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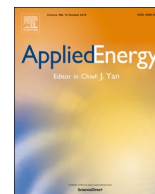
Flashback, burning velocities and hydrogen admixture: Domestic appliance approval, gas regulation and appliance development

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HIGHLIGHTS

- New formulation of appliance standards for flashback in terms of burning velocity.
- Flashback in approval standards and regulated gas quality assessed quantitatively.
- Explicit definition of safety margin for domestic appliances based on limit gas.
- New flashback limit gases for appliance development to extend hydrogen fractions.
- Recommendations to maintain end-use safety and facilitate grid management.

ARTICLE INFO

ABSTRACT

Introducing natural gas/hydrogen mixtures to an installed population of domestic natural gas appliances necessarily implies considering the risk of flashback. Previously, we quantified this risk via an interchangeability analysis using calculated laminar burning velocities. With an increasing contribution of renewable energy, still higher hydrogen fractions will become of interest to improve the economic viability in power-to-gas chains. To extend the possibilities for hydrogen admixture beyond the limits given by extant ranges of Wobbe Index and burning velocity, appliance approval standards and gas regulations must be examined to assess the degree to which higher hydrogen fractions are, or can be, justified. However, the current standards and regulations do not consider the risk of flashback in terms of the laminar burning velocity explicitly, leaving the justification of higher hydrogen fractions to empirical observations followed when the approval standards were codified. Here, we reframe the approval and regulation standards in terms of the calculated laminar burning velocity, which quantifies the notion of a 'safety margin' to safeguard appliance performance with respect to flashback, for a group of natural gases that is commonplace in the European Union (EU) but representative for many international situations. The method presented can be applied for any local regulatory area. In plots of burning velocity vs. equivalence ratio, ranges of regulated gas qualities are represented as a curve for natural gases, while for natural gas/hydrogen mixtures they appear as areas indicating the variations in hydrogen fraction for different gas compositions that do not increase the risk of flashback. To quantify the safety margin, the approval gas used in the EU for flashback (G222) is taken as an example, because of the many decades of experience in using this gas to safeguard appliance performance. Using the assumed range of gas quality and approval gas as an example, for appliances whose primary equivalence ratio is fuel rich (at greatest risk for flashback), a safety margin of 11.5 cm/s is determined and used in analyses for determining the composition of flashback limit gases in approval standards for a situation in which higher hydrogen fractions are desired. Situations considering both variable and constant fractions of hydrogen in natural gas are examined. The end-use demand for a minimum degree of thermal comfort, by having a minimum Wobbe Index in the regulated range of gas quality, automatically complicates grid management schemes for hydrogen addition: the maximum hydrogen admixture is necessarily coupled to the composition of the natural gas to which it is added. The only solution for having a constant hydrogen fraction without regard to the gas composition is by relaxing this demand on thermal comfort; in the example used here, 20% hydrogen admixture reduces the thermal comfort in the worst case by 4.7%. Fuel suppliers, grid operators and end users must agree to this loss of fitness for purpose to maximize the decarbonization of the gas supply by hydrogen admixture.

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Nomenclature

Φ	equivalence ratio (–)
group H	group of model gas compositions characterized by the same Wobbe range as gas group H defined in Ref. [1], and showing similar burning behavior
m^3	cubic meter at 101.325 kPa and 0 °C
S_L	laminar burning velocity (cm/s)
$S_L(\Phi)$	laminar burning velocity (cm/s), indicating its dependence on Φ
$S_L(H_2)$	laminar burning velocity (cm/s), indicating its dependence on H_2 fraction in potential CH_4/H_2 flashback limit gas
$S_L(\Phi)_{NG/H2}$	laminar burning velocity (cm/s) of NG/H_2 mixtures
$S_{L,\,max}^{admix}$	maximum burning velocity (cm/s) for an $\{S_L, \Phi\}$-area of NG/H_2 mixtures, allowing $S_L(\Phi)_{NG/H2}$ to exceed $S_L(\Phi)_{max}^{regulated}$, while keeping $W_{NG/H2} \geq W_{min}^{regulated}$
$S_L(\Phi)_{max}^{group}$	maximum burning velocity (cm/s) appearing in the fuel-rich or fuel-lean domain of premixing for the gas group considered
$S_L(\Phi)_{max}^{regulated}$	maximum burning velocity (cm/s) appearing in the fuel-rich or fuel-lean domain of premixing for the range of gases specified by a jurisdiction under consideration
$S_L(\Phi)_{min}^{regulated}$	minimum burning velocity (cm/s) appearing in the fuel-rich or fuel-lean domain of premixing for the range of gases specified by a jurisdiction under consideration
$\Delta S_{L,\,s.m.}$	lightback safety margin (cm/s)
W	Wobbe Index (MJ/m^3 (25 °C, 0 °C))
W_{min}^{group}	formal minimum Wobbe Index for the gas group considered
W_{max}^{group}	formal maximum Wobbe Index for the gas group considered
ΔW^{group}	Wobbe Index range for the gas group considered
$\Delta W^{group\,H}$	Wobbe Index range for the gas group H considered
W_{NG}	Wobbe Index of a natural gas
$W_{NG/H2}$	Wobbe Index of a natural gas/hydrogen mixture
ΔW_{NG}	range of natural gas Wobbe Indices
$W^{regulated}$	Wobbe Index of a gas within the range specified by a jurisdiction under consideration
$W_{min}^{regulated}$	minimum Wobbe Index for a range of gases specified by a jurisdiction under consideration
$W_{max}^{regulated}$	maximum Wobbe Index for a range of gases specified by a jurisdiction under consideration
$\Delta W^{regulated}$	Wobbe Index range of gases specified by a jurisdiction under consideration
EU	European Union
GAR	European Gas Appliance Regulation
G222	group H lightback limit gas (CH_4/H_2 = 77/23 vol %/vol%) [1]
IGU	International Gas Union
NG	natural gas
RGQ	regulated gas quality
UK	United Kingdom
USA	United States of America

Subscripts

adj	adjustment of appliance

1. Introduction

Admixing hydrogen obtained from renewable sources of energy to natural gas (NG) is considered as a possibility for large-scale storage of renewable energy (see [2–6], for example), as a solution for the inherent intermittency in wind and solar energy generation. Practical implementation of this idea in the current natural gas distribution system means that the installed population of domestic appliances would receive NG/H_2 mixtures. Studies addressing grid management with the injection of hydrogen obtained by power-to-gas energy conversion, point out the importance of and at the same time the uncertainty about the maximum hydrogen fraction that can be accommodated by residential appliances without adverse consequences [2,7,8]. As discussed in Ref. [9], the maximum hydrogen fraction in the existing population of domestic appliances is limited by the historical ranges of natural gas composition that have been distributed, and necessitates complex grid operation. The gas interchangeability method described in Ref. [9] shows that the current level of thermal comfort (hot water, indoor temperature) can be maintained by respecting the extant minimum value of the Wobbe Index. Regarding safety, hydrogen addition to natural gas is related to the combustion phenomenon of flashback [9] (also known as lightback), in which the flame physically enters the burner, usually prior to extinguishing; this results in spillage of combustible mixture into the living space creating an explosion hazard. The method in Ref. [9] permits quantification of the risk of flashback, as compared to the existing range of natural gas being distributed, depending on the composition of the natural gases in this range. To quantify the risk of flashback, the method uses the changes in (computed) laminar burning velocity, S_L, with changes in the composition of these mixtures.

The method of Ref. [9] is an interchangeability method allowing conclusions by comparing *fuel properties* without the need of considering the vagaries of the millions of individual appliances in the field. On the other hand, while the contribution of renewable energy increases, higher hydrogen fractions are of interest exceeding the limits posed by current natural gas distribution conditions. Higher hydrogen fractions would improve the economic viability of projects with distributed hydrogen injection [10]. Higher hydrogen fractions in relation to the economics of the combined gas and electricity networks in the UK are assessed in Ref. [2]. In an urban example in Germany the current limit on the hydrogen fraction implies a limit on the economic performance of decentralized power-to-gas stations [11]. With an eye towards a future in which a higher hydrogen fraction, preferably with straightforward grid operation, is realizable, it is essential that one anticipates this future by developing compliant gas appliances. Additionally, as will be demonstrated below, simple grid operation while maintaining safety requires a (modest) sacrifice in fitness for purpose in the interest of decarbonization. Increasing the amount of renewable energy that is distributed and utilized as renewable hydrogen beyond that which is "interchangeable" with the current generation of appliances unequivocally requires addressing appliance approval, gas regulation and appliance development with respect to the risk of flashback.

Current (inter)national standards for the approval of domestic appliances for use are often closely related to current ranges of gas composition that are indicated in gas *regulation*. A recent study examining the injection of renewable fuels into the UK gas grid [10] emphasized the need for methods to analyze the impact of the admixture of alternative fuels, like hydrogen, in the regulatory framework. In the context of European gas quality harmonization, it has also been emphasized that appliance approval should contain standards for hydrogen in natural gas in the medium term [12]. The HyLAW project [13] further observed that there was no body of evidence upon which to determine an acceptable upper threshold on hydrogen concentration and it was recommended that a revised Gas Appliance Regulation [14] may be needed to allow (a transition to) higher hydrogen concentrations. An assessment of the feasibility of market introduction of

hydrogen in the transport and natural gas sectors for the USA, Europe, Japan and China [15] concluded that the development of the natural gas/hydrogen market is hindered by the uncertainty regarding the allowed concentration of hydrogen. As the current approval standards were developed in the decades when only hydrogen-free natural gases were distributed, it is unclear how hydrogen admixture fits in this context. In the present work the principles exposed in [9] are applied to set appliance approval standards and gas quality regulations to permit deliberately higher hydrogen fractions in NG than those derived from the interchangeability considerations for the current situation of natural gas distribution and regulation. In this way the knowledge gap mentioned [1,12,13] is addressed here, especially considering flashback.

