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Combustion Control Based on Flame Ionization

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Keywords

Flame Ionization, combustion control, gas quality adaptation, condensing heating appliance

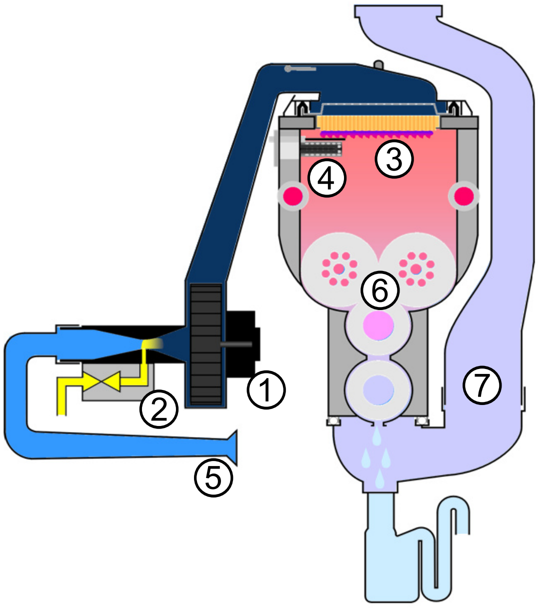
1. Abstract

In this paper we present a method for a reliable gas-adaptive combustion control applicable in condensing heating appliances. As for the monitoring of the combustion quality, we look into the concept of flame ionization detection which aims at the extraction of an equivalence ratio dependent current measured across a flame. We show approaches for the dynamic modelling of the overall system, the ion current sensing and discuss the adaptation on a detailed combustion model for the purpose of detailed analysis of charged species reactions in flames. An experimental setup is presented which allows the measurement of the ionization signal and the test of closed-loop system controllers based on this feedback signal.

2. Background & Motivation

Gas-fired condensing appliances constitute the state-of-the-art technology for household heating and domestic hot water generation purposes in Europe. They account for the largest share of installed heating devices in many European markets [1] (United Kingdom: 97%, Netherlands: 95%, Germany: 66%) with a sales volume of about 2.8 million units per year [2]. The high market acceptance is mainly attributed to the high efficiency achieved by the additional condensation of the water vapour in the exhaust gas. Figure 1 illustrates the design and working principle of a condensing appliance: An air fan (1) transports the fresh air through the air intake (5) to the burner (3). On its way to the fan, gas is added by the gas valve (2) and the mixture is properly mixed in a mixing chamber. The burner (3), usually a flat metal or ceramic plate with a hole-pattern, guides the mixture into the combustion volume and anchors the flame. In the heat exchanger (6), the heat is transferred from the hot gas to the circulating water and the cooled exhaust gas leaves the appliance through the flue pipe (7).

In terms of the combustion control, most installed appliances are equipped with a pneumatic gas valve, which means that the applied fuel flow is solely adjusted in reference to the applied air flow rate, with no continuous monitoring of the combustion quality. Therefore, the gas valve must be adjusted manually during installation based on the local conditions for the gas quality in order to operate the appliance with a specific equivalence ratio. Afterwards, a calibration of the settings can only be done with additional measurement equipment as part of the appliance maintenance (usually every 2-3 years) while in the meantime there is no possibility to respond to possible temporary changes in the fuel quality.



1: air fan
2: gas valve
3: burner
4: ionization electrode
5: suction pipe
6: heat exchanger
7: flue pipe

Figure 1: Cut through a condensing heating appliance.

Due to the missing combustion monitoring and inability of the system to actively control the fuel supply, variations in the gas quality can lead to significant deviations in the emissions quality, efficiency and also heat output characteristics, i.e. the defined minimum and maximum load. As a result, the system reliability and lifetime of components due to excessive temperatures at non-optimal operating conditions can be affected.

It is obvious that the fuel composition in local gas distribution systems is strongly dependent on the origin of the fuel and can therefore vary significantly, also over time. The ongoing deregulation of the gas market and the increasing trade of natural gas across continents (see Figure 2) results in the supply of gas from various sources around the world with unique compositions. Central European countries like Germany and the Netherlands are mainly supplied with gas from the North Sea and Russia via pipelines. In other countries such as the United Kingdom, Spain and Italy, liquefied natural gas (LNG) constitutes a considerable share of the supplied gas, again with a source-dependent quality. Furthermore, there are plans to increase the amount of biogas distributed in the gas grid. In Germany, for example, the goal is to increase its share in reference to the overall gas supply to 6 % by 2020 and to 10% by 2030 [3]. Depending on the source, the variation in the composition of the fuel can be significant. The methane content of natural gas from the North Sea, for example, is usually below 90% while it can be above 98% for gas originating from Russia.

If expensive efforts in the conditioning of the gas quality are to be avoided, a combustion system must be able to detect and adapt to fluctuations in the gas quality reliably. Besides that, an active combustion control offers the possibility to extend the modulation range of heating appliances, which is the ratio of minimum to maximum heat output, in order to run the appliance for longer hours at very low loads where the operating efficiency is at its maximum. Constructional limitations restrict this range to a factor of about 4 in the case of the pneumatic gas valve, while an electronic gas valve in combination with a feedback-control allows a significant extension of this range.

3. Combustion control based on flame ionization

An active combustion control requires a continuous monitoring of the combustion quality so that the air and fuel supply can be adjusted individually in order to compensate for the variations in the fuel quality. The fuel supply can be controlled with an electronic gas valve, which allows the adjustment of the gas flow independent of the air flow. In terms of the combustion monitoring, there are different possibilities that come under consideration. Taking into account the requirements in terms of reliability, lifetime, electric energy consumption and cost, the concept of flame ionization sensing offers an interesting solution in comparison to other common combustion monitoring techniques, such as oxygen- or CO_2-sensors.

