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Optimal control of fuel gas mixing systems

Abstract: There is an increasing need to design and analyze fuel gas mixing systems where a variety of gases are mixed in highly varying proportions in order to serve mixed gas users in different operating conditions. One source of high variability is electrolyzer-produced hydrogen, which may induce variations of 0 to 100% produced hydrogen depending on the power market situation.

Keywords: Gas mixing systems; gas quality control; Wobbe index

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1 Introduction

Mixing of fossil and/or non-fossil fuel gases for combustion in industrial systems, such as furnaces and boilers, is becoming more demanding as hydrogen comes into the picture. There is a fairly good coverage in literature on the subject of mixing small amounts of hydrogen into natural gas pipelines. A challenge case for an industrial gas mixing system and its control and optimization was presented by Ricker et. al. [1] for small amounts of hydrogen feed but with multiple combustible recycle gases with varying properties.

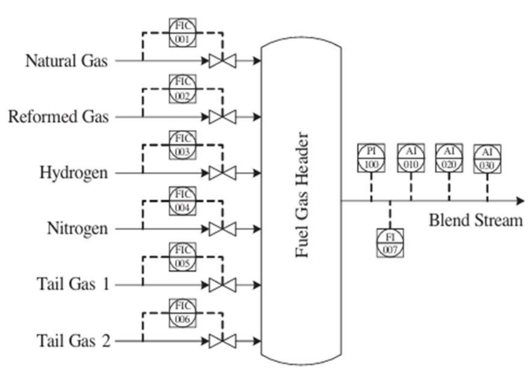

Figure 1. Gas mixing system, from [1]. Flow-controlled inlet gases and on-line property analyzers (AI) on the mixed gas outlet stream.

2 The role of hydrogen

Hydrogen provides a viable option to reduce fossil fuel gas usage in industrial heating systems. The technology and engineering challenges start from selecting proper materials for piping, mixing vessel, valves and instruments in order to minimize hydrogen escape. Safety is of very high priority in hydrogen service. If the hydrogen share must be allowed to vary in a wide range, even the extreme case 0…100%, the rangeability of control valves and gas flow meters must be secured either by finding such single devices with performance guarantee or designing parallel gas flow paths for small and large gas flows. Add to this the scenario of highly varying flow of the mixed gas, which is everyday routine in steel industry where the fuel gas consumption is highly periodic.

One reason for a high variability of the hydrogen content is generation of hydrogen with an electrolyzer for which production may depend on the power price – at low price the hydrogen generation is high and vice versa. The wider the allowed range of hydrogen generation, the better is the economics.

3 Wobbe index

The Wobbe index W of a gas is defined as:

$$W = \frac{LHV}{\sqrt{\rho/\rho_{AIR}}}$$

Where LHV is the lower heating value (MJ/kg) of the gas, ρ is the density of the gas and ρ_{AIR} is the density of air. The Wobbe index is commonly used as a measure of interchangeability of fuel gases with different compositions. The Wobbe index is one of several quality variables of the mixed gases which must be monitored for instance using a dedicated on-line Wobbe index analyzer in the mixed gas stream. It can also be calculated using the mass or volume fractions of inlet gases based on flow measurements and known heating values and densities of them. For instance, for a mixture of hydrogen (LHV_1, ρ_1) and natural gas (LHV_2, ρ_2) we can write, using molar masses M_1 and M_2 and M_{AIR} for the molar mass of air:

$$W = \frac{R * LHV_1\rho_1 + (1-R) * LHV_2\rho_2}{\sqrt{[RM_1 + (1-R)M_2]/M_{AIR}}}$$

Where R is the volume fraction of hydrogen and 1-R is the volume fraction of natural gas.

Plotting W as a function of R, we find a minimum point for R = 87 %, see figure 2. It is obvious that this minimum point challenges any closed loop control and/or optimization of W. As a minimum, process gain following is required, and automatic re-tuning if the measured or calculated W can be trusted.

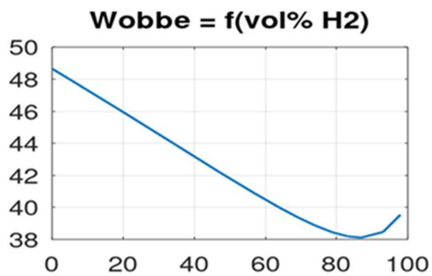

Figure 2. Wobbe index as a function of volumetric percentage of hydrogen.

4 Other mixed gas properties

Other important mixed gas properties include adiabatic flame temperature, flame speed and flammability limits, the latter playing an important role if air is one of the inlet gases. Air is sometimes used to decrease the Wobbe index when propane is one of the feed gases. Since a large fraction of hydrogen in the mixed gas increases the volumetric flow in the piping downstream the mixing vessel, some maximum limits of pipe speeds can be applied.

5 Optimal control

Energy balance, i.e. the total energy of inlet gases, must be equal to total consumed energy, averaged over some time period. Wobbe index may be required to be controlled to some target value or stay within some narrow min/max limits, but the other mixed gas properties can typically float between given minimum and maximum limits. If the number of inlet gases, N, is high enough to enable degrees of freedom for on-line optimization, a cost function:

$$J = \sum_{i=1}^{N} P_i F_i$$

can be minimized where P_i are gas prices (Eur/kg) and F_i are inlet gas flows (kg/h). CO2 cost, which also depends on F_i can be added to the cost function.

6 Mixed gas distribution system

The mixed gas distribution system may be a complex pipe network with multiple branches and sub-branches. The changes in gas composition, initiated at the mixing station, propagate through the system partially as a “time constant” flow (single- or multiple capacity process) and partially as plug flow. This puts challenges on how to estimate the gas compositions at the gas user positions along the network.

7 Bibliography

[1] Ricker, N.L,, C.J. Muller and I.K. Craig, Fuel gas blending benchmark for economic performance evaluation of advanced control and state estimation, *Journal of Process Control, 22(2012),* pp. 968-974.