf{s}, \Omega') \Phi(\Omega', \Omega) d\Omega' \quad (1)$$

where I_λ is the spectral radiation intensity, $I_{b,\lambda}$ is the blackbody spectral radiation intensity, κ_λ is the spectral absorption coefficient, $\sigma_{s,\lambda}$ is the spectral scattering coefficient, and Φ is the scattering phase function. The terms on the right-hand side represent emission, absorption, out-scattering, and in-scattering, respectively.

For gas-phase NH_3 and NH_3/H_2 flames, scattering is usually negligible because the dominant radiators are gaseous species rather than carbonaceous particles [15]. In contrast, ammonia/solid-fuel co-combustion may involve strong particle radiation and scattering from char, ash, fly ash, or soot, which must be considered in radiative-transfer analysis.

The blackbody spectral radiation intensity in Eq. (1) is described by Planck's law [13,14]:

$$I_{b,\lambda}(T) = \frac{2hc^2}{\lambda^5} \frac{1}{\exp\left(\frac{hc}{\lambda k_B T}\right) - 1} \quad (2)$$

where h is Planck's constant, c is the speed of light, k_B is Boltzmann's constant, λ is the wavelength, and T is the local temperature. This

equation indicates that flame radiation is strongly dependent on both temperature and wavelength. Therefore, changes in flame temperature caused by variations in fuel composition, equivalence ratio, pressure, or combustion intensity can directly affect the spectral distribution and intensity of flame radiation.

For a simplified grey surface, the total emitted radiative power can be described by the Stefan–Boltzmann law:

$$E = \varepsilon \sigma T^4 \quad (3)$$

where E is the total emitted radiative power per unit area, ε is the emissivity, and σ is the Stefan–Boltzmann constant. The fourth-power dependence on temperature highlights the sensitivity of radiation to flame temperature. However, gas flames are non-grey participating media, and molecular radiation from H_2O , CO_2 , NH_3 , and NO occurs mainly within discrete spectral bands rather than through a single grey-body emissivity.

2.2. Spectral gas radiation and optical thickness

In combustion gases, the spectral absorption coefficient is jointly determined by the local temperature, pressure, gas composition, and wavelength. For a gas mixture, the total spectral absorption coefficient can be expressed as the sum of the contributions from individual radiating species:

$$\kappa_\lambda = \sum_i p_i \kappa_{\lambda,i}(T, p, \lambda) \quad (4)$$

where p_i is the partial pressure of species i , and $\kappa_{\lambda,i}$ is the spectral absorption coefficient of that species. This relationship is important for ammonia-based flames because the dominant radiators vary with fuel composition: H_2O dominates pure NH_3 and NH_3/H_2 flames, CO_2 and possible soot become important in NH_3 /hydrocarbon flames, and char, ash, or fly ash can contribute strongly in ammonia/solid-fuel co-combustion [16–18].

The importance of absorption and reabsorption can be characterized by the spectral optical thickness:

$$\tau_\lambda = \int_0^L \kappa_\lambda(s) ds \quad (5)$$

where L is the optical path length. For a homogeneous medium, Eq. (5) can be simplified as:

$$\tau_\lambda \approx \kappa_\lambda L \quad (6)$$

When $\tau_\lambda \ll 1$, the medium can be regarded as optically thin, and the radiation emitted by the flame can escape with limited self-absorption. When τ_λ approaches or exceeds unity, radiative reabsorption becomes important, and the local radiation field becomes strongly coupled with the temperature and species fields. This distinction is important for ammonia flames: small atmospheric NH_3 and NH_3/H_2 laboratory flames may be approximated as optically thin, whereas high-pressure combustors, confined furnaces, and large-scale boilers can have larger optical path lengths and gas densities, making the optically thin assumption less reliable.

Under the optically thin approximation, the divergence of radiative heat flux can be approximated as:

$$\nabla \cdot \mathbf{q}_{rad} = 4\kappa_p \sigma (T^4 - T_\infty^4) \quad (7)$$

where κ_p is the Planck mean absorption coefficient, T is the local gas temperature, and T_∞ is the background or ambient temperature. This approximation is computationally efficient and is commonly used for small-scale flames where reabsorption is weak. However, for ammonia combustion relevant to furnace applications, especially in high-pressure or long-path confined systems, more detailed non-grey radiation models are generally required [14,19].

The radiative heat flux received by a detector or wall surface can be expressed as the integration of spectral intensity over wavelength and solid angle:

$$q_{rad} = \int_{\lambda_1}^{\lambda_2} \int_{\Omega} I_\lambda \cos\theta d\Omega d\lambda \quad (8)$$

where θ is the angle between the direction of radiation propagation and the surface normal. This expression indicates that the measured radiative heat flux depends not only on radiation emitted by the flame itself, but also on the detector wavelength range, field of view, optical path, wall radiation, and background radiation. Therefore, radiative heat-flux values reported in different studies are not necessarily directly comparable unless the measurement configuration, viewing angle, calibration method, background subtraction, and wall effects are carefully considered.

2.3. Relevance to ammonia-based flames

The above equations explain why ammonia-based flames differ from conventional hydrocarbon flames. Hydrocarbon flames radiate strongly through H_2O and CO_2 , with possible broadband continuum radiation from soot or other carbonaceous particles [13,20]. In contrast, pure NH_3 combustion contains no carbon and therefore does not form CO_2 or soot under ideal complete-combustion conditions. Its radiation is mainly controlled by H_2O , residual NH_3 , NO , and other minor nitrogen-containing species, leading to lower total radiative heat flux and stronger spectral selectivity [11].

Hydrogen addition can improve the combustion intensity of ammonia by increasing flame propagation speed, flame temperature, and radical production [21,22]. However, H_2 is not a strong infrared radiator, so its radiation enhancement is mainly indirect through higher temperature and increased H_2O formation. This explains why NH_3/H_2 flames may radiate more strongly than pure NH_3 flames but often remain weaker than hydrocarbon flames [23]. In contrast, carbon-containing blends such as CH_4 or COG modify radiation more directly by introducing CO_2 and possible soot or continuum radiation, although this reduces the carbon-free fuel fraction and may affect NO_x formation [24,25]. In ammonia/solid-fuel co-combustion, char, ash, fly ash, soot, and suspended particles can contribute significantly to radiation, although increasing the NH_3 co-firing ratio may reduce flame temperature, particle loading, and particle-radiation intensity [16–18].

Visible flame appearance should not be directly equated with thermal radiation. The yellow or orange appearance of ammonia flames is usually associated with NH_2 chemiluminescence or other visible emission, whereas furnace heat-transfer performance is mainly determined by infrared radiative heat flux [26,27]. Therefore, when interpreting ammonia flame radiation data, visible luminosity, chemiluminescence, spectral gas radiation, and total thermal radiation should be clearly distinguished.

A schematic comparison of the main infrared radiation features of NH_3 -based and carbon-containing flames is shown in Fig. 1. The figure is intended to clarify the dominant spectral bands and continuum contributions rather than to provide quantitative spectral data.

Overall, ammonia flame radiation is governed by temperature, radiating-species concentration, spectral absorption, optical thickness, particle loading, and system geometry. These concepts provide the basis for the following discussion of radiative characteristics, controlling factors, measurement methods, modelling strategies, and furnace implications.

3. Radiative characteristics of Ammonia flames

Before examining the radiative characteristics of ammonia flames in detail, many studies have compared the physicochemical properties of ammonia with those of other fuels, as summarized in Table 1 [28].

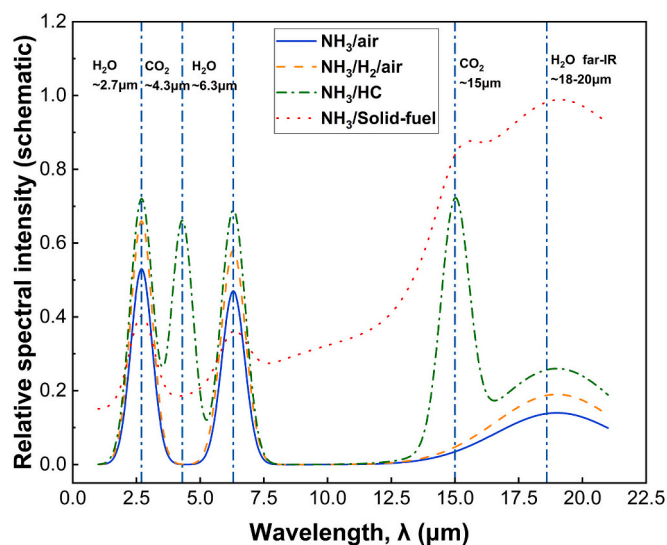


Fig. 1. Comparison of the main infrared radiation features of NH_3 -based and carbon-containing flames.

Table 1

Comparison of physicochemical and radiative properties of ammonia and typical fuels. Adapted with permission from Chai et al. [28]. Copyright 2021 Elsevier Ltd.

Fuel	NH_3	H_2	CH_4	C_3H_8
Density (g/L)	0.703	0.082	0.657	1.88
Lower heating value (MJ/kg)	18.8	120	50	46
Maximum laminar burning velocity (m/s)	0.07	2.91	0.37	0.43
Flammability limit (Equivalence ratio)	0.63–1.4	0.10–7.1	0.50–1.7	0.51–2.5
Auto-ignition temperature (K)	924	844	723	743
C/H ratio	0	0	0.25	0.375
Main radiating species	H_2O , NH_3 , NO	H_2O	H_2O , CO_2	H_2O , CO_2
Soot formation tendency	Negligible	Negligible	Low	Moderate–high
Dominant radiation type	Banded radiation	Banded radiation	Banded + weak continuous radiation	Banded + continuous radiation

Table 1 compares the properties of NH_3 , H_2 , CH_4 , and C_3H_8 , highlighting the zero carbon content of NH_3 and the resulting absence of CO_2 and soot radiation in pure NH_3 combustion [28]. Fig. 2 further shows that oxygen enrichment can improve the burning velocity of $\text{NH}_3/\text{O}_2/\text{N}_2$ flames, but this combustion enhancement does not remove the fundamental radiation limitation caused by the absence of CO_2 and soot [29–31].

Representative studies on radiation behaviour, measurement, and modelling in ammonia-based combustion are summarized in Table 2 to highlight the main physical trends and knowledge gaps discussed in the following sections.

Table 2 shows that the existing literature is unevenly distributed across different ammonia-based fuel systems. Pure NH_3 and NH_3/H_2 studies mainly provide information on flame appearance, combustion enhancement, and H_2O -dominated radiation, whereas fewer studies

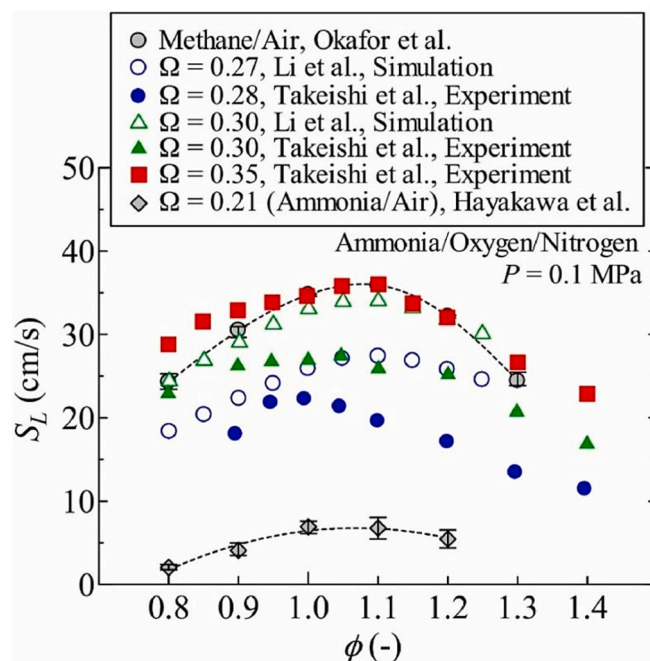


Fig. 2. Variation of laminar burning velocity of oxygen-enriched $\text{NH}_3/\text{O}_2/\text{N}_2$ flames in terms of equivalence ratio. The experimental results obtained by Takeishi et al. [29] and the numerical results obtained by Li et al. [32] are plotted. The laminar burning velocities of CH_4/air and NH_3/air flames are also plotted for reference [30,31]. Mixture temperature and pressure were 298 K and 0.10 MPa, respectively. Adapted with permission from Kobayashi et al. [33].

directly quantify radiative heat flux under furnace-relevant conditions. NH_3 /hydrocarbon and COG-NH_3 studies provide clearer evidence of the role of CO_2 and soot-related radiation, while NH_3 /solid-fuel co-combustion studies highlight the importance of particle radiation and furnace-scale heat-transfer redistribution. Overall, the available data indicate a consistent trend that increasing the NH_3 fraction generally weakens radiative heat transfer unless additional radiating species or particles are introduced. However, directly comparable radiative heat-flux data remain limited, especially for elevated-pressure, confined, and large-scale furnace conditions.

3.1. NH_3/air flames

Pure NH_3/air flames form the low-radiation baseline for ammonia-based combustion. As shown in Figs. 3 and 4, ammonia flames can exhibit yellow–orange luminosity, and fuel preheating can alter the visible flame structure and OH^* chemiluminescence region. However, these visible features should not be directly interpreted as infrared radiative heat flux. The yellow–orange appearance is mainly associated with NH_2 -related visible emission, whereas the engineering concern in furnaces is thermal radiation in the infrared range.

