Approaches to optimize natural gas utilization for varying operation conditions

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Abstract

Natural gas is a widely used primary energy source for industrial, commercial and domestic applications. According to technical standards natural gas is a methane-rich gas with some permissible variations of composition. Due to liberalized gas trading, changes in gas supply structure, like e.g. increasing LNG shares and the introduction of regenerative gases, gas utilization has to face increasing gas quality fluctuations. On the other side more restrictive requirements for efficiencies and for emissions force gas utilization processes especially in industrial and commercial environments to be run at their optimum specifications.

Modern sensor and control technologies allow gas utilization technologies to operate within their optimum, reducing gas consumption, lowering emissions and providing optimum process qualities even under varying operating conditions. The report shows the advances of process control by gas quality assessment (pre-combustion), by in-process measurement (in-situ combustion) or by analysis of the flue gas composition (post-combustion) for domestic, commercial and industrial process control. In general the process control has to adjust the required power at low emissions, ideally controlling both gas feed and gas-air-ratio. The actual trends are the wider use of advanced combustion controls especially within the domestic appliance market. Besides the emission regulations (NO_x, CO) and evolving efficiency requirements (funding programs, ErP) a further driver for the integration of advanced combustion process controls is the emerging issue of gas quality fluctuations. The challenges are the price competiveness of process controls and especially for gas quality measurements the possible injection of hydrogen at the percent level to natural gas within the Power-to-Gas concepts.

Recent developments of sensors for gas quality measurement will be shown, which are of interest for commercial and industrial processes. The various available in-situ combustion and post-combustion sensor technologies will be presented. The integration of the control technologies into an already running process as an upgrade is technically challenging and poses often furthermore the need for recertification. The economic benefits of modern sensor and control technologies will be covered with regard to the process type and scale.

An outlook for new developments of sensor and control technologies will be given with a focus on the research activities of DVGW and of the Karlsruhe Institute of Technology financed by industrial partners and public funding.

Introduction

Natural gas (NG) is an important primary energy carrier for domestic, commercial and industrial use at an annual rate of nearly one petajoule for Germany [1], see fig. 1. Consisting mainly of methane, ethane, nitrogen and further gaseous components NG provides the lowest carbon-to-hydrogen ratio of all carbon containing fuels and the specific carbon dioxide emissions are therefore lower than for oil or coal. By anaerobic digestion, pyrolysis of biomass, Power-to-Gas routes fossil NG can be substituted or enriched by renewable gases like biomethane, SNG[1] or hydrogen. But even fossil NGs differ in their chemical compositions depending on the source, the exploitation state and their transport and mixing routes, which is complemented by the injection of renewable gases, see table 1 [2]. Depending on the composition various gas properties are likely to change like e. g. the calorific values, the air resp. oxygen demand, flame speed and ignition delay time. Technically the gas quality is not defined by composition specifications but by some key numbers like upper or lower calorific value, Wobbe index, methane number and relative density.

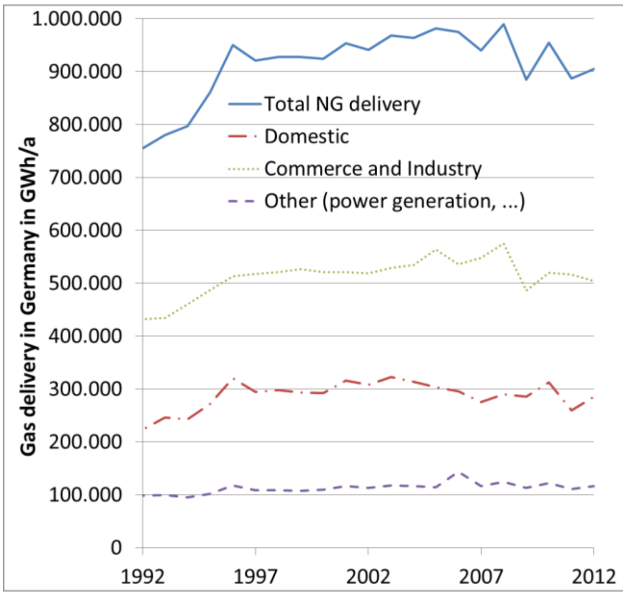

Table 1: Some examples of gas compositions of H-gases

Vol-%	Russian gas [2]	North Sea [2]	Bio-methane [3]
N_2	0,81	0,86	
CO_2	0,06	1,59	~3
CH_4	98,37	84,84	~96,5
C_2H_6	0,51	9,23	
C_3H_8	0,17	2,62	
C_4H_{10}	0,06	0,69	
C_5H_{12}	0,02	0,13	
C_6H_{14}	0,01	0,04	
O_2			<0,5

