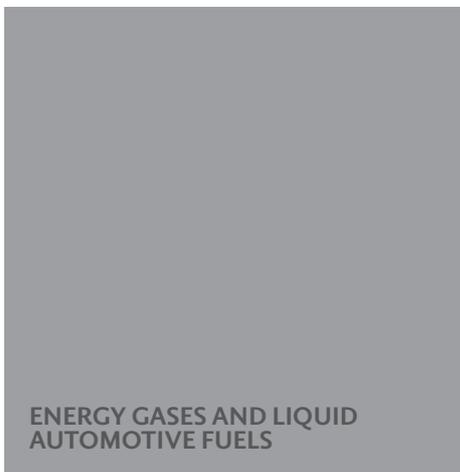


HYDROGEN GAS AS FUEL IN GAS TURBINES

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Hydrogen gas as fuel in gas turbines

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Authors' foreword

This project started in July 2014 and has been performed by Combustion Physics, Lund University, Siemens Industrial Turbomachinery AB and Göteborgs Energi. The governing idea of the project, to go into detail in investigating laminar burning velocities and the chemistry of laminar flames of natural gas with hydrogen addition, came up after a successful earlier study on a Siemens gas turbine, in a project financed by SGC (SGC report 2013:256). Göteborgs Energi was involved since they use Siemens gas turbines for power generation at Ryaverken, Göteborg. Siemens as well as Göteborgs Energi have a strong interest in fuel flexibility in gas turbines and thus support research related to future fuel mixtures. Combustion Physics at Lund University has been the academic partner in the project, responsible for production of the major project results using experimental and computational facilities in Lund. Siemens have contributed by results from a full scale test with hydrogen gas at Siemens in Finspång. The project time was 9 months and it was ended in March 2015.

The reference group following the project has been;
Anna-Karin Jannasch, Energiforsk (project coordinator)
Martin Rokka, Göteborgs Energi
Victor Karlsson, Göteborgs Energi
Jenny Larfeldt, Siemens Industrial Turbomachinery AB

Summary

The project concerns laminar burning velocities of fuel mixtures relevant to gas turbine combustion. Today the main gas turbine fuel is natural gas with methane as the dominating component and smaller fractions of heavier hydrocarbons. Future gas turbine fuels will likely include hydrogen gas and biogas with large fractions of carbon dioxide. In particular hydrogen gas is of interest because it will alter the combustion properties of the gas turbine fuel, broadening the flammability limits and increase burning velocity.

Therefore laminar flames of different fuel mixtures were studied at standard conditions, pressure of 1 atm and initial gas mixture temperature of 298 K. Mixtures were varied in the aspects of natural gas composition, and these different mixtures were then enriched with hydrogen in varying amounts. Chemical kinetics simulations were performed for the same conditions, but also for a range of elevated pressures and temperatures.

The main conclusion from the experimental study is that addition of hydrogen promote some fuel mixtures more than others. The strongest effect is seen on pure methane+air flames, slightly weaker on methane/ethane+air flames, and even weaker on mixtures incorporating propane. These experimentally determined trends were supported by the simulations.

For efficient computations, the chemical kinetics mechanisms need to be as small as possible, the ones tested in the present study include about 50 species, but a fast mechanism should ideally have fewer than 20. Smaller mechanisms can be obtained through a reduction procedure where species are systematically removed from the larger mechanisms. A method for this was developed and tested within the project, it was concluded that this method could reduce the mechanism size and computational time by about one third.

Among the three kinetics mechanisms tested, the so called San Diego mechanism was the one that showed to give good results over a wide ranging conditions, and it is recommended for further use.

Sammanfattning

Förbränning i gasturbiner är en viktig del av elproduktionen och med världens ökade energibehov kommer gasturbinförbränning troligtvis att öka i framtiden. Dagens gasturbiner drivs främst på fossil naturgas vars främsta beståndsdel är metan, med mindre andelar av andra kolväten som etan och propan. På senare år har man kunnat se att sammansättningen av naturgasen har varierat alltmer, både med avseende på tyngre kolväten och på mindre reaktiva komponenter som kvävgas och koldioxid. Dessa variationer leder till variationer i gasens värmevärde och därmed variation i driften av gasturbinerna. På grund av ökad användning av förnybara bränslen är det troligt att man framöver kommer att elda biogas från rötning samt restgaser från olika industriella processer i befintliga gasturbiner. Detta ställer krav på flexibilitet i driften av gasturbinerna. En gas som är högaktuell är vätgas. Ett intresse finns att öka halten vätgas i naturgasnätet och att lokalt elda stora andelar vätgas i situationer där tillgången är stor. Siemens har på grund av detta undersökt hur stor andel vätgas som kan blandas in i deras standardbrännare och efter en studie inom ett SGC projekt (SGC report 2013:256) kunde man garantera en inblandning på 15%. Vätgas är en liten gasmolekyl i jämförelse med metan och de andra kolvätebränslena, den brinner med betydligt högre flammhastighet och är mer påverkad av diffusion än de andra gaserna. Dessa egenskaper behöver undersökas mer och flammorna behöver testas under laboratorieförhållanden för att öka förståelsen. Utöver experiment är även simuleringar av flammorna viktiga eftersom det ökar detaljförståelsen samt möjliggör undersökning av förhållanden som kan vara svårt eller kostsamt att utföra experimentellt.

Projektet handlar om att studera laminära, endimensionella, laboratorieflammar av naturgas med olika inblandning av vätgas. På så sätt ökas förståelsen av hur vätgasinblandning ökar flammhastigheten hos naturgasflammar av olika sammansättning. Dessa flammar har i projektet undersökts experimentellt samt med simuleringar. Ett viktigt syfte med simuleringarna var att undersöka vilken av flera kemiska mekanismer av olika komplexitet som bäst och mest tidseffektivt förutsäger de experimentella resultaten.

Naturgasblandningar med olika förhållanden metan:etan:propan undersöktes, med 0-50% vätgasinblandning. Naturgasblandningarna utan vätgas hade alla ca samma flammhastighet, något snabbare än ren metan. Inblandning av tyngre kolväten öka alltså flammhastigheten något. Inblandning av vätgas ökar i alla fallen flammhastigheten signifikant, för 10% vätgas ökas flammhastigheterna 2-15% och för 50% vätgas är ökningen upp till 160%. En tydlig trend är att de största ökningarna sker i flammar med syreunderskott, moderata ökning vid syreöverskott, och minst ökning vid stökiometriska förhållanden.