From a heat-transfer perspective, pure NH_3 flames contain neither CO_2 nor soot; their radiation is therefore mainly governed by H_2O , with possible minor contributions from residual NH_3 , NO , and other nitrogen-containing species [11,42]. This explains why pure NH_3 flames generally show lower radiative heat flux and stronger wavelength-selective non-grey behaviour than hydrocarbon flames.

3.2. NH_3/H_2 flames

To overcome the limitations of pure ammonia combustion, a large number of studies on ammonia–hydrogen co-combustion have emerged in recent years [43–50]. Hydrogen addition improves the combustion

Table 2

Summary of representative studies on radiation behaviour, measurement, and modelling in ammonia-based combustion

Topic	Fuel system	Reference	Configuration	Main radiation-related contribution	Relevance to this review
Pure NH ₃ radiation and flame appearance	NH ₃ /air	Hayakawa et al. [27,31]	Swirl combustor; flame imaging and emission analysis	Reported the yellow–orange appearance and emission characteristics of NH ₃ /air flames, mainly associated with NH ₃ -related visible emission.	Supports the discussion on distinguishing visible chemiluminescence from infrared thermal radiation.
Pure NH ₃ flame structure	NH ₃ /air	Chen et al. [34]	Non-premixed NH ₃ combustion with fuel preheating	Showed that fuel preheating changes the visible flame structure and OH* chemiluminescence region.	Relevant to the interpretation of flame appearance and reaction-zone indicators in NH ₃ flames.
Pure NH ₃ radiative baseline	NH ₃ /O ₂ /N ₂ , CH ₄ /air comparison	Kobayashi et al. [33]	Experimental comparison of flame temperature and emission characteristics	Compared NH ₃ and CH ₄ flames and showed the lower-temperature and different emission characteristics of NH ₃ combustion.	Supports the low-radiation baseline of pure NH ₃ flames compared with hydrocarbon flames.
Pure NH ₃ spectral radiation	NH ₃ flame	Xia et al. [15]	Spectral measurement; HITRAN database; optically thin model	Measured radiation spectra and estimated total radiation intensity of NH ₃ flames using spectral calculations.	Provides evidence for the non-grey and wavelength-selective radiation behaviour of NH ₃ flames.
NH ₃ /H ₂ combustion enhancement	NH ₃ /H ₂ /air	Ichikawa et al. [21]	Premixed flames under atmospheric	Showed that H ₂ addition increases the unstretched laminar burning velocity of NH ₃ flames.	Relevant because H ₂ influences radiation indirectly through flame temperature and H ₂ O formation.
NH ₃ /H ₂ combustion characteristics	70/30 NH ₃ /H ₂	Syed et al. [22]	Laminar burning velocity and combustion-characteristic analysis	Demonstrated improved flame speed and combustion stability for NH ₃ /H ₂ blends compared with pure NH ₃ .	Supports the interpretation that H ₂ addition improves combustion intensity rather than acting as a direct radiator.
NH ₃ /H ₂ reaction zone effects	NH ₃ /H ₂	Wang et al. [35]	Numerical simulation of preferential diffusion and flame structure	Showed that H ₂ addition increases temperature, heat release rate, and radical concentrations.	Explains the indirect radiation enhancement mechanism in NH ₃ /H ₂ flames.
NH ₃ /H ₂ and cracked NH ₃ radiation	NH ₃ /H ₂ and cracked NH ₃	Sato et al. [23]	Premixed swirling flames; radiative heat-flux analysis	Compared radiative heat fluxes of CH ₄ , NH ₃ /H ₂ , NH ₃ , and cracked NH ₃ flames; ammonia-based flames showed lower radiation than CH ₄ .	Key evidence for weaker radiative heat transfer in gaseous NH ₃ -based flames.
NH ₃ /hydrocarbon combustion	NH ₃ /CH ₄ and NH ₃ /biogas	Zhao et al. [24]	Numerical simulation of swirl combustion	Investigated flame structure, temperature distribution, and NO formation in NH ₃ /hydrocarbon swirl flames.	Relevant to how hydrocarbon blending modifies temperature fields and radiating-species distributions.
NH ₃ /hydrocarbon furnace conditions	NH ₃ /CH ₄	Xie et al. [25]	MILD and swirl combustion; conjugate heat-transfer modelling	Showed that increasing NH ₃ fraction decreases furnace temperature under NH ₃ /CH ₄ combustion conditions.	Supports the furnace-scale implication that replacing hydrocarbon fuel with NH ₃ may weaken thermal intensity and radiation.
NH ₃ /hydrocarbon radiation fraction	NH ₃ /CH ₄ and NH ₃ /C ₂ H ₆	Zheng et al. [36]	Jet flames; radiation fraction and soot analysis	Showed that NH ₃ addition reduces soot loading and decreases the radiation fraction of hydrocarbon flames.	Supports the role of soot suppression in reducing radiative heat transfer in NH ₃ /hydrocarbon blends.
NH ₃ /hydrocarbon radiative heat flux	NH ₃ /CH ₄ and NH ₃ /C ₂ H ₆	Fang et al. [37]	Jet flames; radiative heat flux, emissivity, and view-factor analysis	Reported that radiative heat flux, emissivity, and view factor decrease as the NH ₃ fraction increases.	Provides direct evidence that increasing NH ₃ content generally weakens radiation in hydrocarbon blends.
COG–NH ₃ spectral radiation	COG–NH ₃	Sato et al. [38]	Premixed swirling flames; infrared measurement; LBL and Hottel-model analysis	Separated H ₂ O and CO ₂ radiative contributions and showed that CO ₂ strongly affects radiation differences among blends.	Important for understanding species-specific radiation contributions in NH ₃ /carbon-containing fuel blends.
NH ₃ /solid-fuel heat transfer	NH ₃ /coal	Chae et al. [16]	80 kW _{th} pulverized-coal furnace	Showed that NH ₃ co-firing reduces furnace temperature and wall heat flux.	Supports the engineering implication that NH ₃ co-firing can weaken radiative heat transfer in coal-fired systems.
NH ₃ /solid-fuel spectral radiation	NH ₃ /coal	Pu et al. [17]	4 MW pilot boiler; spectral analysis	Reported reduced particle radiation with increasing NH ₃ co-firing ratio.	Key evidence that particle radiation is strongly affected in NH ₃ /solid-fuel co-combustion.
Utility-scale NH ₃ co-firing	NH ₃ /coal	Lin et al. [18]	300 MW coal-fired boiler analysis	Showed that NH ₃ co-firing shifts boiler heat transfer from radiation-dominated behaviour toward stronger convective contribution.	Supports large-scale furnace and boiler implications of NH ₃ co-combustion.
Measurement reliability	General confined combustion chambers	Yang et al. [19]	Theoretical model and CFD analysis of flame radiation measurement	Demonstrated that wall emission and wall reflection can strongly contaminate measured flame radiation in confined chambers.	Supports the discussion of measurement uncertainty, wall effects, and cross-study comparability.
Radiation modelling	NH ₃ , H ₂ O/NH ₃ , NH ₃ -containing flames	Wang et al. [35]; Di et al. [39]; Modest [13]; Chu et al. [40].	WSGG / FSCK / LBL / DNS	Evaluated radiation-model applicability and showed limitations of grey-gas assumptions.	Supports the model-selection discussion for ammonia-based combustion.
Pressure / optical-thickness effects	General combustion / ammonia-relevant confined systems	Yang et al. [19]; Andersson and Johnsson [41]; Chu et al. [40].	Confined chamber / oxy-fuel / non-grey gas radiation modelling	Showed that pressure, path length, gas density, and wall effects can change optical thickness and radiative reabsorption.	Supports the discussion of elevated-pressure and furnace-scale data gaps.

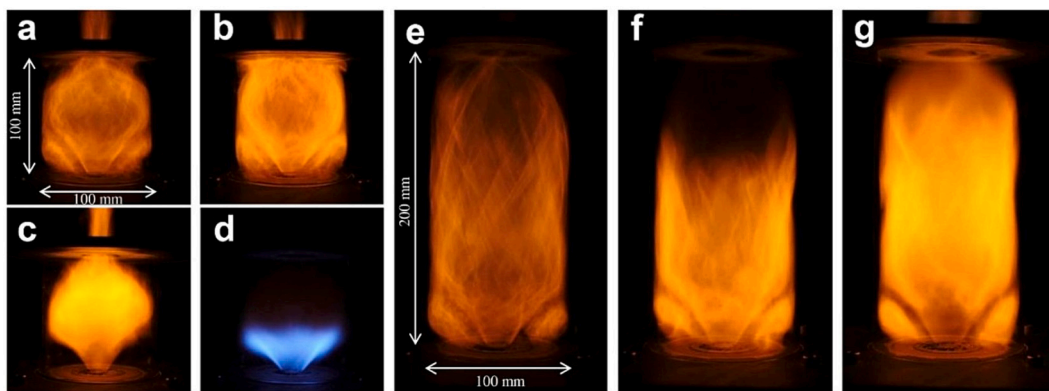


Fig. 3. Flames stabilized in the swirl burner with cylindrical liners: (a) ammonia/air flame, $\phi = 1.0$, $h = 100$ mm, $U_{in} = 3.14$ m/s; (b) ammonia/air flame, $\phi = 1.2$, $h = 100$ mm, $U_{in} = 3.14$ m/s; (c) ammonia/air flame, $\phi = 1.2$, $h = 100$ mm, $U_{in} = 3.35$ m/s; (d) methane/air flame, $\phi = 1.0$, $h = 100$ mm, $U_{in} = 3.14$ m/s; (e) ammonia/air flame, $\phi = 0.8$, $h = 200$ mm, $U_{in} = 3.14$ m/s; (f) ammonia/air flame, $\phi = 1.0$, $h = 200$ mm, $U_{in} = 3.14$ m/s; (g) ammonia/air flame, $\phi = 1.2$, $h = 100$ mm, $U_{in} = 3.14$ m/s. Adapted with permission from Hayakawa et al. [27]. Copyright 2017 Hydrogen Energy Publications LLC. Published by Elsevier Ltd.

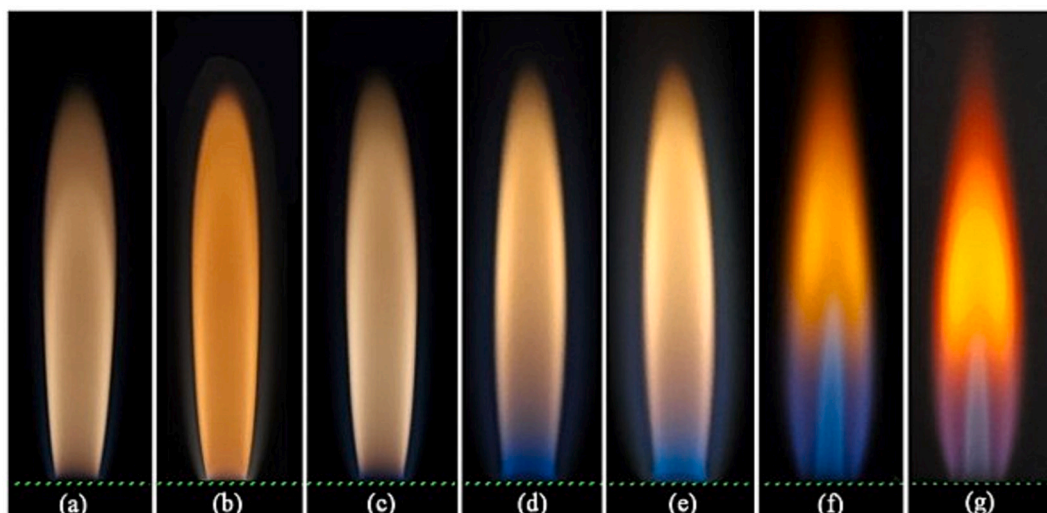


Fig. 4. Flame images at different preheating temperatures under 200 ml/min NH_3 : (a) 593 K flame image; (b) 623 K flame image; (c) 653 K flame image; (d) 683 K flame image; (e) 713 K flame image; (f) 743 K flame image; (g) 773 K flame image. Adapted with permission from Chen et al. [34]. Copyright 2021 Elsevier Ltd.

intensity of NH_3 flames, as reflected by the increased laminar burning velocity, higher flame temperature, stronger heat release, and enhanced radical production shown in Figs. 5 and 6.

However, from a radiation perspective, H_2 is not a strong infrared radiator. From a spectral perspective, combustion of NH_3/H_2 blended fuels still exhibits pronounced non-grey radiative behaviour because it lacks broadband emitters such as soot. Its influence on NH_3 flame radiation is therefore mainly indirect, through increasing temperature and promoting H_2O formation. Available radiative heat-flux data show that NH_3/H_2 and cracked- NH_3 flames can radiate slightly more strongly than pure NH_3 under some conditions, but they still remain weaker than methane flames because they contain no CO_2 or soot. Therefore, H_2 addition improves combustion performance more directly than it improves radiative heat-transfer capability.

3.3. NH_3 /hydrocarbon blends

Blending ammonia with hydrocarbon fuels is widely seen as an effective way to improve ammonia combustion performance, because adding hydrocarbons can reduce the low reactivity, narrow flammability limits, and poor flame stability of pure ammonia combustion [51–55].