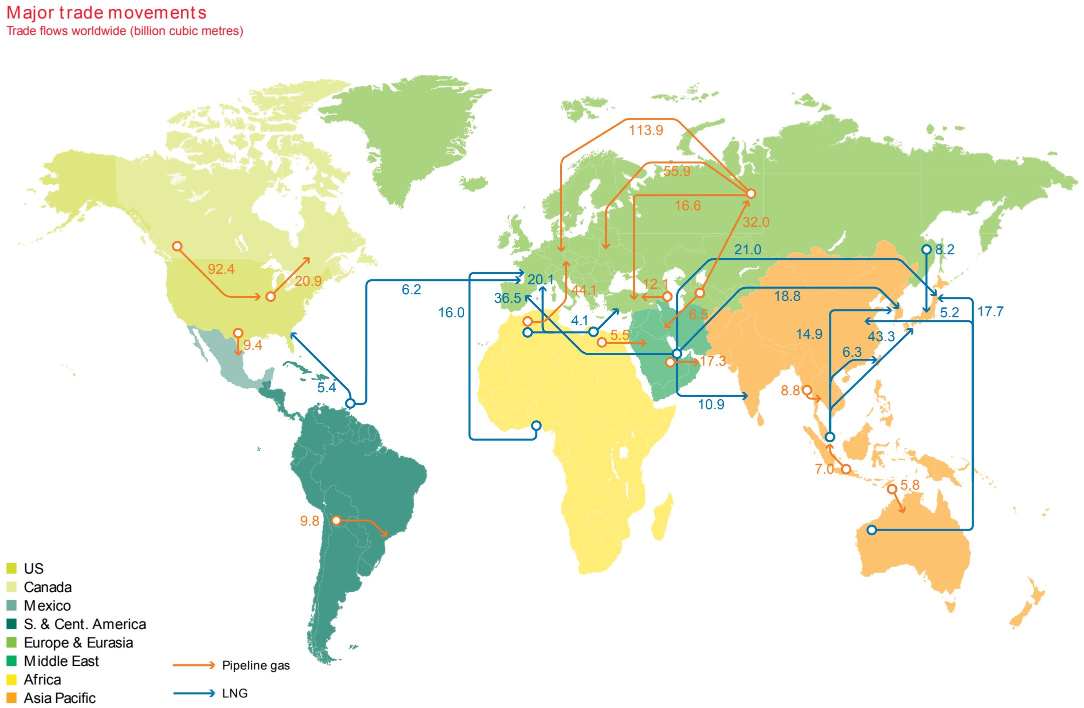


Figure 2: Overview of major trade movements for natural gas in 2010 [4].

It is based on the observation that if a potential is applied across a flame, e.g. between a burner and an electrode rod positioned in the flame, a current which is characteristic for the load and equivalence ratio can be measured. By continuously monitoring this ionization current and comparing it with pre-defined set values in a closed-loop controller, the electronic gas valve can be adjusted to set a defined equivalence ratio as depicted in Figure 3.

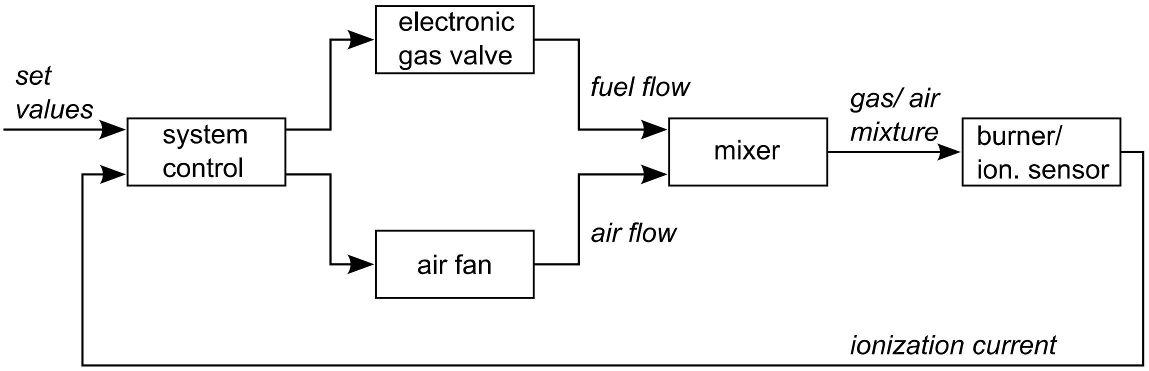


Figure 3: Schematic for combustion control based on flame ionization.

In the following we present an approach for the development of an active combustion control based on flame ionization. Since the control relies on an ionization current as a feedback signal for the combustion quality, it is of crucial importance to understand how this signal is generated. We make use of a model that can predict the measured current for given sensing setup and charged species concentrations in the flame (see section 4). Since the charged species, which are responsible for the conductivity of the flame, are generated by chemical reactions in the course of combustion, we look into this process by simulations with an adapted 1-D flame model that is able to provide detailed simulations of charged species profiles at different combustion conditions (see section 5). The obtained results are useful for the design of the burner and sensing setup in order to obtain an optimal signal quality. Finally, for the simulation of the overall system behaviour and implementation of combustion control algorithms relying on this feedback signal, we make use of a dynamic system model which is composed of all individual subcomponents (see section 6).