De undersökta kemiska beräkningsmekanismerna gav alla ganska bra överensstämmelse med experimenten, förutom att en av dem överpredikerade alla fall där propan var med i gasblandningen. Överlag var slutsatsen att den mekanism som kallas San Diego var den som bäst predikerade flammhastigheter under alla aktuella förhållanden och konklusionen är att denna mekanism ska användas i framtida studier.

Då biogas med högt koldioxidinnehåll kan vara aktuellt för gasturbinförbränning undersöktes dessa gasblandningar med hjälp av simuleringar. Koldioxid minskar flammhastigheter men simuleringarna visar att genom att tillsätta vätgas till dessa

flammar kan flamhastigheten åter ökas och därmed stabiliseras flamman och ger en mer stabil drift i gasturbinen.

Som en del av projektet gjordes försök att minska de kemiska mekanismernas storlek medan deras förmåga att förutsäga flamhastigheter skulle behållas. Det program som utvecklades för detta minskade en standard naturgasmekanisms storlek med ca en tredjedel, med en minskning i beräkningstid som var i samma storleksordning. Slutsatsen från den delen av projektet är att den typen av reduceringar av mekanismstorlek och beräkningstid inte leder till några drastiska minskningar i beräkningstid.

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1. Background

1.1 Motivation

Gas turbines are important for power generation and as a result of increasing energy demand it is likely that their importance will grow in the coming decades. A gas turbine can run on a range of fuels, but currently the common fuel is natural gas from fossil fuel sources. For future energy security and environmental concerns other gases like biogas and hydrogen gas are likely to be used. One clear trend in demand on power generation systems like gas turbines is the increasing need for fuel flexibility. This is strongly linked to security of energy supply since the power production becomes vulnerable if it has to rely on fuel of a certain composition, from one or a few sources. Systems that can work efficiently for a range of fuel compositions ensure power production less sensitive to political factors.

In section 1.2 the composition of current gas turbine fuels will be reviewed and possible composition of future fuels will be outlined. One important gas that can be produced from renewable energy is hydrogen gas. The hydrogen molecule, H_2 , is the smallest existing gaseous fuel component and as a result it has combustion characteristics that differ from the ones of more common hydrocarbon fuels, as outlined in section 1.3. In a previous study a test with a full scale gas turbine was performed and it was found that up to 15 vol% hydrogen can be allowed in Siemens standard combustion system [1]. During that project it was realized that there is poor data in literature on combustion properties for such mixed gases particularly at relevant gas turbine conditions, this will partly be addressed in the present study. The purpose and aims of the present project are outlined in section 1.4.

1.2 Composition of gas turbine fuels

The composition of natural gas varies between different sites [2]. The main component is methane (CH_4) with variations in the range 80 to 99%. Ethane (C_2H_6) and propane (C_3H_8) are the two other main hydrocarbon constituents and can vary from trace amounts and up to 15% for ethane and 10% for propane. Other compounds present can be carbon dioxide (CO_2) with up to a few percent and nitrogen (N_2), commonly a few percent but up to 10%. The composition of the natural gas will influence the heating value as well as the combustion characteristics.

As the national and international gas transportation grids include gas from many sources there will inevitably be a variation in gas mixture composition and properties delivered to the customer. It has been reported that the variation has grown in the US [3], and the same is reported for the Swedish transmission gas grid owner, Swedegas [4]. Figure 1 presents higher heating values (HHV) for the period 2010 to 2014. 2010-2012 the HHV mostly varied in the range 12.1 to 12.3, and the weekly variation is seldom more than 0.5. From 2013 the HHV started to vary more, and mostly to lower values. An extreme case is about a week in December 2014, shown in the inset in Figure 1, here the HHV ranges from the very low value 11.4 to the standard value of 12.2. The variations are very fast, with extremes only a few hours apart.

Future gas turbine fuels can be of more strongly varying composition compared the mentioned natural gas mixtures [3]. Raw biogas can for example have a methane content of about 50% and the rest being mainly CO_2 and N_2 , these gases may need to be upgraded before use. Another possible fuel source is refinery waste gas

with high hydrogen gas content, up to 90%, and the same hydrocarbon compounds as in natural gas. Synthesis gas (syngas) mixtures with varying H₂ and CO levels can also be considered.

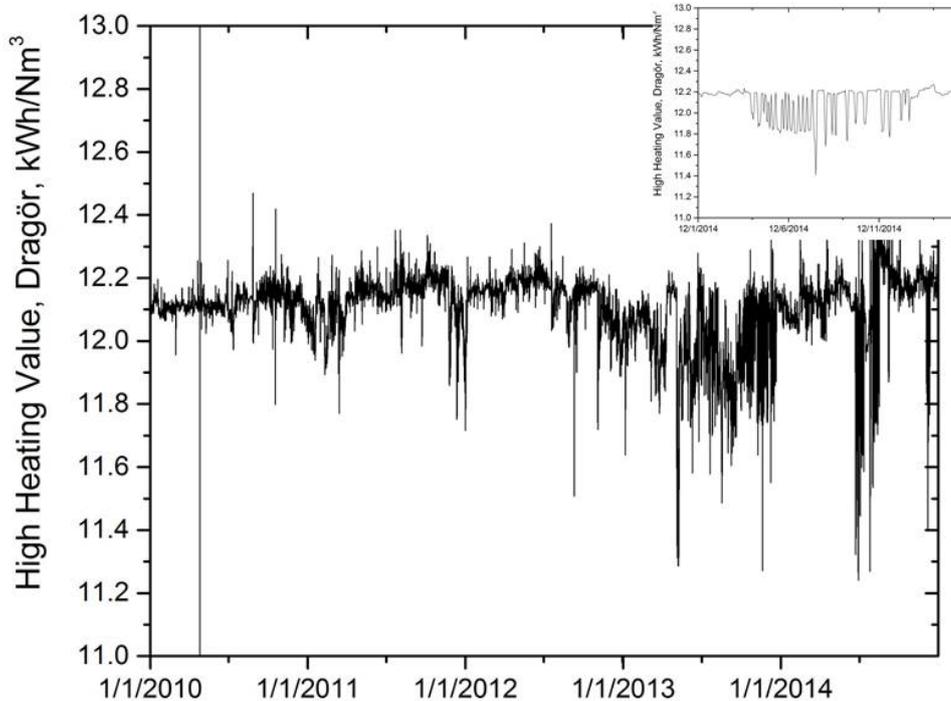


Figure 1. Higher heating values for Dragör 2010-2014 [4]. Inset show a zoom of 1-15 December 2014.