3.3.1. NH_3 co-combustion with gaseous hydrocarbon fuels

Hydrocarbon blending modifies ammonia-flame radiation more directly than H_2 addition because it introduces carbon-containing radiators [56]. Although NH_3/CH_4 , $\text{NH}_3/\text{biogas}$, and other NH_3 /hydrocarbon flames are often studied from the perspectives of flame stability, temperature distribution, and NO_x formation, their radiation relevance lies mainly in the formation of CO_2 and possible soot-related continuum emission [24,25]. As shown in Fig. 7, replacing CH_4 with NH_3 can reduce furnace temperature under NH_3/CH_4 MILD combustion conditions, indicating that the thermal field and radiative environment are both sensitive to the hydrocarbon fraction.

The experimental studies summarized in Figs. 8 and 9 show a consistent trend: increasing the NH_3 fraction in hydrocarbon- or COG-blended flames generally reduces CO_2 -related radiation, soot loading, emissivity, view factor, and total radiative heat flux. However, the contributions of individual radiating species do not always change in the same direction. In COG- NH_3 flames, H_2O radiation can remain significant or even increase with NH_3 fraction, whereas CO_2 largely controls the radiation differences among blends.

Therefore, hydrocarbon and COG blending can partially recover the radiative output of ammonia flames, but this benefit comes with a trade-off between radiation enhancement and maintaining a high carbon-free fuel fraction [36–38].

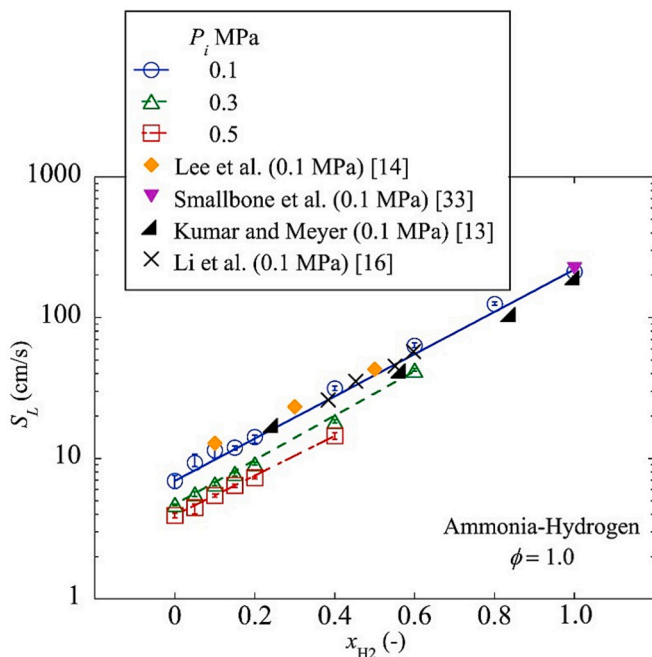


Fig. 5. Relationship between unstretched laminar burning velocity, S_L , and hydrogen ratio, x_{H_2} , in initial pressure varies from 0.1 MPa to 0.5 MPa on semilog graph. Adapted with permission from Ichikawa et al. [21]. Copyright 2015 Hydrogen Energy Publications, LLC. Published by Elsevier Ltd.

3.3.2. NH_3 co-combustion with solid hydrocarbon fuels

It should be noted that the radiative behaviour of ammonia co-combustion with solid or particle-laden fuels can be very different from gaseous ammonia/hydrocarbon flames. In pulverized-coal systems, radiative heat transfer depends on gaseous emitters such as H_2O and CO_2 , and on the radiation from char, fly ash, and other solid particles. Adding ammonia changes furnace radiation through changes in gas composition, and through decreases in particle concentration, particle radiation, and flame temperature.

In pulverized-coal systems, total radiation depends not only on H_2O and CO_2 , but also on char, ash, fly ash, and soot. Existing furnace- and boiler-scale studies show that increasing the NH_3 co-firing ratio can reduce furnace temperature, wall heat flux, and particle-radiation intensity, as illustrated in Fig. 10. These changes can shift boiler heat transfer from radiation-dominated furnace regions toward stronger downstream convective contribution [16–18].

Other ammonia/coal experimental and numerical studies also show that NH_3 addition alters ignition, flame structure, temperature distribution, and emissions; however, radiation-specific datasets remain much more limited than studies on NO_x , ignition, ash behaviour, and combustion efficiency [57–60]. Therefore, ammonia/solid-fuel co-combustion remains an important but underdeveloped area for ammonia radiation research.

Overall, these studies show that ammonia co-combustion with solid or particle-laden fuels directly affects furnace radiation through changes in flame temperature, particle loading, and particle radiation intensity. However, compared with gaseous ammonia flames, radiation studies on ammonia/coal systems are still limited. Most current work focuses on NO_x , ignition, ash behaviour, and combustion efficiency, and systematic studies of total radiative heat flux, spectral radiation, and the relative roles of gas-phase and particle radiation are still few. Ammonia co-combustion with solid or particle-laden fuels therefore represents an important but still underexplored area in ammonia radiation research.

Based on the studies reviewed in this section, the dominant radiation mechanisms in different ammonia-based combustion systems are summarized in Fig. 11.

The radiation mechanisms discussed above show that pure NH_3 and NH_3/H_2 flames establish a low-radiation baseline because they lack CO_2 , soot, and particle radiation. Hydrogen addition can enhance radiation indirectly by increasing flame temperature and H_2O formation, but it does not introduce a strong infrared radiator. Hydrocarbon or COG blending can partially recover radiative heat transfer through CO_2 and possible soot-related emission, although this reduces the carbon-free fraction of the fuel. In ammonia/solid-fuel co-combustion, particle radiation can become a dominant mechanism, but increasing the NH_3 co-firing ratio may reduce particle loading and flame temperature. These trends indicate that the radiative behaviour of ammonia-based combustion is controlled not only by fuel composition, but also by the coupled effects of temperature, radiating-species concentration, soot or particle loading, optical thickness, pressure, and wall interaction.

4. Factors governing radiation in Ammonia combustion

The radiative behaviour of ammonia combustion is not controlled by one variable, but by several interacting factors. Besides flame temperature, the equivalence ratio, fuel blending ratio, pressure, and the formation of radiatively active combustion products such as H_2O , CO_2 , and other radiating species can all strongly affect ammonia flame radiation. These factors together determine the concentration of radiating species and the overall radiative heat flux. Understanding their individual effects and their combined interactions is important for improving radiation in ammonia combustion and improving the prediction ability of radiation models.

4.1. Temperature

Temperature is one of the most important factors governing flame radiation, as radiative emission increases significantly with increasing temperature. In ammonia combustion, the lower flame temperature of pure NH_3 flames compared with conventional hydrocarbon flames is one of the main reasons for the weaker radiative output of ammonia fuel combustion. Kobayashi et al. [33] reported that, at the same equivalence ratio, the maximum temperature of a CH_4 /air flame is 100–200 K higher than that of an NH_3 /air flame, as shown in Fig. 12.

Any factor that increases flame temperature, such as hydrogen addition, oxygen enrichment, or hydrocarbon blending, can therefore enhance radiation intensity [11,37,61–63]. However, the effect of temperature in ammonia flames cannot be considered in isolation, because even if the flame temperature increases, the overall radiative output may remain limited in the absence of strong carbon-based radiators such as CO_2 and soot.

In practical furnaces and boilers, not only the flame temperature but also the spatial temperature distribution is important for radiative heat transfer. Experimental analysis of a large coal-fired boiler showed that the uniformity of the furnace temperature field strongly affects radiative heat-transfer efficiency. As the standard deviation of the temperature distribution increases, the irreversibility of radiative transfer increases and the radiation heat-transfer efficiency decreases, and the burner region, where the temperature is highest, shows the strongest radiative heat transfer [64]. As shown in Fig. 13, increasing the ammonia co-firing ratio reduces the furnace temperature and reduces the high-temperature region in the furnace. In particular, the region above 1100 °C becomes smaller at higher co-firing ratios, and this shows that ammonia addition weakens the thermal intensity of the coal flame.

4.2. Equivalence ratio

Changes in the equivalence ratio alter flame temperature, combustion efficiency, and product composition, thereby significantly affecting the radiative characteristics of the flame. In general, the radiation intensity of ammonia-containing flames increases as the equivalence ratio approaches stoichiometric conditions and usually reaches a maximum in

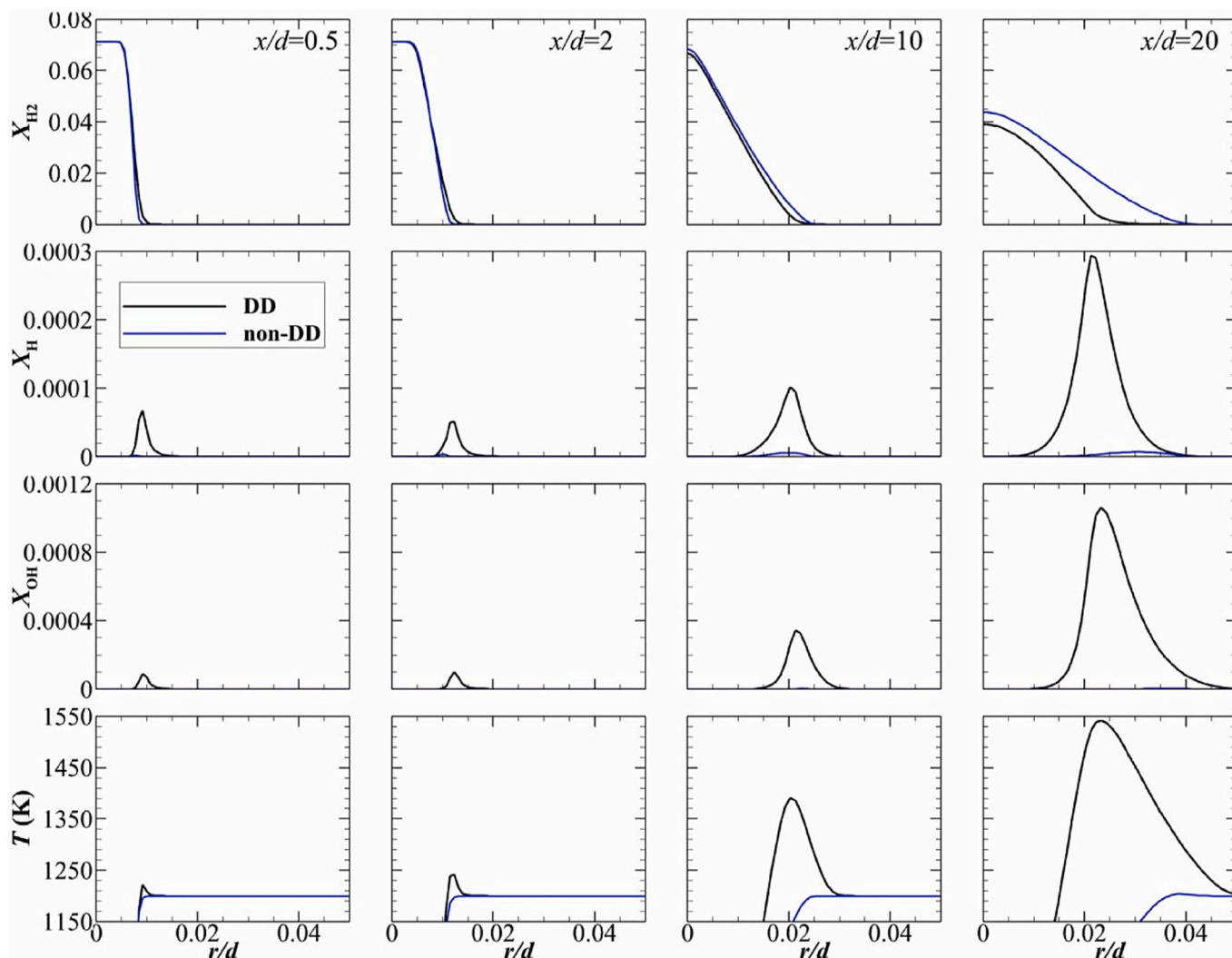


Fig. 6. Radial distributions of X_{H_2} , X_H , X_{OH} , and T for the DD and non-DD cases at $X_{H_2/F} = 30\%$. Adapted with permission from Wang et al. [48]. Copyright 2024 Hydrogen Energy Publications LLC. Published by Elsevier Ltd.

this region; under lean conditions, radiation often decreases rapidly because of reduced reaction intensity and lower concentrations of radiating products [23,38,65]. Sato et al. [23] reported that the radiative heat flux to the inner wall reached a maximum at $\Phi = 0.9$, consistent with the measured temperature, H_2O emission, and infrared spectral results, as shown in Fig. 14.

In ammonia combustion, the effect of equivalence ratio is often more pronounced because ammonia flames generally exhibit lower reactivity, narrower flammability limits, and poorer lean stability. Under fuel-lean conditions, incomplete combustion and unburned ammonia may further reduce the radiative output; under fuel-rich conditions, by contrast, the variation in radiation tends to become more gradual, depending on the flame structure and fuel blending ratio.

4.3. Blending ratio

The fuel blending ratio is another key factor governing radiation phenomena in ammonia combustion, because it directly determines the concentration of radiating species. In NH_3/H_2 flames, increasing the hydrogen fraction mainly affects radiation indirectly through changes in flame temperature and water-vapour formation [23]. In contrast, in NH_3 /hydrocarbon flames, the influence of blending ratio on radiation is more direct [37,38]. The results shown in Figs. 15 and 16 [37], the radiative heat flux of both CH_4-NH_3 and $C_3H_8-NH_3$ jet flames decreases

as the NH_3 volume fraction increases. Under the same flow-rate conditions, $C_3H_8-NH_3$ flames show higher radiative heat flux than CH_4-NH_3 flames, indicating that propane is more effective than methane in restoring the radiation capability of ammonia-containing flames. Increasing the hydrocarbon flow rate also increases radiative heat flux because of the enlarged flame size and higher flame temperature.

