SAFE OPERATION OF NATURAL GAS APPLIANCES FUELED WITH HYDROGEN/NATURAL GAS MIXTURES (PROGRESS OBTAINED IN THE NATURALHY-PROJECT)

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ABSTRACT

Considering the transition towards the hydrogen economy, dependent on hydrogen penetration scenario, the cost of a new hydrogen pipeline infrastructure in Europe may amount to several thousands of billions of EURO's. Therefore, the examination of the potential contribution of the existing natural gas assets is a practical and logical first step. As the physical and chemical properties of hydrogen differ significantly from those of natural gas, it is not at all possible to simply exchange natural gas by hydrogen in the existing infrastructure. In this paper first a brief overview will be given of the NATURALHY-project. Further the focus will be on the impact of added hydrogen on the performance of existing natural gas domestic end user appliances, which is related to the operation of the natural gas grid connecting the different types of appliance. The application of the fundamental insights and carefully designed experiments, comparing the behaviour of gases using justified reference conditions, have been shown to offer essential progress. The Wobbe index limits of the natural gas distributed pose a first limiting factor upon the maximum allowable hydrogen concentration. Constant-Wobbe index and decreasing-Wobbe index options of H_2 admixture have been studied. Considering the appliance light back H_2 limiting factor for domestic appliances, fuel-rich appliances are the critical ones. Also taking into account stationary gas engines, gas turbines, industrial applications and natural gas grid management, it is *not yet* justified to present statements on what level of hydrogen concentration could be safely allowed in which specific natural gas distribution region. But more clarity has been obtained on combustion safety aspects of existing domestic appliances, on the connection with Wobbe distribution conditions and on the bottlenecks still to be handled.

1.0 THE NATURALHY PROJECT

The project "Preparing for the hydrogen economy by using the existing natural gas system as a catalyst (NATURALHY)" is the main European project on H_2 delivery that aims to provide the natural gas industry with the necessary information to enable the sector to accommodate hydrogen in the existing natural gas grid with acceptable consequences. The project has been selected by the European Commission for financial support under the sixth Framework Programme, and has been recognised by the International Partnership for the Hydrogen Economy (IPHE). As the physical and chemical properties of hydrogen differ significantly from those of natural gas, it is not at all possible to simply exchange natural gas by hydrogen in the existing natural gas system. However, using the existing system to transport mixtures of natural gas and hydrogen would offer the possibility to accommodate significant volumes of hydrogen and a unique opportunity to connect hydrogen producers and end users on the short term and at relatively low cost. These mixtures would have to be used as such in the existing natural gas appliances but the mixtures could also be used to supply high purity hydrogen to hydrogen end users by applying membranes to split the gas stream near the end user. At least during the transition phase leading to the situation when hydrogen becomes an important energy carrier, the latter option is interesting and will promote public acceptance of hydrogen due to the excellent safety record of the natural gas industry. It will also catalyse developments in hydrogen production and end use, and will give more time to define the future energy system and the requirements in sufficient

detail. In this respect the competition of hydrogen with other sustainable energy carriers including large volumes of mainly methane containing biogas will be of particular importance.

The changing gas properties upon admixing hydrogen will have major effects on:
• the safety aspects related to the transmission, distribution and end use of the gas;
• the durability of the transmission and distribution pipeline systems and of the end user infrastructure (hydrogen may diffuse into materials and change the mechanical properties);
• the gas quality management issues related to the gas delivery;
• the performance of end use appliances;
• the effectiveness of current standards and regulations.

The main objectives of the NATURALHY project are: Preparing for the hydrogen economy by:
• identifying and removing the potential barriers inhibiting the development of hydrogen as an energy carrier, using the existing natural gas system as a catalyst for change;
• initiating the near-future practical transition towards the hydrogen economy.
More specifically:
• to define the conditions under which hydrogen can be added to natural gas in the existing natural gas system (transmission-distribution-end use infrastructure and appliances) with acceptable safety risks, impact on the integrity of the system and consequences for gas quality management and to the end user. The main technical deliverable of the project concerns an expert system (called the "Decision Support Tool") that determines the maximum percentage of hydrogen that can be added to natural gas supplied in a given section of a natural gas pipeline system and identifies the factors that limit the percentage;
• to develop techniques (membranes) to separate hydrogen from hydrogen/natural gas mixtures;
• to assess the socio-economic and Life Cycle aspects of the NATURALHY approach.

The following work packages, consisting of several coherent tasks, were defined (each shown with its work package leader):
• Socio-economic and Life Cycle Analysis (Loughborough University)
• Safety (Loughborough University)
• Pipeline durability (Gaz de France)
• Pipeline integrity (DBI-Gut)
• End Use and membranes (Oxford University)
• Decision Support Tool (ISQ)
• Dissemination (Exergia)
• Project Management (N.V. Nederlandse Gasunie)

The NATURALHY project, with 39 organisations participating, started on May 1st , 2004. Its duration will be 5 years. The total project budget amounts to 17.3 M€ .

For more information please consult the project website [1], and the other papers on NATURALHY work presented at this conference.

In this paper we particularly focus on the impact of admixing hydrogen to natural gas as connected to the performance of domestic end user appliances. Actually this paper necessarily contains just a part of our work in the work package End Use as it will be reported in the NATURALHY deliverable concerned. We do not take into account any limitations on hydrogen addition as posed by, for instance, durability and integrity requirements of natural gas network elements.