1.3 Hydrogen combustion

Hydrogen gas is highly reactive and therefore has a very high laminar burning velocity. When added to slower burning fuels the hydrogen will extend the flammability limits and enhance flame propagation. This can result in a more efficient combustion, giving lower emission of hazardous air pollutants and greenhouse gases.

It has been shown [5] that hydrogen increase the laminar flame speed through kinetic, thermal and diffusion effects. The kinetic effect is the largest contributor to flame speed enhancement, while diffusion effects are so small they are considered negligible [5].

1.4 Purpose and aims

The purpose of the project is to investigate laminar flame speeds of natural gas mixtures, with particular focus on hydrogen enriched flames. This was done using experiments where laminar burning velocities were measured, and by numerical simulations of the flames using several kinetic mechanisms. The performance of the mechanisms are evaluated using a new set of experimental data on laminar burning velocities. The understanding gained from experiments and modeling should ultimately result in development of a reduced chemical kinetics mechanism, a smaller

and less computationally demanding version of the advanced mechanism. This issue is in the present study approached by development of an automatic reduction tool for creation of smaller mechanisms from the well-known and reliable detailed mechanisms.

The project is divided into three main parts, A-C:

- A. Modeling of laminar flames of the natural gas components methane, ethane and propane with air and the same flames with different amounts of hydrogen gas.
- B. Experimental determinations of laminar flame speeds for gas mixtures of the natural gas components methane, ethane and propane with air and with hydrogen gas.
- C. Initial experiments of laminar flames at high pressures (up to 25 bar) to enable evaluation of the possibilities of future experimental studies of these flames.

Main focus of the present project is laminar flames at standard conditions, meaning an operation pressure of 1 atm and an initial gas mixture temperature of 298 K. The gas mixtures given in Table 1 were all investigated using flame simulations and the first four mixtures were measured experimentally. In addition several mixtures were simulated also at elevated temperatures and pressures to investigate the performance of the mechanisms and increase the understanding of the chemistry behind.

The particular choice of gas mixture compositions are based on several considerations. For the natural gas (NG) mixtures comparably high concentrations of ethane and propane were chosen, on the upper limit for what can be present in real natural gas. In a comparative study of several components with similar characteristics it is important to investigate these extreme cases since it is important to identify differences that are large enough to be outside the error bars of the measurements. Another motivation is that all these mixtures, with the exception of NG 3, have to some extent been investigated previously, which enable a verification of the quality of the experimental data by comparison with other experimental datasets at some conditions.

Table 1. Composition of the gas mixture used in experiments and simulations.

	CH ₄	C ₂ H ₆	C ₃ H ₈	CO ₂
CH ₄	1			
NG 1	0.8	0.2		
NG 2	0.8		0.2	
NG 3	0.8	0.1	0.1	
BG 1	0.8			0.2
BG 2	0.6			0.4

2. Experimental

2.1 Laminar flames

Laminar flames of the fuel mixtures given in Table 1 were experimentally investigated using the heat flux method, section 2.1.1, and simulations, section 2.1.2.

2.1.1 Heat flux experiments

The heat flux method for determination of laminar burning velocities is a method where the property is determined directly in a stretch free flame under adiabatic conditions [6]. A schematic of the experimental setup is presented in Figure 2, showing the mixing panel for setting the gas mixture composition, and the burner with water baths controlling the temperature of the unburnt gas mixture and of the burner plate.

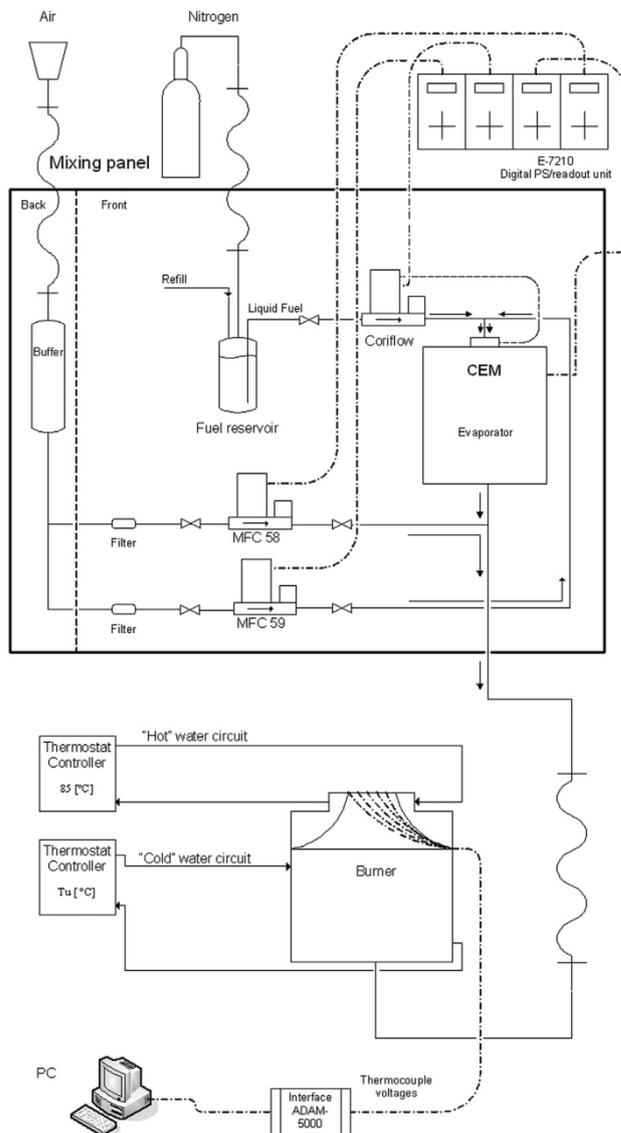


Figure 2. Schematic of the Heat Flux setup used in the present work.

A one dimensional flame, see Figure 3, is stabilized on a perforated plate burner heated to a temperature at least 20 K above the temperature of the combustible gas mixture. Heat transfer between the flame and the burner head is at adiabatic conditions equal in both directions, which means there is no net heat transfer. At these conditions the temperature of the burner plate is uniform. By varying the flow of gas while monitoring the temperature profile, measured by eight thermocouples in the burner plate, the adiabatic laminar burning velocity is found.



