

Improvement of energy efficiency of natural gas combustion by applying a homogeneous combustion

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Abstract. In many heat devices designers and operators meet the problem of low efficiency of combustion and restricted emission standards. This process should be improved to maximize its efficiency and satisfy additional requirements as, for example, uniform temperature field in combustion chamber, low noise level or very low NO_x emission. These requirements are satisfied by homogeneous combustion. Such combustion method is particularly attractive for the steel or glass industry or power industry based in particular on natural gas. In this paper factors, which have the biggest influence on performance of flameless combustion, are discussed, among others: momentum of fuel and oxidizer, composition of the mixture, the temperature of the inlet gases. Additionally, blind simulations of combustion in a combustion chamber of a furnace are run to assess how high is the influence of these factors individually. Numerical simulations are performed in a CFD code AVL Fire. The detailed chemical kinetics mechanism GRI-mech 3.0 is used for combustion calculations. Calculations results are correlated with experimental data. Blind simulations and experiment provide similar level of NO_x emission (~6-8 ppm). Experiments showed that the effect of the addition of ethylene to fuel on emissions of NO_x, CO, THC is not significant. Similarly, numerical simulations predict that influence of ethylene is negligible. CO, THC and CO₂ were on a stable level across all cases. NO_x emissions increase when mass flow of air and fuel increases due to higher heat release in the same volume, what results in higher temperature of combustion products. When temperature of fuel increases NO_x level decreases.

1 Introduction

Restricted emission standards and improvement of efficiency are one of the key issues in combustion. One of the methods which help to fulfil these requirements is homogeneous combustion, often called flameless combustion because of not visible flame front

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in combustion area. Such combustion method is particularly attractive for the steel or glass industry or power industry based in particular on natural gas.

In the literature, flameless combustion (FLOX) has some other names: MILD (Moderate and Intense Low Oxygen Dilution) combustion [1], [2], HPAC combustion (Highly Preheated Air Combustion) [3], HTAC (High Temperature Air Combustion) [4], FDI (Fuel Direct Injection) [5]. Several reviews have also been published [1, 6, 7].

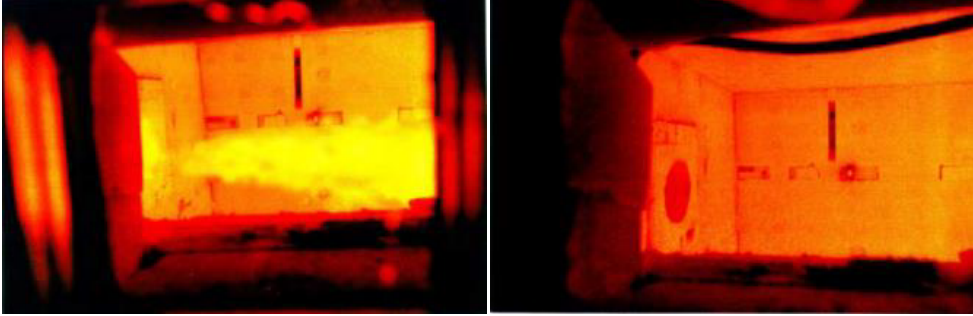


Fig. 1. Comparison flame (left) and flameless (right) firing natural gas [8].

The comparison of flame and flameless combustion is presented in Fig. 1. The difference between conventional flame and flameless combustion is recirculation ratio [9]:

$$K_v = \frac{M_E}{M_F + M_A} \quad (1)$$

where: M_E - mass of exhaust gas, M_F - mass of fuel, M_A - mass of air

For conventional combustion K_v is about 0.3, but in flameless combustion K_v should be more than 2 [7]. Fuel-air equivalence ratio is more than 1 in stable flameless combustion. Flameless combustion occurs when very dilute reactants are preheated to very high temperatures [1].

The main advantage of flameless combustion is reduction of NO_x emission. Moreover, the researchers noted more homogenous temperature distribution, reduced thermal stress for the burner or less burner faults [10]. Also typical combustion roar disappears due to not visible flame front.

In this paper an experiment performed at University of Michigan in Ann Arbor is described. The influence of doping of ethylene to natural gas on emissions is analyzed. Than blind simulations in a commercial CFD code AVL Fire were performed using the same geometry and boundary conditions. The influence of temperature of fuel, doping of ethylene and mass flow of fuel and air on emissions level (NO_x , CO, THC) was analyzed.

