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# Pollutant Emissions Reporting and Performance Considerations for Ammonia-Blended Fuels in Gas Turbines

*To limit climate change and promote energy security, there is widespread interest toward transitioning existing fossil fueled combustion systems to sustainable, alternative fuels such as hydrogen ( $H_2$ ) and ammonia ( $NH_3$ ) without negatively impacting air quality. However, quantifying the emission rate of air pollutants such as nitrogen oxides ( $NO_x$ ) is a nuanced process when comparing pollutant emissions across different fuels, as discussed in our paper GT2022-80971 presented last year. That study indicated that the standardized approach for measuring combustion emissions in terms of dry, oxygen-referenced volumetric concentrations (i.e., dry ppmv at the reference  $O_2$  concentration (ppmvd)) inflates reported pollutant emissions by up to 40% for hydrogen combustion relative to natural gas. In this paper, we extend our prior analysis of these so-called “indirect effects” on emissions values to ammonia ( $NH_3$ ) and cracked ammonia (i.e., molecular hydrogen and nitrogen,  $3H_2$  per  $N_2$ ) fuel blends. The results reveal that ppmvd-based pollutant reporting approaches have a less prominent influence on emissions interpretations for molecular ammonia–methane blends than for hydrogen–methane blends. Nonetheless, we still find that ppmvd reporting induces up to a 10% relative increase in apparent emissions when comparing 100%  $NH_3$  and 100% methane ( $CH_4$ ) fuels at an equal mass-per-work emission rate. Cracking the ammonia is shown to increase this relative bias up to 21% in comparison to a methane system. Further analysis shows how drying, dilution, thermodynamic, and performance effects each influence the relationship between ppmvd and mass-per-work emissions across the spectrum of fuels and fuel blends. Following discussion of these findings, we conclude that quantifying combustion emissions using ppmvd is generally inappropriate for emissions comparisons and advise the combustion community to shift toward robust mass-per-energy metrics when quantifying pollutant emissions. [DOI: 10.1115/1.4063417]*

## 1 Introduction

Today, despite serious climate change and energy security concerns, fossil fuel combustion represents the world's dominant mode of the primary energy conversion, as well as its greatest source of greenhouse gas (GHG) emissions [1]. Lower-cost renewable energy sources, such as solar and wind, remain fundamentally intermittent and often depend upon supplemental gas turbines to dispatch fossil-based power when renewable energy availability is low. This intermittency issue has led to significant momentum in policy and industry circles to replace fossil fuels with alternative carrier fuels like hydrogen ( $H_2$ ) and ammonia ( $NH_3$ ). Such fuels can

be synthesized sustainably with excess renewable power, have high energy densities suitable for efficient transport and storage, and are suitable for on-demand use in gas turbines without contributing to carbon dioxide ( $CO_2$ ) or methane ( $CH_4$ ) emissions. Nonetheless, several important issues besides GHG emissions also arise in the context of a large-scale switch to “green” alternative fuels.

Among these, the main emphasis of this study is toward quantifying the potential air quality impacts associated with burning alternative fuels. In general, combustion releases a smattering of pollutants that are harmful for environmental and public health, and a variety of ordinances spanning international to local codes exist to limit such emissions. (For example, the US EPA's CFR Part 60 Subpart KKKK and European Council's Directive 2010/75/EU set emissions limits for stationary gas turbine operators [2,3].) Compared to fossil fuels, burning alternative fuels, such as  $H_2$  and  $NH_3$ , release a smaller range of pollutants since these fuels do not contain the carbon

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Manuscript received August 2, 2023; final manuscript received September 2, 2023; published online October 17, 2023. Editor: Jerzy T. Sawicki.

atoms or impurities necessary to produce, for example, carbon monoxide (CO), particulate matter (PM<sub>x</sub>), and sulfur oxides (SO<sub>x</sub>). The possibility of eliminating such pollutants from combustion exhaust streams is a major draw for alternative fuels.