Figure 1: Evolution of German NG deliveries [1]

Within the recent decades the gas quality within the natural gas grid in Germany was often locally relatively constant, only a small portion of the permissible range of gas quality variations according to the German technical rule DVGW G 260 was used [4]. A new survey in 2013 has revealed that

Table 2: Combustion related gas properties specifications according to german technical rule DVGW G 260 (March 2013) [5]

reference conditions 0 °C/25 °C, 1013,25 hPa		permissible range (rated value)
Wobbe index	/kWh/m^3	13,6 – 15,7 (15,0)
upper calorific value	/kWh/m^3	8,4 – 13,1
relative density	/1	0,55 – 075

[1] SNG: Substitute Natural Gas

a wider range of permissible gas qualities is in use and that more frequently and with higher amplitudes gas quality fluctuations do occur [6]. The reasons are changed market situations, unbundling of gas suppliers and grid operators, more short-term gas contracts, new and increasing gas supplies as like the injection of renewable gases or increasing LNG[2] imports [2, 6]. Later may cause a specific higher oxygen demand of up to 25 % compared to the reference gas G 20 (100 % methane), which can have a severe effect on the gas-air-ratio.

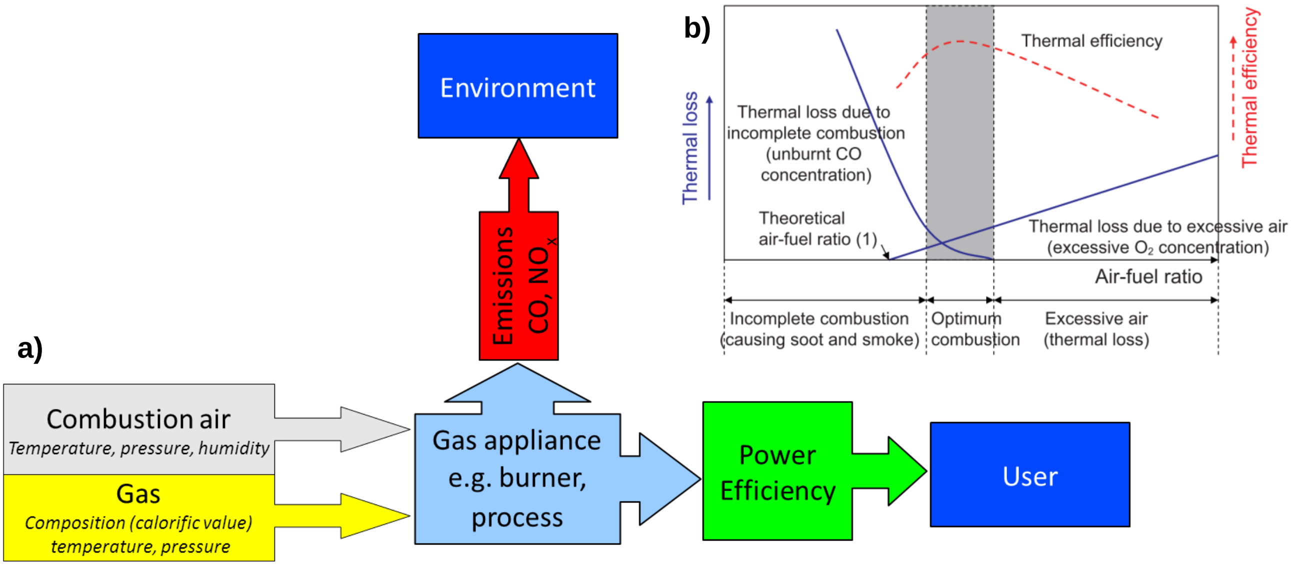

Figure 2: a) Simplified scheme of combustion [6], insert b) shows optimal gas-air-ratio range [7]