Figure 3. A 1D flame stabilized on a heat flux burner.

The combustible mixture of fuel and oxidizer is created using a mixing panel with gas Mass Flow Controllers (MFCs). All these components are from Bronkhorst. The gas MFCs are regularly calibrated for air, using a piston meter, Definer from Bios. The setup used for the present experiments has been described previously [7]. Uncertainties in gas mixture composition and laminar burning velocity were assessed, as previously described [8]. Typical uncertainties are $\pm 1 \text{ cm s}^{-1}$ for laminar burning velocity and ± 0.01 in equivalence ratio.

Experiments were performed at 1 atm pressure, initial gas mixture temperatures of 298 K and ϕ in the range 0.7-1.5. The temperature of the burner head was kept constant at 368 K.

The three natural gas component mixtures NG 1, NG 2 and NG 3, were bought in premixed bottles from AGA.

2.1.2 Chemical kinetics modeling

Modeling of laminar flames was performed using the CHEMKIN software for combustion simulations [9]. Three different chemical kinetics mechanisms were used, for their main characteristics see Table 2. San Diego [10] is today regarded as the most versatile and reliable natural gas mechanism, it is continuously improved and developed to cover wider range of conditions. GRI3.0 [11] is widely used, it is no longer being updated and has shown to have some flaws compared to the more up to date San Diego, but due to its wide use and fast calculations it is still considered an important mechanism for natural gas applications. The mechanism of Wang et al. [12] is recently developed and has not yet been used very much.

Table 2. Three detailed mechanisms used in the present study. “#species” and “#reactions” refer to the number of unique molecular species and number of reversible reactions involving these species, for each mechanism. The fourth column gives the time for computing the laminar burning velocity at $\phi=1.1$, at standard conditions using CHEMKIN with the same set of initial parameters for all three mechanisms.

Mechanism	# species	# reactions	Time (s)	Reference
San Diego	40	180	55	[10]
GRI3.0	53	325	45	[11]
Wang et al.	56	428	63	[12]

3. Results and discussion

3.1 Experimental laminar burning velocities

Laminar burning velocities at standard conditions were determined for methane+air flames and for the three natural gas mixtures NG 1, NG 2 and NG 3 defined in Table 1. The four mixtures were also mixed with hydrogen gas, 10, 35 and 50%. Finally a higher hydrogen gas mixture of 65% was approached, but due to acoustic instabilities the experiments were terminated until possible safety issues related to burning these high hydrogen mixtures have been investigated.

Figures 4 and 5 present laminar burning velocities of methane and NG 1 and NG 2, together with literature data [13, 14] for the same mixture compositions. For the case of methane, Figure 4, the agreement with literature is good at the lean side, while the study by Bosschaart et al. [13] give higher values at the rich side. In that study the same experimental method was used as in the present study. The method has been improved, in particular with respect to calibration of mass flow controllers to yield correct gas mixture composition, therefore it is likely that the present dataset is more accurate. For natural gas mixtures presented in Figure 5 the literature data are higher at rich side and lower at lean side, it looks like a shift in data, possibly as a result of larger uncertainties in gas mixture composition in the earlier study.

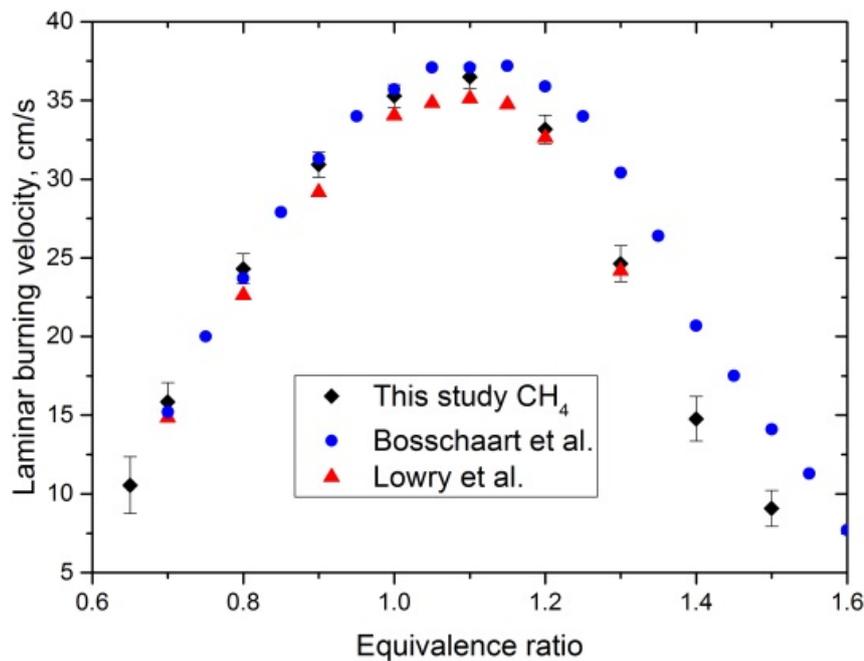


Figure 4. Laminar burning velocities of methane determined in the present study, together with literature data.

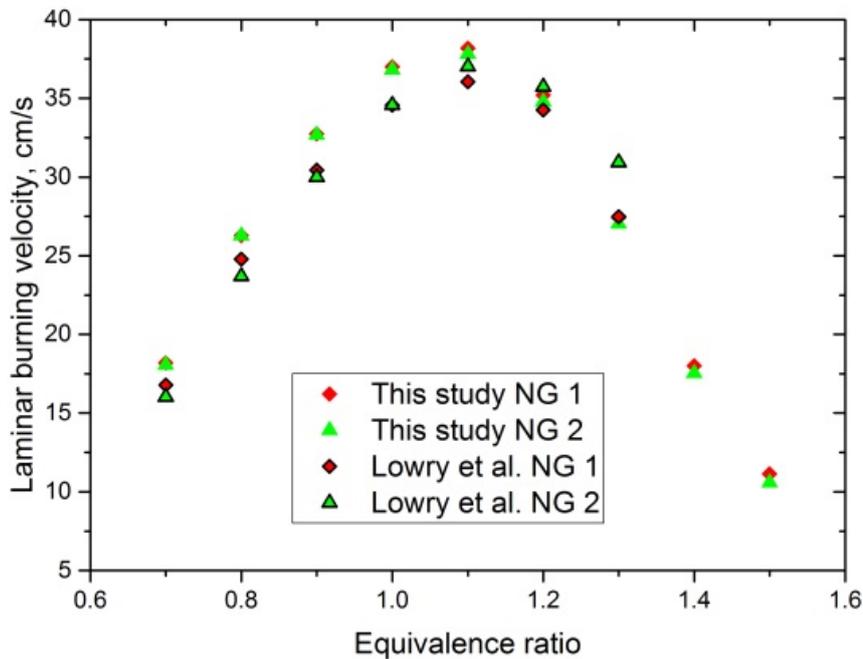


Figure 5. Laminar burning velocities of methane/ethane and methane/propane mixtures determined in the present study, together with literature data.