2 Experimental investigation

The experimental furnace is installed at University of Michigan in Ann Arbor. It is used mainly for simulation of flameless combustion.

All experiments were run in the vertical, 120 cm height furnace (Fig. 2a and b). The furnace was built as reversed bucket, where the fuel and oxidizer nozzles were installed vertically on the top of combustion chamber and exhaust gases left the furnace through windows in the lower part. The lowest element of the furnace was a moveable tub with simple heat exchanger made of the copper pipes. The role of heat exchanger was cooling down and - more important - measuring of the radiation level. The water flow was kept

on a stable level of 0.5 kg/s. On the top of the combustion chamber one fuel vertical nozzle (in the axis) and four vertical oxidizer nozzles (symmetrical on diameter 560 mm) were installed. Each pipeline went through the hood and there was possibility to preheat each of them.

The aim of experiments, among others, was to achieve the temperature field and the content of O_2 and pollutants (NO_x , CO, THC) in each measuring port (probe) on 4 depths - on the fuel axis ($r = 0$ mm), 75, 160, 230, 280 mm (oxidizer nozzle axis). These probes were installed on the sidewall in three sets, where each set has 5 probes. Fuel flow in the nozzle was ~ 0.11 kg/min and oxidizer ~ 1.56 kg/min, fuel and oxidizer nozzles diameter was 16 mm.

During experiments there was a possibility to measure all parameters in 4 levels: in the highest – 220 mm, 430 mm, 640 mm and 850 mm from the top. The lowest probe (1060 mm from the top) showed on fig. 2a was not used.

The process of flameless combustion demands under stoichiometric conditions, where the mixture is rich and excess air ratio $\lambda < 1$ (equivalence ratio $\phi = 1/\lambda > 1$). Starting procedure (about 1 hour) did not allow to keep fixed rich mixture because of safety and the probability of explosion but when temperature reached more than $850^\circ C$ conditions could be slowly changed from lean toward rich mixture. When temperature was higher than minimal ($850^\circ C$) flameless combustion could occur.

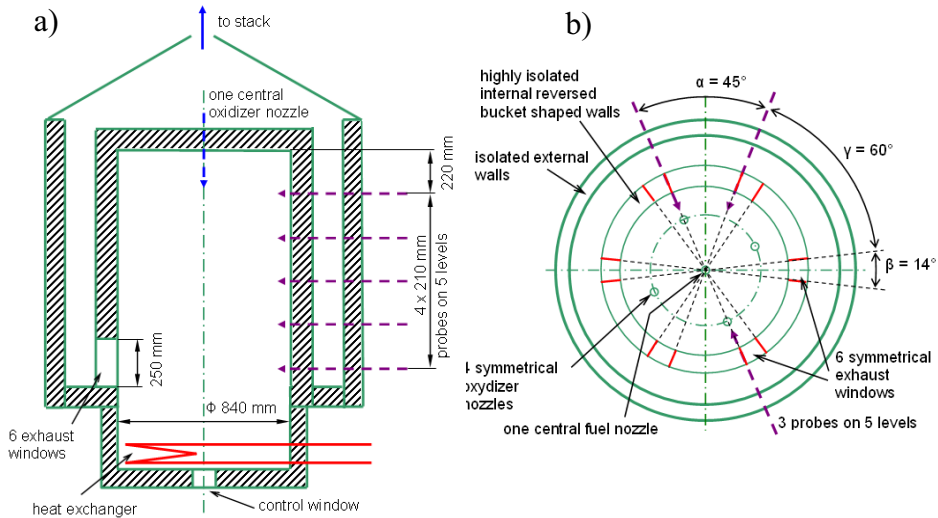


Fig. 2. Testing furnace: a – vertical view, b - horizontal view.

The literature [7, 11, 12] shows that combustion in enhanced oxygen can be more effective and radiation can be stronger compared to combustion in normal air (21% oxygen and 79% nitrogen). But the radiation could be enlarged more after adding heavier hydrocarbons to fuel. In this experiment the influence of ethylene doping was investigated. Fuel was preheated up to $473^\circ C$ for radiation enhancement. In Table 1. cases measured during experiment are summarised.

Table 1. Cases measured during experiment.