4. Flame ionization sensing

The basic setup for the ionization current sensing is depicted in Figure 4. There are two electrodes, one is usually the burner surface and the second one is a cylindrical metal probe positioned downstream of the burner so that it is exposed to the flames.

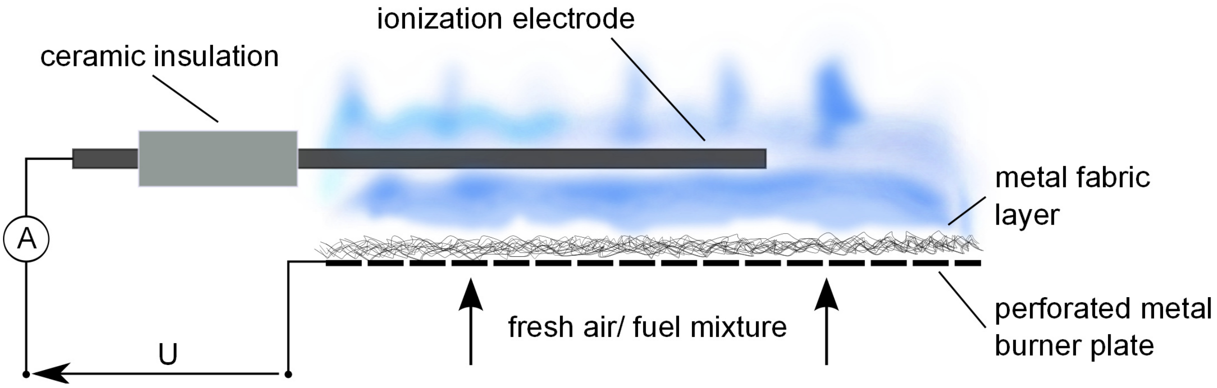


Figure 4: Ionization current sensing setup with metal burner and cylindrical rod as electrodes.

We use a flat metal burner with a uniform hole-pattern and an additional metal fabric attached to the downstream side as can be seen in Figure 5. Similar burner designs are commonly used in condensing heating appliances.

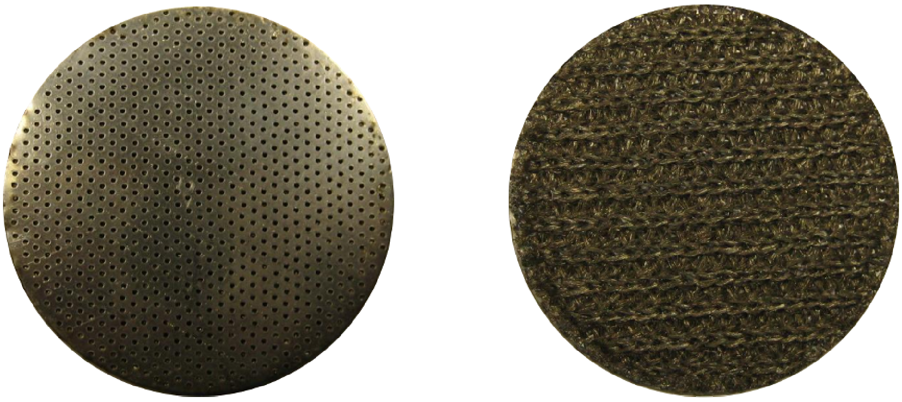


Figure 5: Metal burner plate with uniform hole-pattern (left) and attached fabric at the downstream side (right).

A cylindrical metal rod of constant diameter (~ 3mm) made of heat resistant material is used as a second electrode (see Figure 6). For the insulation of this electrode from the burner we use a ceramic jacket that can be mounted in the wall of the heat exchanger. An electric circuit generates a defined bias voltage between the two electrodes and measures the flowing current continuously, thereby providing the feedback signal for the combustion control. Ionization electrodes find widespread use in combustion applications for the purpose of flame detection where the so-called ‘diode effect’ of the flame [5] guarantees the unambiguous detection of a flame for safety related functions.

Figure 6: Electrode rod that is positioned in the flame.

It should be noted that we measure a significantly higher current if the electrode rod in the flame is charged positively which is in accordance to the general observation that electrons, due to their higher mobility, generate a much higher current for the same absolute bias voltage [6]. Even though the ion current to a negatively biased probe shows superior saturation behaviour with respect to the bias voltage, a positive polarity is still favourable because of the easier measurement of a higher current, typically µA for the electron current instead of nA for the ion current, and the better signal to noise ratio [6]. Alternatively, an alternating voltage can be used in order to concurrently use the measurement for the flame detection while still obtaining a strong enough signal for the reliable combustion quality monitoring.

The presence of charged species in flames has been known for a long time and there is a lot of literature available on the topic. Fialkov [7] presents a comprehensive overview on the subject, discussing measurement techniques, observable ionic species for different fuel types and a number of applications. Besides gas fired applications, there have been efforts to make use of ionization sensors in the internal combustion engine for the purpose of cylinder-specific equivalence ratio detection but also as a potential replacement for pressure sensors for engine knock detection [8,9].

Basically, our application resembles a Langmuir probe configuration which has been widely studied in the literature, mainly in the context of plasma physics where such probes are used for the measurement of charged species concentrations in plasmas [10]. Since flames can be regarded as low-density (in terms of the charged species concentration), high-pressure plasmas, those theories can be adapted for the investigation of flames. Different analytical models have been developed for the calculation of the ionization current to a probe with given geometry and bias potential and have been compared with experimental results [11,12,13].