When applying the quantitative methods defined in [9] to these situations, we first note that current gas regulations and appliance approval procedures ([1,14,16,17], for example) for natural gases and utilization equipment do not consider flashback in terms of S_L, the relevant parameter to assess flashback. Flashback was approached on empirical grounds, generally based on the Wobbe Index of the expected range of natural gases and empirical observations regarding hydrogen. While this approach has been successful in the practice of *natural gas* distribution during the past decades, the addition of hydrogen to natural gas as a distribution fuel reveals the shortcomings of the method. As will be shown below, analyzing the changes in flashback caused by the presence of hydrogen in natural gas explicitly in terms of changes in burning velocity permits transparent quantification of the relation of regulatory limits and approval procedures for such 'new' fuel compositions. To our knowledge, such quantification is not given in the current literature, and addressing this knowledge gap is essential to determine physical-chemically justified hydrogen fractions that maintain the same level of safety as currently enjoyed. The shortcomings of the current approval system in this regard are illustrated by the possible interpretations of the limit gas for flashback in the EU approval standards for appliances designed for gas group H. This limit gas, nominally having 23% H_2 in methane [1], is used in a short-term testing protocol to ensure the robustness of domestic appliances regarding flashback *for natural gases* distributed so far as determined by gas quality regulations. However, in spite of this regulatory restriction, a successful flashback type test with this limit gas $CH_4/H_2 = 77/23$ is often [18,19] construed to mean that, in practice, the appliance type tested is then guaranteed to operate without flashback with gases containing 23% of H_2, regardless of the composition of the NG in the mixture. Ref. [9] demonstrates that this guarantee does not exist. This example shows that the mere presence of a hydrogen-containing limit gas in the EU approval regime for natural gas appliances is a source of confusion regarding which range of gases this limit gas is intended to safeguard.

Note that to accommodate the deployment of 100% hydrogen-energy systems, there has been a focused effort in the international hydrogen community to develop codes and standards based on clear scientific principles [20]. The knowledge gap indicated above implies uncertainty, not only for appliance manufacturers, as to what H_2 fractions in NG/H_2 mixtures their new appliance types should be able to handle safely, but for countries as well, when considering future distribution limits for safe and fit-for-purpose distribution of NG/H_2 mixtures to end users.

Building on the analysis framework described in Ref. [9], the aim of the present work is to decrease the uncertainties illustrated above and provide a way forward by expressing the propensity for flashback in terms of laminar burning velocities. For this purpose, we perform a quantitative assessment of appliance approval considering the gases for which appliances have been designed, including limit gases to be applied in appliance testing. Also, we quantify the 'safety margins' between the limit gas compositions for flashback used in appliance approval and the regulatory limits for natural gas quality using the same methodology. Before applying this new approach for future NG/H_2 mixtures, the current situation, considering the relation between regulatory limits and approval limit gases for natural gases without hydrogen, is analyzed; this is an essential aspect of defining the safety margins in the current practice. During the analysis, it will become clear that the Wobbe Index, now used as the primary (and de facto only) parameter to quantify gas ranges in appliance approval and gas regulation, is not suited to quantify the impact of hydrogen content when considering limit gases and safety margins with respect to flashback. The translation to the picture in terms of burning velocities is not a simple one from one fuel gas property to another one as burning velocities depend on the gas/air premixing of appliances. This approach has not been reported before in the present context.

While the analysis concerning appliance approval and national gas regulation presented is of general significance, it has been performed for the EU as an example situation.

Section 2 briefly addresses the current situation concerning nationally or regionally regulated gas distribution and appliance approval that is expressed in terms of the Wobbe Index, including the definition of the notion of a 'regulated gas quality'. Applying the new flashback approach, ranges of natural gas currently characterized in terms of a range of Wobbe Index are 'translated' to ranges of burning velocities (Section 3). Then, for natural gases, a fictitious national situation is assessed and results are shown for the limit levels of flashback propensity, the 'translated' definitions of the regulated gas quality and the safety margins (Section 4), in terms of S_L. Finally, in Section 5 appliance approval and nationally regulated gas distribution are addressed for NG/H_2 mixtures. The limits set by current conditions are challenged to explore directions of appliance development and research to extend the possibilities for hydrogen admixture, based on the physical-chemical principles underlying the methods, thus providing hydrogen levels for increased economic performance in the field of power-to-gas [2,10,11]. Moreover, grid management issues are addressed, for the cases of variable and constant hydrogen fractions, and related to energy availability for the end user.

While the current analysis focuses on NG/H_2 mixtures, it will be clear that the approach is also useful for considering mixtures of H_2 and biomethane in a non-fossil future [21].

2. Current appliance approval and gas regulations

During the rise of the large-scale natural gas infrastructure in the last century, gas quality regulations and approval procedures for newly developed gas-utilization appliances were developed, to ensure the safety and fitness for purpose for appliances in the field.

First, we discuss gas regulation. As is well-known, the most important parameter characterizing a (natural) gas, is the Wobbe Index, defined as the ratio of the calorific value of a gas per unit volume and the square root of its relative density. In many jurisdictions, such as in the USA [16,17], European countries [22], Australia [23] and New Zealand [24], ranges of natural gas quality are given in terms of Wobbe Index (Wobbe bands). These ranges can be implemented in tariffs (USA) or regulations (Europe, Australia). In the present paper, minimum and maximum Wobbe limits, and the resulting bandwidth, are indicated by $W_{min}^{regulated}$, $W_{max}^{regulated}$ and $\Delta W^{regulated}$, respectively. These limits are the outcome of processes where available gas qualities on the one hand, and the condition of the appliance population on the other hand, have been considered. In the European example considered below, the expression 'national gas regulation' will also be used; using the term 'local tariffs' in the US context has the same connotation in the context of the discussion.

The other notion that will be used below regards the way in which appliances are approved for use. Approval procedures are in force for testing appliance types newly designed by manufacturers to acquire a certificate for introduction of the new type on the market. Depending on the intended function of the appliance (e.g., cooking, heating sanitary water) tests for the individual types of appliance regarding the combustion characteristics incomplete combustion (CO emissions),

sooting, flame lift, flashback, and thermal load have been standardized, using a given range of gas compositions. When a new type of appliance has been tested successfully and obtained its certificate, it is regarded to operate safely and deliver the comfort intended during its lifetime when fueled with gases from the Wobbe band for which this appliance type was designed. In the discussion below, the notion 'type test' is used with exactly this meaning. It is not necessary that a newly designed appliance is based on a new operating principle; it could just concern a cooking stove with newly designed pan grates. 'New' means nothing more or less than that the appliance type is meant to appear in the market for the first time.

Type testing is performed in short-term tests under well-controlled conditions. Lifelong operation in the field, however, is impacted by such aspects as variations in ambient conditions (air temperature and humidity), incorrect settings and the wear and tear of components during a lifetime of normal operation. Therefore, a form of a 'safety margin' must be taken into account [25] between the type testing conditions on the one hand, and the regulated fuel gas quality ($\Delta W^{regulated}$) on the other hand, where the latter is the lifelong operational factor with the least uncertainty. It should be noted that a quantitative understanding of the practical aspects contributing to national safety margins is lacking. To the authors' knowledge, there have been no representative systematic studies investigating the actual changes in the response of appliances to varying gas quality and varying weather conditions *during the lifetime* of the appliances [26,27], while practical conditions like the variation in atmospheric conditions do show significant impact on the safety margins [26,28]. Several factors contributing to safety margins depend on national particulars: legislation, rules issued, legal responsibility for product liability, and the degree to which installation and maintenance are in strict accordance with the manufacturer's instructions [22,29,30].

As mentioned above, the present work considers the situation in the EU as an example. This case concerns 28 countries with a common gas appliance approval system, presently known as the Gas Appliance Regulation (GAR) [14,31].

As described in Ref. [32], managing the wide variation in distributed gases, the International Gas Union (IGU) proposed in 1976 a classification scheme based on the Wobbe Index, whereby gases were divided into three families with one or more groups per family. Appliances were then also classified according to the gas families to which they are intended. This paper focuses on group H gases, which use pure methane as a standard gas for comparison, since this is the largest group of natural gases distributed internationally. In the European example, each country has its own gas regulation, including a national Wobbe band $\Delta W^{regulated}$, within group H [22].

Type tests include tests with limit gases, defined to span the group H Wobbe range $\Delta W^{group\ H}$. These limit gases define the limits of the variations in the (combustion) characteristics of the gases for which appliances have been designed. A flame lift limit gas has its Wobbe Index at the lower limit W_{min}^{group}, while a limit gas for incomplete combustion and sooting has its Wobbe Index at the upper limit W_{max}^{group}. Generally, $\Delta W^{regulated} < \Delta W^{group}$ [22]. The margins ($W_{max}^{group} - W_{max}^{regulated}$) and ($W_{min}^{regulated} - W_{min}^{group}$) are de facto formal representations of the safety margin [22], with respect to incomplete combustion/sooting, and flame lift, respectively. Thus, for these combustion characteristics the safety margins are effectively defined as the difference between the Wobbe Indices of the limit gas and the regulated limit. Despite the quantitative uncertainty regarding the definition of this kind of safety margin, as indicated above, to facilitate the discussion below, here we use this definition of the safety margin without further discussion. The relations between the regulated range of gas quality and the safety margins are illustrated in Fig. 1.