Fig. 2 illustrates in a simplified manner the relationship between combustion air and gas, which are influenced by their respective properties especially composition, temperature and pressure. The insert in fig. 2 indicates the gas-air-ratio range for optimal combustion [7]. Ideally all properties of gas and air should be measured and both flows of gas and air should be adjusted by a closed feedback control to maintain optimal combustion [8, 9]. The sensitivity of the process against gas quality fluctuations is strongly affected by the burner type, size and the control design. Figure 3 shows for a simplified and investigated H-gas matrix effects on the changed air demand due to a gas quality fluctuation when a system uses a differential pressure regulator or a balanced pressure regulator for the gas feed. With the differential pressure regulator the effects are due to the concept of the Wobbe number damped compared to the volume flow controlled scenario. It is obvious that even quite small variations in the Wobbe number (e.g. G 20 to H-Gas 3+2%_EBI) can cause larger effects to processes, as for example the air requirement is increased by 15 %.

National emission and efficiency requirements are prone to be replaced by European regulations as directive 2009/125/EG with lowest emission limits as 50 mg/kWh for CO and 56 mg/kWh for NO_x for some types of appliances [6], whereas for efficiency reasons a rated air number $\lambda = 1,15$ is suggested for industrial furnaces [10]. This demonstrates the necessity of advanced combustion controls especially for fluctuating gas qualities, whereas most installed and even new systems do

[2] LNG: Liquified Natural Gas

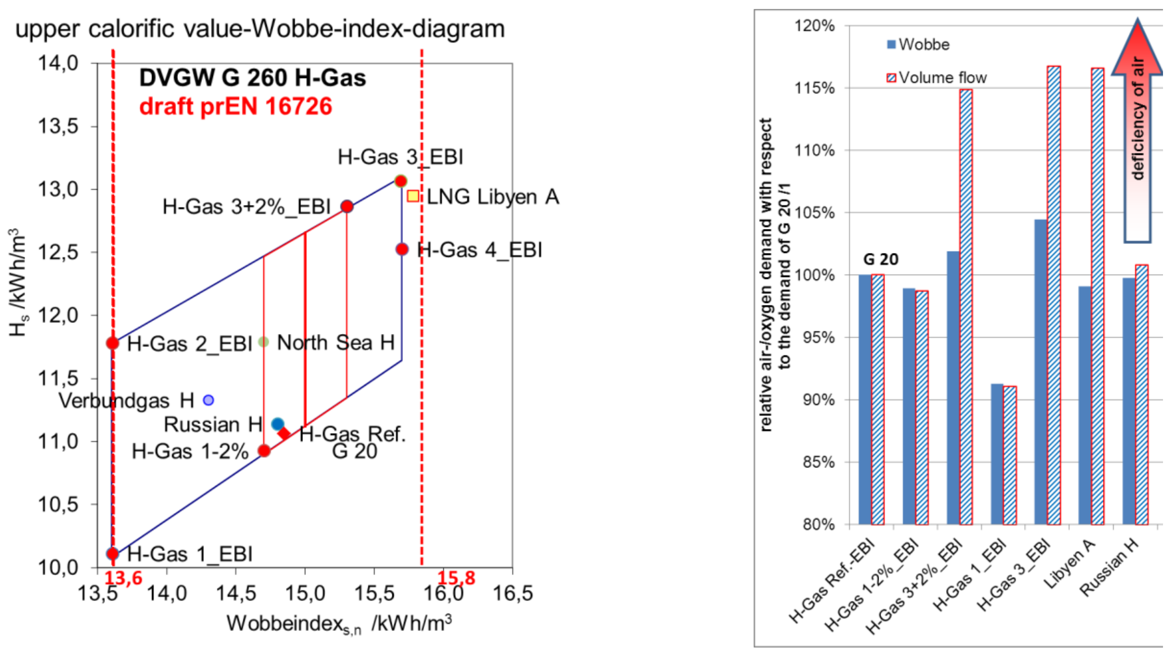

Figure 3: Simplified gas quality diagram with some test gases and effects by gas compositions on air demand with 2 control regimes, Wobbe: differential pressure regulation, Volume flow: balanced pressure regulation.

lack such systems and rely on relative stable gas qualities. One has to keep further in mind that gas appliances are typically more than 20 years in service and the exchange rates are quite low.