When modelling the ionization current sensing, different aspects need to be taken into account: the properties of the moving flame plasma around the electrode (pressure, charged species density) and related boundary layer effects, the diffusive flow of the charged species due to the electric field, the position and geometry of the electrode within the flame, the distribution of the charged species across the flame and the electric field properties which are strongly dependent on the electrode alignment and applied bias voltage.

Based on these conditions, an appropriate model must be selected and accordingly adapted. Available models from the literature assume a uniform distribution of the charged species concentration in the complete flame domain, i.e. the volume between the sensing electrodes. Moreover, those descriptions only consider one specific load for the sample burner operation which is why further adaptations seem necessary when considering a modulating burner. As a first approach, we can make use of a model that is based on a setup that closely resembles the configuration we're looking into and which is based on the theory for an ion current I_i per unit length to a negatively biased cylindrical probe [14] with ion mobility μ_i, permittivity of free space ε_0, electron concentration n_0, electron charge e, relative plasma velocity v, bias voltage V_p and probe diameter r_p:

$$I_i = \frac{2(\pi \mu_i \varepsilon_0)^{1/3}(n_0 e v V_p)^{2/3}}{\left[\ln\left(I_i / (2 n_0 e v r_p)\right)\right]^{2/3}} \tag{3.1}$$

In order to derive an approximation for the corresponding electron current to an equally, but positively biased probe, one can make the assumption that the currents are directly related to the electron and ion mobility μ_e and μ_i , respectively. For the ion and electron current density j_i and j_e to a probe at otherwise similar conditions, we can write [6]:

$$\frac{j_e}{j_i} = \frac{\mu_e}{\mu_i} \tag{3.2}$$

It is often assumed that in a flame plasma, the mobility of electrons is more than two orders of magnitude higher than the mobility of the ions [6]. For the current to a positively charged cylindrical probe in a moving flame plasma with given charged species density, we can insert (3.2) in (3.1) what yields:

$$I_e = \left[\frac{\mu_e}{\mu_i}\right]\left[\frac{(2\pi\mu_i\varepsilon_0)^{1/3}(n_0 evV_p)^{2/3}}{\left[\ln\left\{I_e(\mu_i/\mu_e)/(2n_0 evr_p)\right\}\right]^{2/3}}\right] \tag{3.3}$$

This equation can be used to derive a characteristic relationship between the applied bias voltage and measured current for given electrode geometry and flame properties. For first qualitative considerations, we assume an electron density of n_0 = 2.3·10^{15} m^{-3} which, as outlined in the reference [6], can be considered as typical for a flat, stoichiometric propane-air flame. Figure 7 illustrates the current-voltage relationship for a probe with specific dimensions (radius r_p = 0.0015m, length L = 0.05m) at two different velocities of the flame plasma (v = 3.5ms^{-1} and v = 1.75ms^{-1}) passing the electrode. The electron and ion mobility was chosen as μ_e = 0.4m^{2}V^{-1}s^{-1} and μ_i = 1.6·10^{-3} m^{2}V^{-1}s^{-1}, respectively [6].

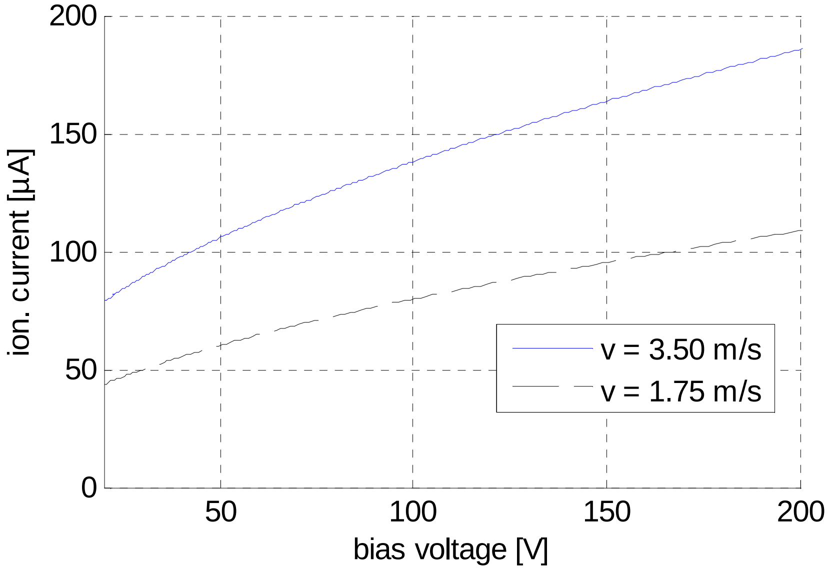


Figure 7: Ionization current as a function of bias voltage for a positively charged electrode rod immersed in a moving flame plasma at two different velocities. The electron density is assumed to be n_0 = 2.3·10^{15} m^{-3}, a typical value for a stoichiometric propane-air flame [6].

As can be clearly seen in the figure, the predicted current to the probe according to this model is strongly dependent on both, the applied bias voltage and the velocity of the surrounding plasma. This means that one needs exact information about the flame plasma motion in the vicinity of the probe, what can be difficult for our setup, since the flow conditions are strongly influenced by the applied load. It must be further investigated what adaptations can be done in order to use the model for the simulation of ionization current measurements at different loads. In section 7 we will discuss this topic in more detail when we look at measurement results obtained with our experimental setup.