Often, the range of gases actually distributed spans a smaller Wobbe band than defined in the nationally regulated band, being the result of the specific traditional sourcing of natural gas [22].

The range of variation $\Delta W^{regulated}$ will be called the 'regulated gas quality' (RGQ). In the present work an RGQ indicates a range of gases for which the appliances in the population are intended to show (lifelong) safe and fit-for-purpose operation after successful type tests with the respective limit gases. The RGQ represents the variation in the severity of the different combustion characteristics upon fueling appliances that are designed for the respective family/group. The RGQ, and the variation of the severity of the different combustion characteristics resulting from it, is the essential concept when considering the safe use of distributed gases in appliances for which the design is intended.

The interpretation of the RGQ explained here enables expressing flashback in terms of the laminar burning velocity, rather than in Wobbe Index, in appliance approval procedures, as well as in national regulations, as elaborated in the following sections.

3. From Wobbe Index to burning velocity in natural gas appliances

The basic issue to be assessed is which gas compositions can be used safely in which appliances. We therefore analyze the changes in appliance behavior when fueled with different gas compositions. The most
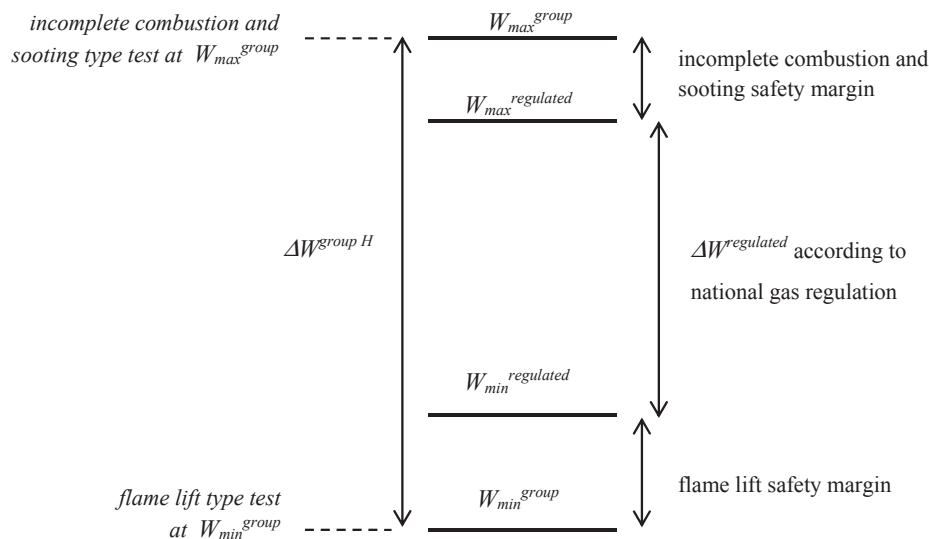

Fig. 1. Illustration of the Wobbe range related to appliance type testing, the range regulated by a country taking into account its national practical conditions, and the resulting safety margins, in current situations.

significant change in combustion behavior caused by changes in gas composition regards the equivalence ratio, Φ, the ratio of the actual fuel/air ratio to its stoichiometric value. Changes in equivalence ratio with fuel composition impact changes in flame stability (through the changes in burning velocity, S_L [9,33]) and emissions behavior (CO and NO_x). The vast majority of domestic appliances show the same general response to another gas, by a change in Φ [9,32,34]. This similarity in response forms the basis of the analysis in Ref. [9] of the introduction of NG/H_2 mixtures to an installed population of appliances intended for natural gas in terms of $S_L(\Phi)$. As demonstrated below, the general response of the equivalence ratio in appliances also allows transposing the discussion of flashback in the current appliance approval procedures and gas quality regulations from Wobbe Index ([1,14] for example) to $S_L(\Phi)$.

The change in equivalence ratio upon changing gas composition [9,32,34] is the most important factor affecting the change in flashback propensity for domestic appliances, due to the pseudo-parabolic path of S_L vs. Φ. Therefore, as discussed previously [9], a shift of equivalence ratio changes $S_L(\Phi)$ in opposite directions depending whether the appliance operates in the fuel-rich or fuel-lean domain. To assess the effects of hydrogen addition to natural gas and to quantify the safety margin, both domains of premixing have to be considered separately, both in appliance type testing and assessing gas regulation.

How changes in (natural) gas composition translate into changes in burning velocity is illustrated below, using a model group of high-calorific value gases whose range was reported previously [9]. Values of W and Φ are calculated as indicated in Ref. [9], and shown in Table 1.[1] Here, the appliances are assumed to be adjusted with methane at either $\Phi = 0.85$ or $\Phi = 1.25$.

3.1. The fuel-rich domain

In Fig. 2, the curves[2] of S_L vs. Φ are shown for the gases "48.17", "53.45" and "57.66" (whose compositions are given in Table 1), spanning the range of equivalence ratio 1.10 to 1.35. The burning velocity for the adjustment gas (CH_4) at $\Phi = 1.25$ is indicated by the black diamond in the Figure. Using the shifted equivalence ratios from Table 1, the burning velocities were calculated [9] and plotted in the Figure, denoted as "Phi-shifted SLs". Horizontal arrows indicate the shifts in equivalence ratio, while dashed vertical arrows represent the changes in S_L.

The effect of the shift in equivalence ratio on the flashback propensity of natural gases becomes transparent by comparing the resultant shifted burning velocities with the range of burning velocity at constant equivalence ratio. The shift in equivalence ratios from the highest Wobbe gas ("57.66") to the lowest ("48.17") is 0.223, which

results in a difference in the burning velocity between these two compositions of 15.7 cm/s, in this region of premixing. This change is 8 times the difference in burning velocity between these two compositions at $\Phi = 1.10$ and 4 times that difference at $\Phi = 1.30$.

At a constant equivalence ratio, of all gases in the Wobbe band the maximum-Wobbe gas has the maximum burning velocity $S_L(\Phi)$. Taking into account equivalence ratio shifts, the maximum value $S_L(\Phi)_{max}{}^{group} = 37.1$ cm/s is obtained for the minimum-Wobbe gas "48.17".

Each individual fuel composition has its own pseudo-parabolic $S_L(\Phi)$-curve but *only the point at the shifted value of the equivalence ratio* is relevant for the analysis, since the shifted burning velocity determines the impact on flashback. In Fig. 2, these Φ-shifted burning velocities are connected by a polynomial trendline ("Phi-shifted SLs" in the Figure) representing the set of the Φ-shifted $S_L(\Phi)$-points of all fuel compositions in the model gas group H. We note in passing that using a different adjustment gas or equivalence ratio yields a family of "Phi-shifted SLs" curves that are essentially parallel; at the same time, the use of actual natural gas compositions in this exercise would reposition these curves slightly. This curve represents the translation of the Wobbe range to a range of burning velocities for this range of natural gas compositions. These "Phi-shifted SLs" will be used below to quantify flashback in the approval regime for the range of 'intended' compositions for acceptable appliance operation in the field (Section 4).

The "Phi-shifted SLs" curve offers the possibility to estimate relative fuel-rich flashback propensity levels for natural gases within the $\Delta W^{group\ H}$ band, which will be used to consider a safety margin for a national range of regulated compositions.

3.2. The fuel-lean domain

In Fig. 3, the $S_L(\Phi)$ curves are shown for the same gases in Table 1, now spanning the fuel-lean range of equivalence ratio from 0.75 to 1.00. Appliances are assumed to be adjusted at $\Phi = 0.85$ with CH_4, as indicated by the black diamond marker. As done in Fig. 2, the burning velocities were calculated using the shifted equivalence ratios in Table 1.

Analogous to the discussion following Fig. 2, the shift in equivalence ratios from the highest Wobbe gas ("57.66") to the lowest ("48.17") is 0.152, which results in a difference in the burning velocity between these two compositions of 11.8 cm/s, in this region of premixing. This change is 7 times the difference in burning velocity between these two compositions at $\Phi = 0.80$ and $\Phi = 1.0$.

Note that the range of shifted equivalence ratios and the concomitant range of burning velocities are significantly narrower as compared to the fuel-rich case. This is predominantly caused by the smaller shift of equivalence ratio (being proportional to the initial value of this ratio, which here is the value at appliance adjustment [9]).

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[1] Wobbe Indices 48.17 and 57.66 MJ/m^3 are the formal group H limits according to Ref. [1]. The approval limit gases used in appliance testing in the EU, for flame lift and incomplete combustion and sooting, respectively, have a slightly different Wobbe Index of 48.13 MJ/m^3, respectively 57.72 MJ/m^3, and slightly different compositions. In the rest of this paper, $W_{min}{}^{group}$, $W_{max}{}^{group}$ and ΔW^{group} indicate 48.17 MJ/m^3, 57.66 MJ/m^3, and the group Wobbe range, respectively.

[2] Values of $S_L(\Phi)$ are calculated by applying the PREMIX code [35] from the CHEMKIN II suite [36], using the GRI Mech 3.0 reaction mechanism [37]. This reaction mechanism can be considered to yield realistic laminar burning velocities for the gas/air mixtures in this work [38,39]. With 15 calculated $S_L(\Phi)$ points for the Φ range from 0.6 to 1.4 representative polynomial trendlines, as shown in the Figures, are obtained.For all natural gases and natural gas/hydrogen mixtures the calculations were performed with the CHEMKIN II/ PREMIX parameter settings: no thermal diffusion (Soret effect) and *mixture averaged* formulations for the transport properties. Taking into account thermal diffusion and multicomponent formulations for the transport properties yielded differences in S_L-results of < 0.4 cm/s while calculation times increased from less than a minute up to almost an hour.