2.0 COMMON SAFETY PRACTICE IN NATURAL GAS APPLICATION, AND HYDROGEN

Just admitting, say, 20 or 30 percent hydrogen to an existing natural gas network could threaten personal safety and cause equipment damage for end users. The combustion phenomena causing these effects upon hydrogen addition are light back and spontaneous (undesired) ignition. Domestic appliances and lean-premixed gas turbines are particularly sensitive to light back, that is, unstable

combustion and the escape of fuel gas, while the flame tends to enter the burner causing overheating and damage. Spontaneous (undesired) ignition can occur in gas turbines as well as in gas engines and causes serious damage. Thus a thorough consideration of these phenomena is needed in order to understand the extent to which all existing appliances, which are set up to work with the present range of pipeline natural gases, can cope with the admixture of hydrogen.

Common practice in developing safely operating *new* natural gas *appliances* is taken as a starting point. This includes the EEC Gas Appliances Directive (GAD) [2] and the classification of test gas groups (EU Harmonised Standard EN437 [3]) and distribution gases according to their Wobbe index (gross calorific value divided by the square root of the relative density) values. The GAD applies to gas-fired appliances used for cooking, heating, hot water production, refrigeration, lighting or washing. Admixing hydrogen means the introduction of *new gases* to *existing* appliances. This poses the issue of the interchangeability of gases. Considering this issue in an international perspective, empirically based national methods are of limited value. Therefore the actual *fundamental* understanding of combustion phenomena is applied. Laminar burning velocities, adiabatic flame temperatures, methane numbers and ignition delay times of the gas mixtures have been considered. Essential in this context is the operational fuel/air ratio of an appliance. Along these lines the impact of the hydrogen addition on the performance of existing natural gas appliances has been evaluated in the framework of the NATURALHY project. This paper will focus on domestic appliances, where light back is the potential problem upon H_2 admixture. In this respect, it is important to realize that with domestic appliances personal health and safety at home are at stake, large numbers of appliances are involved, and information on (types, years in use, maintenance record) appliances in use in each house is quite limited.

Basic fuel gas properties needed here are the *relative density* d and the *gross calorific value* H_s. The relative density d is defined as the ratio of the masses of equal volumes of dry gas and dry air under the same conditions of temperature and pressure: 0 °C and 1013.25 mbar [3]. The gross calorific value H_s is defined as the quantity of heat produced by the complete combustion, at a constant pressure equal to 1013.25 mbar, of a unit volume or mass of gas, the constituents of the combustible mixture being taken at reference conditions and the products of combustion being brought back to the same conditions and where the *water* produced by combustion is assumed to be *condensed* [3]. In this work H_s is expressed in megajoules per cubic metre (MJ/m^3) of dry gas under the reference conditions. Often two reference temperatures are specified, denoting the thermodynamic reference temperature for combustion, and the gas volume (metering) reference temperature, respectively. In this work, these reference temperatures are (25 °C, 0 °C). The main combustion related property as it is used in the natural gas industry, is the *Wobbe index* W. It is defined according to [3]:

$$W = H_s / \sqrt{d} ,$$ (1)

where W – Wobbe index, (25 °C, 0 °C) MJ/m^3; H_s – gross calorific value, (25 °C, 0 °C) MJ/m^3; d – relative density, (0 °C) dimensionless.

The reason that in European countries W was taken to be the main combustion related property is the fact that W indicates *the effect of gas composition changes on appliance heat input with a constant pressure gas supply and is especially useful in comparing gaseous fuel mixtures* [4]. This generally applies to domestic appliances upon interchanging natural gases as well as upon admixing H_2.

In order to facilitate market access, "Harmonised Standards" provide a presumption of conformity with the GAD. About 70 standards on appliances and fittings have been published in the Official Journal of the European Union. Among these standards is the already mentioned EN437; this standard plays a central role here as it links gas compositions to appliances. It defines gas families and gas groups as classified according to their W values. Natural gases comprise the 2nd family, with groups H, L and E having the W value (25 °C, 0 °C) (MJ/m^3) ranges shown in Table 1. For each group a reference gas is defined as well as a series of "limit gases". These limit gases are necessary as

considering just W is insufficient to characterize the combustion properties of a gas concerning its safe use in an appliance. Limit gases have been defined for the following safety threatening phenomena: incomplete combustion and sooting, burner overheating, light back (flashback) and flame lift (blow-off). Specific tests for specific appliance types are described in the specific Harmonised Standard for that type of appliance. *Test conditions* are prescribed applying the test gases defined in EN437 for the gas family(ies)/ group(s) matching the category the appliance belongs to.

Table 1. EN437 second family (natural gases)

	Wobbe index (25 °C, 0 °C) (MJ/m^3) range
Group L	41.21----------------------47.22
distribution NL	43.46---44.41
Group H	48.17----------------------------57.66
distribution UK	49.75--------------54.19
Group E	43.11--57.66

These appliance tests are *short term tests* (minutes, hours) of *new appliances*: they *only cover type testing*. The reference gas of the appropriate group is used with the appliance operating under *nominal conditions* (the nominal heat input and nominal output are the heat input and useful output as stated by the manufacturer, expressed in kilowatts (kW)). Using the limit gases the extreme variations are tested of the characteristics of the gases for which the appliance is designed, *during this short term type testing*. When an appliance is type tested accordingly, and as long as it is "normally used" ("correctly installed and regularly serviced in accordance with the manufacturer's instructions"), the appliance is supposed to "operate safely and present no danger to persons, domestic animals or property". However, in practice since the type testing, appliance design and production changes cannot be ruled out, the manufacturer's instruction can be inadequate as can be the appliance installation and servicing while also the appliance will show wear, ageing and fouling. For these reasons considering the *user conditions*, in national situations a Wobbe range of the distribution gas is chosen to be narrower than the Wobbe range of the corresponding test gas group, the width of the *safety margins* being subject to national considerations: $W_{min}^{group} < W_{min}^{distr} \leq W_{NG} \leq W_{max}^{distr} < W_{max}^{group}$. Examples for The Netherlands and the UK are shown in Table 1. In this way safety risks of appliances showing deviating behaviour as compared to their original type testing are assumed to be minimized to a justified level.