5. Combustion modelling

The combustion in the appliance can be considered as lean premixed while the distinction between laminar and turbulent combustion is strongly dependent on the load (see also section 7). Commonly used combustion models don't take into consideration charged species because of their low concentration in combustion processes and their unimportance for most applications. The crucial difficulty in the consideration of charged species in combustion processes is the modelling of transport coefficients for ions and electrons in a flame plasma. Binary transport coefficients such as the diffusivity D, heat conductivity λ and viscosity μ can be modelled with the kinetic theory of rigid sphere gases [15] under additional consideration of real gas effects by inclusion of so called 'reduced collision integrals' Ω^* [16]. For neutral species a Lennard-Jones 6-12 potential is usually used to describe the interaction of two particles, where the interaction potential is characterized by the molecular diameter σ and the depth of the intermolecular potential ε. For a Lennard-Jones potential, the reduced collision integrals $\Omega^{(2,2)*}$ and $\Omega^{(1,1)*}$ can be calculated as unique functions of the reduced temperature $T^* = kT/\varepsilon$ [17], independent of further species properties. Empirical laws can then be used to calculate the transport properties for a gas mixture of specific composition [16]. However, the assumption of a Lennard-Jones potential does not hold if we consider the interaction of charged species among each other or with neutral species. Effects arising from electrodynamics have to be additionally taken into account in order to properly describe all possible interactions: neutral-neutral, ion-neutral, ion-ion, electron-electron, electron-neutral and electron-ion. In case of the electrons, quantum-mechanic scattering effects also need to be accounted for, which is why their interaction needs to be treated individually. Selle [18] developed a detailed model for the calculation of transport coefficients of gaseous mixtures including ionized species which Prager [19] extended and integrated in a combustion model together with an extended reaction mechanism for the simulation of one-dimensional lean methane-oxygen flames.

We make use of the above mentioned transport model and integrate it in INSFLA, a program which allows the detailed simulation of steady and unsteady 1-D flames [20]. The integrated software package then allows the detailed study of air-premixed laminar flames under different boundary conditions (fuel type, equivalence ratio, mixture temperature, burner characteristics) regarding the concentration and distribution of charged species in flames. Simulations with this model help us to investigate the parameters defining the ionization characteristics during combustion. Charged species profiles obtained with this model can further be used in combination with the sensing model (see section 4) for the prediction of the signal characteristics of the overall setup. This allows the optimization of the burner, electrode and measurement circuit design in order to achieve the optimal ionization signal quality.

6. System Modelling and Control

The goal of our research is the development of a combustion control that guarantees a reliable, clean and safe appliance operation at all times, also in case of variations in the fuel quality. In the early stage of the controller development, relying on an experimental setup seems impractical which is why we make use of on a model for the initial implementation and test of control algorithms. For this we first built a model of the overall system in MATLAB/Simulink® which allows the simulation of the dynamic system behaviour under various conditions. The system model is composed of the individual subcomponents such as the air fan, electronic gas valve, burner, ionization sensor and flow channels as depicted in Figure 8. Individual component characteristics are either based on analytical models (e.g. air flow, heat output) or experimental data (e.g. ionization current, dynamic fan response).

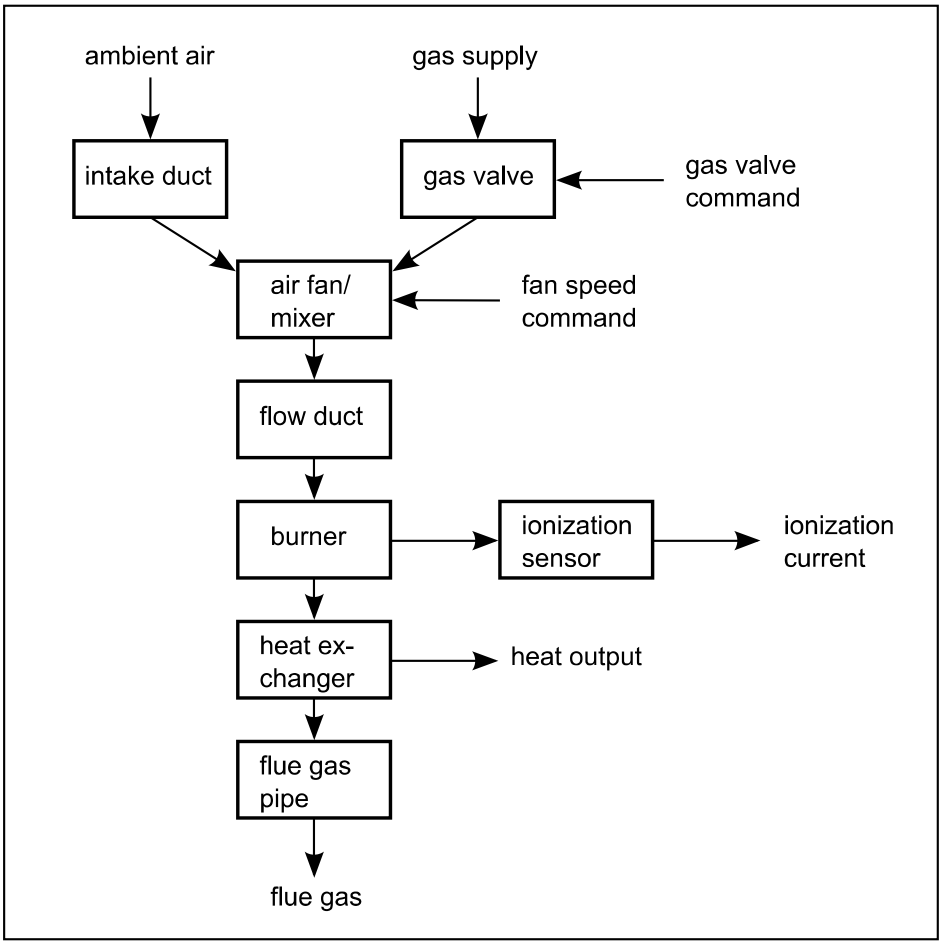


Figure 8: Schematic overview of system model with individual subcomponents.