Name	Oxygen/nitrogen (vol)	Ethylene [%]
35O2NG	35/65	0
35O2NG15E	35/65	15

In Fig. 3 (NO_x) the influence of ethylene on NO_x emissions is shown. Measuring points were located not so close to the top (to fuel and oxidizer nozzles) and one set of points was located straight below fuel nozzle and the second set – straight below oxidizer nozzle. Presented experimental results and results described in [7] show, that for some oxygen/ethylene ratios ethylene can lower NO_x emission by about 3 ppm in comparison to flameless combustion in pure air. In this case adding ethylene in some levels decreases NO_x content but on the bottom of the furnace this influence is much smaller probably because temperatures are smaller and the temperature field is more flat. The highest values of NO_x after ethylene adding were in fuel nozzle stream and they were between around 5 ppm and 6.8 ppm and were similar to the case where ethylene was not added [7]. The highest concentration of NO_x is on the top and drops when distance from the top H rises. Overall NO_x generation during flameless combustion compared to flaming combustion was low (about 1–3 ppm in comparison to 110–130 ppm [7]).

In this case the increase of NO_x concentration after adding of ethylene can be observed for H1060 mm, R0 mm case so this is quite opposite than overall tendency shown in Fig. 3. During the experiment semi-waves of exhaust gases were observed in the combustion chamber what suggests that it was not flameless homogenous combustion. On the other hand, small gradients of temperature and low values of NO_x show, that it was also not flaming combustion.

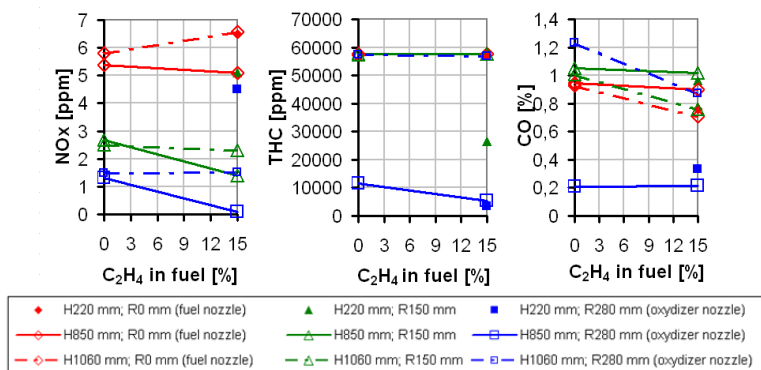


Fig. 3. Concentration of NO_x , THC and CO in exhaust gases in dependence on the content of ethylene in the fuel mixture based on natural gas in three distances from the top H (220 mm, 850 mm and 1060 mm) and three radii R (0 mm, 150 mm and 280 mm).

In Fig. 3 (CO) the influence of ethylene on CO emissions along the furnace radius is also shown. It is observed that the CO concentration in measuring points is on the low level.

In all measuring points (except for point straight below the oxidizer nozzle) adding of ethylene to fuel decreases CO concentration. In the oxidizer nozzle stream CO concentration first is small (near the top) and going down rises to reach nearly similar values independently on radius. Adding of ethylene causes lowering of CO in one height, but has no influence on the bottom near the outflow windows.

Analysis of THC showed that the concentration profile is flat in almost the whole volume. The only difference is in two points – heights 220 mm and 850 mm in oxidizer nozzle stream, 10000 ppm. There is observed very large gradient of concentration between H = 850 mm and the bottom, and is equal to 125,2 ppm/mm.

It is interesting that there is increase of radiation and efficiency of combustion (in the meaning of transporting heat to heated water) after adding of ethylene. It was observed that the temperature of exit water in heat exchanger rises at a higher value in case 35O2NG15E unlike case 35O2NG from 26°C to 28.5°C. This increase is caused by ethylene but also

by preheating of fuel and oxygen enhancement. Each of these elements can increase intensity of heat generation and radiation but not always causes drop of NO_x emission.

3 Simulation

Numerical simulations of combustion were performed using the AVL Fire code. AVL Fire is the leading CFD simulation tool in the field of combustion analysis. It specializes in the accurate prediction of processes as injection nozzle flow, fuel injection, combustion, emission and exhaust gas aftertreatment.

In this study real geometry of furnace (described in previous section) was investigated. Number of mesh elements and nodes is 368993 and 373305 respectively.