Nonetheless, not all pollutants are derived from fuel-borne carbon or impurities. Any air-breathing combustion system—even one burning an alternative fuel—produces nitrogen oxides (NO<sub>x</sub>) due to spontaneous reactions of atmospheric nitrogen (N<sub>2</sub>) and oxygen (O<sub>2</sub>) that occur at high temperatures. Additionally, in the case of NH<sub>3</sub>, fuel-bound nitrogen atoms are also partially converted to NO<sub>x</sub> during combustion. Since NO<sub>x</sub> is a poisonous and reactive gas that detrimentally affects human respiratory health and contributes to acid rain, there is widespread interest in quantifying the NO<sub>x</sub> emissions from alternative fuels and comparing them to those of conventional fuels.

Even so, formulating a consistent and practicable framework for comparing NO<sub>x</sub> and other combustion emissions from a fleet of distinct systems burning a variety of different fuels is not trivial. In general, combustion emissions assessments are ultimately concerned with the pollutant mass emitted per unit of delivered energy (e.g., ng NO<sub>x</sub>/J), which is equivalent to the mass emission rate per unit of delivered power. However, quantifying combustion emissions on a mass-per-energy basis involves separate measurements of the exhaust gas composition, the exhaust flowrate, and the delivered power—a triad that is not always feasible to obtain in an operational system.

To circumvent this difficulty, the combustion community adopted a surrogate volumetric emissions reporting approach in the 1970s that is based only on gas analyzer measurements of the exhaust composition. In this now-standard framework, combustion emissions are quantified in terms of a pollutant's adjusted concentration after first drying the exhaust gas sample (i.e., removing all H<sub>2</sub>O) and subsequently diluting (or concentrating) the dry sample to a reference O<sub>2</sub> concentration (typically 15% O<sub>2</sub> for gas turbines and 3% for industrial processes). In the U.S., the resulting emissions are reported on a volumetric basis in terms of the dry parts-per-million at the reference %O<sub>2</sub> (here 15%), a unit abbreviated as ppmvdr. In Europe, another functionally equivalent metric based on emitted pollutant mass per dried and O<sub>2</sub>-referenced normal cubic meter (mg/drNm<sup>3</sup>) is often used. These metrics can be related via a simple conversion factor involving the pollutant molecular weight. For example, for NO<sub>x</sub>, 1 ppmvdrNO<sub>x</sub> = 2.05 mgNO<sub>x</sub>/drNm<sup>3</sup>. In either case, in the context of traditional fossil fuels, these adjustments tend to offset the effect of variations in fuel equivalence ratio, bypass air ratio, and steam injection on the resulting concentration values. This property manifests a robust correlation between a pollutant's dry, O<sub>2</sub>-referenced volumetric concentration and its mass-per-energy production rate within a wide range of gas turbine systems firing hydrocarbon fuels—a fact that is exploited in numerous active emissions codes, including Refs. [2,3]. Crucially, however, this correlation is not fuel-independent [4,5].

On this subject, the authors of this study recently assessed approaches for quantifying combustion emissions from hydrogen–hydrocarbon fuel blends [6]. That work demonstrated that dry, O<sub>2</sub>-referenced volumetric pollutant concentration values are strikingly improper for comparisons among high-hydrogen fuels and hydrocarbon fuels, with a penalty of 40% against hydrogen systems. More precisely, this 40% discrepancy was shown to be an artificial bias introduced indirectly by the drying and dilution adjustments rather than by any physical increase in the mass-per-energy emission rate. It is important to emphasize that these *indirect* effects are independent from changes to true pollutant production rates, and instead arise from how changes in other combustion or system parameters feed back into the variables used to quantify adjusted volumetric emissions. The *direct* effects that do follow from fuel- or condition-specific changes in the chemical pathways involved in pollutant formation are a separate issue that is not discussed here but has been considered elsewhere [7–9].

In this paper, we build from our earlier study of indirect emissions assessments from hydrogen fuel blends and consider how pollutant

**Table 1 Chemical equilibrium results for methane, propane, hydrogen, ammonia, and cracked ammonia fuels at T<sub>ad</sub>=1800 K. Percentages are indicated on a volumetric (molar) basis.**