Table 1
Group H model natural gases.

| W (MJ/ m^3)[1] | Composition (vol%) | | | Shifted Φ's (–) | |
	CH_4	C_3H_8	N_2	Fuel-lean $\Phi_{adj}(CH_4) = 0.85$	Fuel-rich $\Phi_{adj}(CH_4) = 1.25$
48.17	92.6	–	7.4	0.766	1.126
49.93	95.1	–	4.9	0.794	1.168
51.69	97.6	–	2.4	0.822	1.209
53.45	100.0	–	–	0.850	1.250
54.50	96.9	3.1	–	0.867	1.275
55.56	93.7	6.3	–	0.884	1.300
56.61	90.5	9.5	–	0.901	1.325
57.66	87.2	12.8	–	0.918	1.349

[1] In this work, the thermodynamic and volumetric reference temperatures of 25 °C and 0 °C, respectively, apply to values of the Wobbe Index, at the reference pressure of 1013.25 mbar.
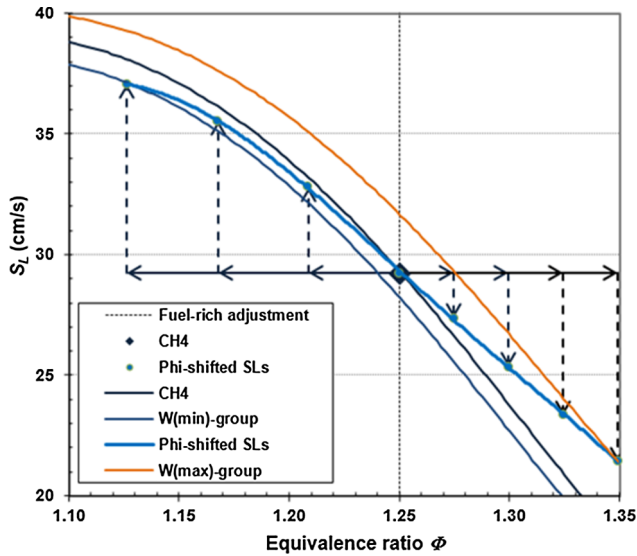
Fig. 2. Effect of equivalence ratio shifts on burning velocities for the gas compositions in Table 1, in the fuel-rich domain.

Fig. 3. Effect of equivalence ratio shifts on burning velocities for group H natural gases in the fuel-lean domain.

Finally, for the fuel-lean domain, Fig. 3 shows the Φ-shifted points of the burning velocity for the gas compositions considered here, also connected by a polynomial trendline. In this domain the maximum value in this range $S_L(\Phi)_{max}^{group} = 35.9$ cm/s is obtained for the maximum-Wobbe gas "57.66".

As for the fuel-rich case, the "Phi-shifted SLs" trendline allows estimating the relative fuel-lean flashback propensity for natural gases within the $\Delta W^{group\ H}$ band. Here too, different fuel compositions or equivalence ratios at adjustment yield parallel curves, but do not alter the discussion presented here.

4. National gas regulation and flashback safety margins for natural gas

National gas regulation and safety margins, as connected with appliance testing, were illustrated in Fig. 1 in terms of the Wobbe Index. We note in this regard that current natural gas distribution in European RGQs does not include H_2 fractions > 0.1% [40,41]. As indicated above, to provide a more transparent understanding of the relation of flashback to fuel composition, particularly when considering fuel components such as hydrogen that impact flashback outside of the domain characterized by the Wobbe Index, flashback should instead be characterized by the laminar burning velocity $S_L(\Phi)$. In this Section, the flashback safety margin in terms of $S_L(\Phi)$ will be presented and quantified. For the combustion characteristics considered here, a safety margin is defined as the difference between the RGQ limit and the limit test gas used in appliance approval. Since, as illustrated in Fig. 2, in the fuel-rich domain the gas having $W = W_{min}^{group}$ will show the maximum burning velocity, $S_L(\Phi)_{max}^{group}$, safety margins for flashback in this domain will concern gases in the lower part of the Wobbe band.

For a national situation with $\Delta W^{regulated} < \Delta W^{group}$ (Fig. 1), with the model gas compositions defined in Table 1, $\{S_L, \Phi\}$ curves for the gases "48.17", "53.45" (CH_4) and "57.66" are replotted in Fig. 4, spanning the range of equivalence ratio of 1.10 to 1.35, using the data in Fig. 2 as a starting point. For the purposes of this exercise we have defined an RGQ[3] with $W_{max}^{regulated} = 55.56$ MJ/m³ (CH_4/C_3H_8 mixture in Table 1) and $W_{min}^{regulated} = 51.69$ MJ/m³ (CH_4/N_2 mixture in Table 1). The $\{S_L, \Phi\}$ curves for these mixtures are also plotted in Fig. 4. Appliance adjustment is at $\Phi = 1.25$ with CH_4. Here we clearly see that the burning
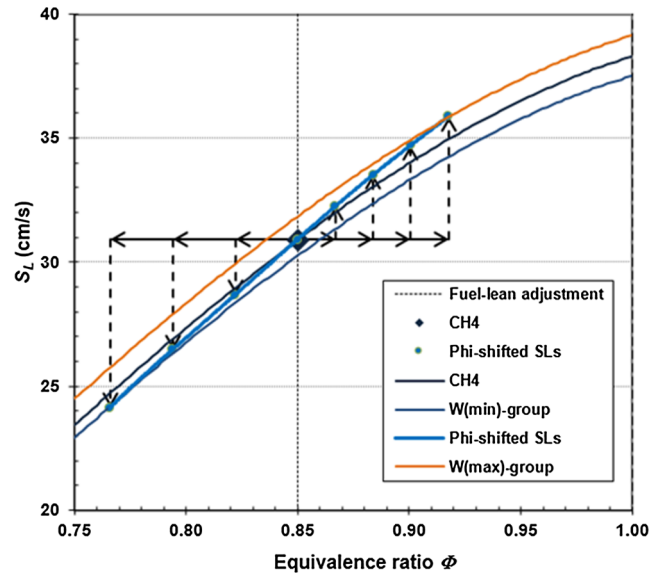
velocities of these RGQ compositions fall between those of the 'group', as expected.

Similar to the curve in Fig. 2, the "Phi-shifted SLs" curve shown in the Figure represents the set of simultaneous variations of the gas quality and the gas/air ratio for the gas compositions experienced in the national range of gases specified by the RGQ; this is a subset of the range in Fig. 2. For the reference gas (methane) at $\Phi = 1.25$, the maximum burning velocity obtained at $W_{min}^{regulated} = 51.69$ MJ/m³ is 32.8 cm/s, defining $S_L(\Phi)_{max}^{regulated}$ in Fig. 4.

The lowest burning velocity in the regulated range, $S_L(\Phi)_{min}^{regulated} = 25.4$ cm/s, belonging to the gas with the highest Wobbe Index, $W_{max}^{regulated} = 55.56$ MJ/m³. The national Wobbe range represents a range of burning velocity of 7.4 cm/s for the range of compositions in this model regulated band. The RGQ is represented by the set of points on the "Phi-shifted SLs" curve; this notion will be further applied when concerning hydrogen admixture in Section 5.

In the European example, the high-calorific value group of gases (the group H) has a flashback limit gas designated as G222 ($CH_4/H_2 = 77/23$ based on volume, $W = 50.44$ MJ/m³). The burning velocity as a function of equivalence ratio for G222 is also shown in Fig. 4. It was used for flashback testing on empirical grounds for fueling domestic appliances with natural gases and has been used for decades. Given the discussion regarding burning velocity above, the fact that its Wobbe Index lies within the group range $\Delta W^{group\ H}$, does not provide probative information for defining a safety margin with respect to flashback. Despite this, a successful test with G222 is intended to provide lifelong flashback-proof operation of the appliance type that has been tested with it for all gases within the band $\Delta W^{regulated}$. However, assessing the issue in terms of burning velocity, computing S_L for G222 in the fuel-rich domain, including the shift in equivalence ratio from $\Phi = 1.25$ for pure methane to $\Phi = 1.157$, gives 44.3 cm/s (indicated as "G222 test limit" in Fig. 4). As indicated in Fig. 4, this value is considerably higher than all possible burning velocities that can occur in the model range of natural gases considered in Table 1, indicating that the choice of this gas as a flashback limit gas for appliance testing *for natural gases* was physically reasonable, albeit empirical. Having assumed that testing with G222 is a guarantee for the regulated range of natural gases, the safety margin expressed in burning velocity ($\Delta S_{L,\ s.m.}$) is the difference in the burning velocities between the test gas and the natural gas in the regulated region with the highest burning velocity given above, that is $\Delta S_{L,\ s.m.} = \{S_L(\Phi)(G222) - S_L(\Phi)_{max}^{regulated}\}$. In this case, $\Delta S_{L,\ s.m.}$ shown in Fig. 4 ("safety margin") is 11.5 cm/s. We

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[3] Compare, for instance, the UK Wobbe limits (25 °C, 0 °C): 49.75–54.19 MJ/m³ [42].