Experimental results reported by Sato et al. [38] showed that, under certain conditions, H_2O -related radiation may remain significant or even increase; however, as the ammonia fraction increases, the overall variation in radiation is generally governed by the reduction in CO_2 -related emission. This makes the blending ratio one of the most sensitive controlling parameters in ammonia-based combustion systems.

4.4. Pressure, optical thickness, and radiative reabsorption

Operating pressure can strongly affect flame radiation by increasing gas density, spectral absorption, and the effective optical thickness of the flame [66]. In general, higher pressure increases the number density of radiating molecules and shortens the mean free path of photons, thereby enhancing both gas radiation and radiative reabsorption. As a result, pressure can change not only the magnitude of the radiative heat flux, but also the spatial distribution of radiative heat transfer and the coupling between radiation, temperature, and species fields. This effect is particularly important in confined combustors and furnace-scale

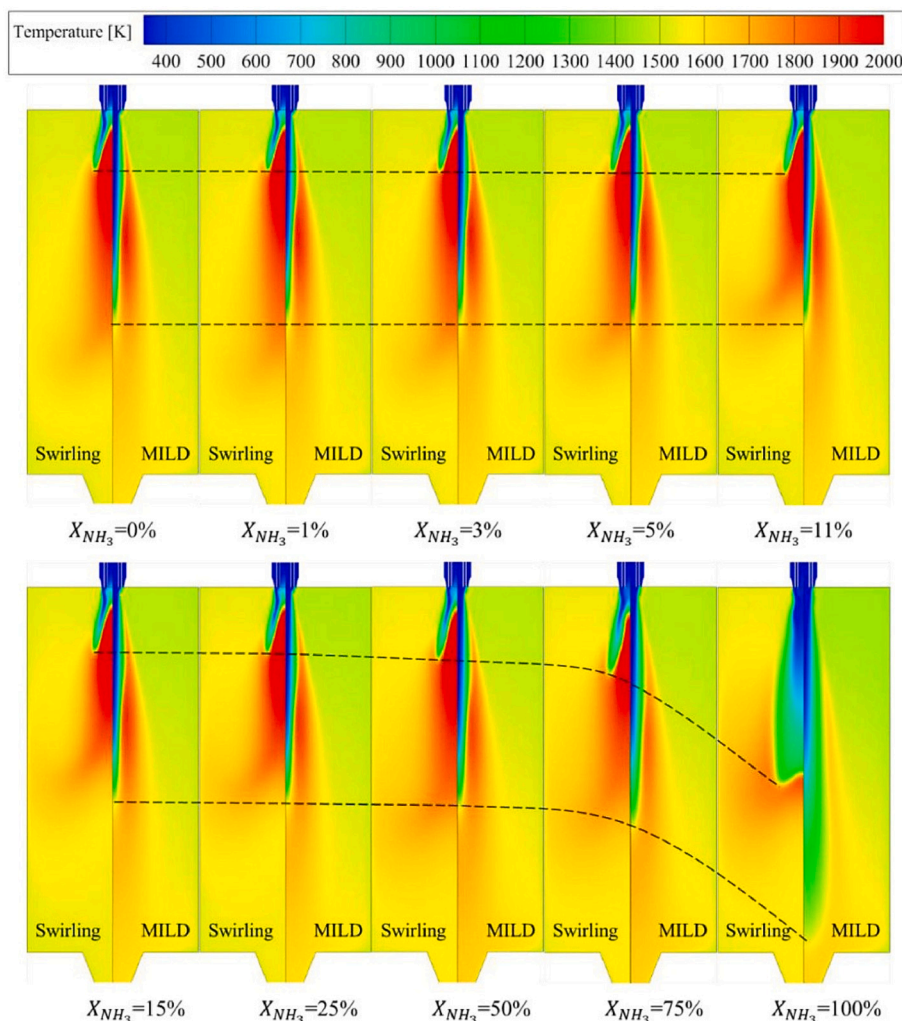


Fig. 7. Temperature distributions on central furnace plane in (left) swirling and (right) MILD combustion modes in various X_{NH_3} conditions. Adapted with permission from Xie et al. [25]. Copyright 2023 The Author(s). Published by Elsevier Ltd.

systems, where the optical path length is much longer than that in laboratory-scale flames [67]. Compared with conventional hydrocarbon combustion, experimental data under high-pressure ammonia combustion conditions remain limited. This lack of data restricts the validation and further development of radiation models for ammonia-based combustion systems.

Therefore, pressure effects in ammonia-based combustion should be discussed not only in terms of stronger radiative emission, but also in terms of optical-thickness variation and radiative reabsorption. Compared with conventional hydrocarbon combustion, experimental data under high-pressure ammonia combustion conditions remain limited. This lack of data restricts the validation and further development of radiation models for ammonia-based combustion systems.

4.5. H_2O , CO_2 and other radiating species

Radiating-species composition provides the direct link between fuel composition and radiation. In pure NH_3 and NH_3/H_2 flames, H_2O is usually the dominant stable gaseous radiator, while NH_3 and NO may contribute in some spectral regions but usually have smaller effects on total radiation [15,23,38,68]. In NH_3 /hydrocarbon and $COG-NH_3$ flames, CO_2 becomes an additional important infrared radiator, and soot may also contribute broadband continuum radiation under soot-forming conditions.

Therefore, changes in product composition do not simply follow

changes in operating conditions; they directly determine the spectral features, optical thickness, and total radiative heat flux of ammonia-containing flames. Overall, ammonia flame radiation is controlled by the coupled effects of temperature, equivalence ratio, blending ratio, pressure, optical thickness, and radiating-species formation. Understanding these interactions is essential for interpreting experimental data and selecting appropriate radiation models under practical combustion conditions.

Table 3 highlights that the radiative behaviour of ammonia-based combustion is controlled by multiple coupled factors rather than by fuel composition alone. Across gaseous fuel systems, increasing the NH_3 fraction generally weakens radiative heat transfer because carbon-based radiators such as CO_2 and soot are progressively removed. H_2 addition can partially compensate for the weak radiation of NH_3 by increasing flame temperature and H_2O formation, but it does not introduce strong carbon-based infrared emitters. Hydrocarbon and COG blending can recover part of the radiative output through CO_2 and possible soot-related radiation, although this comes at the cost of reducing the carbon-free fuel fraction. In solid-fuel co-combustion, particle radiation becomes a dominant consideration, and NH_3 co-firing may weaken radiation by reducing flame temperature and particle loading. Overall, the available data suggest that ammonia-based flames require either flame-side radiation enhancement or furnace-side heat-transfer adaptation for radiation-dominated applications.

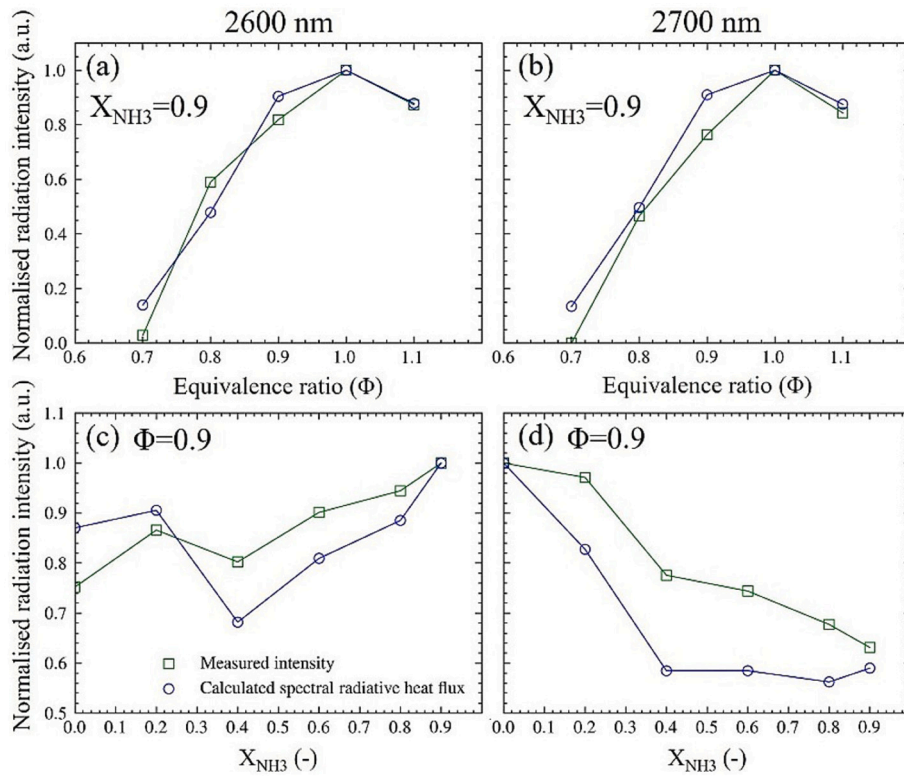


Fig. 8. Infrared spectrometry measured intensity at 2600 nm and 2700 nm wavelength compared with LBL calculated spectral radiative heat flux. (a,b) X_{NH_3} fixed at 0.9. (c,d) Φ fixed at 0.9. All data were normalised by maximum value. Adapted with permission from Sato et al. [38].

5. Measurement methodology

Accurate measurement of flame radiation is essential for evaluating the heat-transfer capability of ammonia-based combustion systems and for validating radiation models. Besides flame temperature and radiative heat flux, the detection of thermal radiative parameters is also an important aspect of combustion diagnostics. In furnace applications, the most relevant parameters include the absorption coefficient (k_a) and scattering coefficient (σ_s) of the combustion medium, as well as the wall (ϵ_w) emissivity (ϵ_w), because these quantities directly affect radiative heat transfer and are required as inputs for combustion modelling [69]. Compared with hydrocarbon flames, ammonia flames present additional diagnostic challenges because their radiative signals are weaker, more spectrally selective, and more sensitive to wall emission, background subtraction, and optical access. This section summarizes total radiative heat-flux measurements, spectral radiation measurements, indirect diagnostics, and the main uncertainty sources affecting data comparability.

5.1. Total radiative heat flux measurements

Total radiative heat-flux measurements provide the most direct assessment of flame-to-wall radiation in furnaces and combustors. Thermopiles, radiometers, and heat-flux sensors have been used to measure the incident radiation from open flames and confined chambers [70,71].

Narrow-angle radiometers, such as the probe shown in Fig. 17, are useful for reducing wall interference because they restrict the field of view and isolate a limited line-of-sight region [72].

For high-temperature or high-pressure environments, narrow-beam radiometers can be combined with a view tube, cold background, and optical window, as shown in Fig. 18, to improve the separation between flame radiation and background radiation [71].

Radiation measurements are generally easier in open flames than in

confined chambers. In enclosed burners, furnaces, or practical combustion systems, the detected signal may be affected by wall emission, wall-reflected flame radiation, and uncertainties in radiative-property estimation, including local absorption and scattering coefficients of gases and particles [41,72–77].

As shown in Fig. 19, the incident radiation received by a radiometer consists of radiation from the flame and combustion products, radiation emitted by the walls, and radiation reflected by the walls. Therefore, the surface incident radiation, G_{total} , measured by a radiometer can be expressed as in the eq. (9).

$$G_{total} = E_{flame} + G_{wall} \quad (9)$$

where E_{flame} represents flame radiation, that is, radiation emitted directly by high-temperature combustion products as well as radiation partially absorbed and scattered by the medium during propagation, while G_{wall} represents the combined contribution of wall emission and wall reflection to the incident surface radiation [19].

In ammonia-based combustion studies, total radiative heat-flux measurements have been used to compare ammonia flames with methane flames, quantify the radiation fraction of NH_3 /hydrocarbon jet flames, and evaluate H_2/NH_3 flames under crosswind conditions [11,25,36,78]. These studies collectively show that direct heat-flux measurements are necessary for assessing ammonia flames in radiation-dominated systems, but the measured signal must be interpreted carefully because it can include both flame radiation and wall-related contributions.

5.2. Spectral radiation measurements

Spectral radiation measurements provide wavelength-resolved information and are therefore essential for identifying the contributions of H_2O , CO_2 , NH_3 , NO , soot, and particles. This is especially important for ammonia flames because their radiation is strongly non-grey and

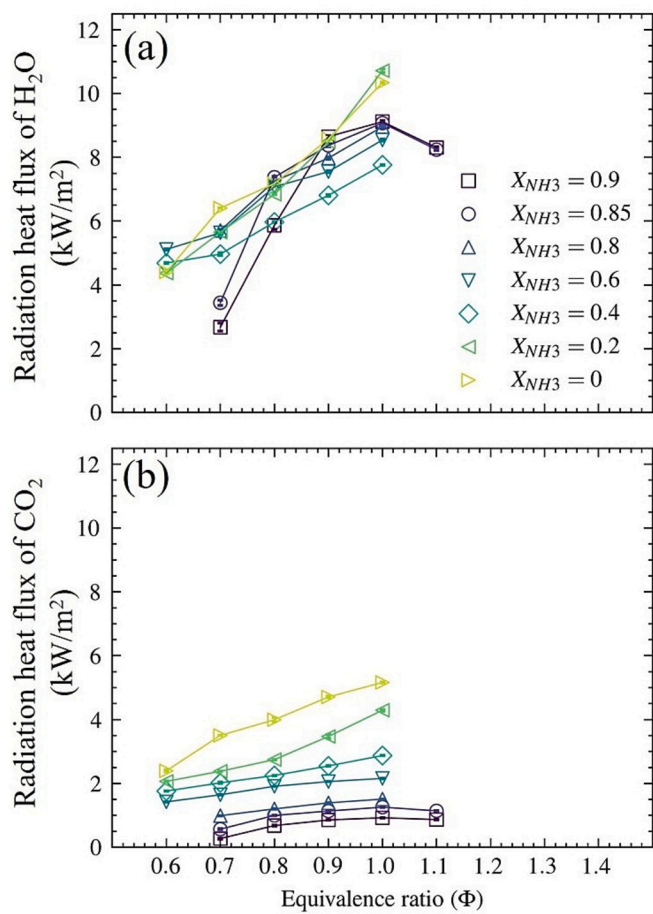


Fig. 9. Radiation heat flux of (a) H_2O and (b) CO_2 . Adapted with permission from Sato et al. [38].

concentrated in discrete molecular bands rather than broadband soot continuum emission [79–83].