Figures 6-9 present experimental results for all investigated mixtures. Figure 6 shows mixtures with air, the laminar burning velocity for methane is slightly lower than the others. The three mixtures with 80% methane and different proportions of ethane and propane all have similar laminar burning velocities. Figures 7-9 show the same mixtures with hydrogen gas enrichment of 10, 35 and 50%. As expected an increased amount of hydrogen leads to an increase in laminar burning velocity. The interesting trend here is that hydrogen seems to promote methane more than the other gas mixtures, and ethane more than propane. Methane that was the slowest burning one without hydrogen becomes the fastest at hydrogen content of 50%, while the propane containing mixtures NG 2 and NG 3 burn significantly slower than the ones with no propane.

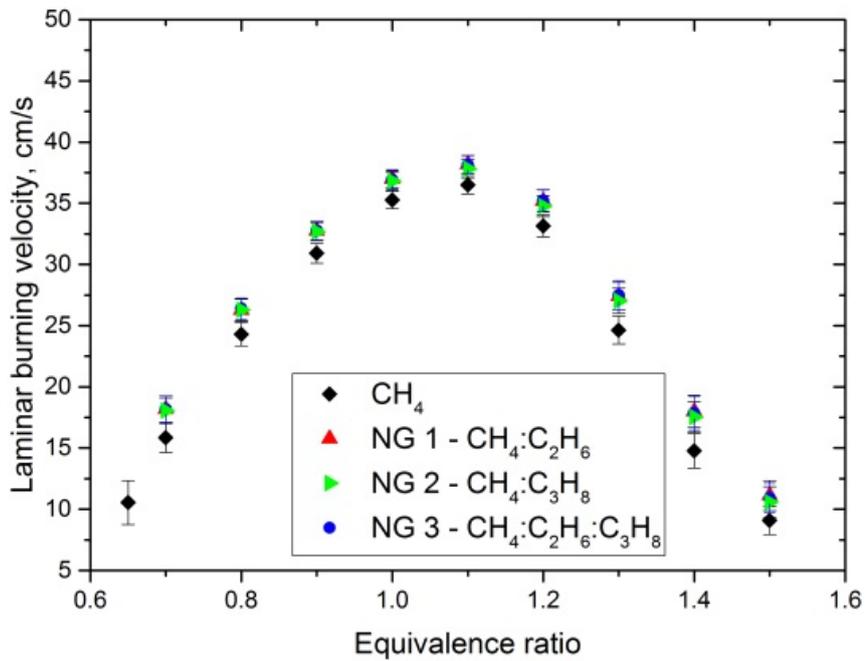


Figure 6. Experimental results of laminar burning velocities for pure methane+air flames and the three mixtures with 20% ethane and/or propane.

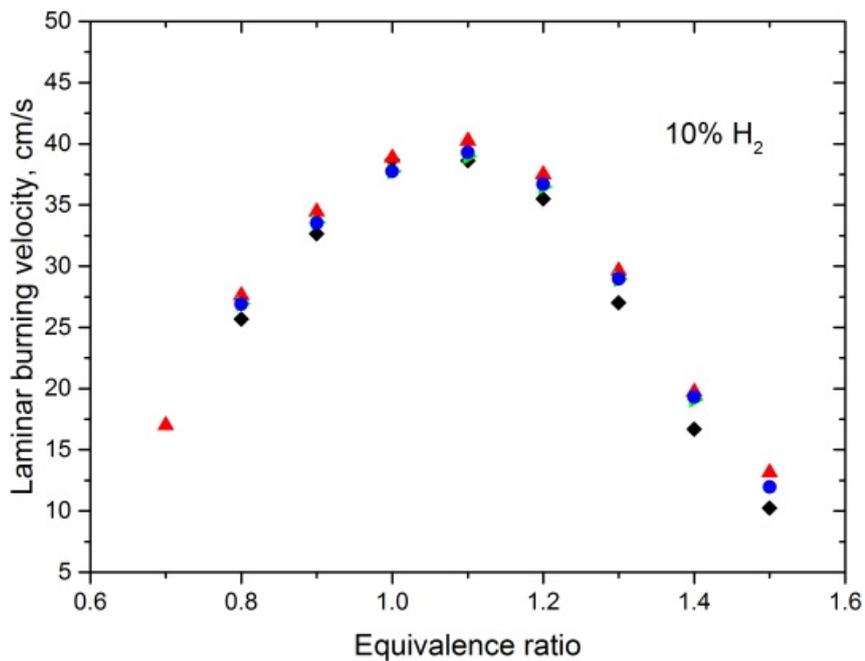


Figure 7. Experimental results of laminar burning velocities for pure methane+air flames and the three mixtures with 20% ethane and/or propane, enriched with 10% H₂.