After validation and adaptation of the model with measurement data, we can use this model for the implementation and test of control algorithms. This means that a timesaving implementation and immediate test of functions is possible without the necessity of costly and time-consuming tests on an experimental setup. Furthermore, this allows simulating the control performance and robustness for defined worst case conditions (e.g. gas quality changes, changes in flow path resistance etc) in order to avoid extensive lab testing and to theoretically safeguard the required performance. As for the steady-state operation, the load is defined by adjusting a specific fan speed which corresponds to a known air flow rate at nominal flow path resistance since there is usually no air flow rate meter available. Regarding the adjustment of the fuel supply, we need a controller for the electronic gas valve that precisely adjusts the fuel flow depending on the load and required equivalence ratio. As outlined before, we can use load- and equivalence ratio dependent ionization current set values and compare them to the latest measured value in order to define the control signal for the gas valve as depicted in Figure 9.

As a major requirement, the control should allow the system to immediately respond to changes in the gas quality in order to maintain a clean and safe combustion, but it must also allow a fast modulation of load in order to guarantee high user comfort without causing excessive emissions or flame loss.

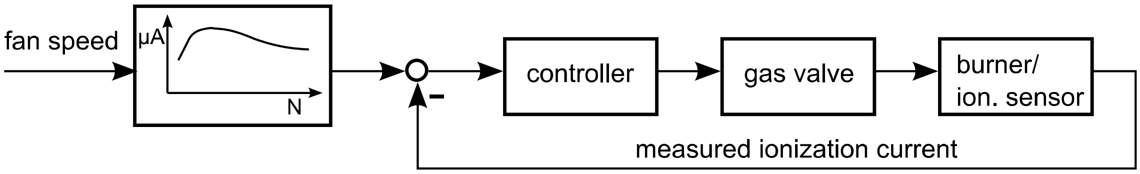


Figure 9: Closed-loop control of electronic gas valve based on pre-defined ionization current set values.

Non-linearities in the system behaviour, in particular the fan actuation and ionization current characteristics complicate the definition of optimal controller parameters for a fast but also precise operation. We observed that the ionization signal, for example, requires some time to stabilize after changes in modulation or equivalence ratio before it can be used to derive the actual present conditions. Besides the control for the steady closed-loop operation, additional control algorithms are needed for start-up and calibration sequences. Furthermore, the system control has to monitor the operation continuously and check the measured data for consistency in order to guarantee a safe system operation at all times.

7. Experimental studies

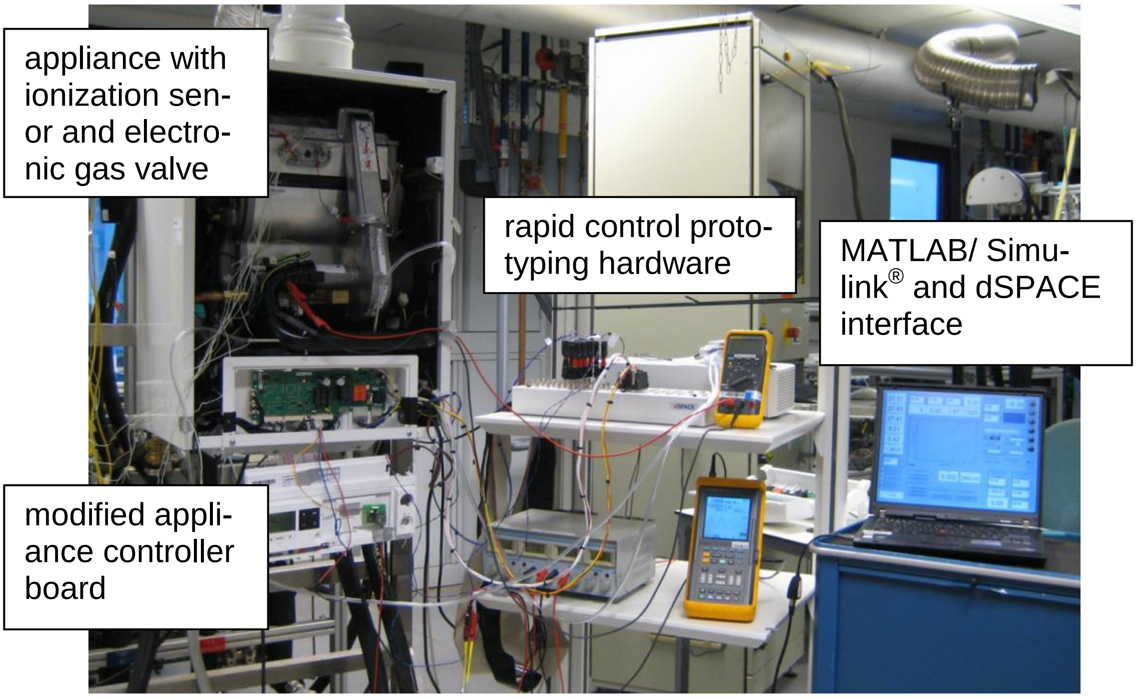


Figure 10: Experimental setup for the model validation and test of combustion control algorithms.