Representative ammonia studies have combined infrared spectroscopy, gas-temperature and species measurements, LBL calculations, and Hottel-type analysis to interpret post-flame radiation and estimate species-specific contributions [11,23,38]. These approaches are useful because they connect measured spectral intensities with radiative-transfer calculations, but their accuracy depends on calibration, background subtraction, wall radiation correction, and spectroscopic data. Visible and infrared spectral measurements also help distinguish flame luminosity from thermal radiation. Hayakawa et al. [26] linked the orange appearance of NH_3/air flames mainly to NH_2 -related visible emission, whereas Xia et al. [15] showed that most ammonia-flame radiation is concentrated in the infrared region and mainly associated with H_2O .

Overall, spectral diagnostics are important for separating visible chemiluminescence from infrared thermal radiation and for validating non-grey radiation models of ammonia-based flames.

5.3. Indirect diagnostics of radiation-related quantities

Indirect diagnostics can complement direct heat-flux and spectral measurements when wall interference, limited optical access, or particle radiation makes direct interpretation difficult. These methods infer radiation-related quantities from measurable temperature, species concentration, spectral intensity, or boundary radiation information.

Sato et al. [38] combined exhaust-gas temperature, $\text{H}_2\text{O}/\text{CO}_2/\text{NH}_3$ concentrations, selected infrared intensities, LBL calculations, and a Hottel model to estimate wall radiative heat flux and separate H_2O and

CO_2 contributions in $\text{COG}-\text{NH}_3$ flames. This type of approach is valuable for confined combustors because it links measurable thermochemical quantities to radiative-transfer analysis.

Inverse-radiation methods have also been used in practical furnaces to infer internal thermal and radiative-property fields from boundary radiation information [84–87]. These studies show that, in practical furnaces, indirect methods can move beyond temperature alone and estimate radiation-relevant parameters such as the absorption coefficient (k_a), scattering coefficient (σ_s), and wall emissivity (ϵ_w). Although most of these studies are not ammonia-specific, they provide useful diagnostic strategies for future furnace-scale ammonia radiation measurements.

5.4. Measurement challenges, reliability, and comparability

Although several measurement approaches are available, ammonia flame-radiation diagnostics remain challenging because NH_3 flames are generally weak radiators under carbon-free conditions. Small errors in detector calibration, background subtraction, or wall-radiation correction can therefore lead to large relative errors in the net flame-radiation signal [15,23,38]. In confined chambers, the measured radiation may include direct flame radiation, wall emission, and wall-reflected radiation, and the result can be affected by wall temperature, wall emissivity, chamber geometry, detector field of view, and optical path length [19,41,71,88–90].

Spectral diagnostics can help separate the contributions of H_2O , CO_2 , residual NH_3 , NO , soot, and particles, but they are also affected by line-of-sight integration, window transmissivity, gas reabsorption, spectral overlap, and non-uniform temperature fields. These limitations are especially important in practical furnaces, swirling flames, staged combustion, and particle-laden systems, where a single radiometer position or spectral line of sight may not represent the total radiative heat transferred to the wall or heated material.

Visible flame appearance and chemiluminescence should also be distinguished from infrared thermal radiation. The yellow or orange appearance of ammonia flames is mainly related to NH_2 visible emission, and OH^* chemiluminescence may indicate reaction-zone structure; however, these signals should not be interpreted as direct evidence of thermal radiative heat-transfer capability [26,27]. Therefore, ammonia flame-radiation measurements are more reliable for comparing trends within the same experimental setup than for direct cross-study comparison. These key uncertainty sources and their effects on literature comparison are summarized in Table 4. Future studies should report measurement geometry, detector spectral response, calibration method, background-correction procedure, wall conditions, and uncertainty range to support database development and radiation-model validation.

6. Radiation modelling for Ammonia flames

Accurate radiation models are essential for predicting heat transfer, flame temperature, and combustion behaviour in ammonia-based fuel combustion. However, modelling radiation in ammonia flames remains challenging because most classical radiative property models were originally developed for hydrocarbon combustion, in which CO_2 and soot are the dominant radiating species. In ammonia combustion, by contrast, the absence of carbon-based emitters, the stronger dependence on selective molecular bands, and the limited availability of ammonia-relevant spectroscopic data all require a reassessment of model applicability. This section reviews the applicability of classical models, the current limitations of spectroscopic databases, and the role of optical thickness in ammonia flame radiation.

6.1. Applicability of classical models

Radiation modelling for ammonia flames requires careful reassessment of classical gas-radiation models. WSGG models are

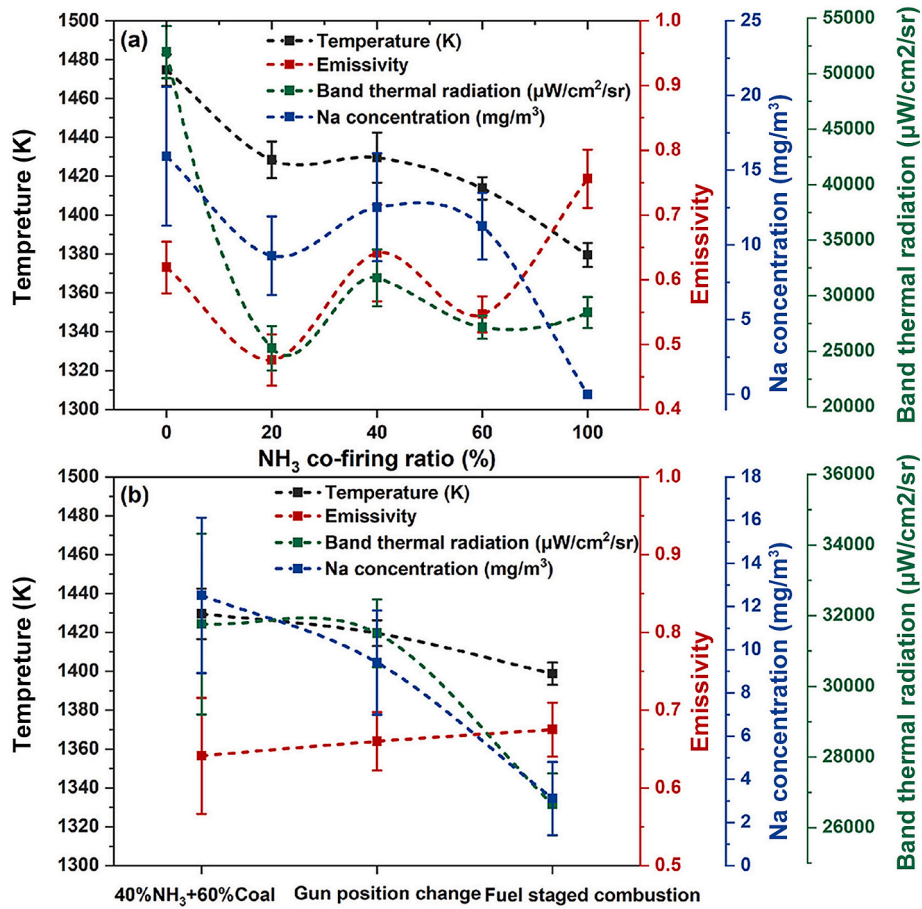


Fig. 10. Temperature (T), emissivity (ϵ), spectral radiative power (E), and gas-phase sodium concentration (C) obtained from spectral analysis. Adapted with permission from Pu et al. [17]. Copyright 2024 The Combustion Institute. Published by Elsevier Inc.

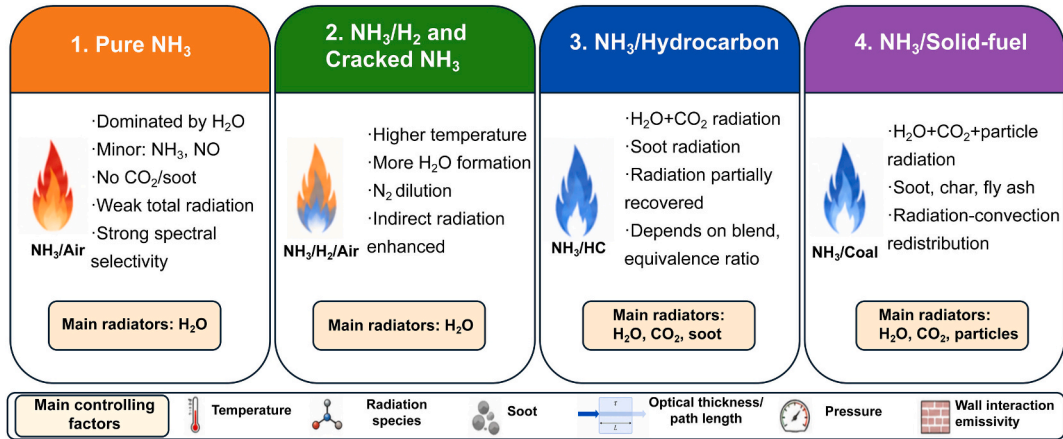


Fig. 11. Summary of dominant radiation mechanisms in ammonia-based combustion systems.

computationally efficient and widely used in CFD, but conventional formulations are mainly fitted for $\text{H}_2\text{O}/\text{CO}_2$ systems and may be less reliable for pure NH_3 , NH_3/H_2 , or NH_3 -rich flames where NH_3 , NO , and H_2O dominate the spectral behaviour [91–94].

SNB and FSCK models retain more spectral information and are therefore more suitable for strongly non-grey ammonia flames, but they require more reliable spectroscopic data and higher computational cost [66,95,96]. LBL calculations provide the most accurate benchmark for model validation, although they remain too expensive for routine multidimensional combustion CFD [40,97].

Table 5 shows that no single radiation model is universally applicable to all ammonia-combustion conditions. OTM/OTA may be acceptable for small atmospheric flames with weak reabsorption, whereas high-pressure, confined, humidified, hydrocarbon-blended, or furnace-scale flames require more detailed non-grey treatment. In this context, LBL is best used as a benchmark, while WSGG, SNB, and FSCK represent different compromises between spectral accuracy and computational cost [13,98,99].

Radiation is still neglected or treated using simplified grey-gas or optically thin assumptions in many numerical studies of NH_3 and $\text{NH}_3/$

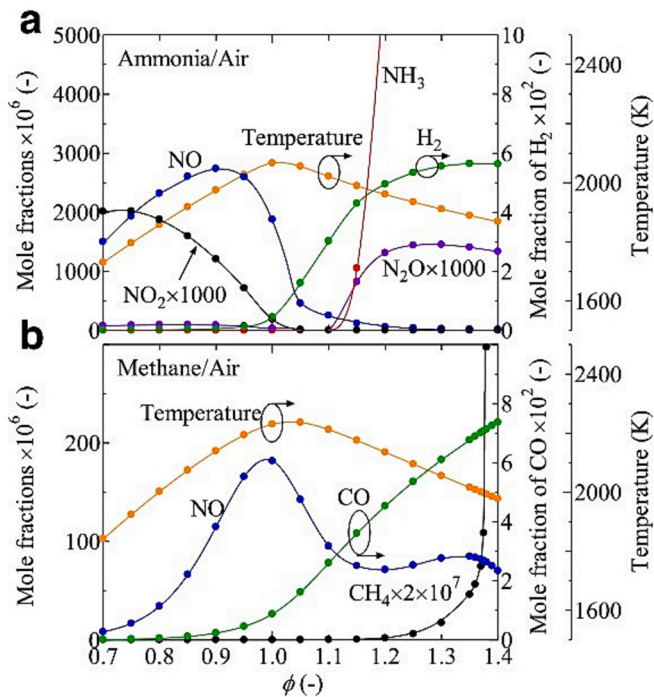


Fig. 12. Emission characteristics in terms of equivalence ratio at 0.1 MPa and 40 mm downstream of the position of maximum heat release rate: (a) NH_3/air ; (b) CH_4/air . Adapted with permission from Kobayashi et al. [33].

H_2 combustion. Such simplifications may be acceptable for small atmospheric-pressure laboratory flames, where the optical path length is short, soot is absent, and radiative heat loss is relatively weak compared with convective transport and chemical heat release [100,101]. However, their validity becomes less certain for confined combustors, elevated-pressure systems, humidified flames, hydrocarbon-blended ammonia flames, and furnace-scale applications, where optical thickness, wall radiation, and radiative reabsorption can become more important. Under these conditions, neglecting radiation may lead to overprediction of gas temperature because radiative heat loss from H_2O , CO_2 , NH_3 , NO , or particles is not included in the energy equation. It can also affect flame-to-wall radiation, wall re-radiation, local density and heat-release distributions, flame structure, and recirculation-zone behaviour, especially in confined or swirling flames. In addition, NO_x predictions may be affected because thermal NO formation, fuel- NO_x

pathways, and radical-pool chemistry involving O , H , and OH are strongly temperature-dependent. Therefore, radiation-combustion coupling should be considered carefully when ammonia-based flames are modelled under furnace-relevant or high-pressure conditions [13,25,38,102].