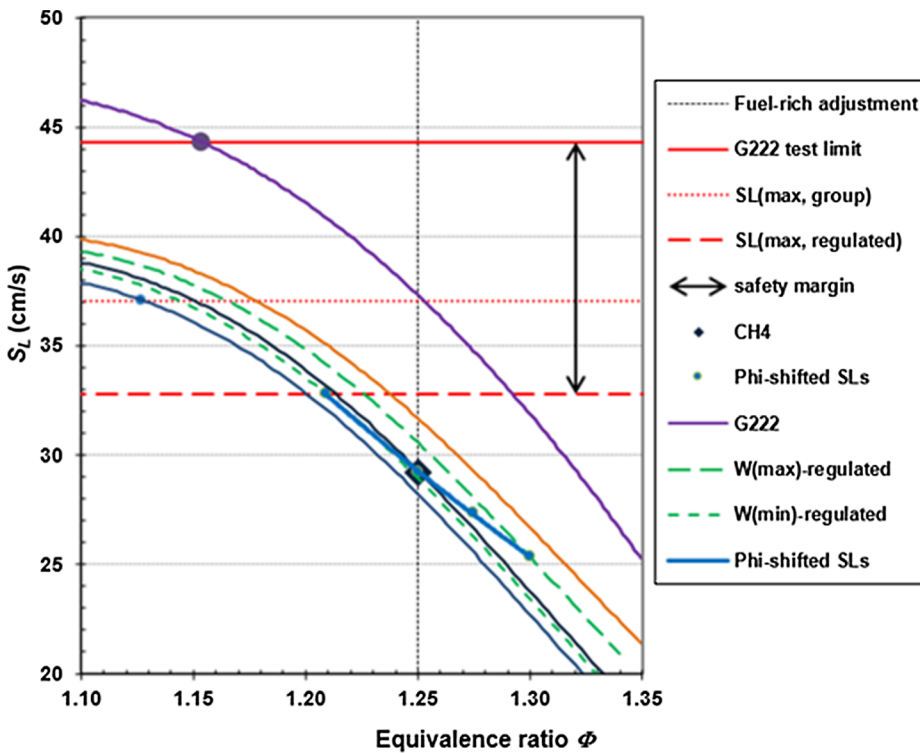**Fig. 4.** Consequences of a national gas regulation set at $51.69\,\text{MJ/m}^3 \leq W^{regulated} \leq 55.56\,\text{MJ/m}^3$ for the flashback propensity expressed in terms of the burning velocity, in the fuel-rich domain. Compared to Fig. 2, trendline curves have been added for the gases at $W_{min}^{regulated}$, $W_{max}^{regulated}$, and for the group H flashback limit gas G222. The Φ-shifted G222 test level is specifically indicated by the large dot. The meaning of the "Phi-shifted SLs" trendline curve, and of the horizontal S_L-levels is explained in the text. Previously introduced gas curves are left out of the legend.

reiterate that the safety margin cannot be derived from examining the Wobbe Indices of these gases but only from the actual changes in burning velocity, the quantity that is responsible for flashback. Thus, we see that consideration of $S_L(\Phi)$ quantifies the relation between the RGQ and the test gas for flashback in a straightforward fashion.

We note that this explicit expression of the safety margin has not been performed previously, which has implications for how individual regulating authorities assess an RGQ for natural gas. For example, the choice of $W_{min}^{regulated} = 49.93\,\text{MJ/m}^3$ (Table 1), rather than

$W_{min}^{regulated} = 51.69\,\text{MJ/m}^3$ as done above, would have been closer to the regulated lower Wobbe limit in the UK. This would have led to an increase in $S_L(\Phi)_{max}^{regulated}$ to 35.5 cm/s, decreasing the safety margin, $\Delta S_{L,\,s.m.}$, to 8.8 cm/s. A decision to extend the RGQ to the lower limit of the group, to $W_{min}^{group} = 48.17\,\text{MJ/m}^3$, increases the maximum burning velocity that appliances would see under the conditions described here to 37.1 cm/s ("SL(max, group)" in Fig. 4), decreasing the safety margin even further. To our knowledge, the potential consequence of expanding the Wobbe range in RGQs on the safety margins
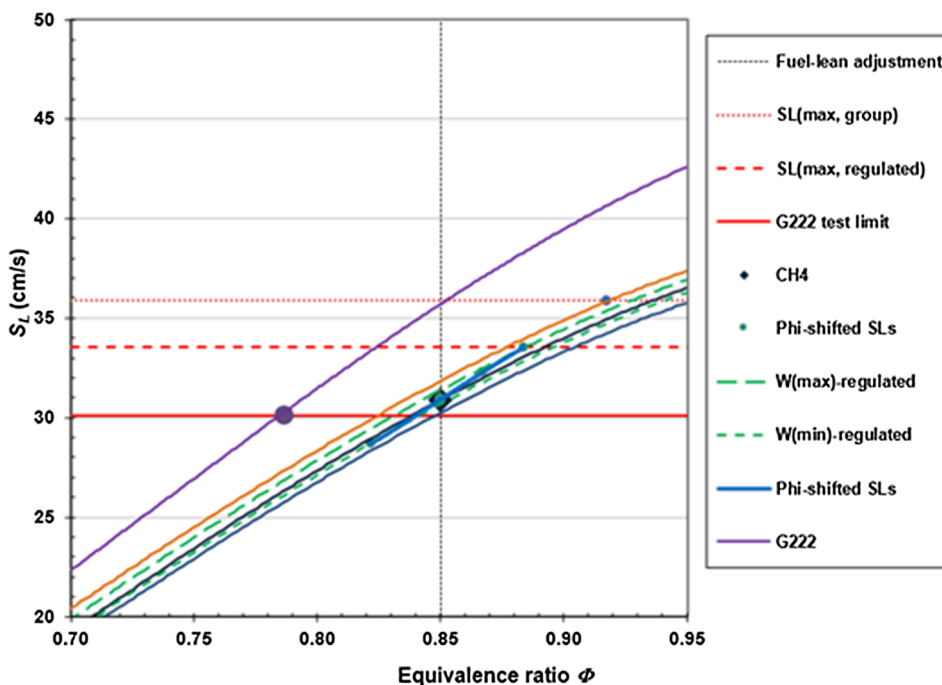

Fig. 5. Consequences of a national gas regulation condition set at $51.69\,\text{MJ/m}^3 \leq W^{regulated} \leq 55.56\,\text{MJ/m}^3$ for the flashback propensity expressed in terms of the burning velocity, in the fuel-lean domain. Compared to Fig. 3, trendline curves have been added for the gases at $W_{min}^{regulated}$, $W_{max}^{regulated}$, and for the group H flashback limit gas G222. The Φ-shifted G222 test level is specifically indicated by the large dot. The meaning of the "Phi-shifted SLs" trendline curve, and of the horizontal S_L-levels is explained in the text. Previously introduced gas curves are left out of the legend.

for flashback have not been considered to date. In the present analysis, we will continue to use the example regulated Wobbe band of 51.69–55.56 MJ/m^3, with a safety margin of $\Delta S_{L, \, s.m.} = 11.5$ cm/s. Clearly, having made the impact of changes in Wobbe Index on burning velocity explicit, the analysis of the potential risks is straightforward.

Because of the decades of experience in applying G222, a successful approval test with this flashback limit gas can be considered to cover flashback-robustness demonstrated in practice for fuel-rich appliances fueled with regulated Wobbe bands of natural gases, $\Delta W^{regulated}$. Considering the lack of quantitative knowledge on the situations occurring in the field that contribute to deciding upon a (national) safety margin, as mentioned in Section 2 [22,26–30], here we are forced to assume that this safety margin is adequate.

The fuel-lean counterpart of Fig. 4 is shown in Fig. 5, spanning the range of equivalence ratio of 0.70–0.95, including data from Fig. 3, above. In this domain, the gas having the highest Wobbe Index will, after allowing for the shift in equivalence ratio, have the highest burning velocity, as illustrated in Fig. 3. Safety margins for flashback in this domain therefore will concern gases in the *upper* part of the Wobbe band.

As was shown in Fig. 3, in Fig. 5, appliance adjustment is at $\Phi = 0.85$ with CH$_4$. Fig. 5 also includes the national part of the "Phi-shifted SLs" trendline in the lean domain. Considering the shift in equivalence ratio, the maximum burning velocity for the 'group' compositions (Table 1) is 35.9 cm/s for the model gas with Wobbe Index $W_{max}^{group} = 57.66$ MJ/m^3 ("SL(max, group)" in Fig. 5), as indicated in Fig. 3. Now, in the national distribution band of Wobbe Index 51.69–55.56 MJ/m^3, the maximum burning velocity for $W_{max}^{regulated} = 55.56$ MJ/m^3, shifted from $\Phi = 0.85$, is calculated to be 33.5 cm/s, indicated as "SL(max, regulated)" in Fig. 5. The lowest point $S_L(\Phi)_{min}^{regulated} = 28.7$ cm/s of the "Phi-shifted SLs" curve is determined by the regulated gas with the minimum Wobbe Index, $W_{min}^{regulated} = 51.69$ MJ/m^3. The variation in burning velocity in this regulated Wobbe range is 4.8 cm/s in the fuel-lean domain.

For G222, the equivalence ratio shifts from 0.85 for methane to 0.787, giving a burning velocity of 30.1 cm/s ("G222 test limit" in Fig. 5); this is lower than the majority of the burning velocities that would obtain in a fuel-lean appliance using the gases within the regulated band. Thus, the test gas G222 does not safeguard against flashback in these appliances. This finding clearly indicates a flaw in current appliance approval.

5. Natural gas/hydrogen mixtures: Appliance approval, gas regulation, appliance development

As indicated in Section 1, the main question is whether existing approval procedures for new appliances and regulated gas quality limits set by (local) authorities will need any change when considering flashback propensity of NG/H$_2$ mixtures. The discussion in Section 4, above, in which flashback is analyzed in terms of S_L, shows that reconsideration of the current procedures and limits is indeed necessary. We perform this analysis below, including a perspective of how to allow for possible higher hydrogen admixtures in the future. Before starting, we emphasize that any possible specific interactions of H$_2$ with materials in domestic appliances (metals, fitting materials) are not considered here.