The furnace runs with equivalence ratio of EQR = 1.15 (air excess number of $\lambda = 0.87$). In total 14 simulations were run. Table 2. presents composition of fuel, mass flow of fuel and air (35% O₂), temperature of fuel for each case. Temperature of air was the same in every case and was of 300 K. Temperature of combustion chamber wall was 1100 K, with exception of the bottom wall (a location of a heat exchanger in experiment) - 298 K. Pressure was of 1 bar. The cases: C_a (base case without ethylene) and C_a15_C2H4 (15% of ethylene in fuel) are the most similar to the experimental ones.

The compressibility is solved for a weak compressible flow where density is a function of temperature only. Wall treatment is set to Hybrid Wall Treatment. In this model the "fitting" function between laminar and turbulent part of the boundary layer is derived from the relation of the friction velocity. This wall treatment should ensure a gradual change between viscous sublayer formulations and the wall functions. The default Standard Wall Function heat-transfer model is chosen, as recommended by the AVL Fire manual [15].

Turbulence is a key issue in CFD modeling. In this work turbulence is modeled by using k- ζ -f turbulence model. The k- ζ -f model is recommended by the AVL Fire manual for application in combustion simulations [15].

The General Species Transport Module and the General Gas Phase Reaction Module are used to calculate combustion. In this study the GRI-Mech 3.0 was used [13]. This the latest version and most commonly used detailed reaction model for natural gas combustion with 325 reactions and 53 species. The homogeneous chemical reactions are solved in the whole computational domain. The enthalpy sources resulting from the homogeneous reactions are taken into account in the gas-phase enthalpy equation.

Table 2. Analyzed cases (green color informs on a changed value in comparison to the base case).

Case	%CH ₄ in fuel	%C ₂ H ₄ in fuel	Mass flow fuel [kg/s]	Mass flow air [kg/s]	Temperature fuel [K]
C_a (base)	100	0	0.00183062	0.0166613	760
C_a05	100	0	0.00091531	0.0083307	760
C_a08	100	0	0.0014645	0.0133290	760
C_a12	100	0	0.00219674	0.0199936	760
C_a15	100	0	0.00274593	0.0249919	760
C_a20	100	0	0.00366124	0.0333226	760
C_a360	100	0	0.00183062	0.0166613	360
C_a560	100	0	0.00183062	0.0166613	560
C_a860	100	0	0.00183062	0.0166613	860
C_a960	100	0	0.00183062	0.0166613	960
C_a05_C2H4	95	5	0.00184765	0.0166613	760
C_a10_C2H4	90	10	0.00186880	0.0166613	760
C_a15_C2H4	85	15	0.00198900	0.0166613	760
C_a20_C2H4	80	20	0.00190833	0.0166613	760