Recent high-fidelity simulations further show that simplified grey-gas or optically thin treatments may be insufficient for ammonia-containing flames when fuel absorption, pressure, confinement, or wall interaction becomes important.

As summarized in Table 6 and illustrated in Figs. 20 and 21, different treatments of spectral resolution and NH_3 fuel absorption can lead to different temperature fields, radiative source terms, and flame locations [103]. These results indicate that ammonia radiation modelling should consider not only non-grey effects, but also NH_3 absorption and the applicability range of each model.

Overall, no classical model can yet be considered universally reliable for radiation modelling in ammonia flames. WSGG is computationally efficient, but its assumptions, developed for hydrocarbon flames, clearly impose limitations; SNB offers superior spectral accuracy, while LBL remains the most reliable reference standard [104,105]. Therefore, for ammonia-flame radiation modelling, the key issue is not whether

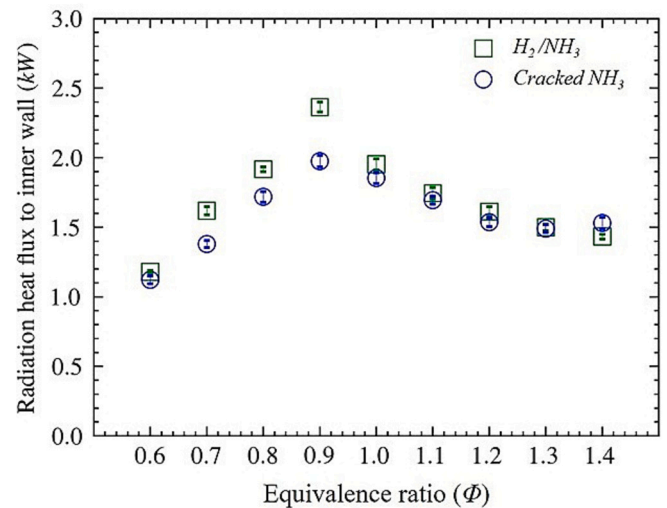


Fig. 14. Radiative heat flux to inner wall calculated by theoretical analysis method. Adapted with permission from Sato et al. [23].

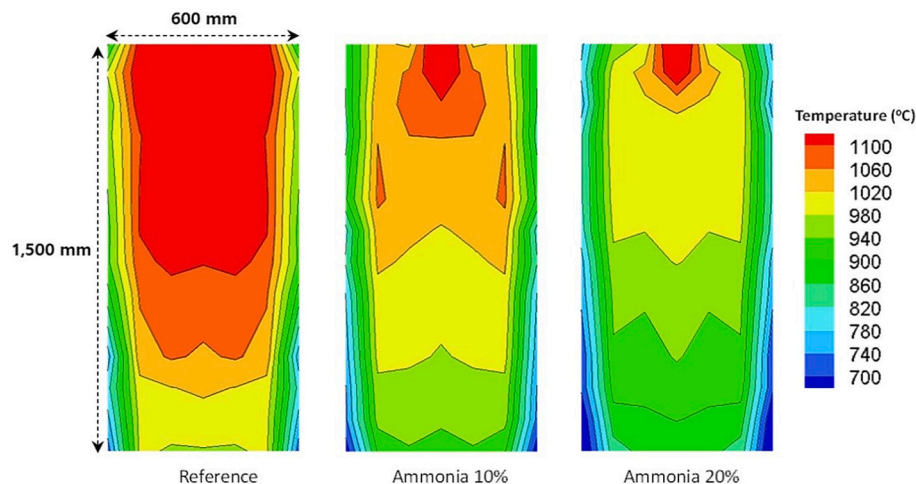


Fig. 13. Temperature distribution in the furnace for various ammonia co-firing ratios (N4). Adapted with permission from Chae et al. [16]. Copyright 2024 Elsevier Ltd.

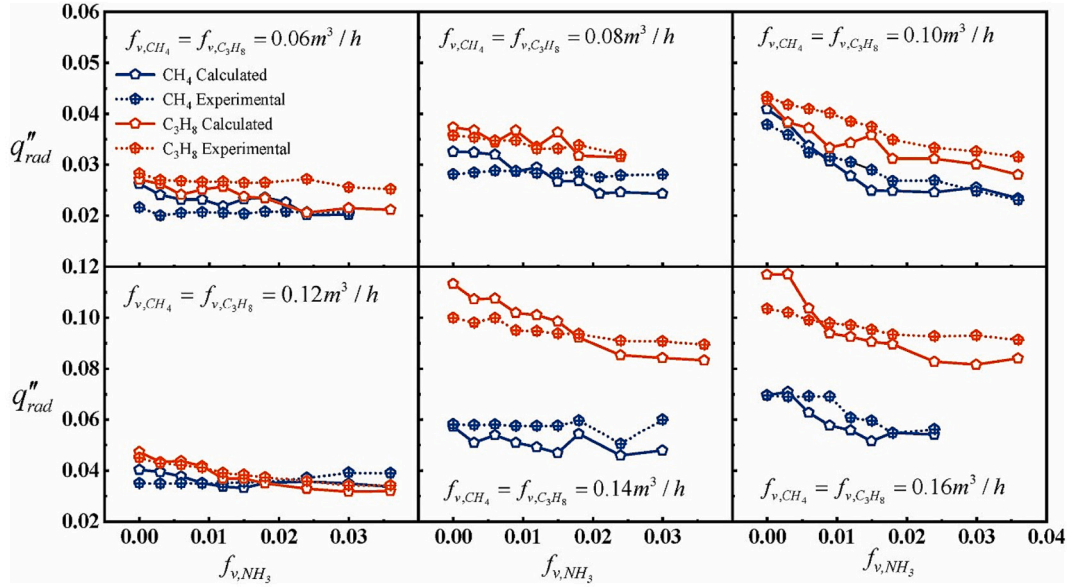


Fig. 15. The variations of radiative heat flux under different f_{v,CH_4} , f_{v,C_3H_8} and f_{v,NH_3} . Adapted with permission from Fang et al. [37]. Copyright 2024 Hydrogen Energy Publications LLC. Published by Elsevier Ltd.

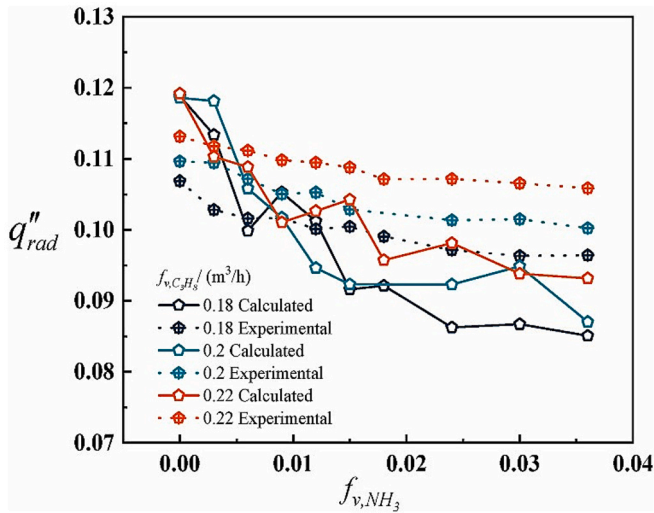


Fig. 16. The evolution of ϵ and F under different f_{v,C_3H_8} and f_{v,NH_3} . Adapted with permission from Fang et al. [37]. Copyright 2024 Hydrogen Energy Publications LLC. Published by Elsevier Ltd.

classical models can be used at all, but rather their range of applicability and error bounds under different ammonia-combustion conditions.

6.2. Spectral database gaps

Reliable radiation modelling depends on accurate high-temperature spectroscopic data. Databases such as HITRAN and HITEMP provide mature line data for major combustion species such as H_2O , CO_2 , and CO , and ExoMol has expanded high-temperature line lists for molecules including NH_3 [106–108]. However, ammonia-based combustion also involves NH_3 , NO , H_2O , CO_2 , and sometimes soot or particles, so model accuracy depends on whether these data are validated under high-temperature, high-pressure, and multicomponent flame conditions [23,38,94,109]. Uncertainties in NH_3 - or NO -related line parameters, pressure broadening, and overlapping bands can propagate into predicted emissivity, absorptivity, radiative source terms, and heat flux, especially when simplified WSGG or SNB models are fitted from these

databases.

6.3. Optical thickness issue

Optical thickness is the key criterion for assessing the validity of the optically thin approximation or optically thin model (OTA/OTM). OTA/OTM assumes that emitted radiation escapes from the flame without significant self-absorption or radiative reabsorption. Therefore, many atmospheric, laboratory-scale NH_3 and NH_3/H_2 flames may be approximated as optically thin because they have short optical paths, low soot loading, and radiation mainly from selective H_2O/NH_3 bands. However, this assumption cannot be generalized to all ammonia-based combustion systems. Elevated pressure, longer optical path length, confinement, humidification, hydrocarbon blending, and furnace-scale geometry can increase optical thickness and strengthen radiation–temperature–species coupling. Under these conditions, the use of OTA/OTM should be justified rather than assumed.

Recent studies confirm that optical-thickness effects in ammonia-containing flames depend strongly on pressure, equivalence ratio, fuel composition, and flame configuration. For planar NH_3/H_2 /air flames, radiative reabsorption can increase laminar burning velocity, and its influence becomes more controlled by optical thickness as pressure increases [66]. Increasing the H_2 fraction can reduce NH_3 concentration and optical thickness, thereby weakening upstream radiative reabsorption [67]. In NH_3/CH_4 /air flames, optical thickness changes nonlinearly with equivalence ratio and affects the balance between direct radiation loss and radiative preheating [110]. Spherical-flame studies also show that radiation-induced uncertainty can be significant under lean or rich NH_3 /air conditions, although OTM may still be acceptable for some low-pressure, small-scale flames [111].

Overall, the key modelling consideration is not simply whether ammonia flames can be regarded as optically thin, but rather the range of conditions under which the optically thin assumption remains valid. For small-scale laboratory flames at atmospheric pressure, optically thin models may provide a reasonable first-order approximation. However, in practical combustors and furnace environments, where operating pressures are higher, optical path lengths are longer, and post-flame gases remain at elevated temperatures, the optical thickness may increase substantially, making radiative reabsorption increasingly important. Therefore, careful assessment of optical thickness is essential

Table 3

Comparison of reported radiative heat fluxes and radiation trends in ammonia-based combustion.

Fuel system	Operating conditions	Configuration	Reported radiation trend	Main interpretation
Pure NH ₃	NH ₃ /air or NH ₃ /O ₂ /N ₂ ; atmospheric pressure	Flame/emission measurements and spectral analysis	Radiative heat flux is generally lower than that of hydrocarbon flames. Radiation is mainly associated with H ₂ O, with minor contributions from NH ₃ , NO, and nitrogen-containing species.	The absence of CO ₂ and soot establishes pure NH ₃ as a low-radiation baseline.
NH ₃ /H ₂ blends	NH ₃ /H ₂ /air; different H ₂ fractions and equivalence ratios	Premixed flame studies and radiative heat-flux analysis	H ₂ addition improves flame temperature and combustion intensity, but the radiative heat flux remains lower than that of CH ₄ flames.	H ₂ is not a strong infrared radiator; its effect on radiation is mainly indirect through temperature increase and H ₂ O formation.
Cracked NH ₃	Cracked NH ₃ containing NH ₃ /H ₂ /N ₂ ; varying equivalence ratio	Premixed swirling flames; theoretical radiative heat-flux analysis	Radiation intensity is close to, or slightly lower than, that of corresponding NH ₃ /H ₂ flames, especially under lean conditions.	N ₂ dilution in cracked NH ₃ can reduce gas temperature and weaken radiative heat flux.
NH ₃ /CH ₄ blends	Increasing NH ₃ fraction in NH ₃ /CH ₄ flames	Jet flames, swirl flames, and furnace simulations	Radiative heat flux and furnace temperature generally decrease as NH ₃ fraction increases.	Replacing CH ₄ with NH ₃ reduces CO ₂ formation and suppresses soot-related radiation.
NH ₃ /C ₂ H ₄ blends	Increasing NH ₃ fraction in NH ₃ /C ₂ H ₄ flames	Jet flames; radiation fraction and soot analysis	Radiation fraction decreases with increasing NH ₃ addition.	NH ₃ suppresses soot formation, reducing broadband continuum radiation from hydrocarbon flames.
NH ₃ /C ₃ H ₈ blends	Increasing NH ₃ fraction in NH ₃ /C ₃ H ₈ flames	Jet flames; radiative heat flux, emissivity, and view-factor analysis	Radiative heat flux, emissivity, and view factor decrease as NH ₃ fraction increases. C ₃ H ₈ -containing flames show stronger radiation.	Propane provides stronger carbon-based radiation recovery than methane, but NH ₃ addition still weakens the overall radiative output.