5.1. RGQ with natural gas/hydrogen mixtures while respecting current gas quality limits

As compared to the pure natural gas situation (Sections 3 and 4), changes in $S_L(\Phi)$ resulting from changing the fuel composition behave quite differently in the case of hydrogen admixture. In the fuel-lean domain, admixing hydrogen to a natural gas up to tens of percent affects the burning velocity only modestly, due to the opposing effect of shifting equivalence ratio and the shift in the {S_L, Φ}-curves to

significantly higher burning velocity with increasing hydrogen content[4] [9]. In the rich domain, however, the shift in equivalence ratio reinforces the effect of hydrogen addition, increasing the burning velocities [9] and the flashback propensity of the fuel considerably.

Many official ranges of natural gas composition, whether designated as RGQ or "group", qualify the "similar burning behavior" [1] that constitutes the allowable range of compositions by a range of Wobbe Index. For hydrogen-containing natural gases, clearly, the range of burning behavior is not covered by the specification of the Wobbe Index alone, as discussed above. The requirement of "similar burning behavior" implies that the burning behavior (here, specifically regarding flashback) of NG/H$_2$ mixtures may not exceed that of the natural gases within the Wobbe range. We designate this situation as "hydrogen admixture while respecting current gas quality limits".

Respecting the current gas quality limits implies maintaining the current safety margin between the gases used in appliance testing and a given RGQ, de facto assuming that the requirements for appliance robustness do not change. In this case, the NG/H$_2$ mixtures have to comply with two simultaneous conditions: for RGQ, that the Wobbe Index of all NG/H$_2$ mixtures remains within the RGQ, i.e., $W_{min}^{regulated} \leq W_{NG/H2} \leq W_{max}^{regulated}$, while the burning velocities of NG/H$_2$ mixtures (after considering the shift in equivalence ratio) must always be below the maximum burning velocity of the natural gases in the RGQ, i.e., $S_L(\Phi)_{NG/H2} \leq S_L(\Phi)_{max}^{regulated}$. These are the boundary conditions assumed in this Section. The resulting RGQs will be shown here to cover *areas* in the space obtained by plotting $S_L(\Phi)$ vs. Φ.

First, we consider the fuel-rich domain, continuing to use the range of fuel compositions in Table 1, above. Adding hydrogen to a number of the natural gases within the RGQ whose burning velocities are shown in Fig. 4, we obtain Fig. 6. Burning velocities were calculated for the mixtures of these gases with hydrogen, but only to the point at which S_L for each initial fuel composition reaches the maximum of the RGQ; the {S_L, Φ}-curves are indicated in the Figure by the points calculated and the associated trendlines. As discussed for natural gases in Section 3, above, each natural gas/hydrogen mixture has its own pseudo-parabolic {S_L, Φ}-curve, and that out of every curve *only the point at the shifted value of the equivalence ratio* is relevant for the analysis. Therefore, the RGQ including hydrogen admixture can be expressed in terms of these specific values of $S_L(\Phi)$ for each of these natural gas/hydrogen compositions. The collection of these specific values for all RGQ natural gases with and without hydrogen fills the RGQ area, indicated as shaded area in Fig. 6.

For all mixtures calculated the Wobbe Index remained above 51.69 MJ/m^3, and therefore within $\Delta W^{regulated}$. In the example in Fig. 6, the maximum hydrogen fraction varies from 0 mol% (lowest Wobbe gas composition, $W_{NG} = 51.69$ MJ/m^3) to 10.3 mol% for the highest Wobbe composition ($W_{NG} = 55.56$ MJ/m^3).[5]

Since the burning velocity was capped at the maximum belonging to the concomitant natural gas RGQ, the analysis automatically maintains

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[4] Fuel-lean appliances having active controls to maintain a constant fuel-air ratio are not considered here because of their minimal market share. However, these appliances respond differently to hydrogen admixture than the majority of fuel-lean appliances [9]. Maintaining a constant equivalence ratio negates the flashback-mitigating effect of shifting equivalence ratio, yielding a significant increase in burning velocity with increasing hydrogen fraction in the fuel. Analysis of this situation is straightforward and should be performed when considering installing such appliances in an area of substantial hydrogen admixture.

[5] Given the definition of a "family" or "group" of gas compositions linked by Wobbe Index and similar burning properties, Fig. 4 demonstrates that the gas G222 does not fall within this definition. The use of G222 as an argument that 23% hydrogen in natural gas is simply 'acceptable' for appliances in the field, even without regard to the actual Wobbe Index of the fuel [18,19], is inappropriate and can increase the risk of flashback for appliances approved using this limit gas.
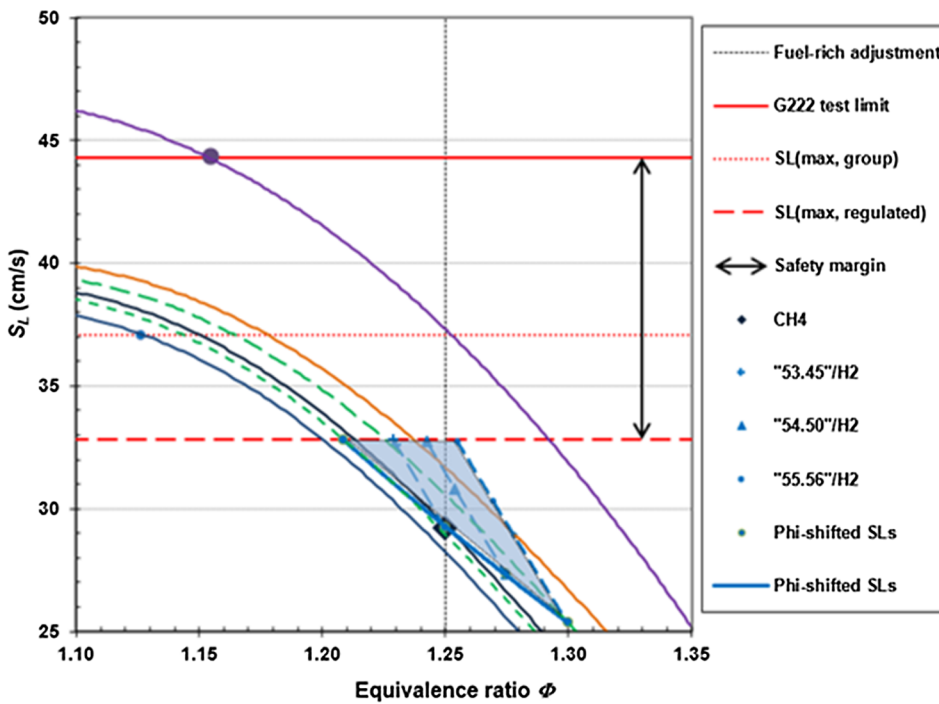
Fig. 6. RGQ set at $51.69 \, \text{MJ/m}^3 \leq W^{regulated} \leq 55.56 \, \text{MJ/m}^3$, in the fuel-rich domain, including natural gas/hydrogen mixtures. The curve "Phi-shifted SLs" represents the regulated variation for the base natural gases. The shaded area represents it for the concomitant mixtures with hydrogen. The Φ-shifted G222 test level is specifically indicated by the large dot. Previously introduced gas curves are left out of the legend.
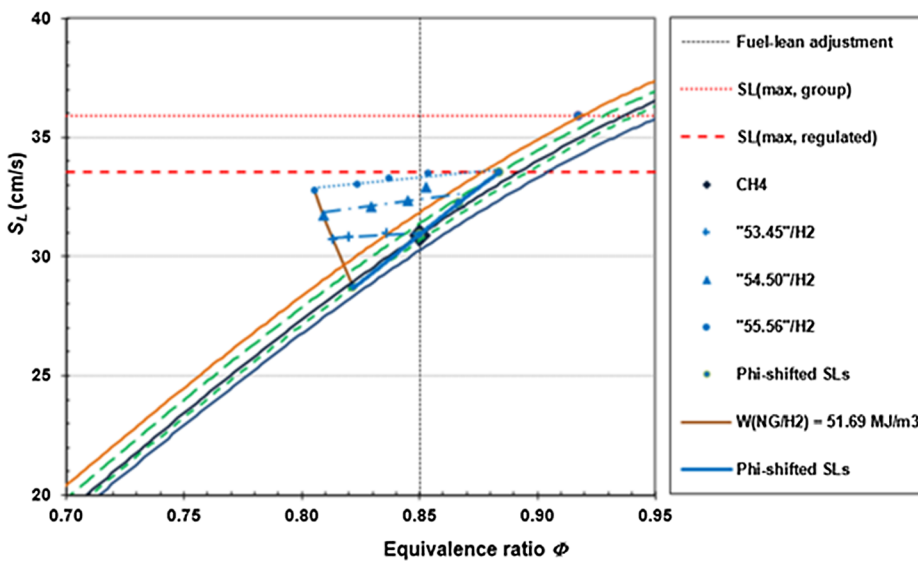

Fig. 7. RGQ set at $51.69 \, \text{MJ/m}^3 \leq W^{regulated} \leq 55.56 \, \text{MJ/m}^3$, in the fuel-lean domain, including natural gas/hydrogen mixtures. The curve "Phi-shifted SLs" represents the regulated variation for the base natural gases. The area representing this variation for the concomitant mixtures with hydrogen is limited by the condition where the Wobbe Index of the mixture equals $W_{min}^{regulated} = 51.69 \, \text{MJ/m}^3$. Previously introduced gas curves are left out of the legend.

the safety margin between the RGQ maximum and the appliance approval test gas, here G222, for all fuel mixtures in the shaded region. Applying this reasoning for any RGQ is straightforward.