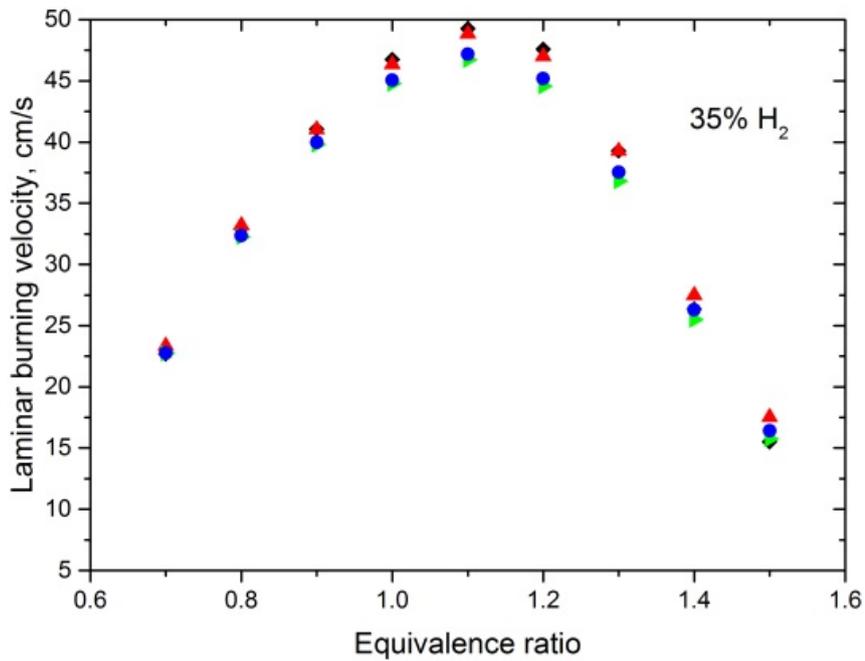


Figure 8. Experimental results of laminar burning velocities for pure methane+air flames and the three mixtures with 20% ethane and/or propane, enriched with 35% H₂.

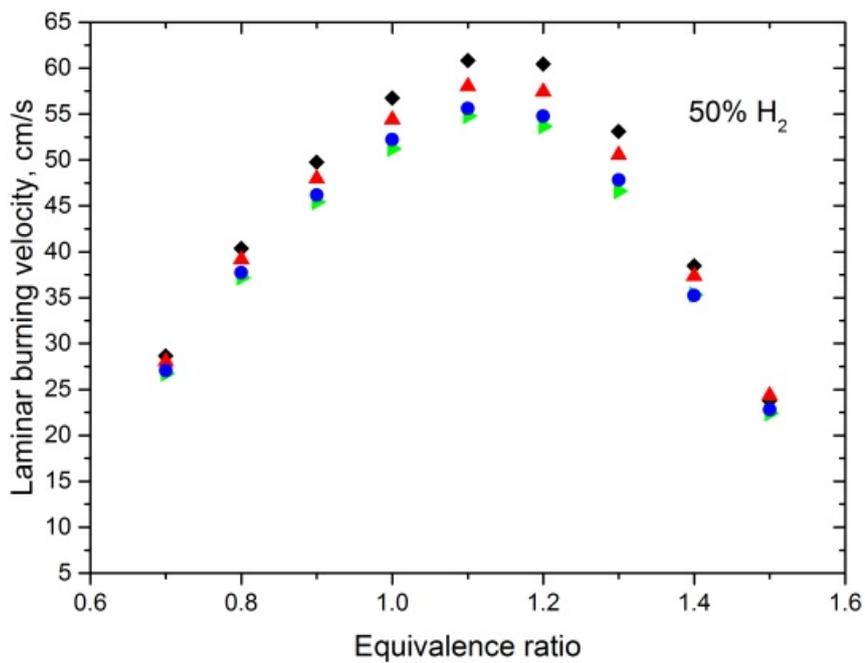


Figure 9. Experimental results of laminar burning velocities for pure methane+air flames and the three mixtures with 20% ethane and/or propane, enriched with 50% H₂.

As evident from above hydrogen gas promotes the natural gas flames differently depending on the hydrocarbon composition. This is further presented in Figure 10 where the increase in laminar burning velocity upon hydrogen enrichment, compared to flames without hydrogen, are plotted as a function of equivalence ratio for the four mixtures. In the first panel, 10% hydrogen gas, the increase in laminar burning velocity is modest, in the range 2 to 20% with stronger promotion at rich conditions. For methane/hydrogen mixture the data point for stoichiometric conditions for 10% mixture seem to be an outlier. Upon examination of the experimental data it is concluded that this is likely as a result of a deviating measurement of the mixture with hydrogen, since this particular datapoint are higher than the general trend showing in Figure 7. The second panel shows an increase of up to 160% for methane. An interesting result when comparing the two figures is that at 10% hydrogen, methane and NG 1 are similarly promoted by hydrogen gas, while at 50% hydrogen, methane is more strongly affected. The full drawn lines, from simulations using the San Diego [10] mechanism, are further discussed in the next section.

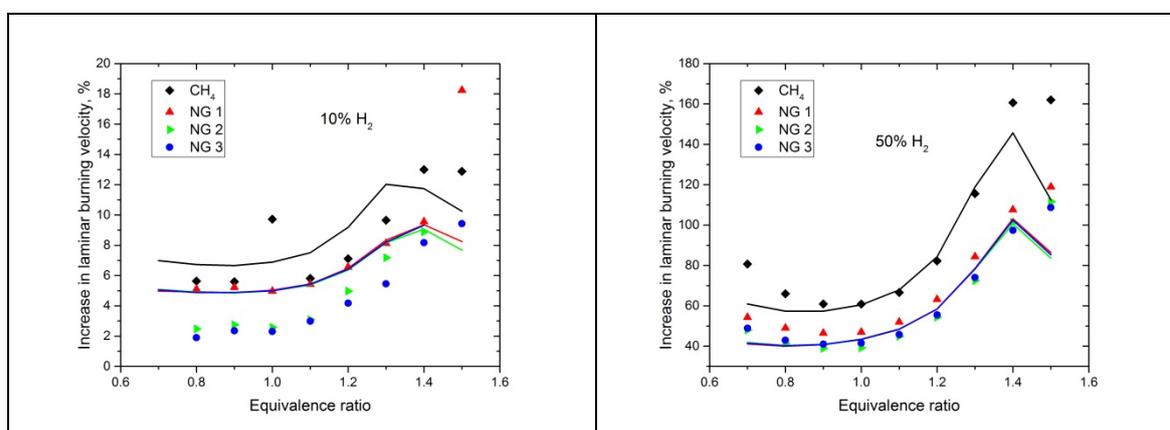


Figure 10. The effect of H₂ on the laminar flame speed of the different fuel mixtures represented by plots of the increase in percent. Lines in figures are modeling using the San Diego mechanism [10], with color coding the same as for the experiments.

3.2 Performance of chemical kinetics mechanisms

The three investigated mechanisms are of similar complexity and performance. As seen in Table 2 the GRI3.0 mech is the least time consuming one for computation of a methane+air flame at a given set of conditions, but a significant drawback of this mechanism is that it overpredicts the laminar burning velocity of all natural gas mixtures containing propane, in the present case NG 2 and NG 3, respectively. In Figure 11 the performance of the three mechanisms with pressure and temperature is shown. San Diego is generally considered to be the best natural gas mechanism and compared to this one the Wang et al. mechanism give to low laminar burning velocities with increasing divergence as pressure increase. GRI3.0 is in agreement with San Diego for NG 1 and BG 1, but not for the propane containing NG 3.