The common practice just described illustrates the necessity to consider appliance operation and the operational (Wobbe) control of the natural gas grid in close connection to each other. During the process of designing the standards mentioned the empirical fact that the amount of hydrogen in natural gas is negligible was taken for granted and therefore not given much attention. In the present context it is of importance to explicitly state that *the amount of hydrogen in natural gas is negligible*. Just admixing H_2 to natural gas causes its W value (and appliance heat inputs) to decrease:

$$W_{NG/H2} < W_{NG} \qquad \text{(at least up to } \sim 90\% \text{ H}_2 \text{ for all natural gases) .} \tag{2}$$

This immediately poses a first limiting factor upon the maximum allowable hydrogen concentration $[H_2]_{max}$, as the NG/H$_2$ mixture still has to obey the distribution condition:

$$W_{min}^{group} < W_{min}^{distr} \leq W_{NG/H2} . \tag{3}$$

Therefore, a $[H_2]_{max}$ limit is reached when $W_{NG/H2}$ reaches the prevailing distribution minimum: $W_{NG/H2} = W_{min}^{distr}$.

3.0 DOMESTIC APPLIANCE OPERATION

The state-of-the-art fundamental understanding of combustion processes was applied instead of considering large numbers of appliance test results. This includes fundamental chemical kinetics calculations as well as experimental results where gases were compared with gases applying reference conditions for the relevant safety aspects, taking distribution limits W_{min}^{distr} / W_{max}^{distr} as a justified basis for these reference conditions. Modern domestic appliances are of the fuel/air premixed type, as schematically shown in Fig. 1. The essential combustion determining appliance operational property is the primary equivalence ratio Φ_{prim} of the fuel/air mixture as it arrives at the flame front.
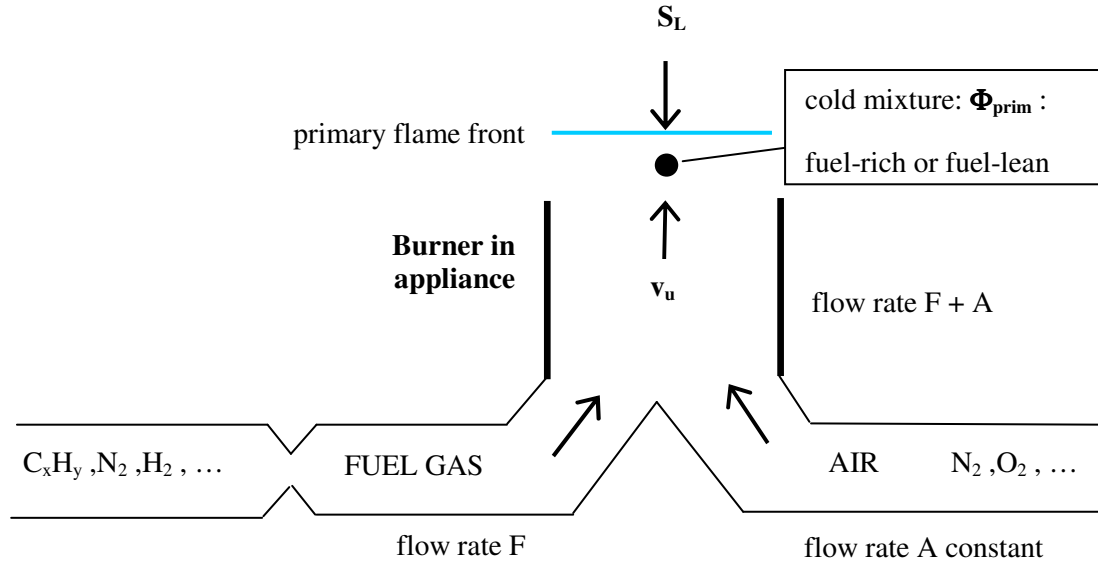

Figure 1. Schematic representation of premixed appliance combustion. Further explanation in the text.

Φ_{prim} can be written as the actual fuel/air ratio as a fraction of the stoichiometric fuel/air ratio:

$$\Phi_{prim} = (F/A) / (F/A)_{stoich} , \tag{4}$$

where F – fuel flow rate, m^3/s; A – air flow rate, m^3/s.