Fuel	$\Delta \bar{h}_c$ [MJ/kmol]	$n_F/n_P$ [vol%]	$\chi_{\text{CO}_2}$ [vol%]	$\chi_{\text{H}_2\text{O}}$ [vol%]	$\chi_{\text{O}_2}$ [vol%]
CH <sub>4</sub>	802.77	4.99	4.99	9.97	9.83
C <sub>3</sub> H <sub>8</sub>	2043.2	1.95	5.86	7.81	10.3
H <sub>2</sub>	242.32	16.0	0	16.0	11.1
NH <sub>3</sub>	320.16	12.5	0	18.8	8.17
$\frac{1}{4}\text{N}_2 + \frac{3}{4}\text{H}_2$	181.74	21.4	0	16.0	10.0

reporting practices based on dry, O<sub>2</sub>-referenced volumetric concentration values affect combustion emissions interpretations from ammonia-based fuel blends. Importantly, ppmvdr values from systems firing NH<sub>3</sub> are not significantly biased by the drying and dilution adjustments relative to systems firing CH<sub>4</sub> [10]. Nonetheless, the present results show that other indirect influences still give rise to a 10% discrepancy against NH<sub>3</sub> when comparing ppmvdr values in ammonia and hydrocarbon fuel at an equal mass-per-work emission rate. Additionally, we consider how the practice of catalytically “cracking” NH<sub>3</sub> into its constituent N<sub>2</sub> and H<sub>2</sub> parts can lead to more significant ppmvdr disparities of up to 21% compared to hydrocarbons at a constant mass-per-work emission rate. In order to establish the source of these differences, a detailed accounting of the indirect influences confounding the relationship between ppmvdr and ng/J emissions values across a range of fuels is provided throughout the analysis. Following our discussion of these results, we conclude that the practice of quantifying combustion emissions using dry, O<sub>2</sub>-referenced volumetric concentrations is generally inappropriate for the purpose of emissions comparisons across different fuels.

## 2 Methodology

As mentioned above, emissions reports based on ppmvdr values are subject to a variety of indirect effects that confound the correlation between emissions quantified by ppmvdr and ng/J under different operating conditions. These include the drying and O<sub>2</sub>-dilution adjustments already mentioned, as well as a variety of additional thermodynamic factors that relate the volumetric concentration of a generic minor exhaust product to the mass of that minor product emitted per unit of delivered energy. We seek to quantify these indirect effects. However, in a head-to-head comparison of real or simulated gas turbine systems firing different fuels, these varying indirect effects are convoluted by physical changes in emissions production rates (i.e., direct effects).

To avoid grappling with such complicated and uncertain influences in a series of detailed experiments or simulations, the approach adopted here and in our earlier work is much simpler. We compute the constant-pressure chemical equilibrium properties of a variety of fuel blends with a fixed adiabatic flame temperature within a simple Brayton cycle using ANSYS CHEMKIN and the NPSS tool [11]. Conditions representative of an F-class gas turbine are considered with a compressor inlet temperature of 300 K, compressor discharge conditions of 17 atm and 700 K, a mixture adiabatic flame temperature of T<sub>ad</sub> = 1800 K, and a turbine inlet temperature of 1600 K. Some sample data obtained for the (unblended) fuels considered in this study under these conditions are presented in Table 1. Nonetheless, it is worth remarking that the main results toward emissions comparisons are not sensitive to the specific conditions chosen, as shown in previous works [4–6].

Using the composition and thermodynamic properties of the reactants and major combustion products and the performance of the cycle, this framework leads to a precise relationship between the ppmvdr and ng/J emissions of an arbitrary minor species *i* of a given fuel. This relationship is expressed as

$$\frac{\text{ppmvd}r_i}{(\text{ng } i/\text{J work})} = \eta_T A_1 A_2 A_3 \quad (1)$$

where  $\eta_T$  is the thermal efficiency of the cycle and  $A_1$ ,  $A_2$ , and  $A_3$  are fuel-dependent proportionality factors representing indirect effects from, respectively, drying, dilution, and thermodynamic adjustments. More specifically, the drying factor is given by

$$A_1 = \frac{1}{1 - \chi_{\text{H}_2\text{O}}} \quad (2)$$

where  $\chi_{\text{H}_2\text{O}}$  indicates the volume (mole) fraction of water in the products. Hence,  $A_1$  describes how removing the  $\text{H}_2\text{O}$  concentrates the other constituents of the exhaust gas. Similarly, the dilution factor that accounts for the  $\text{O}_2$ -referencing of the dried gas is given as