Control concepts

There are several approaches for advanced combustion controls, specifically manufacturing processes like in glass, ceramics or metallurgical industry do need a deep understanding of the complex processes and require often very specific solutions. Ideally a combustion control is capable of controlling both the emissions and the power output of the process. Typically processes can be controlled by measuring the gas quality (pre-combustion) either by gas chromatographs, calorimeter or correlative instruments at the site. The in-process controls use sensor signals within the burner or reaction zone like ionisation probes, temperature sensors or optical flame radiation sensors. The measurement of flue gas components is a widely applied method to control the process by this post-combustion approach.

The three routes are combined in MGARCP and are shown in fig. 4. A condensing boiler with a built-in self-adaptive ionisation control (similar to SCOT, 4) was equipped with temperature probes (3) at the burner as second in-process method, which is complemented by a heat energy meter (9) for thermal power rating. At the gas inlet port a gas quality sensor (11) can be adapted as pre-combustion control. Within the flue gas path several sensors (1 and 1a) are installed to monitor CO, O_2 and other flue gas components at this post-combustion port. Effects by gas quality fluctuations on the respective control technology can be studied with MGARCP in parallel and sensitivity analysis with regard to gas quality parameters (or compositions) are feasible. The gas and air feed can be varied independently by switching to external control of the gas valve (6) or the blower (5). With its flexible in-house developed software control it is possible to control power output and emissions of MGARCP in parallel and to select each sensor as master.