Essential is the behaviour of Φ_{prim} upon changing the fuel gas composition, such as admixing H_2 to natural gas. In this respect, practically all domestic appliances can be characterized as "*constant fuel gas pressure, constant air flow rate*". This will be the assumption from now on; different situations could be evaluated using the same methods, although the outcomes might be considerably different. The fundamental distinction is the one between fuel-rich (partially premixed) and fuel-lean (fully premixed) appliances. In the fuel-rich case ($\Phi_{prim} > 1$) a partial combustion can occur in the primary flame front, whereupon the combustion is completed using secondary air provided downstream. In fuel-lean appliances ($\Phi_{prim} < 1$) the mixture already contains sufficient air to supply complete combustion in the (primary) flame front. The (primary) flame front is the important region in the combustion process: steep gradients of combustion reactant and product concentrations, and of the temperature. A stable flame front downstream of the burner is basic to appliance safety. Under the operational conditions mentioned, upon changing the fuel gas composition, Φ (omitting the subscript 'prim' from now on) can be shown to change (shift) from Φ_1 to Φ_2 according to:

$$\Delta\Phi = \Phi_2 - \Phi_1 = \Phi_1 \times [\{ (L_{dV2} \times \sqrt{d_1}) / (L_{dV1} \times \sqrt{d_2}) \} - 1] , \tag{5}$$

where L_{dV} – volumetric stoichiometric (dry) air requirement of fuel gas mixture, m^3/m^3.

Upon H_2 admixture the Φ-shift is in the fuel-lean direction: $\Delta\Phi = \Phi_{NG/H2} - \Phi_{NG} < 0$.

In domestic appliances the flow of the burning mixture is largely laminar. The stable flame front requires the condition:

$$S_L = v_u \quad \text{(for their absolute values)}, \tag{6}$$

where S_L – laminar burning velocity (the burning of freely burning premixed laminar flat flames into the unburnt fuel/air mixture), cm/s; v_u – unburned gas velocity, cm/s. In flat flames (Fig. 1) both velocities are directed oppositely; this is a very useful model situation considering combustion in domestic appliances.

The safety risk of *light back* appears when everywhere in the flow in the flame front the burning velocity exceeds the unburned gas velocity: $S_L > v_u$: the flame will propagate upstream into the burner. The high S_L value of pure hydrogen is well-known; S_L values were calculated using the CHEMKIN software suite [5]; S_L of a stoichiometric hydrogen-air mixture is 5.6 times higher as compared to that of a stoichiometric methane-air mixture. The risk of light back upon admixing H_2 will be discussed for fuel-rich and fuel-lean domestic appliances. Actually, in this respect, considering CH_4/H_2 model mixtures provides results that can be applied to NG/H_2 mixtures to a sufficient degree of accuracy for the present purposes. A basic result is shown in Fig. 2.
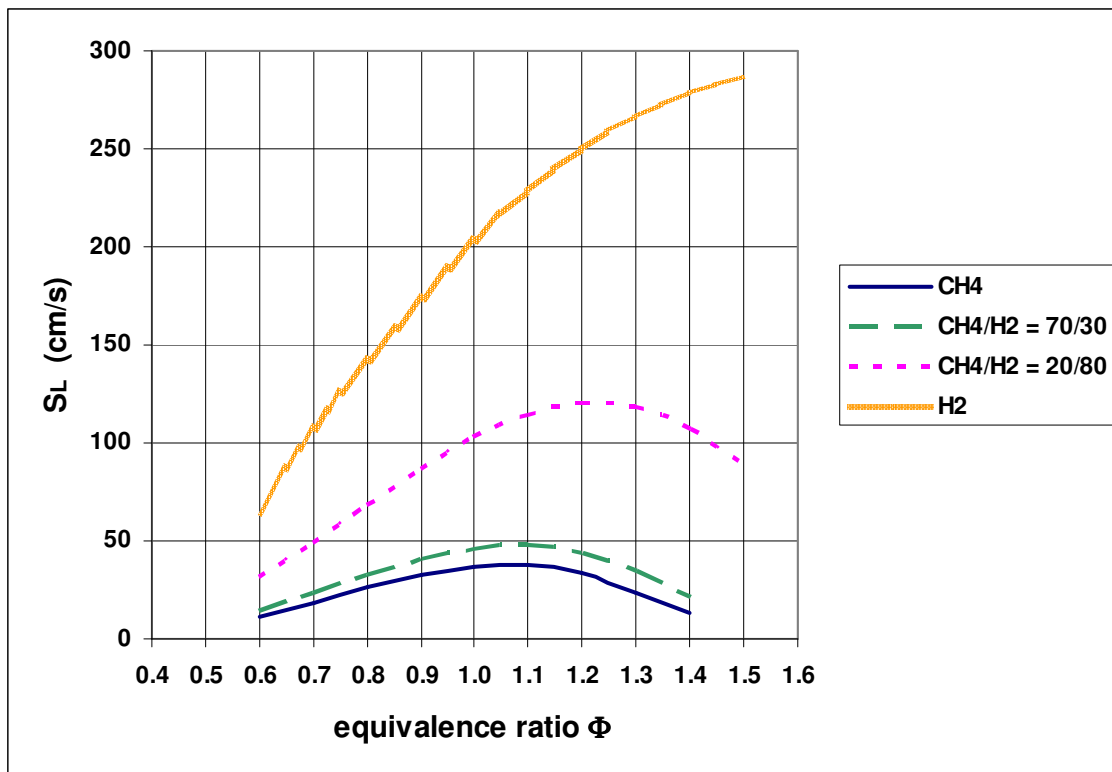

Figure 2. S_L of some CH_4/H_2 fuel gas compositions as a function of Φ.

