MICROSCALE COMBINED HEAT AND POWER SYSTEM FOR LIQUID FUELS

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Conventional central power generation shows a high electrical efficiency, but the transmission of the energy to the consumer is hindered by distribution losses. Decentralized combined heat and power (CHP) generation in proximity to the customer is an alternative to reduce transmission losses. Based on a natural gas-fired micro-CHP system, a liquid fuel burner system is developed. The modification of the natural gas system for operation with light fuel oil (no. 2) is the focus of this project. An innovative vaporization technique, i.e., cool flame vaporization, is used to create a homogenous fuel–air mixture. The combustion of the fuel–air mixture is surface stabilized, using the surface burner of the natural gas system. Different atomization techniques and nitrogen oxide reduction concepts, such as air staging and exhaust gas recirculation, were evaluated. By fulfilling stringent emission targets and safe operation in the complete power range, the concept of micro-CHP aims to achieve an efficient use of limited resources.

KEY WORDS: cool flame, atomization, air staging, micro-CHP, steam engine

I. INTRODUCTION

Supported by the increasing ecological awareness, the necessity for high energy efficiency and more stringent emission targets have arisen. Current technologies, such as condensing boilers, operate near theoretical maximum efficiency, so the interest in developing new, more efficient, systems is increasing. Micro-CHP systems can provide a further increase in efficiency. Micro-CHP is the simultaneous production, also known as cogeneration, of heat and electricity in domestic applications. The term micro-CHP is used for family houses and small office buildings, while mini-CHP or block CHP are located at a higher output level, delivering energy for communities or apartment blocks (Harrison, 2004). Another criterion for micro-CHP systems can be an electrical power output of less than 15 kWel (Pehnt et al., 2006). Micro-CHP units replace conventional boilers of central heating in houses. The generated heat is used in the primary heating and hot water circuit,
while electric power is simultaneously generated. The electricity generation differs from manufacturer to manufacturer. Common systems include internal combustion engines, Stirling engines, fuel cell systems, and steam-driven generators.

Micro-CHP systems are commonly regulated by the current heat request, generating electricity while the heat generation runs. Hence, to increase electricity production time, the burner is required to run as long as possible. This is only possible when the burner operation can be fully modulated.

To increase the market share of micro-CHP systems, a fuel-independent supply of cogeneration systems is necessary. The aim of this presented development is to modify an existing natural gas-fired system to use liquid fuels. Considered fuels in this sector are light fuel oil (no. 2) and renewable liquid fuels, e.g., rapeseed oil or fatty acid methyl esters (FAMEs). The basis for this development is the natural gas–fired micro-CHP system by the company OTAG based in Olsberg, Germany. It exhibits a fully modulating power range of 3–16 kW (±5%) thermal and 0.3–2.0 kW (±10%) electrical power output.

In order to combust liquid fuels, it is necessary to vaporize the fuel. However, this is often connected with well-known technical problems such as deposit building and preignition. Therefore, an innovative vaporization technique, the so-called cool flame vaporization, is applied in this development to overcome these hazards (Lucka et al., 1999a,b; Hartmann, 1999).

Cool flame vaporization allows the homogenous mixture of a liquid fuel with combustion air prior to combustion. For optimal mixing, the liquid fuel needs to be vaporized. Atomization of the fuel by an atomizer of any kind (e.g., swirl-stabilized pressure nozzle) maximizes the fuels’ surface area, decreasing the vaporization time of the fuel. Several observations by Coffee (1979), Fish (1968), and Davey (1817) showed the presence of a two-staged ignition. Affens and Sheinson (1979) described the first stage as a cool flame area. In the cool flame, only a small amount of heat, up to 10% (Lucka, 1999a), is released. In certain operation modes, this heat is sufficient to vaporize the atomized fuel. The heat release is caused by reactions between hydrocarbons and oxygen. During these reactions, the composition of the fuel alters as long-chained molecules of middle distillates break up (Pearlman and Chapek, 1999).
II. OBJECTIVES

Improved building standards reduce the mean domestic heat demand. Current combustion devices, e.g., the blue flame burner in condensing boilers, exhibit high efficiencies and low emissivity, but lack the prerequisite of a high power modulation range to comply with micro-CHP system demands. Blue flame burners allow a modulation range of up to three (Schmitz, 1995). Still, most blue flame burners in the field exhibit a lower modulation range. In order to circumvent the limitations, new combustion designs need a high modulation range and a low minimal power. The physical separation of vaporization and combustion zone permits an interrupting injection, therefore fulfilling these requirements. Additionally, the premix character of this concept allows a well-mixed fuel air supply to the combustion zone, resulting in low-emission combustion (Mengel et al., 2002).

Micro-CHP systems run most economically when they operate without burner shutdown, to avoid a cooldown of the generation unit. With one-stage burners, only an intermittent operation is possible, while a modulating burner concept allows continuous firing.

The aim of this project is to realize a premix surface burner with a cool flame vaporizer in the power range from 3 to 19 kW (overall), suitable for the investigated micro-CHP unit. For this, an evaluation of possible atomizers is executed. Compared to gaseous fuels, liquid fuel-based burners have to be developed more carefully to avoid high nitrogen oxide emissions. The presented adaption proposes modifications to the basic concept to circumvent higher nitrogen oxide levels.

III. EXPERIMENTAL SETUP

The basis for the evaluation is an experimental setup on a test firing tube. The test bench includes a water-cooled combustion chamber with adjustable volume, and optical access to the combustion area.

In Fig. 1, the flowchart of the setup with secondary air path is shown. The system consists of two flowmeters, supplied with pressurized air and downstream electric air heaters. The fuel pumps require standard oil filter systems to avoid particles entering the pump. The inclusion of an oil heater derives from standard oil burner designs, as viscosity influences can be minimized with preheated oil. This is especially important when using renewable fuels with high viscosities.