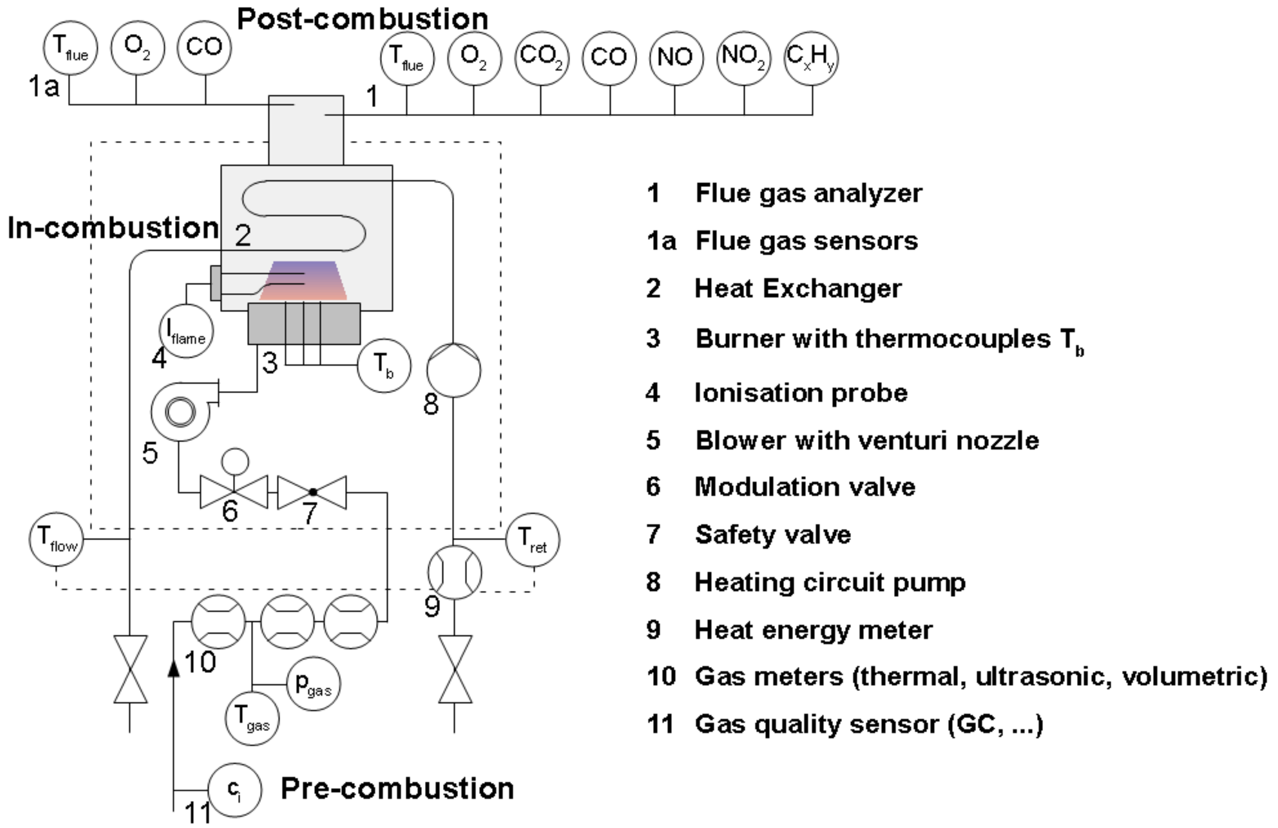

Figure 4: MGARCP[3] of DVGW research station with combined pre-, in- and post-combustion control approaches

Especially the sensitivity of either control concept to anticipated gas fluctuations (local gas grids with higher hydrogen admixture, partially purified biogas, air-gas mixtures) will be investigated within one appliance, whereas each concept itself was already successfully tested during certification testing with test gases of EN 437. By use of MGARCP the advantages of self-adaptive control strategies shall be demonstrated and the applicability for many gas mixtures studied.

In the domestic area the flame ionization based methods (e. g. SCOT) are the most widespread self-adaptive control strategies, having the advantage that ionisation is still in most systems metered to detect the presence of a flame. A thorough signal evaluation and the burner specific parameterization are important. The LambdaConstant-method is based on metering the burner temperature and by thorough parameterization this approach can be used to control the gas-air-ratio as well. Both in-process methods share the need for a thorough parameterization and a limited transferability of the parameterizations to other burners of the same type but different size.

The transferability of parameterizations is given for post- and pre-combustion methods, because

[3] MGARCP: Multi-gas-air-ratio-control-platform

only the products respectively educts of combustion are metered. Flue gas sensors as post-combustion approach measure typically the residual oxygen or the carbon monoxide concentrations by specific λ-probes. Most advanced is the use of combined O_2/CO-λ-probes which are available for this purpose minimizing excess residual oxygen and heat losses and guaranteeing low CO emissions. Optical sensors like NDIR[4] or TDLAS[5] for flue gas constituents are in use for large installations like e.g. power plants. Compared to λ-probes they are not prone to drifts by sensor poisoning, but the costs are typically higher. The gold standard of pre-combustion methods is gas analysis by gas chromatography and the control of the process with regard of the discontinuously – typically every 3 to 10 minutes - determined gas compositions. Continuous gas calorimeters have been nearly completely replaced by gas chromatography but new systems are introduced in the last decade. The continuous calorimeters and the stoichiometric gas analyzers determine the Wobbe index, calorific values and air demand. Recently the trend to develop correlative gas quality sensors with lower requirements to accuracy and a lower price has been pushed forward by the issue of gas quality fluctuations. An overview about gas quality sensors is given in table 2.

Table 2: Overview of available gas quality sensors

Principle of function	Selection of models	Comments
GC: µ-GC/PGC[6]	Agilent CP-490, Agilent CP-790, RMG PGC 9300, Elster Encal 3000, Siemens Sitrans CV, Thermo c2v-200 (discontinued[7]), Thermo Trace GC, Emerson Danalyzer 500 and 700, ABB NGC 8200 Serie, Shimadzu GC-2014(E)NGA, SRI 8610C, PerkinElmer Arnel 8200L, Inficon 3000 Micro-GC	30 - 50 k€ Invest and higher (depending on version, no. of channels , ATEX classification), results are chemical composition analysis versatile instruments work horses in natural gas analysis (billing)
thermal mass flow meters combined with differential pressure metering	Brooks Gas Property Identifier (discontinued), *Gas meter Diehl Smart Metering (in development),* *MEMS gasQS™ gas quality sensor (in development)*	Wobbe number, net / gross calorific value, density
thermal mass flow meters combined with differential	Elster gas-lab Q1, RMG EC 500,	Wobbe number, net / gross calorific value, methane