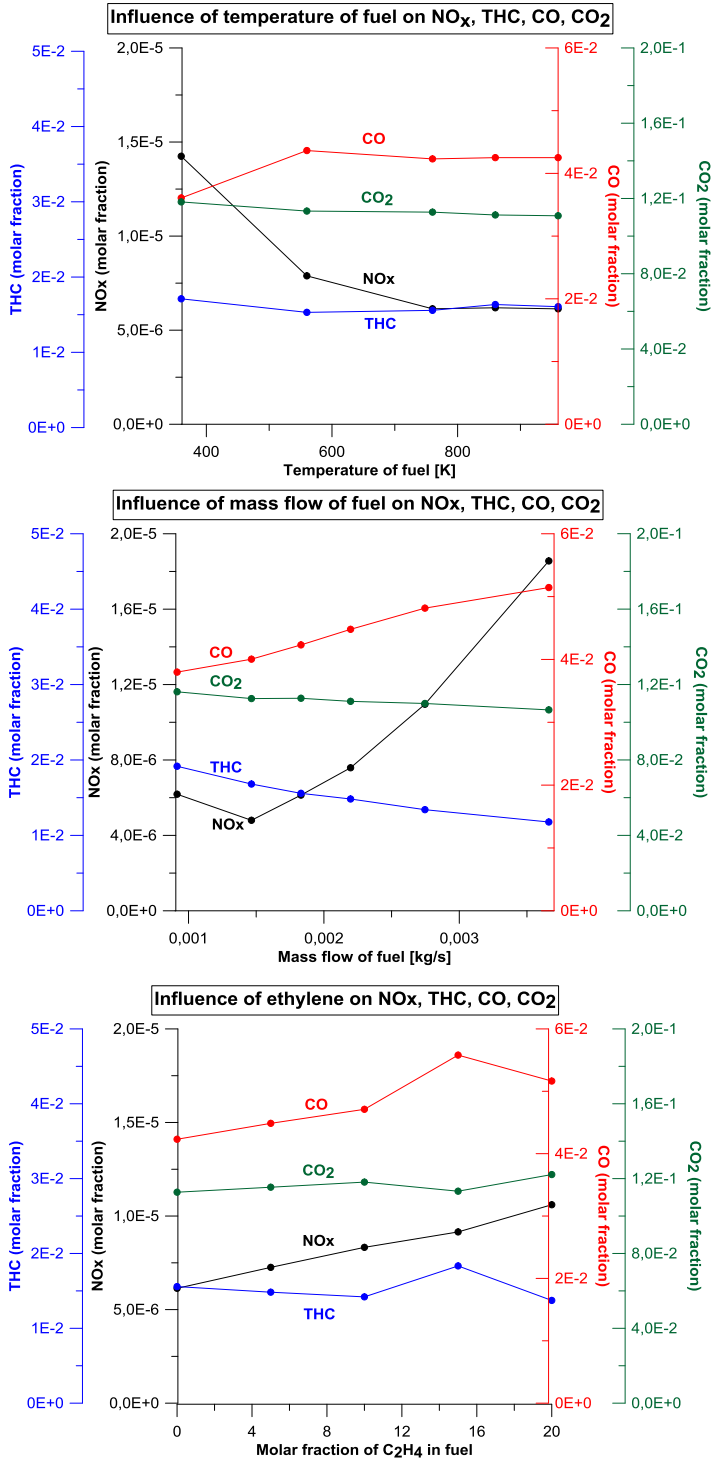


Fig. 4. Influence of temperature of fuel (top), mass flow of fuel (centre) and ethylene doping (bottom) on NO_x, THC, CO and CO₂ emissions.

Results from simulation are presented in Fig. 4 and 5. In Fig. 4, the influences of temperature of fuel, doping of ethylene and mass of fuel on NO_x , THC (Total Hydrocarbon), CO and CO_2 are presented. Emission of NO_x increases with the increase of mass flow of fuel and ethylene doping. Emission of NO_x decreases with the increase temperature of fuel, and then stabilizing for temperature of fuel higher than 760K. Emission of CO_2 is almost constant, only slightly decreases for higher mass flow of fuel. Emission of CO is the lowest for temperature of fuel of 360 K and the highest for temperature of fuel of 560 K. Further increase of temperature of fuel leads to a stabilization of emission of CO. Emission of CO increases with the increase of mass flow of fuel and ethylene doping. Emission of THC decreases with the increase of mass flow of fuel. The influence of temperature of fuel and ethylene doping on THC emission is negligible.

Figure 5. (left) presents NO_x in standard unit (mg/Nm^3) to describe emission of furnaces and boilers. Emission limit values for existing medium combustion plants with a rated thermal input equal to or greater than 1 MW and less than or equal to 5 MW, other than engines and gas turbines for natural gas is $250 \text{ mg}/\text{Nm}^3$ [14]. NO_x emissions in the illustrated furnace is much lower than the limit.

The high influence on mean temperature in combustion chamber (fig. 5. right) has mass flow of fuel. Mean temperature in combustion chamber increases by 174 K when mass flow of fuel increases fourfold. The effect of temperature of fuel and ethylene doping is negligible.