$$A_2 = \frac{0.209 - r_{\text{O}_2}}{0.209 - A_1 \chi_{\text{O}_2}} \quad (3)$$

Here  $r_{\text{O}_2}$  is the reference  $\text{O}_2$  value, which is set to 15% throughout this study. We emphasize that relative differences in ppmvd values across fuels are not influenced by the chosen  $r_{\text{O}_2}$  value, as the numerator on the right-hand side of Eq. (3) represents only a fuel-independent constant of proportionality in the relationship between ppmv and ppmvd values. Note that  $A_2$  is technically a concentration factor if the  $\text{O}_2$  concentration in the dry exhaust exceeds  $r_{\text{O}_2}$  (e.g., oxy-fuel combustion; not considered here). Finally, the thermodynamic adjustment factor is defined as

$$A_3 = \frac{\Delta \bar{h}_c n_F}{M_i n_P} \quad (4)$$

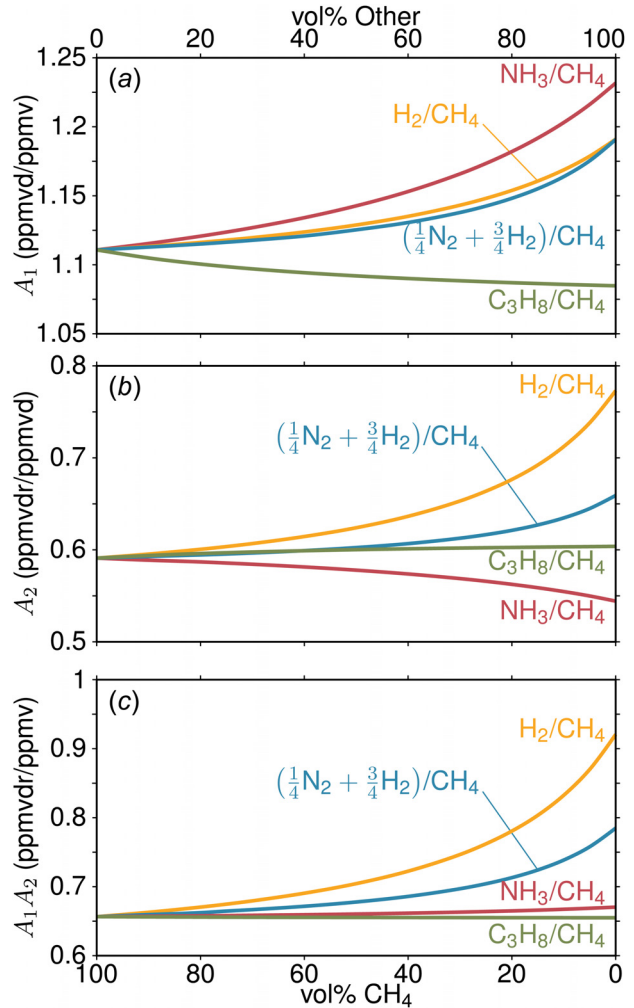
where  $n_F/n_P$  is the ratio of the reaction's fuel to product moles,  $\Delta \bar{h}_c$  is the molar enthalpy of combustion (i.e., the molar lower heating value), and  $M_i$  is the molecular weight of species  $i$ .

### 3 Results

The results of this study consist of assessments of indirect combustion emissions from propane ( $\text{C}_3\text{H}_8$ ), hydrogen ( $\text{H}_2$ ), ammonia ( $\text{NH}_3$ ), and cracked ammonia ( $\frac{1}{4}\text{N}_2 + \frac{3}{4}\text{H}_2$ ) fuels blended with methane ( $\text{CH}_4$ ) in ratios spanning 0% to 100%.