Next, consider the fuel-lean domain. Admixing hydrogen to the same base natural gas compositions as in Fig. 6 in the fuel-lean domain extends the results shown in Fig. 5 to those shown in Fig. 7. As mentioned above, the initial hydrogen addition in this domain causes the burning velocity to decrease slightly. In the fuel-lean domain, the Wobbe Index of the NG/H$_2$ mixtures, which decreases with increasing hydrogen fraction, reaches the lower limit of the RGQ before the burning velocity increases (see [9]). Since reducing the Wobbe Index below that of the RGQ will result in loss of fitness for purpose for the end user (thermal input [7]), the lower Wobbe Index (in this example, $W_{min}^{regulated} = 51.69 \, \text{MJ/m}^3$) forms the limitation for hydrogen addition in the fuel-lean domain. It is attained for hydrogen fractions between 0 ($W_{NG} = 51.69 \, \text{MJ/m}^3$) and 25.8 mol% (hydrogen added to $W_{NG} = 55.56 \, \text{MJ/m}^3$); this range of NG/H$_2$ mixtures is shown in the steeply rising curve in the center of the Figure.

As discussed above, there is no adequate safeguard against flashback using a limit gas for fuel-lean appliances in the current approval regime. However, since in the current discussion hydrogen admixture to natural gas in a given RGQ only decreases (modestly) the burning velocity, the absence of a margin for robustness towards flashback does not impact the conclusions drawn.

An overview of the ranges of hydrogen content in the RGQ considered as an example is presented in Table 2. Clearly, the risk of flashback in the fuel-rich domain limits the maximum hydrogen fraction.

The maximum hydrogen fractions in Table 2 for the example RGQ are obtained in the present context of appliance type testing, national gas regulation and safety margins.

Clearly, if one were to assume that the distribution band were the same as the RGQ, then the results of the ensuing interchangeability analysis [9] would yield the same results in terms of range of maximum

Table 2
Possible hydrogen content in the example RGQ.

Regulated Wobbe range:	$\Delta W^{regulated}$: 51.69–55.56 MJ/m^3	
Domain of premixing:	Fuel-lean	Fuel-rich
Φ_{adj}(CH$_4$):	0.85	1.25
limiting condition:	$W \geq W_{min}^{regulated} = 51.69$ MJ/m^3	$S_L(\Phi) \leq S_L(\Phi)_{max}^{regulated} = 32.8$ cm/s
Model natural gas W (MJ/m^3)	Maximum H$_2$ fraction in NG/H$_2$ mixture (mol%)	
51.69	0	0
53.45	13.5	5.3
54.50	20.0	7.8
55.56	25.8	10.3

hydrogen admixture, although without anchoring the relation of the RGQ with appliance testing and safety margins.

5.2. Extended hydrogen fractions in RGQ and appliance approval

Pursuant to the description of the relation between RGQ and the appliance approval regime, summarized for the RGQ in Table 2 in this section we explore the possibilities of increasing the hydrogen admixture for new generations of appliances. Since the fuel-rich domain is the area sensitive to flashback, we examine the possibilities for increasing the hydrogen fractions for the appliances in this domain for the RGQ example, defined in terms of both a range of Wobbe Index and burning velocity, considered above. Since, to our knowledge, there are no gas-adaptive control systems available to prevent flashback and maintain thermal comfort for these appliances, we assume here that the basic design is similar to those currently in practice. As discussed in Section 4, above, practical experience with G222 as a flashback limit gas infers a safety margin of 11.5 cm/s. We first indicate how the plot of burning velocity as a function of equivalence ratio changes when extending the range of hydrogen in this RGQ. Maintaining a safety margin of 11.5 cm/s, we then indicate which gases could serve as flashback limit gases.

We consider two situations, a variable fraction of hydrogen or a fixed admixture.

5.2.1. Variable hydrogen fractions

Here we discuss the changes in burning velocity when allowing the hydrogen fraction admixed to natural gas to vary from 0 to the maximum fraction depending on the Wobbe Index of the natural gas to which hydrogen is being admixed. The situation depicted in Fig. 6 is
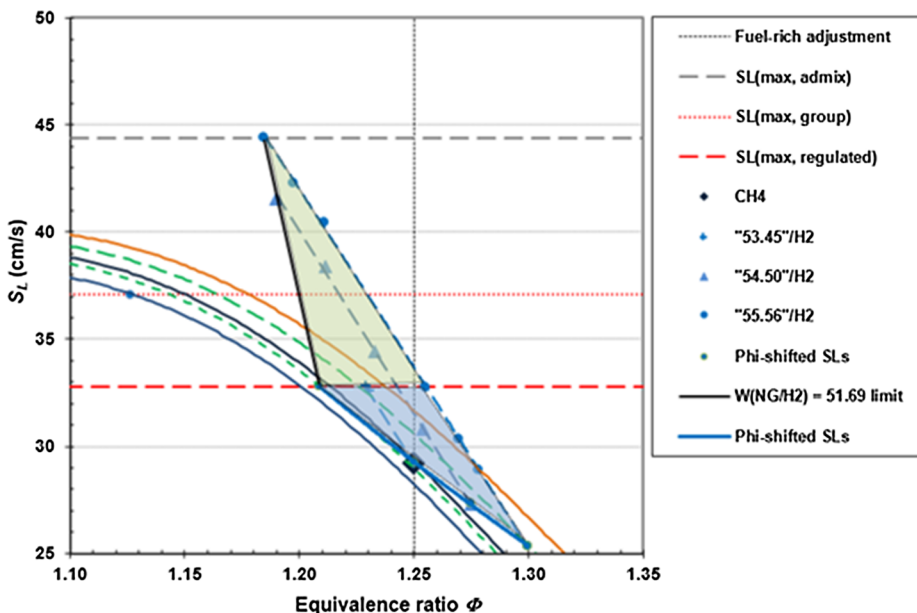
taken as a basis for the case considered here, in Fig. 8.

For the natural gas at $W_{min}^{regulated} = 51.69$ MJ/m^3 any hydrogen admixture would decrease W below this minimum value, which is excluded from consideration due to the loss of fitness for purpose (thermal input). For the other in-band natural gases, $S_L(\Phi)$ has been calculated for all mixtures for which the resulting Wobbe Index is above the minimum of the RGQ, i.e., satisfying $W(NG/H_2) \geq W_{min}^{regulated} = 51.69$ MJ/m^3. The original shaded RGQ area from Fig. 6 is now extended by the pale upper shaded area in Fig. 8. Since the maximum regulated burning velocity, $S_L(\Phi)_{max}^{regulated}$, from Fig. 6 is no longer respected, Fig. 8 does not contain the burning velocity for the limit gas G222 and the safety margin associated with it. The maximum burning velocity for this area of NG/H$_2$ mixtures is $S_{L,\ max}^{admix} = 44.4$ cm/s, for the natural gas with $W_{max}^{regulated} = 55.56$ MJ/m^3, containing 25.8 mol % hydrogen, considerably exceeding the maximum $S_L(\Phi)_{max}^{regulated}$ of Fig. 6. To maintain the safety margin (necessary for lifelong flashback-safe performance) at 11.5 cm/s, a new limit gas would thus have to be defined at 55.9 cm/s.

To determine the CH$_4$/H$_2$ mixture having the right burning velocity, we show the changes in burning velocity for such mixtures, we take the appliance adjustment with CH$_4$ at $\Phi = 1.25$, and calculate S_L as a function of the H$_2$-fraction (mol%), including the shift in equivalence ratio. The results are shown in Fig. 9; S_L as a function of hydrogen fraction is seen to be well represented as linear, $S_L(H_2) = 0.6444 \times$ H$_2$-frac + 29.576. Using this relation, $S_L(H_2)(flashback\ limit\ gas) = 55.9$ cm/s yields the potential limit gas hydrogen fraction of 40.9 mol%.

The challenge is to develop fuel-rich appliances that survive a flashback test with this limit gas, while also being successfully approved with respect to the other combustion characteristics [43]. We mention

Fig. 8. RGQ, from the viewpoint of flashback, in the fuel-rich domain, covering the Wobbe range 51.69 MJ/m$^3 \leq W^{regulated} \leq 55.56$ MJ/m^3.

Admixture with variable hydrogen fractions, allowing $S_L(\Phi)(NG/H_2)$ to exceed $S_L(\Phi)_{max}^{regulated}$, while keeping $W(NG/H_2) \geq W_{min}^{regulated} = 51.69$ MJ/m^3. The original blue-shaded RGQ area from Fig. 6 is now extended by the pale upper shaded area. Indications for previously introduced compositions are left out of the legend for clarity.
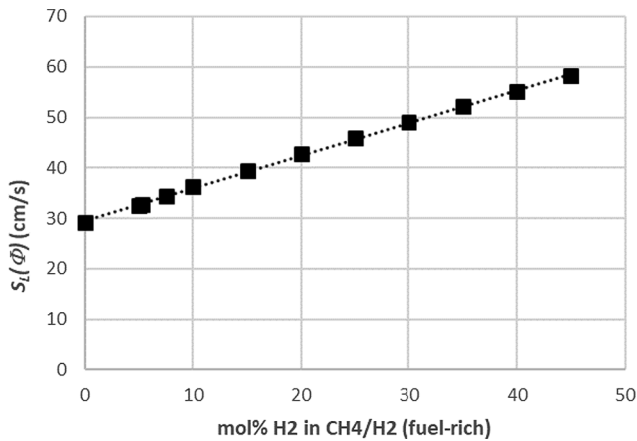
Fig. 9. Burning velocity at shifted Φ vs. hydrogen fraction for potential CH_4/H_2 flashback limit gases and fuel-rich appliance adjustment with CH_4 at $\Phi = 1.25$.

that in the Naturalhy project [4,44] some modern Danish cooking burners were operated during minutes with 40 vol% H_2 in natural gas, without showing flashback. The range of burning velocities between the maximum $S_L(\Phi)_{max}^{regulated}$ of Fig. 6 (32.8 cm/s) and the maximum $S_{L, max}^{admix} = 44.4$ cm/s of Fig. 8 leaves substantial possibilities for an intermediate pale-green area with extended hydrogen fractions being acceptable fuels for appliances to be developed. It can indeed be decided to limit the extended hydrogen fractions in the RGQ to an S_L-level somewhere in between these values, and still obtain a significantly extended RGQ area in combination with future fuel-rich appliances that can be successfully tested.