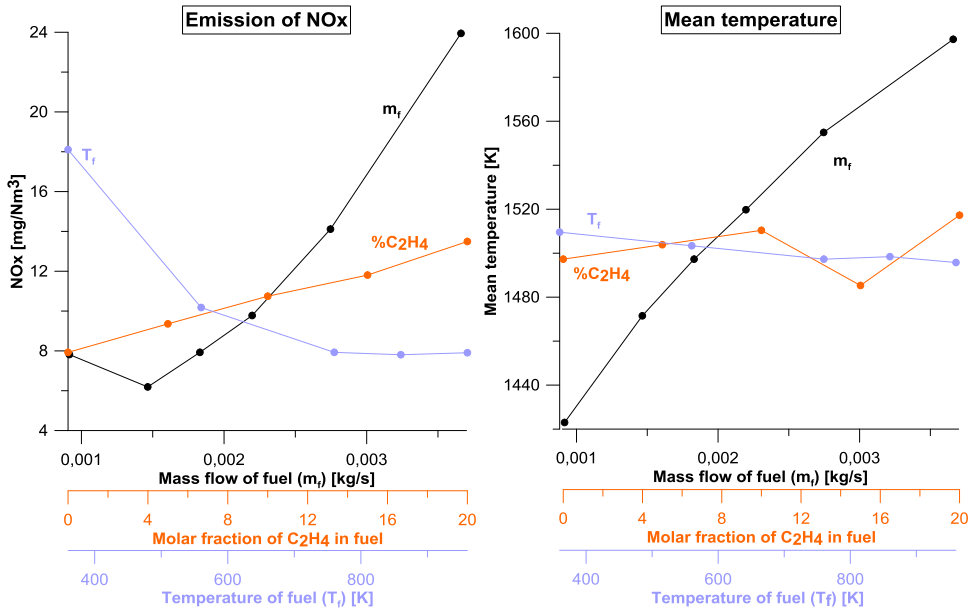


Fig. 5. Influence of temperature of fuel (pastel blue), mass flow of fuel (black) and ethylene doping (orange) on NO_x emission (left) and mean temperature in combustion chamber (right).

4 Conclusion

In the paper experimental and numerical investigations of natural gas combustion in a furnace were performed. The most important conclusion is that blind simulations and experiment provide similar level of NO_x emission (~6-8 ppm). Experiments showed that the effect of the addition of ethylene to fuel on emissions of NO_x , CO, THC is not significant. Similarly, numerical simulations predict that influence of ethylene is negligible.

CO, THC and CO₂ were on a stable level across all cases. NO_x emissions increases when mass flow of air and fuel increases due to higher heat release in the same volume, what results in higher temperature of combustion products. When temperature of fuel increases NO_x level decreases.

In the next step of numerical investigation influence of equivalence ratio, radiation and recirculation ratio will be assessed.

The authors acknowledge professor Arvind Atreya for support in collecting the data needed to write this article.

References

1. A. Cavaliere and M. De Joannon, *Prog. Energy Combust. Sci.* **30** (2004)
2. M. De Joannon, A. Cavaliere, T. Faravelli, E. Ranzi, *Proc. Combust. Inst.* **30** (2005)
3. M. Katsuki and T. Hasegawa, *Symp. Combust.* **27** (1998)
4. H. Tsuji, A. K. Gupta, T. Hasegawa, M. Katsuki, K. Kishimoto, M. Morita, *High temperature air combustion: From Energy Conservation to Pollution Reduction* (CRC Press LLC, 2003)
5. B. A. Fleck, A. Sobiesiak, H. A. Becker, *Combust. Sci. Technol.* **161** (2000)
6. J. A. Wünnig, J. G. Wünnig, *Prog. Energy Combust. Sci.* **23** (1997)
7. J. Szymczyk, P. Olszewski, *Arch. Combust.* **36** (2016)
8. A. Milani, A. Saponaro, *IFRF Combust. J.*, Article Number 200101 (2001)
9. H. Yu, “Flameless Combustion of Natural Gas in the SJ/WJ Furnace” (2008)
10. J. G. Wünnig, *Flameless combustion and its applications*, 14th IFRF Members Conference (2004)
11. A. Atreya, “Ultra-High Efficiency and Ultra-low Emissions Combustion Tech for Manufact Industries” (2013)
12. N. Krishnamurthy, W. Blasiak, A. Lugnet, *Development of High Temperature Air and Oxy-Fuel combustion technologies for minimized CO₂ and NO_x emissions in Industrial Heatin*, The Joint International Conference on “Sustainable Energy and Environment (SEE)”, (2004)
13. G. P. Smith, D. M. Golden, M. Frenklach, N. W. Moriarty, B. Eiteneer, M. Goldenberg, C. T. Bowman, R. K. Hanson, S. Song, W. C. Gardiner, V. V. Lissianski, and Z. Qin, “GRI-mech 3.0 mechanism.” http://www.me.berkeley.edu/gri_mech/
14. European Commission, “Directive of the European Parliament and of the Council on the limitation of emissions of certain pollutants into the air from medium combustion plants”, *Off. J. Eur. Union* 442, 19 (2013)
15. AVL FIRE Manual, version 2014.2