[4] NDIR: nondispersive infrared
[5] TDLAS: Tunable diode laser spectroscopy
[6] PGC: Process Gas Chromatograph
[7] discontinued according to manufacturer

pressure metering and CO_2-NDIR sensor	Vergence Systems GasPT2 (GL Noble Denton)	number, extented precision model available
continuous combustion calorimeter	Union Instruments CWD 2005, Reineke RBM	Wobbe number, net / gross calorific value , density
stoichiometric method	AMS Rhadox 7X00, WIM hobre instruments Compas, *VDEh-BFI Prototype* *, *GWI self-calibrating multi gas control system (combustion air requirement, ionization current)*	combustion air requirement (*extension kit option for *H_2*)*
infrared absorption	Precisive Tunable Filter Spectrometer*, Ruhrgas Methane number-Controller MaC (prototype n.n.)	Wobbe number, net / gross calorific value (*extension kit option for *H_2-Sensor)*, Lab-FTIR-Systems with gas measurement cell are principally usable too
Raman effect	Enwave Optronics GasRaman NOCH-2	chemical composition for components > 0,025 Mol-%, net / gross calorific value, Wobbe number
dielectricity, velocity of sound	*Gasunie/EON Ruhrgas* ε*-Methode* (prototype n.n.)	net / gross calorific value, Wobbe number, rel. density
viscosity	*Bright Sensor S.A. Wobbe Index Sensor*	Wobbe number

Annotations to the table, *italic: devices in development/field test phase*

(prototype n.n. – no newer informations within last 5 years)

The integration of gas or combustion sensors into the process requires often the definition of interfaces [2, 8, 9] and a recertification as part of safety relevant controls according to EN 12067-2 and the respective product/process standard like e.g. EN 746-2 [2]. There are mainly proprietary interfaces to burner controls which have to be adopted, for already installed industrial processes an upgrade is challenging due to missing electronic interfaces and to costs [2]. Especially for processes with flames as tools like e. g. of the glass, ceramic, metal and chemical industry the implementation of pre-, in- or post-combustion compensation approaches is very specific to the respective installation [2].

Besides the increased fuel flexibility the control concepts increase the process efficiency, reduce thereby fuel consumption, emissions and maintenance efforts. A manufacture claims that the invest of a O_2-λ-control into a process will be returned within 2 years in case of a 10 MW plant by fuel savings [11].

Current state and Outlook

Currently roughly 0.4 % of the installed domestic gas appliances in Europe have a self-adaptive gas control [12] and most of the commercial and industrial appliances were setup with the assumption of locally quite stable gas qualities. The later assumption is not valid anymore and processes have to be checked with respect to their sensitivity to gas quality fluctuations and the need of advanced combustion controls. To create a deeper awareness of gas quality fluctuations was one success of recent DVGW research activities [2, 6], furthermore several approaches to compensate the effects have been elaborated and presented [2, 13]. There is still the need of new alignment of standards with respect to gas quality [2], which has required a lot of rethinking [14] and will be pushed forward by the new draft of prEN 16726 [15].

Research on gas quality and optimized combustion is continued by DVGW, its research station and departments at KIT[8] within KIT's Energy Centre. There are several public and industrial research projects about gas quality in general, hydrogen admixture, extended use of biogas, optimized combustion and new sensors. The major objectives are low emissions of CO and NO_x and unaffected operation regarding safety and efficiency even at pronounced varying gas qualities.

Conclusion

Gas quality is strongly affecting combustion processes and due to several reasons gas quality will fluctuate more pronounced in future. There is a strong need to compensate the undesirable effects by use of modern sensor and control technologies. Several pre-, in- and post-combustion approaches are already available and have been presented, some of them have been integrated into the MGARCP as a demonstrator and research tool. To proliferate and further optimize these advanced control technologies for gas utilisation is an important part of DVGW's and KIT's research activities.

Acknowledgements

The author acknowledges the support of DVGW, KIC-InnoEnergy, and industrial partners. He likes to thank for the collaboration on gas quality issues especially Dr. A. Giese, Dr. M. Werschy, T. Kortubash and their colleagues.

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