Up to about 30% H_2 S_L increases very slowly for all Φ values considered. For higher H_2 content the compositional S_L increase for constant Φ conditions shows a large increase, especially towards higher Φ values. It also becomes clear that in situations of small compositional changes in combination with a *changing* Φ value the S_L value can change predominantly by this Φ shift.

3.1 Fuel-lean and fuel-rich appliances

The effect of this Φ-shift $\Delta\Phi$ on the amount of S_L change ΔS_L, in addition to the purely compositional ΔS_L, upon admixing H_2 to the CH_4 fuel under these operational conditions is shown in Fig. 3 for a *fuel-lean* appliance. A large part of modern domestic heating boilers is of the fuel-lean type (punched metal burners, radiant plaques).
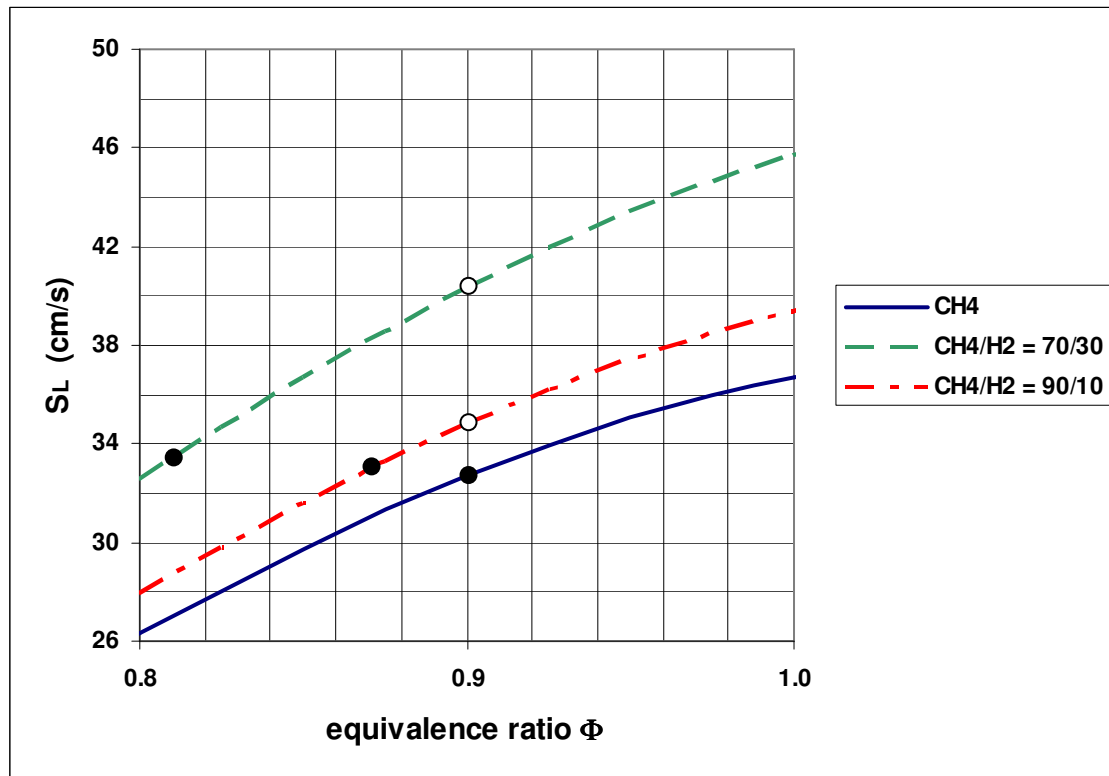

Figure 3. ΔS_L upon admixing 10% or 30% H_2 to the CH_4 fuel when the purely CH_4 fueled appliance operated at $\Phi_1 = 0.9$. Closed circles indicate the Φ-shift effect, open circles indicate the S_L increase neglecting the Φ-shift.

Considering Fig. 3, without the Φ-shift, for a $CH_4/H_2 = 90/10$ mol%/mol% mixture S_L would increase by 2 cm/s compared to using the pure CH_4 fuel. Including the Φ-shift this S_L increase amounts to less than 0.5 cm/s. For a $CH_4/H_2 = 70/30$ mol%/mol% mixture the constant-Φ S_L increase would be about 7.5 cm/s, while including the Φ-shift this only amounts to less than 1 cm/s. A similar effect will apply up to even higher values of mol% H_2. Thus up to about 30-40 mol% H_2 the S_L increase by changing the fuel composition will be largely *compensated* by the effect of the simultaneously changing operational Φ value. For still higher H_2 admixture the Φ-shift will even be higher, but its effect on S_L can no longer compensate the compositional S_L increase.

In the complex reality in a stable flame at different positions in the flame front an equilibrium exists between (projections of) the local unburned gas velocity and the burning velocity. The light back propensity of real burners depends very much on the precise construction of its burner ports. Practical situations cannot simply be treated in terms of "the" unburned gas velocity v_u. Still, a manageable and sufficiently reasonable approximation of it is needed for a meaningful description of light back propensity. The volume flow rate of the primary air/fuel mixture entering the burner can be thought of as the mathematical product of the cross-sectional area of a (mixing) tube and some average flow velocity of the mixture. Therefore, a changing volume flow rate simultaneously means a changing mixture flow velocity. This flow velocity of the mixture approaching the burner deck or burner ports