**3.1 Drying and Dilution Effects.** The most obvious indirect factors influencing the relationship between ppmvd and ng/J emission values in different fuels are those of drying and  $\text{O}_2$ -dilution, which are quantified in Fig. 1. These indirect effects describe the relationship between ppmvd and ppmv values. They occur explicitly because of the differences in the concentrations of steam and oxygen formed when burning hydrocarbon fuels and alternative fuels. For hydrocarbon fuels, heat is released when the fuel atoms are oxidized into both  $\text{H}_2\text{O}$  and  $\text{CO}_2$ . Conversely, alternative fuels like  $\text{H}_2$  and  $\text{NH}_3$  are oxidized simply into  $\text{H}_2\text{O}$ , leading to relatively higher concentrations of steam in the combustion products. Since we consider reactions where the equivalence ratio is adjusted to maintain a constant  $T_{\text{ad}}$ , the fuel composition also has a significant effect on the amount of generated  $\text{H}_2\text{O}$  and leftover  $\text{O}_2$  in the combustion products through its heating value  $\Delta \bar{h}_c$  and the resulting fuel-to-product mole ratio  $n_F/n_P$ . The overall consequence of these differences in steam generation on the drying correction from Eq. (2) for various fuel blends is presented in Fig. 1(a), where the removal of higher proportions of steam from alternative fuels is shown to yield a larger drying correction compared to hydrocarbon fuels.

Besides such differences in steam generation, the properties of the reactant mixture also have significant effects on the reaction's consumption of oxygen. In addition to the effect of the fuel-to-product mole ratio already mentioned above, the presence or absence of carbon in the fuel also impacts the product  $\text{O}_2$



**Fig. 1 Indirect drying and  $\text{O}_2$ -dilution effects as a function of blend ratio for an F-class turbine firing ammonia, cracked ammonia, hydrogen, and propane fuels blended with methane across the spectrum of blend ratios. (a) Drying factor  $A_1$  relating a pollutant's dry concentration to its true concentration. (b)  $\text{O}_2$ -dilution factor  $A_2$  relating a pollutant's dry,  $\text{O}_2$ -referenced concentration at 15%  $\text{O}_2$  to its dry concentration. (c) Combined drying and dilution factor  $A_1 A_2$  relating a pollutant's dry, 15%  $\text{O}_2$ -referenced concentration to its true concentration.**

concentration since the formation of  $\text{CO}_2$  consumes more  $\text{O}_2$  and releases less heat than the formation of  $\text{H}_2\text{O}$ . The net effect of these different influences on the leftover oxygen on the dilution correction from Eq. (3) is shown in Fig. 1(b) for the same range of fuel blends.

It is notable from Fig. 1(b) that the  $\text{O}_2$ -dilution correction for high- $\% \text{NH}_3$  blends shows an opposite trend from that of high- $\% \text{H}_2$  blends. This difference has an important consequence on the combined drying and dilution factor  $A_1 A_2$  shown in Fig. 1(c). While drying and  $\text{O}_2$ -dilution lead to a 40% difference in the ratio of ppmvd values to true ppmv when comparing  $\text{H}_2$  and  $\text{CH}_4$  fuels, this same difference is only 2.1% when comparing  $\text{NH}_3$  and  $\text{CH}_4$ . Hence, unlike in  $\text{H}_2$ - $\text{CH}_4$  blends, drying and  $\text{O}_2$ -dilution do not substantially affect the relationship between ppmvd values and true ppmv values for  $\text{NH}_3$ - $\text{CH}_4$  fuel blends. Nonetheless, there are other sources of indirect effects that relate ppmv values to mass-per-work emissions, and these will later be shown to have significant implications for comparisons of emissions among  $\text{NH}_3$ - $\text{CH}_4$  fuel blends on the basis of volumetric concentrations.

Before advancing further, it is worth briefly commenting on the fact that exhaust from cracked ammonia fuel experiences a smaller drying and  $\text{O}_2$ -dilution correction (20% relative to  $\text{CH}_4$ ) than from

H<sub>2</sub> fuel. This is notable because cracking NH<sub>3</sub> yields H<sub>2</sub>—it is equivalent to H<sub>2</sub> fuel with extra N<sub>2</sub> diluent. This difference in drying and O<sub>2</sub>-dilution behavior arises primarily because the extra N<sub>2</sub> increases the fuel equivalence ratio required to reach  $T_{ad}$ , leading to less excess O<sub>2</sub>. Hence, ppmvdr values from cracked ammonia combustion will generally be less affected by the drying and O<sub>2</sub>-dilution corrections compared to pure H<sub>2</sub> (see Fig. 1(b)).