For the experimental studies we use a conventional condensing heating appliance which we modified in order to make it suitable for our investigations. Instead of the pneumatic gas valve, the appliance is now equipped with an electronic gas valve what allows the decoupling of the fuel and air flow. As shown in Figure 10, all sensors (ionization sensor, thermocouples etc) and actuators (air fan, electronic gas valve, igniter etc) are now directly connected to a real-time rapid prototyping system (dSPACE) which allows the acquisition of measurement data at different operating conditions, but also the online-processing of those signals in control-loop algorithms in order to generate control signals for the air fan and gas valve actuation. We positioned the ionization current sensing electrode rod at a fixed distance of 1 cm downstream and in parallel to the burner surface, similar to the alignment depicted in

Figure 4. The burner was operated at different loads and equivalence ratios in order to get an overview about the flame and ionization characteristics for the specific burner and electrode configuration. Depending on the local power density or burner load, respectively, we could see that the relative position of the electrode within the flame can vary significantly. Also the structure of the flame is strongly depending on the velocity of the gas/air mixture through the burner plate. At low load, the inlet velocity is small, resulting in a flame positioned very close to the burner surface with a laminar, slightly rippled structure. In this case, the position of the electrode rod is clearly far downstream of the flame front. With increasing load, the flame is loosing its laminar structure, transforming into a more ragged shape without a distinct flat flame front. Moreover, the average flame front is moving further away from the burner surface, at some point passing the position of the electrode as schematically depicted in Figure 11.

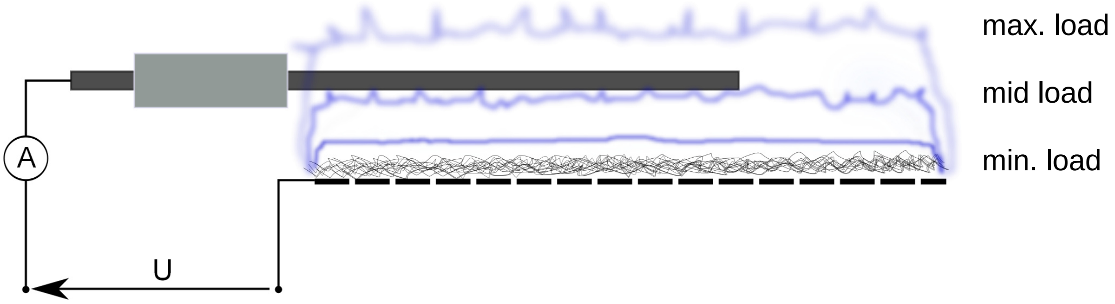


Figure 11: Variation of flame front position and structure as a function of applied burner load.

With respect to the combustion control, there are two properties of the detected ionization signal that are most important: First, the ionization current at a specific equivalence ratio as a function of the load. Since modern condensing appliances aim for a large modulation range, the sensing setup must provide a reliable and repeatable signal across a significant spread in the load. Hence, the conditions for the combustion in the vicinity of the measurement domain can vary considerably, especially regarding the velocity of the hot gas passing the electrode, the position of the electrode with respect to the flame front and the combustion conditions, i.e. transition from laminar to turbulent, as discussed earlier.

Generally, we observe a characteristic curved shape for the measured ionization current across the load range as depicted in Figure 12. As noted above, conditions for the current sensing vary significantly across the modulation range. Simulations of flat flames [19] have shown that the generation and consumption of charged species during combustion is happening very close to the flame front, so the charged species are concentrated there. If you consider a low load condition, for example, one can argue that due to the distant position of the high concentration of charged species from the positive electrode and thereby weak force of the electric field on the electrons, the overall current is relatively low. Also the significant heat transfer into the burner is likely to affect the generation and recombination rates of charged species. With increasing modulation, the distance from the flame front to the electrode rod is decreasing, so the electrons are exposed to stronger electric field forces and moreover the distance for the electrons to overcome in order to reach the electrode decreases, hence the rise in the measured current. Once the flame front passes the electrode, the distance for the electrons to overcome increases again, therefore we observe a decline in the measured signal strength. The turbulent combustion at high load causes the averaged position of the flame front (ragged flame structure) to be less sensitive with respect to variations in load, giving a possible explanation for the flatness of the curve from medium to high load if one considers the flame front position as the decisive factor for the measured current.

Referring to the probe model outlined before (see section 4), we expect a pronounced dependency of the current on the velocity of the plasma passing the electrode. A variation in the flame plasma velocity in our experimental configuration is mainly caused by the modulation of the burner load, i.e. the variation of the fresh gas/air mixture flow rate.

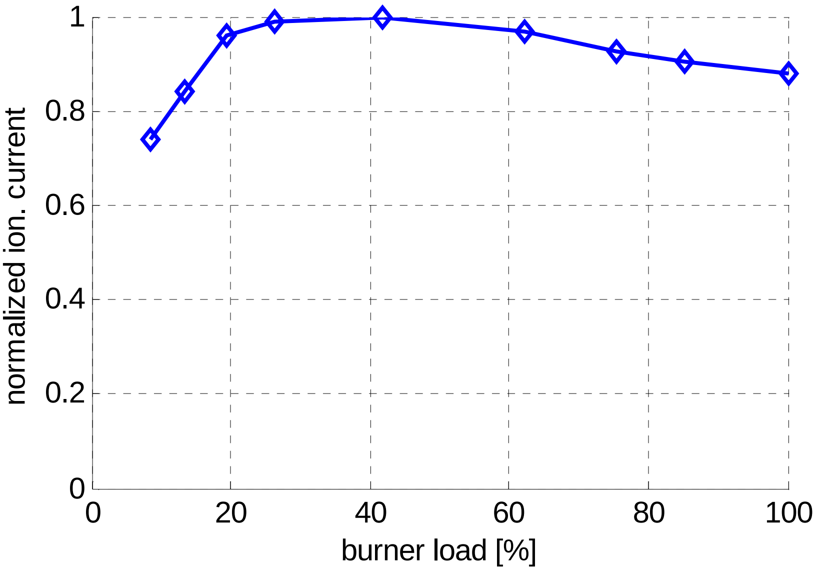


Figure 12: Ionization current across modulation range for λ=1.25.