will be assumed to be proportional to the local flame front unburned gas velocities to a good approximation. Then, these velocities also will be proportional to the volume flow rate (F + A) of the primary air/fuel mixture. This is an important finding as it facilitates the definition of *(F + A)/S_L as a relative measure of light back propensity*, whereby in turn light back propensities of different fuel gas compositions can simply be compared. Results for a fuel-lean appliance are shown in Fig. 4. The effect of the (F + A) flow rate changes is small compared to the effect of the changes of S_L.
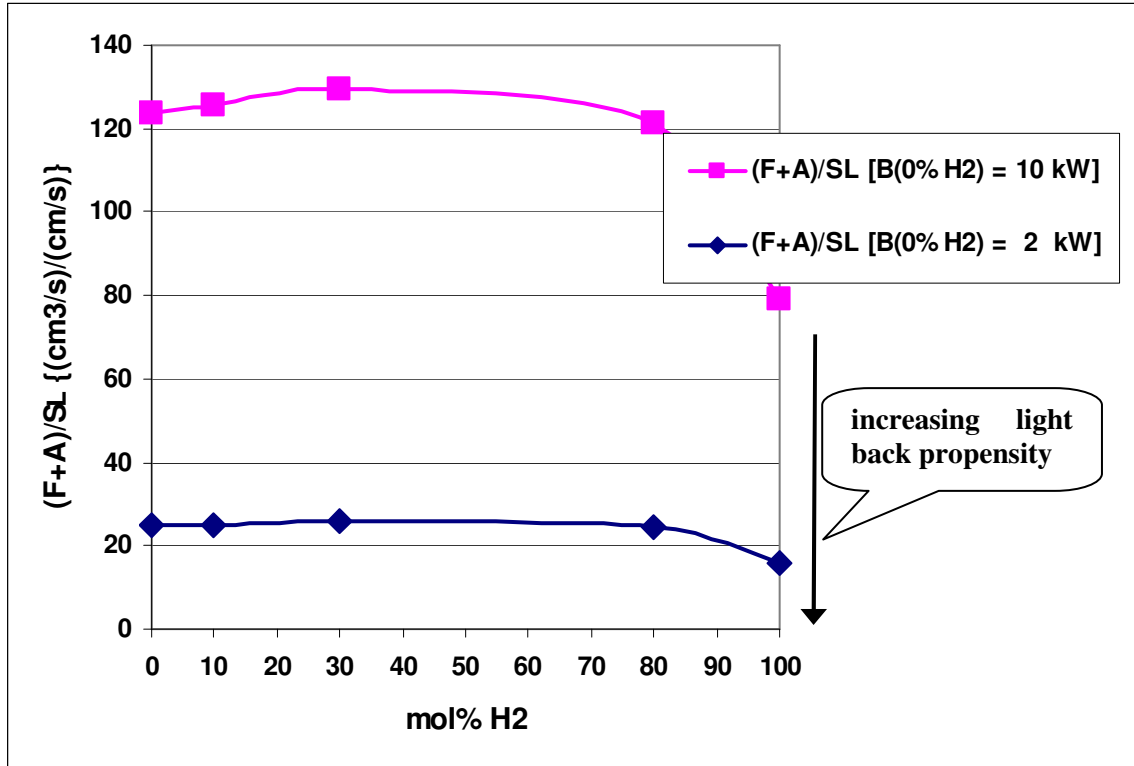

Figure 4. *Relative* light back propensity upon admixing H_2 to the CH_4 fuel when the purely CH_4 fueled appliance operated at $\Phi_1 = 0.8$, for two values of the initial thermal load B. Calculations were performed for mol% H_2 equal to 0, 10, 30, 80 and 100; the connecting curves are meant as a guide to the eye.

It thus turns out that the S_L changes as determined by the compositional changes and by the Φ-shift are the major factor determining the light back propensity in these appliances.

It can be concluded that, thanks to the Φ-shift, for fuel-lean well operating "constant fuel gas pressure, constant air flow rate" appliances light back problems upon admixing hydrogen to the natural gas fuel will fail to turn up, up to amounts in the order 50% H_2. For H_2 contents higher than 70% to 80% this may no longer be the case. Real values will depend on the real operating Φ value and the maintenance condition of the appliance as well as on the precise composition of the natural gas used. Actually, in a separate Naturalhy task, using natural gas in Denmark, new modern residential fuel-lean gas boilers were tested in this respect [6]. The tested boilers were of the "constant fuel gas pressure, constant air flow rate" type. Provided the boiler shut-downs at ~80% H_2 were indeed caused by light back, these test results are in excellent agreement with our theoretical conclusions.

At this point, the $[H_2]_{max}$ limiting factor posed by the natural gas distribution condition (Equation (3)) has to be kept in mind. For the Danish example, the condition $W_{NG/H2} = W_{min}^{distr\ DK}$ was reached at ~20 mol% H_2.

Under *fuel-rich* conditions the Φ-shift effect on S_L *amplifies* the compositional S_L increase. Fuel-rich appliances are, for instance, cooking appliances, hot water heaters and a part of the central heating boilers. For these appliances, the line of reasoning as just described yields the following results. *Without the Φ-shift fuel-rich appliances would already show a considerably increased light back propensity upon admixing hydrogen to the natural gas fuel as compared to fuel-lean appliances. Including the Φ-shift makes the different sensitivity towards light back between fuel-rich and fuel-lean appliances very pronounced. Properly adjusted and functioning fuel-rich appliances might show problems even at H_2 fractions lower than 10% !* Again, real values will depend on the real operating Φ value and the maintenance condition of the appliance as well as on the precise composition of the natural gas used.