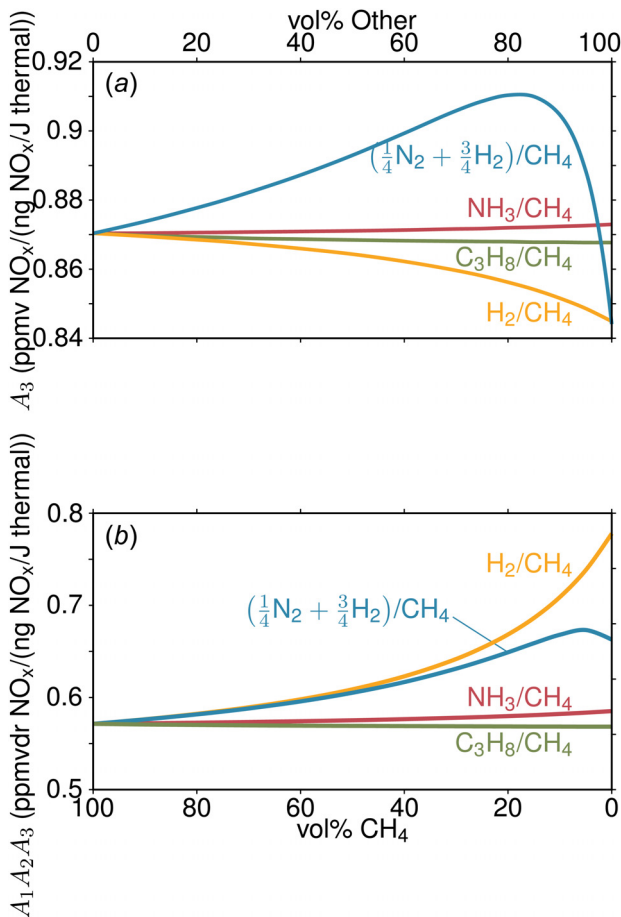
**3.2 Thermodynamic Effects.** The next indirect effect considered accounts for how the thermodynamic properties of the mixture affect the relationship between the true (i.e., wet, undiluted) pollutant concentration in the exhaust and the mass of pollutant formed per unit of fuel energy input. As shown in Eq. (4), these thermodynamic effects arise explicitly due to variations in the fuel heating value and the fuel-to-product mole ratio. Note that the scaling of  $A_3$  by the molecular weight of the pollutant is constant for a given pollutant species regardless of the fuel. To fix the molecular weight in this example, we consider the pollutant species to be NO<sub>x</sub>, for which the approximation  $M_{NO_x} = N_{NO_2} = 46$  g/mol is typical.

It can be observed in Table 1 that  $\Delta h_c$  and  $n_F/n_P$  both vary significantly across the considered fuels. However, the variation of  $A_3$  for different fuels presented in Fig. 2(a) reveals that these effects tend to wash each other out such that the overall contribution of the indirect thermodynamic effect is relatively small. More quantitatively, the relative variation is only 3% between H<sub>2</sub> and CH<sub>4</sub> fuel and

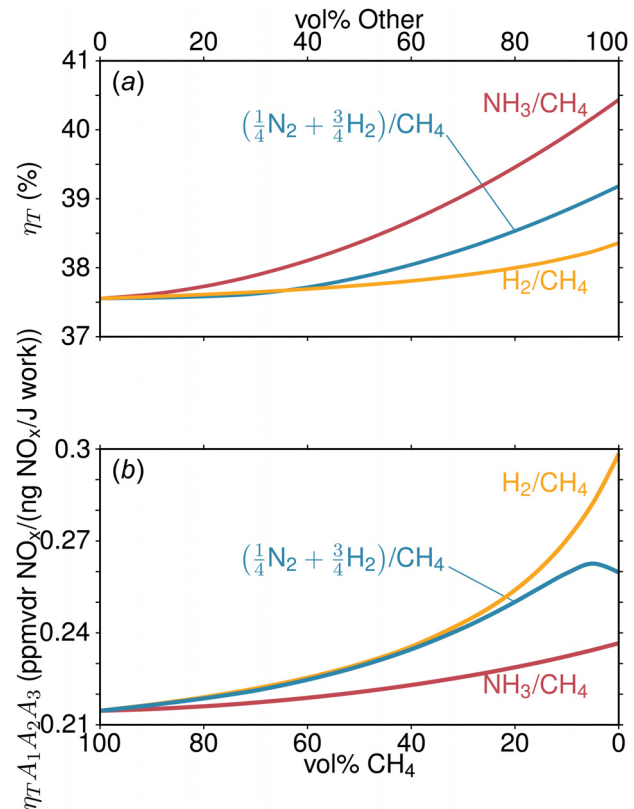
less than 1% between NH<sub>3</sub> and CH<sub>4</sub>. Even less variation is noted in blends of these fuels. Hence, as shown in Fig. 2(b), these indirect thermodynamic effects play a relatively unimportant role in the correlations between ppmvdr and ng/J emissions values among these fuels.