Figure 10 above shows a comparison of results from modeling using San Diego [10] to the comparison of increase in laminar burning velocity as a result of hydrogen addition. The simulations capture the experimental trend that the methane laminar burning velocity is more enhanced compared to the NG mixtures. It fails to separate

the effects of ethane and propane, all three NG mixtures should according to simulations be equally promoted by hydrogen addition. For all cases the simulations predict that at an equivalence ratio of 1.5 the enhancement due to hydrogen should again decrease, while the experimental data at this point for most cases show a levelling out behaviour, but no decrease. The simulated results are closer to the experimental data for the 50% hydrogen case, which indicate that the mechanism has an accurate chemical description of hydrogen, but possibly some minor flaws concerning hydrocarbon combustion. This conclusion is based upon the fact that the chemistry at 10% hydrogen content is still largely hydrocarbon dominated.

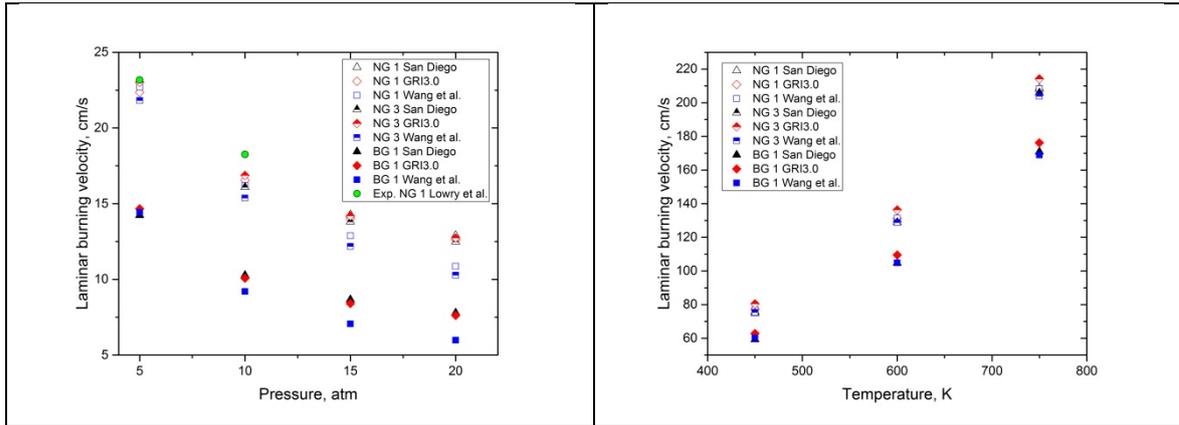


Figure 11. Laminar burning velocities of fuel mixtures NG 1, NG 3 and BG 1, simulated using three mechanisms [10-12]. The left hand side panel show the dependence of pressure and the right hand side the temperature. For pressure dependence two experimental data points from Lowry et al. [14] are also included.

Figure 12 is the simulated (San Diego) counterpart to the experimental data presented in Figures 7 and 9. The trend is similar to the experiments, with methane being more strongly promoted than the natural gas mixtures as the hydrogen fraction increases.

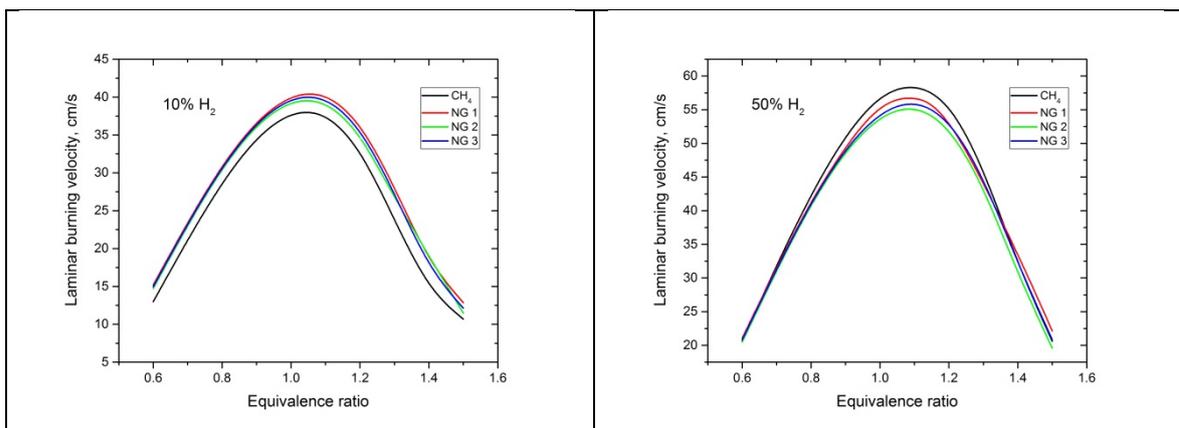


Figure 12. Simulated laminar burning velocities for methane and natural gas mixtures, with 10% (left) and 50% (right) of hydrogen gas.

The Wang et al. mechanism was used to compare biogas mixtures with 20 and 40% CO₂, and investigate how they respond to hydrogen enrichment. In Figure 13 it is

seen that the biogas mixtures burn significantly slower than pure methane. Addition of hydrogen can compensate for this flame retardation, in the case of the higher CO₂ fraction, 40%, it can be seen in the panel to the right that 35% hydrogen enrichment approximately compensate and bring the laminar burning velocity back to that of a pure methane flame.