3.2 Appliances and grid operation: search for $[H_2]_{max}$

The $[H_2]_{max}$ limitation imposed by light back for fuel-rich appliances could at least partly be lifted when the Φ-shift could be limited to a great extent. It turned out that if, when admixing H_2 , W could be kept constant (by, for instance, simultaneously adding C_2H_6 or C_3H_8) the appliance operational Φ-shift can be minimized. This leaves only the compositional S_L increase upon H_2 addition. Model calculations (simultaneously adding H_2 and C_3H_8 to CH_4 , keeping W constant) showed this to be a possibility: the Φ-shift was reduced by a factor of more than 4. However, this way of mixing is limited in itself as the propane concentration $[C_3H_8]$ should remain at values normally encountered in natural gases in order to prevent different problems, like engine-knock in gas engines. This will limit the possibility of *constant-W H_2 admixture* to values of ~30% H_2 , leaving technical and economical implications still out of consideration.

As mentioned before for *constant fuel gas pressure, constant air flow rate* appliances, simply admixing H_2 to natural gas causes both its W value and the appliance operational Φ value to decrease. At this point we will call this the *decreasing-W H_2 admixture* option.

Please note the central role of the fuel gas mixture Wobbe index:
→W indicates the effect of gas composition changes on appliance heat input with a constant pressure gas supply and is especially useful in comparing gaseous fuel mixtures;
→W is the natural gas grid control parameter: $W_{min}^{group} < W_{min}^{distr} \leq W_{NG} \leq W_{max}^{distr} < W_{max}^{group}$;
→W could be used as H_2 admixture control parameter: *constant-W* or *decreasing-W* ;
→the *constant-W* option will cause a small Φ-shift, the *decreasing-W* option will cause a larger Φ-shift.

As EN437 testgas Wobbe bands and Wobbe distribution bands apply on a national or regional scale, and as the appliances of different type all are connected to one and the same national or regional NG distribution grid, it is practical to consider *detailed results from the viewpoint of a W-band*. Within a region with a certain Wobbe distribution band the overall H_2 admixing possibility is *not determined by the safe operation of a single type of appliance*. Instead, next to the distribution condition (Equation (3)), it is the safe operation of *the most critical type of appliance that sets the limit* concentration $[H_2]_{max}$.

Obtaining the $[H_2]_{max}$ limit based on the distribution condition is straightforward for a Wobbe band under consideration, once the composition of the natural gas itself is known. Obtaining practically useful light-back-limited $[H_2]_{max}$ values requires carefully designed experiments, comparing gases with gases. Such experiments were performed at Gasunie Engineering & Technology, supported by the EET (Economie Ecologie Technologie) Program of the Dutch Ministry of Economic Affairs ([7]–[9]). Concerning fuel-rich appliances, being critical in this respect as shown above, systematic light back experiments were performed applying simple Bunsen tubes. The "incipient light back" behaviour of natural gas/H_2 mixtures was compared to that for a light back reference situation, for instance a natural gas with $W = W_{min}^{distr}$. The distribution limits W_{min}^{distr} and W_{max}^{distr} (marking the safety margins) can be considered to imply fair reference conditions as they mark a justified level of safety risks, being in

use for many years. Experiments were performed for the NL distribution band, for the EN437 L-band and for the EN437 H-band. The constant-W as well as the decreasing-W option was considered.

On a European scale, H-band distribution ranges are the most frequent. Therefore, here the focus will be upon a summary of detailed results obtained for the H-band.

Table 2. Detailed H-band results in the search for allowable $[H_2]_{max}$ values. Applicable to new/properly serviced appliances.

EN 437 H-band	Existing NG appliance operation ("constant fuel gas pressure, constant air flow rate") & H_2 admixture possibility	
FUEL GAS: Wobbe conditions and additional mixing conditions	fuel-rich premixed ($\Phi_{prim} > 1$)	fuel-lean premixed ($\Phi_{prim} < 1$)
Constant-W_{mix} : H_2 admixture & $[CH_4]/[N_2]$ increase. $W_{NG} = W_{mix} = W_{min}^H = $ 48.2 MJ/m^3 (G23) **H1**	$\Phi = 1.30$ ($\lambda = 0.769$) (at W = 53.46 MJ/m^3: G20); $< \sim 18\%$ H_2 : no light back problems expected.	No results available. Probably not light-back-limitative ($[H_2]$) compared to fuel-rich appliances. Burner overheating limit not studied. More work needed.
Decreasing-$W_{NG/H2}$. $W_{NG} = 56.8$ MJ/m^3 **H2**	$\Phi = 1.30$ ($\lambda = 0.769$) (at W = 53.46 MJ/m^3: G20); $< \sim 27\%$ H_2 : no light back problems expected.	$[H_2]_{max}$ ~52% depending on actual NG composition
Decreasing-$W_{NG/H2}$; W_{NG} value arbitrary within H-band. $48.2 \leq W_{NG} \leq 57.7$ MJ/m^3 **H3**	Not explicitly studied. Can be compared with situation **H2**. $0 < [H_2]_{max} < \sim 27\%$ (maybe upper limit somewhat higher): no light back problems expected. Depending on actual value W_{NG} and on actual NG composition.	$0 < [H_2]_{max} < \sim 56\%$ depending on actual value W_{NG} and on actual NG composition

For the constant-W situation H1, for fuel-rich appliances $[H_2]_{max}$ will be ~18%. However, for fuel-lean appliances more work is needed on burner overheating in order to pose an overall $[H_2]_{max}$ value for this constant-W situation. For the decreasing-W option (situation H2) $[H_2]_{max}$ will be ~27%. Here light back in fuel-rich appliances is the limiting factor as in this case $[H_2]_{max}$ for fuel-lean appliances is only limited by $W_{NG/H2}$ dropping below W_{min}^H . For situation H3, $[H_2]_{max}$ will also depend on the actual value W_{NG} : for $W_{NG} = W_{min}^H$ $[H_2]_{max}$ will be = 0. Of course, relevant distribution bands will range *within* the H-band because of the safety margins. A narrower distribution band is expected to show smaller $[H_2]_{max}$ possibilities.