For cracked ammonia–methane blends, on the other hand, Fig. 2(a) reveals that the thermodynamic correction experiences wider variations of about 7% and displays nonmonotonic behaviors as a function of the blend ratio. This nonmonotonicity of thermodynamic indirect effects manifests a corresponding non-monotonic influence on the relationship between ppmvdr and ng/J values, as seen in Fig. 2(b). This is significant because it indicates that, unlike H<sub>2</sub> and NH<sub>3</sub> blends, which both experience the largest differences in indirect effects compared to CH<sub>4</sub> at the extreme of purity (i.e., 100% H<sub>2</sub> or NH<sub>3</sub>), the “worst case” for cracked ammonia occurs at an intermediate blend ratio. Hence, this demonstrates that it is not generally sufficient to only evaluate indirect effects in pure fuels in order to bound the amplitude of possible indirect effects among the various blend ratios of those fuels. Depending on the thermodynamics of the mixture, the relationship between ppmvdr and ng/J may vary in a complex way as the blend ratio is varied.

**3.3 Performance Effects.** The final indirect effect visible in Eq. (1) is the cycle efficiency, which describes the performance of the gas turbine. The cycle’s thermal efficiency is a function of the fuel composition because the varying composition of the combustion products of different fuels leads to changes in the mixture specific heat, particularly due to changes in its H<sub>2</sub>O content. Such changes control how much enthalpy the exhaust carries at a fixed



**Fig. 2** Indirect thermodynamic effects as a function of blend ratio for an F-class gas turbine firing ammonia, cracked ammonia, hydrogen, and propane fuels blended with methane across the spectrum of blend ratios. (a) Thermodynamic factor  $A_3$  relating the true NO<sub>x</sub> concentration to the mass of NO<sub>x</sub> emitted per unit of fuel thermal energy. (b) Combined drying, dilution, and thermodynamic factor  $A_1A_2A_3$  relating the dry, O<sub>2</sub>-referenced concentration of NO<sub>x</sub> to the mass of NO<sub>x</sub> emitted per unit of fuel thermal energy.



**Fig. 3** Indirect performance effects as a function of blend ratio for an F-class gas turbine firing ammonia, cracked ammonia, and hydrogen fuels blended with methane across the spectrum of blend ratios. (a) Thermal efficiency  $\eta_T$  relating shaft work output to thermal energy input. (b) Overall ratio of the indirect to direct emission rate  $\eta_T A_1A_2A_3$  relating the dry, O<sub>2</sub>-referenced concentration of NO<sub>x</sub> to the mass of NO<sub>x</sub> emitted per unit of turbine shaft work.

turbine inlet temperature, which directly alters how much work the turbine can extract per unit of thermal energy input.

The thermal efficiencies resulting across the spectrum of considered fuel blends for the conditions described in Sec. 2 is presented in Fig. 3(a). These results indicate that the alternative fuels all experience an efficiency boost compared to methane. For H<sub>2</sub>, this leads to an efficiency increase of less than 1% (a 2.1% relative increase). However, for NH<sub>3</sub>, a more significant efficiency increase of almost 3% arises (a 7.4% relative increase). As indicated above, these rises in efficiency can be attributed to the increased specific heat of the NH<sub>3</sub> exhaust due to its higher steam content. As may be expected, the efficiency of the cracked ammonia cycles lies in between the efficiencies of the hydrogen and ammonia cycles.

Including these performance effects, the overall relationship between ppmvdr and ng/J emissions output can be quantified using Eq. (1). The resulting relationships for all of the considered fuel blends are shown in Fig. 3(b). These results indicate significant indirect effects for all of the alternative fuels considered. The most heavily affected fuel relative to CH<sub>4</sub> is H<sub>2</sub> with a relative discrepancy of 39% as reported in our earlier work [6]. However, both ammonia and cracked ammonia still do experience substantial indirect effects that penalize them relative to methane on the basis of ppmvdr values. For NH<sub>3</sub>, this effect amounts to a 10% bias, while for cracked ammonia it is 21%.