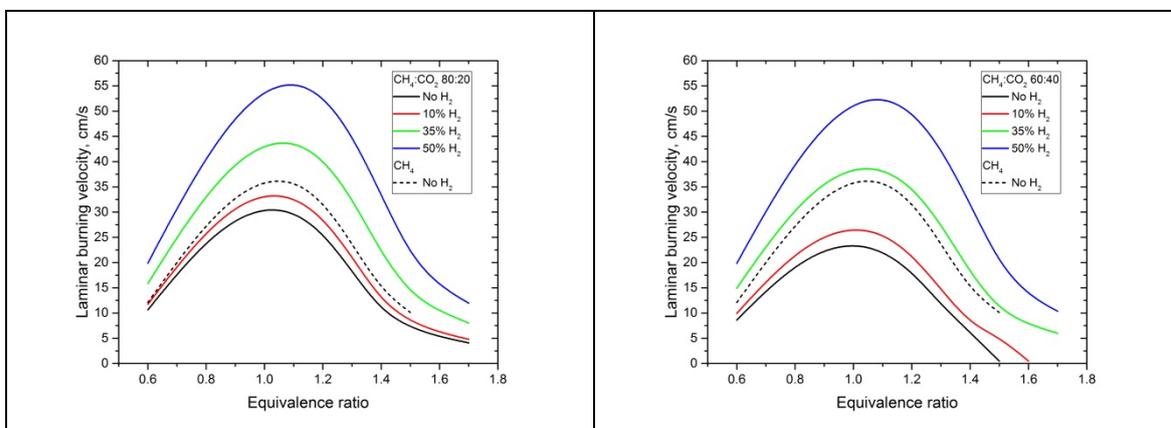


Figure 13. Simulated (Wang et al.) laminar burning velocities for BG 1 and BG 2, and the mixture of those with hydrogen gas.

3.3 A tool for generation of reduced mechanisms

Smaller kinetic mechanisms can be generated from the above investigated advanced mechanisms. In the present work a reduction tool was developed. The program builds on removal of unimportant species and the reaction these species take part in. The target for the reduced mechanisms is set in the program, most commonly it was chosen to produce laminar burning velocities within a few percent of the results from the advanced mechanism. Species that are known to be of importance are marked not to be removed and then the program iterate through the rest of the species, testing if the mechanism still reproduce the target results after removal of species.

When tested on the GRI3.0 mechanism for methane+air flames the reduced mechanism had 42 species and 266 reactions, before the results was outside the given limits. This gave a time reduction of a third for the test case, 30 s instead of the 45 s for the full GRI3.0.

From this, it became obvious that a truly reduced mechanism of in the range 10-20 species can hardly be produced from an advanced mechanism using automatic reduction. A further reduction requires modification of the true reaction rate constants, to lump several reactions into an overall reaction representing several reaction steps.

4. Conclusions and outlook

The most important outcome of the experimental laminar flame study is that hydrogen enrichment promotes the hydrocarbon mixtures differently. Pure methane is more strongly promoted than the ones containing ethane and propane. The practical use of this knowledge is that in a situation where hydrogen gas is added to a natural gas fuel, the strength of the flame promoting effect depends on the composition of the natural gas mixture. A larger amount of heavier hydrocarbons will to some extent inhibit the flame promoting effect of hydrogen gas.

The investigation of three chemical kinetics mechanisms for natural gas combustion reveal that they have about the same performance, but GRI3.0 fail for propane containing flames and Wang et al. mechanism diverge from the others at high pressures. The trends seen in the experiments, regarding stronger promotion of methane flames, is supported by the simulations, which indicate that they are indeed representing the chemistry correctly at standard conditions.

For simulations of biogas mixtures it is concluded that hydrogen gas can compensate for the decreased reactivity resulting from the CO₂ content. Balancing CO₂ content in biogas or natural gas with H₂ to get ideal flame properties might be a way to compensate for CO₂ contaminated fuels. This will allow the fuels to be burnt directly, instead of first using a CO₂ removing process.

Regarding mechanism reduction it is concluded that the tool developed in the present project does not manage in large reduction of mechanisms. It is able to cut the computational time by about one third, still keeping satisfying performance.

The present study will be a stepping stone to further work concerning understanding of effects of hydrogen gas on hydrocarbon flames. An important continuation is the determination of flame properties at pressures relevant to gas turbine combustion. It has been shown that a high pressure burner [13] for laminar flame studies are suitable for studies related to this. Experimental data at high pressures will enable further validation of kinetic mechanisms and identification of parameters of importance.

5. Literature

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6. Appendix Siemens' project contribution

With the purpose to find the maximum concentration of hydrogen in natural gas that Siemens gas turbines SGT-700 and SGT-800 can handle with standard combustion system a test was performed in 2012 [A1]. During that test the system was operated with up to 40 % by volume of H₂, and it was investigated how the flame position change as a result of increasing hydrogen content. The understanding developed during the test resulted in that Siemens today offers the standard SGT-700 and SGT-800 with up to 15 % by volume of H₂. Siemens has continued the development effort to enable operation on higher hydrogen contents.

To achieve stable operation at higher hydrogen content a slightly modified burner was developed. The burner was installed into a full scale gas turbine and tested in October 2014. The test set up described in [A1] was used, but with larger quantity of hydrogen. The hydrogen storage at the fuel feeding facility is shown in Figure A1.

The tests were performed for a range of hydrogen fractions in the fuel, and for various gas turbine loads. A wide range of test conditions is important to ensure stable operation. The test proved the capability of the concept burner to operate with at least 45 % by volume hydrogen in natural gas. It was also concluded that the NO_x emissions could be kept below 24 ppm@15 % O₂ at 70-100 % gas turbine load with the hydrogen rich fuel. Normal operation including transients and load cycling was also demonstrated with the hydrogen rich fuel.



Figure A1. Siemens delivery test beds in Finspång during test with hydrogen co-firing 3rd to 8th of October 2014.

The burner design showed to be suitable for long term operation with high hydrogen fuels since material temperatures, for instance at the burner tip, were acceptable and sometimes even lower than for the standard burner.

Work is in progress at Siemens to realize the concept burner in a gas turbine product that can be offered to the market in near future.

References

A1 Andersson, Larfeldt and Larsson, "Co-firing with hydrogen in industrial gas turbines", SGC Rapport 2013:256

HYDROGEN GAS AS FUEL IN GAS TURBINES

Intresset för gasturbiner för kraftgenerering ökar. Inte minst för att möta det växande behovet av reservkraft i takt med att den förnybara elproduktionen byggs ut i Europa. Idag drivs gasturbinerna mestadels med fossil naturgas, men allt oftare efterfrågas möjligheten att också kunna driva turbinerna med andra energigaser såsom förnybar vätgas, biogas samt blandningar av dessa. Man ser också ett ökat behov av att kunna hantera en kontinuerlig drift med en med tiden varierande gaskvalité. För att kunna anpassa och säkerhetsställa driften för dessa nya villkor krävs en ökad förståelse för hur olika gaskomponenter påverkar förbränningsförloppen i turbinen. I den här studien har man studerat inverkan av vätgasinblandning i naturgas och biogas av olika sammansättning.

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