As a prudent starting point, the systematic experimental results described can be considered to apply to *new/properly serviced appliances*: *an appliance in practical use and still showing the operational*

behaviour of the units during EN437 type testing. The distribution limit based reference conditions will cover domestic appliances in the field still operating within their respective safety limits (although they might have "drifted away" from the type testing condition by, for instance, wear and aging). For these appliances safety risks would remain at a justified level.

Little representative information is available on the real operational condition of domestic appliances in the field. Limited studies indicate that a substantial part of the appliance population does not operate within the respective safety limits. Accepting the present results based on distribution limit reference conditions as being applicable to *all* existing appliances in the field would imply the assumption that appliance owners have taken their responsibility for their appliances to operate within the safety limits. The implementation of a hydrogen admixing strategy would have to involve this issue and probably nation-wide operations (check/adjustment/repair/replacement to be performed for all appliances).

4.0 OTHER APPLIANCES AND APPLICATIONS

In studying possibilities for admixing hydrogen in the natural gas grid stationary gas engines (cogeneration), gas turbines (large power generation plants, mini turbines) and industrial combustion applications (burners in kilns, furnaces and ovens in ceramics, cement clinker, steel, glass industries, burners for industrial drying processes, burners in steam boilers, burners for space heating inside large halls, etc.) cannot be left out of consideration. These applications all have in common a major lack of knowledge: knowledge on fundamental process parameters (ignition delay times, turbulent burning velocities, methods of calculating Methane Numbers) relevant to gas engines and gas turbines, as well as process knowledge relevant to large gas turbine systems, industrial combustion applications and using the gas as a chemical feedstock (fertilizer industry). Upon admixing H_2 to the natural gas will require at least installation readjustments, very often redesign and often it is even unknown yet what will be required. Thus, serious (potential) bottle-necks considering admixing H_2 are involved. The present work is about *existing* natural gas appliances in the sense that *no* adjustments are assumed to be made upon admixing hydrogen, in other words the appliances just continue their operation while the fuel gas composition changes. For the great majority of the appliances and applications mentioned this is just *not* an option.

5.0 CONCLUSIONS

The common safety practice in natural gas application illustrates the necessity to consider appliance operation and the operational (Wobbe) control of the natural gas grid in close connection to each other. It poses a limiting factor upon $[H_2]_{max}$ as the distribution condition $W_{min}^{EN437\ group} < W_{min}^{distr} \leq W_{NG/H2}$ has to be obeyed.

Exploring the impact on domestic appliances of admixing hydrogen to the natural gas, the application of the fundamental insights and carefully designed experiments comparing the behaviour of gases using justified reference conditions have been shown to offer essential progress. This can save a lot of testing effort.

According to the fundamental insights, for fuel-lean, properly operating "constant fuel gas pressure, constant air flow rate" appliances light back problems upon admixing hydrogen to the natural gas fuel will fail to turn up, up to amounts in the order 50% H_2 , maybe even up to 80%. This was probably confirmed by boiler tests in Denmark (Naturalhy Task 5.1). But, as Wobbe bands apply on a national or regional scale, and as the appliances of different type all are connected to one and the same national or regional natural gas distribution grid, it is necessary to consider detailed results from the viewpoint of a Wobbe band. The Danish example covers the H-band. Fuel-rich appliances are the light-back-critical ones, as shown in the present work. Moreover, in the Danish case the minimum value $W_{NG/H2} = W_{min}^{distr\ DK}$ was already reached at ~20 mol% H_2.

Fundamental H-band results obtained up to now are presented. Completing this picture as well as the picture for the L-band and for relevant distribution bands would require additional work.

Accepting the results based on distribution limit reference conditions as being applicable to *all* existing appliances in the field would imply the assumption that appliance owners have taken their responsibility for their appliances to operate within the safety limits. The implementation of a hydrogen admixing strategy would have to involve this issue. Clarity on the real condition of existing natural gas domestic appliances in the field is necessary.

Stationary gas engines, gas turbines and industrial applications pose serious (potential) bottle-necks considering admixing H_2. Major knowledge gaps have to be elaborated in order to obtain clarity in this matter.

The $[H_2]_{max}$ possibility will be determined by the application with the most limiting requirement. One option is to inject the hydrogen into the network at the highest level (long distance lines). Then the H_2 will appear everywhere in the underlying grid and it will be supplied to all applications connected. The other option is to inject the hydrogen at lower network levels. This would possibly increase the $[H_2]_{max}$ possibilities by uncoupling application requirements, but at the same time it would limit hydrogen transport volumes and distances. Thus also studies of grid management in relation to H_2 transport and distribution would be essential in considering hydrogen admixing strategies.

ACKNOWLEDGEMENTS

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