At low load conditions (10-30% burner load, see Figure 12) we do observe a pronounced load dependency of the measured current, similar to the relationship between current and plasma velocity predicted by the theory (Figure 7) if one assumes that the plasma velocity is proportional to the burner load. However, from medium to increased load we don't see a further increase in the current as would be expected by a further increasing plasma velocity. Instead, the current reaches a maximum at medium load and decreases again for even higher loads. Looking at the variation in the flame position and structure as discussed earlier, it is obvious that the local velocity of the flame plasma around electrode is not only defined by the overall flow rate through the burner, but also by the local structure of the flame and gas flow pattern at the exact electrode position. Therefore, an increase of the fresh mixture flow rate doesn't necessarily result in an increased flow velocity of the plasma at the electrode. For a detailed analysis, the load-dependent conditions of the plasma motion at the probe position have to be known precisely. Moreover, it seems questionable whether for a modulating burner the basic assumption in the model of a constant and uniform charged species distribution between the electrodes is valid. It rather seems likely that the charged species generation rate, but also their distribution is considerably affected by the load-dependent flame structure and position.

In order to ensure a precise control of the equivalence ratio, it is further important to have a pronounced and ideally constant sensitivity of the ionization signal in reference to the equivalence ratio. Hence, a deviation in the equivalence ratio from the set value should be clearly detected as a deviation in the ionization signal from the set value so that the control (see Figure 9) can precisely compensate for the error. Figure 13 shows a typical sensitivity curve at a defined load, where it can be seen that the sensitivity is not constant but rather depending on the equivalence ratio. We also observed that the characteristic gradient of the sensitivity curve differs as a function of the burner load. In addition to the obvious influence of the equivalence ratio on the reaction rates for the charged species which we want to further investigate with detailed combustion simulations, similar effects as the ones affecting the 'ionization current vs. load' curve are likely to play a major role in the sensitivity characteristics. It must be kept in mind that a variation of the equivalence ratio causes a shifting of the flame front in reference to the burner and also influences the level of turbulence in the combustion.

With the help of additional combustion simulations (see section 4) and measurements to characterize the flame structure as a function of the load, we aim to gain a deeper understanding with regard to the impact of the burner modulation and mixture composition on the measured ionization current and its sensitivity characteristics.

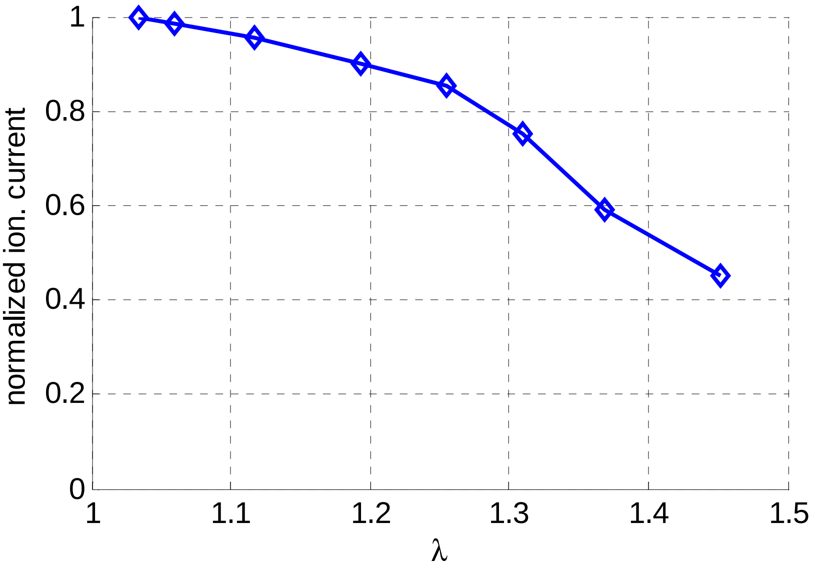


Figure 13: Ionization current sensitivity curve. The graph shows the measured ionization current for a constant load as a function of the equivalence ratio.

In terms of the closed-loop combustion control, we could demonstrate that the implemented control concept (see Figure 9) in combination with the observed characteristics in the ionization current sensing allows a quick and precise adaptation to changing fuel qualities within the same gas family across an extended modulation range. The low load operation turned out to be most critical because of the poorer ionization signal quality and longer stabilization times. A major requirement for the burner design is therefore to provide a strong and reliable ionization signal across the complete modulation range.

8. Summary and conclusions

Our investigations showed that the combustion control based on flame ionization has the potential for a reliable and cost-competitive method to guarantee a safe, clean and robust operation of condensing heating appliances with the ability to compensate for variations in the fuel quality. A major challenge turns out to be the design of a burner and sensing setup that guarantees a reliable and representative detection of the ionization current at all times. Our experimental investigations showed that the ionization signal not only shows a distinct sensitivity with respect to the load and equivalence ratio, also the electrode design and alignment and the bias voltage have a major influence. The topic of flame ionization is complex and further modelling and simulation work needs to be done in order to better understand and predict ionization current measurements for different configurations. We intend to address this issue by detailed numerical investigations in the combustion and further adaptations on the model for the signal sensing setup.

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