Table 3 (continued)

Fuel system	Operating conditions	Configuration	Reported radiation trend	Main interpretation
COG–NH ₃ blends	$0 \leq X_{\text{NH}_3} \leq 0.9$; $0.6 \leq \Phi \leq 1.4$	Premixed swirling flames; infrared measurement with LBL and Hottel-model analysis	H ₂ O radiation can remain significant or increase with NH ₃ fraction, while CO ₂ radiation decreases as NH ₃ fraction increases. Overall blend-to-blend radiation differences are strongly influenced by CO ₂ .	H ₂ O is often the dominant radiator, but CO ₂ controls much of the radiation difference in carbon-containing NH ₃ blends.
NH ₃ /coal co-firing	Increasing NH ₃ co-firing ratio	80 kW _{th} pulverized-coal furnace	Furnace temperature and wall heat flux decrease with increasing NH ₃ co-firing ratio.	NH ₃ co-firing reduces flame temperature and weakens particle and gas radiation.
NH ₃ /coal co-firing	Up to high NH ₃ co-firing ratios	4 MW pilot boiler; spectral analysis	Particle radiation decreases significantly as NH ₃ co-firing ratio increases.	Reduction in char, ash, fly-ash, and particle radiation is a key mechanism behind weakened furnace radiation.
NH ₃ /coal utility boiler	Large-scale boiler operation	300 MW coal-fired boiler analysis	Boiler heat transfer shifts from radiation-dominated behaviour toward stronger convective contribution. Directly comparable radiative heat-flux data remain sparse.	Furnace-scale heat-transfer redistribution becomes important when NH ₃ reduces radiative intensity.
Elevated-pressure NH ₃ -based flames	Elevated pressure; limited available data	Experimental and numerical studies	Higher pressure is expected to increase gas density, optical thickness, and radiative reabsorption.	Pressure effects are a major knowledge gap for validating radiation models under practical combustor and furnace conditions.

for selecting an appropriate radiation model for ammonia combustion systems.

7. Key challenges and knowledge gaps

Although research on ammonia flame radiation has increased in recent years, a systematic framework for engineering design and model validation is still lacking. The remaining challenges can be grouped into four main areas: experimental databases, model applicability, spectroscopic data, and radiation–combustion coupling.

At present, the number of experimental studies on ammonia flame radiation is still limited, especially under high-pressure conditions, furnace-scale systems, and conditions close to real applications, where

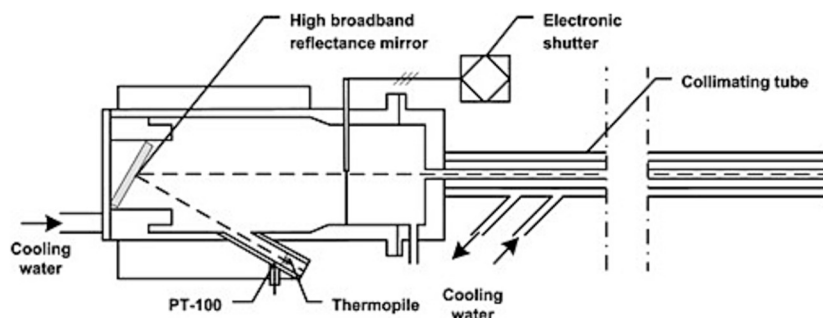


Fig. 17. The narrow angle probe. Adapted with permission from Andersson et al. [72]. Copyright 2008 Elsevier Inc.

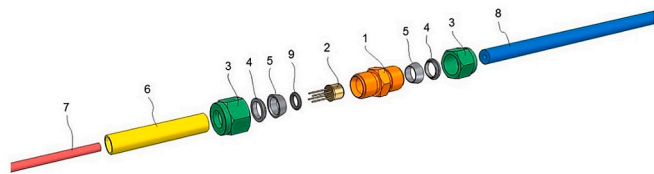


Fig. 18. Radiometer assembly. 1 – Compression fitting body; 2 – Thermopile; 3 – Compression fitting nut; 4 – Compression fitting rear ferrule; 5 – Compression fitting front ferrule; 6 – Standard 3/8" tubing; 7 – Cable; 8 – View tube; 9 – O-ring. Adapted with permission from Zsolt Dobó [71]. 2018 Elsevier Ltd.

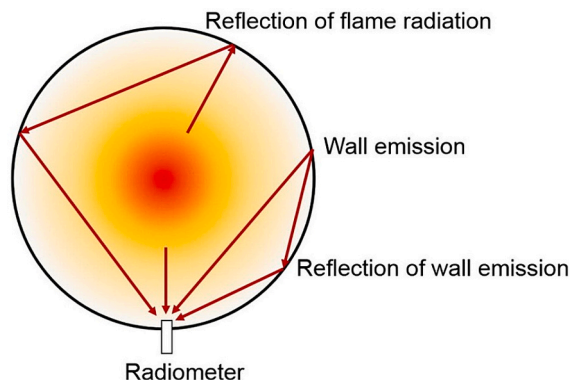


Fig. 19. Illustration of the influence of walls on total incident radiation received by a radiometer. Flame is depicted by red zone. Adapted with permission from Yang et al. [19]. Copyright 2017 Elsevier Ltd. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

systematic data remain insufficient. Some studies have examined radiative properties of ammonia flames by measuring total radiative heat flux, infrared spectra, and radiating species, but the data are still mostly from a small number of burners or lab furnaces. A full database that covers different pressures, equivalence ratios, blending ratios, and flame types has not been built yet. The current experimental database remains insufficient to fully support a complete understanding of ammonia flame radiation and the full validation of engineering models.

Most simple radiation models now in use were first developed for hydrocarbon combustion, and their basic assumptions depend on carbon-based radiating species such as H_2O , CO_2 , and soot. But in ammonia flames, the lack of CO_2 and the very small or zero soot formation limit the use of these models. Some recent studies have tried to develop WSGG models for $\text{H}_2\text{O}/\text{NH}_3$ systems and tested them with LBL methods, but the overall radiation modelling system for ammonia flames is still at an early stage and not as mature as for hydrocarbon combustion. The main issue now is not only whether models exist, but whether they can be used reliably under different ammonia combustion

Table 4

Key measurement uncertainties affecting ammonia flame radiation studies.

Measurement issue	Main influence	Why it is important for NH_3 flames	Effect on literature comparison
Wall emission	Adds background radiation	NH_3 flame radiation is weak	May overestimate flame radiation
Wall reflection	Reflects flame and wall radiation into detector	More serious in confined chambers	Depends on wall material and geometry
Background subtraction	Determines net flame signal	Small errors become significant for weak signals	Reduces comparability
Optical-access limitation	Restricts line-of-sight measurement	Furnace flames are spatially non-uniform	Local data may not represent total radiation
Detector wavelength range	Captures different spectral bands	H_2O , CO_2 , NH_3 radiate at different wavelengths	Broadband and spectral data differ
Chemiluminescence interference	Visible emission may be confused with radiation	NH_2 gives yellow/orange appearance	Visible luminosity is not equal to IR heat flux

Table 5

Applicability and limitations of radiation models for ammonia-based combustion.

Model	Main feature	Suitable conditions	Limitations for NH_3 -based flames
OTM / OTA	assumes optically thin medium	small-scale atmospheric flames	neglects reabsorption
WSGG	grey-gas weighted model	CFD furnace simulations	coefficients mainly for $\text{H}_2\text{O}/\text{CO}_2$, less reliable for NH_3/NO
SNB	spectral band model	detailed gas radiation	needs spectral data
FSCK	non-grey model	accurate furnace-scale CFD	computationally more complex
LBL	highest spectral accuracy	benchmark / validation	too expensive for full CFD

conditions.

Another important limit in ammonia flame radiation modelling comes from the spectroscopic databases. Databases such as HITRAN, HITEMP, and ExoMol give detailed line-by-line data for molecules like H_2O , CO_2 , and NH_3 , but the issue is not only if data exist, but if they are well tested and can be used directly for high-temperature radiation calculations. For species related to ammonia combustion, such as NH_2 and NO , there are still uncertainties in high-temperature line data, pressure broadening, and overlapping bands in mixtures. Even when

Table 6

Radiation treatments for non-grey effects in ammonia combustion. Adapted with permission from Di et al. [103]. Copyright 2026 The Combustion Institute. Published by Elsevier Inc.

Treatment	Fuel radiation	Spectral resolution
FSCK - Wfuel	Considered	FSCK
FSCK - Ofuel	Neglected	FSCK
Grey - Wfuel	Considered	Plank - Mean
Grey - Ofuel	Neglected	Plank - Mean

LBL methods are used, errors in these data can affect predicted emissivity, absorptivity, and radiative heat flux. For simpler models such as WSGG and SNB, this effect can be stronger, because their parameters still depend on accurate spectroscopic data.

At present, the understanding of ammonia flame radiation is still mainly about radiation intensity and species composition, and the deeper link between radiation and combustion behaviour remains insufficiently understood. Some studies show that radiation and reabsorption can affect flame temperature, radiative heat flux, flame speed, radical distribution, and NO formation. But how this

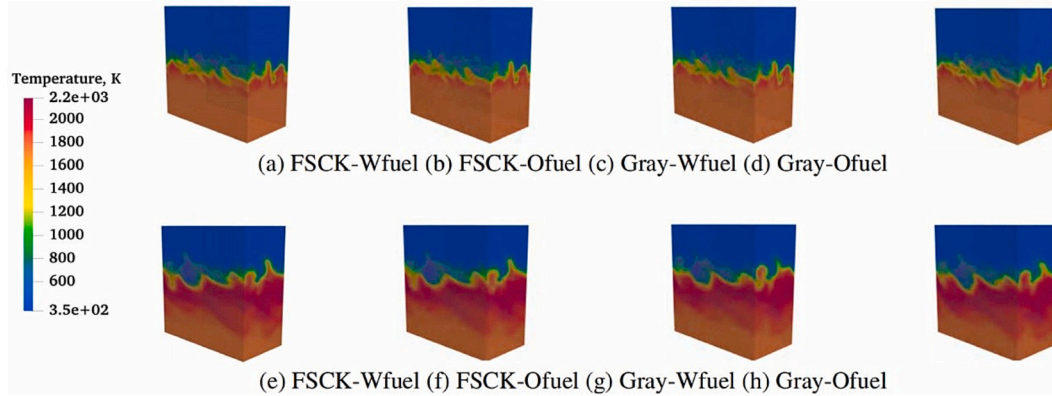


Fig. 20. Three-dimensional instantaneous temperature fields predicted by the four radiation models at $t = 3$ ms (Top Row) and $t = 7$ ms (Bottom Row). Adapted with permission from Di et al. [103]. Copyright 2026 The Combustion Institute. Published by Elsevier Inc.

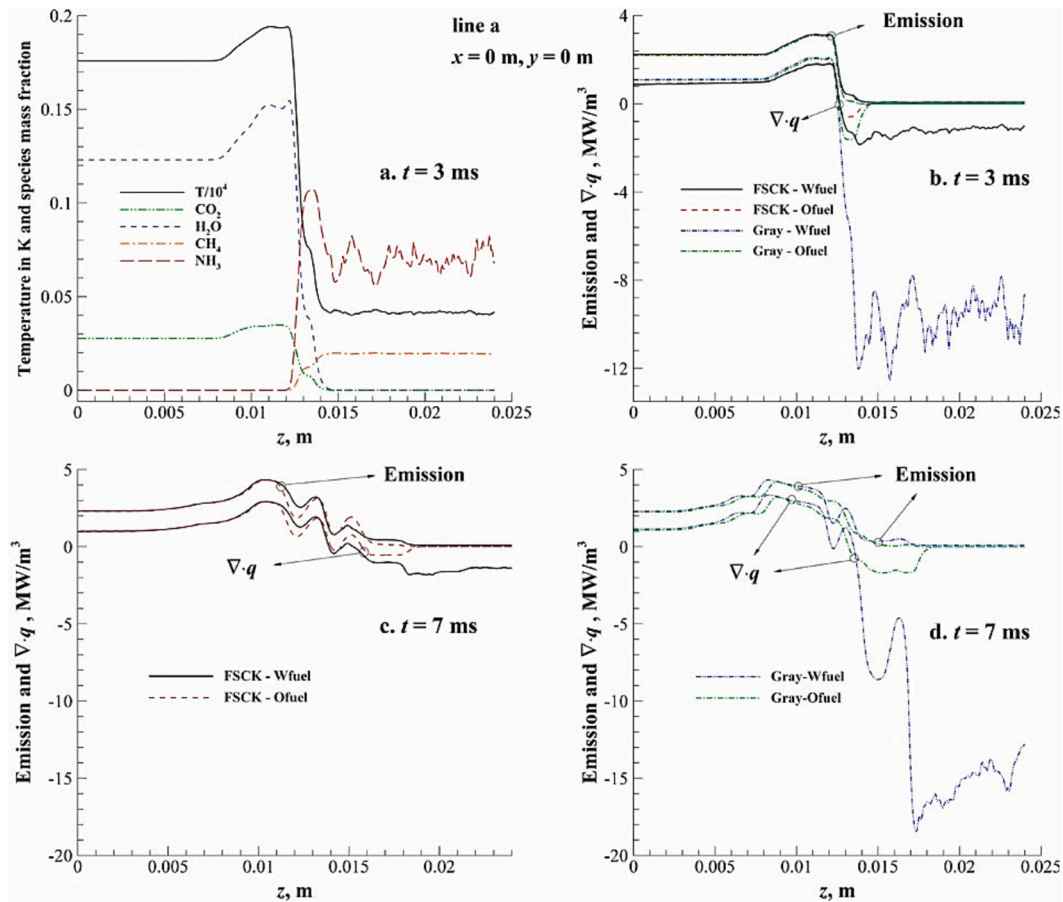


Fig. 21. Distribution of the radiation source term (S_{rad}) along line at $t = 3$ ms and $t = 7$ ms for the four models. Adapted with permission from Di et al. [103]. Copyright 2026 The Combustion Institute. Published by Elsevier Inc.

radiation–combustion link changes with pressure, equivalence ratio, blending, and flame type is still not clear. In real combustors and furnaces, the interaction between radiation, flow, chemistry, and wall heat transfer becomes more complex, and this is still a major open problem in ammonia combustion radiation research.