Although the range of hydrogen fraction can be significantly extended (from a maximum of 10.3% to 25.8%), the Wobbe dependence of the maximum hydrogen fraction is not altered by this exercise: this is a necessary consequence of the changes in equivalence ratio with Wobbe Index of the natural gas, which is then compounded by hydrogen addition.

5.2.2. Constant hydrogen fractions

In this case, an RGQ including hydrogen content is considered that consists of NG/H_2 mixtures with a constant hydrogen fraction, irrespective of the Wobbe Index W_{NG} of the natural gas involved. The Wobbe constraint $W(NG/H_2) \geq W_{min}^{regulated} = 51.69$ MJ/m^3 is still

maintained. The relevance of this option is contingent upon the permanent availability of enough hydrogen, which in many practical situations cannot be guaranteed. Regardless, presenting this option is a useful example of how this situation would work out in practice.

Consider hydrogen fraction fixed at 20 mol%, for which the results are shown in Fig. 10. Since the range of Wobbe Index in the RGQ must still be maintained, 20 mol% H_2 mixtures are only possible with 54.50 MJ/m$^3 \leq W(NG) \leq 55.56$ MJ/m^3. Now only the 20 mol% mixtures with this relatively narrow Wobbe range of natural gases comprise the RGQ, as represented in Fig. 10 by the short solid black line segment with its maximum at $S_{L, max}^{admix} = 41.5$ cm/s. Since 20% hydrogen fraction is assumed always to be present, this small range of NG Wobbe Index maintains, upon hydrogen admixture, the fitness for purpose of the original RGQ without hydrogen. This excludes the other NG compositions, i.e. 51.69 MJ/m$^3 \leq W(NG) < 54.50$ MJ/m^3. We note that this is a drastic limitation of the supply of natural gas compositions that had hitherto been accepted, requiring rejection of these compositions that cannot admit 20% hydrogen. The only way to maintain the original range of fitness for purpose (the RGQ Wobbe range) is to admit the hydrogen via an on/off system, adding 20% only to the range of Wobbe Index 54.50 MJ/m$^3 \leq W(NG) \leq 55.56$ MJ/m^3, while admitting the rest of the NGs without H_2. At the same time, we observe that the burning velocity of NG/H_2 mixtures with $< 20\%$ H_2 for natural gases in the range 54.50–55.56 MJ/m^3 will always be below the maximum. Consequently, in this small range of Wobbe Index de facto 0–20% H_2 admixture is permitted. This should be considered advantageous, since we anticipate that a guarantee of a supply of 20% H_2 will not be realistic.

Thus, while the notion of admixture of a constant H_2 fraction seems "simpler" than variable, the implied grid operation is not simple.

Despite these complications in grid operation, we illustrate the consequences of this scenario for limit gases in appliance approval. The 20% admixture situation would require a flashback limit gas having a burning velocity 53.0 cm/s (to maintain the 11.5 cm/s safety margin as done above), implying a potential CH_4/H_2 limit gas with a hydrogen fraction of 36.4 mol%. Lowering the constant hydrogen fraction widens the range of applicable natural gas Wobbe Index ΔW_{NG}, while decreasing the maximum burning velocity $S_{L, max}^{admix}$ attained, and reducing the hydrogen fraction needed in the associated limit gas, as shown in Table 3.

Clearly, a constant hydrogen fraction while maintaining the original RGQ Wobbe range does not simplify the grid management complexity. This can be alleviated by relaxing the Wobbe constraint for $W(NG/H_2)$
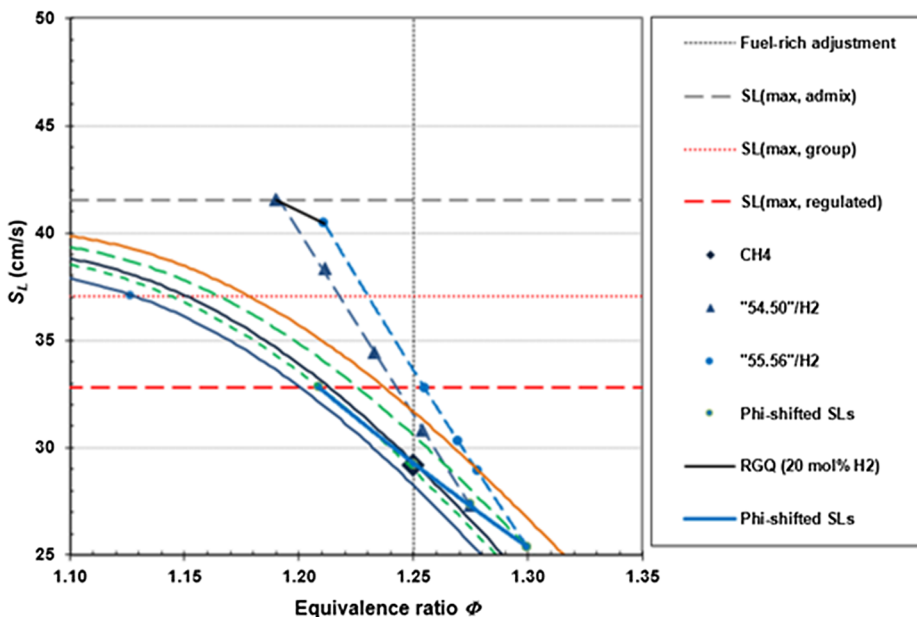

Fig. 10. RGQ, from the viewpoint of flashback, in the fuel-rich domain, and a national gas regulation condition set at 51.69 MJ/m$^3 \leq W^{regulated} \leq 55.56$ MJ/m^3. Hydrogen fraction constant at 20 mol%, allowing $S_L(\Phi)(NG/H_2)$ to exceed $S_L(\Phi)_{max}^{regulated}$, while keeping $W(NG/H_2) \geq W_{min}^{regulated} = 51.69$ MJ/m^3. The concomitant RGQ is represented by the short solid black line segment with its maximum at $S_{L, max}^{admix} = 41.5$ cm/s. Indications for previously introduced items are left out of the legend.

Table 3
RGQ with constant H$_2$ fraction.

H$_2$ in NG/H$_2$ (mol%)	ΔW_{NG} (MJ/m^3)	$S_{L,\,max}^{admix}$ (cm/s)	H$_2$ in CH$_4$/H$_2$ limit gas (mol%)
5	52.32–55.56	34.9	26.1
10	53.00–55.56	37.1	29.5
20	54.50–55.56	41.5	36.4

and allowing the RGQ to include NG/H$_2$ mixtures with a constant hydrogen fraction for all natural gases in the regulated band 51.69–55.56 MJ/m^3. However, as mentioned above, this would compromise the level of thermal comfort for the end user by letting $W(NG/H_2)$ to decrease below $W_{min}^{regulated}$, which is currently not considered acceptable. Despite this, it is useful to calculate the size of the loss of thermal comfort. Constant hydrogen fractions of, respectively, 5, 10 or 20 mol% in a mixture with $W(NG) = W_{min}^{regulated} = 51.69$ MJ/m^3 result in $W(NG/H_2) = 51.08$, 50.47 or 49.26 MJ/m^3, respectively, implying a loss of thermal input of 1.2%, 2.4%, or 4.7%, respectively. These options could be taken into account by the regulatory authorities, grid operators and consumers, to facilitate uptake of renewable hydrogen in the grid while greatly simplifying grid management.

6. Conclusions

In this paper, we show that reframing the definition of a regulated range of gas quality (an RGQ), traditionally expressed by a range of Wobbe Index, in terms of burning velocities allows the unambiguous assessment of maximum hydrogen fractions in a given RGQ. Assessing the differences in burning velocity between those of the RGQ and the test gas for flashback in appliance approval standards, which here is taken as an empirically accepted safeguard, permits the definition of a safety margin for flashback. Maintaining this safety margin, we demonstrate how new test gases can be defined to increase the maximum hydrogen fraction in a given RGQ, for both variable and fixed hydrogen fractions. A significant consequence of this analysis is that, when considering the minimum Wobbe Index in an RGQ as an inviolable limit, hydrogen addition to any extent is always dependent upon the composition of the natural gas to which it is added: either the fraction itself depends on the Wobbe Index of the gas, or, for a 'constant' fraction, this fraction of hydrogen can only be added to a limited range of gas compositions – the higher the fraction, the narrower the range. Thus, rigorously following the simultaneous requirements of burning velocity and thermal comfort results in complex grid management.

The only way to maintain safety and ease the complexity of grid management is to sacrifice the requirement on thermal comfort; a truly fixed fraction 5, 10 or 20 mol% of hydrogen across the entire RGQ used as an example in this paper results in 1.2%, 2.4%, or 4.7% reduction in thermal input to a domestic appliance, respectively. While easily achievable, the relevant stakeholders must agree to this loss of fitness for purpose for the possibility of enhancing the sustainability of natural gas as a fuel.

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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