#### 4 Conclusion

As gas turbine systems begin to transition to green alternative fuels, significant interest has arisen toward assessing the potential air quality impacts of this decarbonization strategy. Nonetheless, the decades-old standard practice of quantifying combustion emissions using dry, O<sub>2</sub>-referenced volumetric concentration measurements (i.e., ppmvdr) does not yield a robust or accurate comparative metric across all fuels. This paper has detailed how different fuels influence the relationship between a gas turbine system's ppmvdr values and its emitted mass-per-delivered energy emission rate. Placing particular emphasis on ammonia-based fuels, the individual drying, dilution, thermodynamic, and performance effects indirectly controlling this fuel-dependent relationship were quantified separately in order to establish mechanisms before assessing their combined influences.

The results of this analysis revealed that gas turbines burning ammonia fuels experience 10% higher ppmvdr emissions values compared to their hydrocarbon-fueled counterparts at an equal mass per delivered energy emission rate. This analysis was also repeated for turbines firing cracked ammonia fuel, which corresponds to H<sub>2</sub> fuel with additional N<sub>2</sub> playing the role of a diluent in the reaction. Compared to methane, cracked ammonia showed 21% higher ppmvdr values at the same mass-per-work emission rate. While these differences are both smaller than the 39% increase previously reported for hydrogen fuels [6], they are still significant for air quality assessments.

It is also interesting to note that the H<sub>2</sub>–CH<sub>4</sub> and NH<sub>3</sub>–CH<sub>4</sub> discrepancies are dominated by different indirect effects. For the H<sub>2</sub>–CH<sub>4</sub> comparison, the dominant indirect effect stems from how drying and dilution corrections lead to a relative concentration of pollutants in hydrogen exhaust in comparison to hydrocarbon exhaust. For NH<sub>3</sub>–CH<sub>4</sub> comparisons on the other hand, drying and dilution only contribute a bias of less than 3% compared to hydrocarbon fuels. The main driver of increased ppmvdr values in ammonia systems is instead mostly a performance effect driven by the efficiency boost linked to the increased specific heat of the ammonia exhaust compared to hydrocarbon exhaust.

Based on these results, we conclude that assessments of combustion emissions relying on volumetric emissions metrics are fundamentally inappropriate for comparisons of emissions involving alternative fuels. Nonetheless, there are a large number of recent studies available in the literature that have improperly compared pollutant emissions among traditional and alternative fuels solely on the basis of ppmvdr values. This is especially important today as

these flawed reports—which we have shown exaggerate emissions from alternative fuels—are being cited in policy decisions that affect the penetration of renewable power systems. To avoid the possibility of further misinterpretations of emissions due to convolutions with indirect effects, we encourage the combustion community to organize a concerted shift toward robust metrics for comparing emissions in terms of the pollutant mass emitted per unit of energy delivered.

#### Acknowledgment

The authors thank Christopher A. Perullo from Turbine Logic for sharing cycle calculation data that were used in this paper.

#### Funding Data

- This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under the Marie Skłodowska-Curie Grant Agreement No. 899987; Funder ID: 10.13039/501100007601.

#### Nomenclature

$A_1$	= drying factor
$A_2$	= 15% O <sub>2</sub> -dilution factor
$A_3$	= thermodynamic factor
$\chi_i$	= volumetric (molar) concentration of species $i$
GHG	= greenhouse gas
$\Delta\hat{h}_c$	= molar heat of combustion
$\eta_T$	= thermal efficiency
$M_i$	= molecular weight of species $i$
$n_F/n_P$	= mole ratio of fuel to products
NPSS	= numerical propulsion system simulator
ppmv	= parts per million (volumetric)
ppmvd	= dry ppmv
ppmvd <sub>r</sub>	= dry ppmv at the reference O <sub>2</sub> concentration
$r_{O_2}$	= reference O <sub>2</sub> concentration (15% in this study)
$T_{ad}$	= adiabatic flame temperature

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