8. Engineering implications for furnace applications

The weak radiative characteristics of ammonia flames have important implications for furnace applications, because industrial furnaces are typically high-temperature thermal systems in which radiative heat transfer is dominant [112]. Compared with hydrocarbon flames, ammonia flames generally provide lower flame-to-wall radiative heat flux because they lack strong carbon-based radiators such as CO_2 and soot [68]. Therefore, ammonia-fired furnaces may require either flame-side radiation enhancement or furnace-side heat-transfer adaptation. These two pathways are discussed below.

8.1. Enhancing the radiative output of ammonia flames

The first pathway is to increase the radiative output of ammonia-based flames themselves. Pure ammonia combustion lacks strong carbon-based radiators such as CO_2 and soot, and its radiation is mainly governed by H_2O , with smaller contributions from residual NH_3 , NO , and other nitrogen-containing species. As a result, the radiative heat transferred from the flame to the wall is generally lower than that in conventional hydrocarbon flames. Under the same heat input, ammonia-fuelled industrial furnaces may therefore experience reduced wall-heating capability, altered temperature distributions, and decreased thermal loading on heating surfaces. For industrial processes that rely on high radiative heat flux for rapid heating, such changes may affect thermal efficiency, heating rate, and temperature uniformity.

Sato et al. [23] compared the inner-wall radiative heat flux of CH_4 , NH_3 , NH_3/H_2 , and cracked NH_3 flames at $\Phi = 1.0$ and 15 kW, and also reported the corresponding equilibrium flame temperatures calculated using the Okafor et al. mechanism [113], as shown in Fig. 22. Their results showed that CH_4 produced approximately 25% higher radiative heat flux than the ammonia-based fuels, while the differences among NH_3 , NH_3/H_2 , and cracked NH_3 were small and within the methodological uncertainty. This indicates that both pure ammonia and ammonia-derived blends may require compensation when retrofitting methane-fuelled furnaces.

Several flame-side strategies may be used to enhance ammonia-flame radiation. Hydrogen addition and partial cracking can improve flame

stability, burning velocity, radical production, flame temperature, and H_2O formation, but their radiation enhancement is mainly indirect because H_2 is not a strong infrared radiator. Hydrocarbon or COG blending provides a more direct route by introducing CO_2 and possible soot or carbonaceous continuum radiation, although this reduces the carbon-free fraction of the fuel and may affect CO_2 emissions, NO_x formation, and decarbonization benefits. Solid-fuel co-combustion can also enhance furnace radiation through char, ash, fly ash, or soot radiation, but increasing the ammonia co-firing ratio may reduce particle loading and flame temperature. Other strategies, including oxygen enrichment, fuel or oxidizer preheating, staged combustion, and humidification, can modify radiative behaviour but involve trade-offs among radiating-species concentration, flame temperature, stability, and emissions.

8.2. Adapting furnace and process design to weaker ammonia flame radiation

When a high carbon-free fuel fraction is required and hydrocarbon blending is undesirable, furnace-side adaptation becomes essential. In this pathway, the objective is not only to increase flame radiation, but also to redistribute and utilize the available heat more effectively within the furnace and downstream heat-transfer sections. Because ammonia flames may shift the relative importance of flame-zone radiation, post-flame gas radiation, wall re-radiation, and convective heat transfer, furnace heat-transfer zoning, residence time, and heating-surface arrangement may need to be reassessed [114,115].

Burner arrangement and flame-wall interaction are also important because radiative heat flux depends on flame temperature, radiating-species distribution, optical path length, view factor, and wall temperature. Burner designs that extend the high-temperature region, improve flame stabilization, or distribute heat release more uniformly may help compensate for weaker local flame radiation. At the furnace level, high-emissivity refractory materials, optimized wall-temperature control, and repositioned heat-transfer surfaces can improve the use of available radiative energy [116–119]. For boiler or furnace retrofits, downstream heat-transfer surfaces may also require reassessment because high ammonia co-firing ratios can alter heat-transfer distribution and reduce boiler efficiency [120]. Therefore, the engineering value of ammonia flame-radiation research lies not only in identifying weak flame radiation, but also in supporting burner design, furnace retrofit, heat-transfer optimization, and emissions control for future ammonia-fuelled thermal systems.

9. Conclusions and future perspectives

Research on ammonia flame radiation is still largely at the stage of fundamental investigation. Although preliminary studies have explored the radiative characteristics of ammonia flames, their governing factors, measurement techniques, and modelling frameworks, many unresolved issues remain when moving toward practical applications in real combustors and industrial furnaces. Based on the literature reviewed in this work, the current understanding and future research needs can be summarized from four aspects: radiation mechanisms, engineering applications, experimental diagnostics, and radiation modelling.

9.1. Main conclusions

First, pure ammonia flames provide a low-radiation baseline for ammonia-based combustion. Because NH_3 contains no carbon, pure NH_3 flames do not produce CO_2 or soot under ideal combustion conditions. Their radiation is therefore mainly governed by H_2O , with possible minor contributions from residual NH_3 , NO , and other nitrogen-containing species, leading to weaker radiative heat flux and stronger non-grey spectral selectivity than hydrocarbon flames.

Second, hydrogen addition improves combustion intensity but only indirectly enhances radiation. In NH_3/H_2 and cracked-ammonia flames,

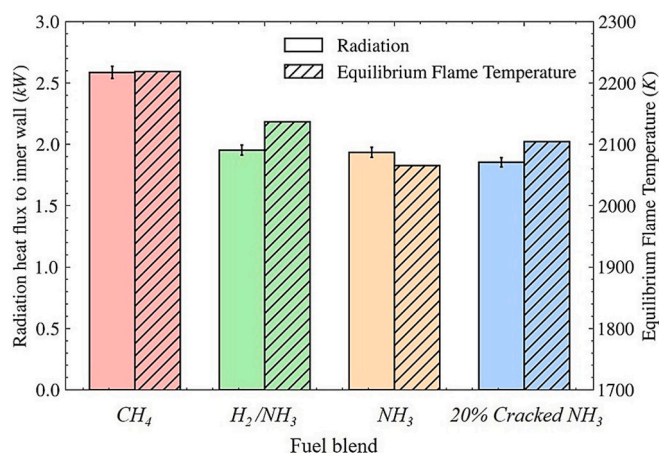


Fig. 22. Radiation heat flux to the inner wall obtained by internal radiation theoretical analysis and calculated equilibrium flame temperature of the four blends at LHV = 15 kW and $\Phi = 1.0$. Adapted with permission from Sato et al. [23].

H₂ can increase burning velocity, flame temperature, radical production, and H₂O formation. However, because H₂ is not a strong infrared radiator and cracked ammonia introduces N₂ dilution, the radiative enhancement remains limited compared with hydrocarbon combustion.

Third, hydrocarbon or COG blending can partially recover the radiative output of ammonia-based flames by introducing carbon-containing radiators. CO₂ radiation and, under some conditions, soot-related continuum radiation can increase flame emissivity and radiative heat flux. However, this route introduces a trade-off between radiation recovery, CO₂ emissions, NO_x formation, and maintaining a high carbon-free fuel fraction.

Fourth, ammonia co-combustion with solid fuels involves coupled gas–particle radiation. Char, ash, fly ash, soot, and particles can contribute strongly to total radiation, but increasing the NH₃ co-firing ratio may reduce flame temperature, particle loading, and particle radiation intensity. Therefore, ammonia/solid-fuel co-combustion should be evaluated at the furnace scale rather than only from flame-scale radiation.

Fifth, measurement reliability and cross-study comparability remain major limitations. Reported radiative heat flux and spectral radiation can be affected by burner geometry, pressure, equivalence ratio, fuel composition, detector field of view, spectral range, optical access, wall temperature, background subtraction, and wall re-radiation. These effects are particularly important for ammonia flames because their weak intrinsic radiation makes the measured signal more sensitive to wall and background contributions.

Finally, radiation modelling for ammonia flames remains less mature than for hydrocarbon flames. OTM/OTA may be acceptable for some small atmospheric flames, but confined, high-pressure, humidified, hydrocarbon-blended, or furnace-scale systems require careful assessment of optical thickness, radiative reabsorption, non-grey effects, and NH₃/NO absorption. WSGG, SNB, FSCK, and LBL approaches therefore need clearly defined applicability ranges and error bounds for ammonia-relevant conditions.

9.2. Engineering perspectives

From an engineering perspective, future research should move beyond identifying weak ammonia-flame radiation and focus on how to compensate for insufficient radiative heat transfer in practical thermal systems. Because ammonia flames generally lack strong carbon-based radiators such as CO₂ and soot, ammonia-fired furnaces may require both flame-side radiation enhancement and furnace-side heat-transfer adaptation.

For flame-side enhancement, possible strategies include hydrogen addition, cracked-ammonia combustion, hydrocarbon or COG blending, oxygen enrichment, fuel or oxidizer preheating, humidification, and ammonia/solid-fuel co-combustion. These approaches can modify flame temperature, H₂O concentration, CO₂ concentration, soot formation, or particle radiation. However, they must be evaluated together with flame stability, NO_x emissions, NH₃ slip, carbon-free fuel fraction, and overall furnace efficiency.

For furnace-side adaptation, future work should consider burner configuration, flame-wall distance, residence time, heat-transfer surface arrangement, wall emissivity, and the redistribution of radiative and convective heat transfer. In ammonia-fired or ammonia-co-fired furnaces, it may be necessary to extend the high-temperature region, improve post-flame gas radiation utilization, adjust heating-surface positions, or increase downstream convective heat exchange. Therefore, the central engineering goal should be radiation compensation and overall thermal optimization through combustion organization and furnace design.

9.3. Experimental directions

Future experimental studies should broaden the operating conditions

investigated for ammonia flame radiation. More systematic data are needed for elevated pressure, confined geometry, furnace-scale systems, staged combustion, and application-relevant burner configurations, because most existing measurements remain concentrated under atmospheric laboratory conditions. Pressure effects on radiative intensity, optical thickness, spectral absorption, and radiative reabsorption should therefore be clarified for pure NH₃, NH₃/H₂, cracked NH₃, NH₃/hydrocarbon, and ammonia/solid-fuel systems.

Wet or humidified ammonia combustion also deserves particular attention. H₂O can appear as a combustion product, diluent, cracking-related species, or recirculated-gas component [121,122]. Because H₂O is a major stable radiator in ammonia flames, humidification may increase molecular radiation and post-flame gas radiation. However, it can also reduce flame temperature, so future experiments should distinguish the competing effects of increased H₂O concentration and reduced thermal intensity.

Future measurements should combine total radiative heat flux, spectral radiation, temperature fields, gas composition, species distributions, flame structure, wall temperature, and wall heat flux. Measurement protocols should report burner configuration, detector field of view, wavelength range, calibration method, optical access, wall emissivity, wall temperature, background correction, and uncertainty. Such standardization is essential for comparing results across different fuel blends, pressures, equivalence ratios, and furnace configurations.

Further experiments may also extend to particle-laden and intensified combustion systems, including ammonia/coal or ammonia/biomass co-combustion, metal-particle-assisted combustion, and plasma-assisted ammonia combustion [123–127]. These systems may introduce additional particle radiation, alter flame luminosity, modify radical distributions, or change heat-release structure. However, visible luminosity and chemiluminescence should still be distinguished from infrared thermal radiation when evaluating furnace heat-transfer performance.

9.4. Modelling directions

From a modelling perspective, future work should develop and validate NH₃-specific radiation models over wider ranges of pressure, equivalence ratio, fuel composition, humidification level, and optical path length. Although WSGG-type models for H₂O/NH₃ systems have begun to appear, their applicability under multicomponent ammonia-combustion conditions remains insufficiently validated.

Because ammonia flames exhibit strong spectral selectivity and non-grey behaviour, greater effort should be devoted to SNB, FSCK, and LBL-based approaches. These models can better represent wavelength-dependent radiation from H₂O, NH₃, NO, CO₂, soot, and particles, but they require more complete spectroscopic data and higher computational cost. Future studies should therefore clarify the applicability range, error sources, and accuracy–cost trade-offs of different radiation models.

Radiation–combustion coupling is another important modelling need. Radiation affects not only heat flux, but also gas temperature, flame structure, radical distributions, residence time, wall heat transfer, and NO_x formation. While radiation neglect or OTA/OTM treatment may be acceptable for some small optically thin flames, coupled flow–chemistry–radiation–wall heat-transfer modelling may be required for confined, high-pressure, humidified, hydrocarbon-blended, or furnace-scale systems.

Further progress also depends on high-temperature spectroscopic databases. Data for NH₃, NO, H₂O, CO₂, soot, and particles should be linked with LBL benchmark calculations and engineering-oriented WSGG, SNB, FSCK, or OTA/OTM models. Overall, future model development should proceed through an integrated chain of high-temperature databases, high-fidelity spectral modelling, simplified engineering models, and experimental validation.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used ChatGPT to assist with language polishing, text condensation, readability improvement, and organization of the response to reviewers. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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