Fuel and preheated air enter the cool flame vaporizer, as shown in Fig. 2. Essential for a system shutdown is the existence of fuel injector cooling since all investigated injection systems require to be maintained at a temperature below 120°C. Beside material limitations, temperatures above 120°C can lead to thermal cracking of fuel inside the fuel injector. The cool flame vaporizer is designed as a loop-type vaporizer with the fuel injection in the vaporizer head. The advantages of this setup are an easily modifiable injector setup and a stable cool flame reaction inside the vaporizer. In the case of split air operation, only the primary air
enters the cool flame vaporizer, while downstream the secondary air is mixed with the cool flame product. The fuel is injected into the vaporizer (Fig. 2) by an atomizer. The fuel droplets mix with electrically preheated air and form the cool flame reaction. The loop inside the vaporizer allows a recirculation of the cool flame product. The heat energy released by the cool flame assists the vaporization

FIG. 1: Flowchart of the experimental setup with secondary air path

FIG. 2: Vaporization process of liquid fuel with preheated air, supported by cool flame reactions inside a loop-type vaporizer
of the fuel droplets injected into the vaporizer and the mixing of the fuel and air, by convection and volume expansion of the hot gases inside the vaporizer. In the setup, the cool flame product enters a surface burner. The surface burner is slightly modified in diameter compared to the version used in the natural gas micro-CHP system. Increasing the burner surface area results in enhanced flame cooling by radiation. The necessity for this modification derives from the higher combustion temperature of fuel oil in comparison to natural gas. The burner mounting was modified to suppress condensation of the cool flame product between the cool flame vaporizer and the burner surface. The combustion of the cool flame product is surface stabilized, allowing a high percentage of the thermal energy to radiate from the burner to the combustion chamber. By this, the surface-stabilized combustion reduces the flame temperature, hence reducing the thermal nitrogen oxide formation (Issendorf, 2002).

IV. EVALUATION OF ATOMIZATION TECHNIQUES

An investigation of different atomization techniques is necessary because the low minimal power requirements demand a modified fuel preparation. Achieving a quick phase transition from liquid state to gaseous state requires an atomization of the liquid fuel. The atomization increases the fuels’ surface and by this supports the phase transition.

The evaluation includes common oil burner technology, either as an atomizing nozzle (pressure-stabilized swirl nozzle) or as a fuel pump (gear pump). The evaluation compares four different techniques, i.e., high-pressure injection valve (HPIV) with a gear pump, low-pressure injection valve (LPIV) with a gear pump, swirl-stabilized pressure atomizers (simplex nozzles) with a microdosage piston pump, and ultrasonic atomization. The atomization of the fuel depends not only on the atomizer type, but also on the fuel pump.

The HPIV and LPIV originate from the automotive sector. Due to the good spray quality and reproducible fuel dosing, automotive injectors are predestined for intermittent injection. The fuel flow is controlled by the opening intervals of the injectors. A major drawback for automotive injectors is the expected limited lifetime. Automotive parts are designed for approximately 5000 operation hours, while micro-CHP systems can easily reach this limit within two years time, while the lifetime expectancy for CHP systems should be more than 10 years. The fuel supply for the automotive injectors is realized by a gear pump, commonly used in oil burner applications.

The simplex nozzle is a standard oil burner component. Different types of simplex nozzles were tested. Additionally, the sintered filters of the simplex nozzle were replaced by antidrip valves (Hago Ecovalves HC and Danfoss LE system). These valves require a minimum pressure to open, allowing an intermittent fuel injection. The fuel is supplied by a piston pump, dosing the fuel amount by piston
stroke frequency and displacement. The nozzle by itself would only limit the fuel flow to a maximum value.

Ultrasonic atomization is investigated for feasibility. The key benefit of ultrasonic atomization is the monodisperse spray formation. Disadvantageous is the low momentum of the fuel spray, requiring a high gas momentum to carry the fuel to the combustion zone. Critical for ultrasonic atomization is the surface tension of the fluid. Ultrasonic atomization is tested for applicability in the system. The initial step is a monitoring of the required electrical power consumption for the system, since this is regarded as critical.

Figure 3 depicts three of the evaluated fuel injectors. To ensure equivalent nozzle tip positioning, the injector mounting requires modification for each injector. The mounting includes the water-cooling geometry for the injection device and is interchangeable in the vaporizer head.

For the investigation of the different atomizers, the vaporizers’ outer liner was changed into a glass cylinder, allowing an optical accessibility to the nozzle. The spray geometry and quality were documented and evaluated. The emissions were analyzed beside spray quality. The optical accessible vaporizer is not fully comparable to the steel vaporizer of the final setup, but it allows the comparison between the different atomization techniques. Figure 4 shows the test bench with the glass vaporizer and an exemplary view of an HPIV tip during injection.
V. NITROGEN OXIDE EMISSION

In order to compensate the higher tendency of liquid fuels to form nitrogen oxides, two methods are investigated. First, air-staged vaporization is investigated, followed by an investigation of simulated exhaust gas recirculation.

A. Secondary Air

One method to reduce the thermal nitrogen oxide formation is to lower the flame temperature. A liquid fuel premix system, such as the described cool flame vaporizer, will deliver the evaporated fuel at a temperature above the end point of the boiling range (for middle distillates). Typical temperatures of ~420°C are reached at the burner entrance, when the cool flame product is not cooled. The result of this is an increase in flame temperature. To reduce this effect, secondary air can be added to lower the temperature of the cool flame product flow. A minimum mixture temperature of 250°C avoids condensation of hydrocarbons in the flow.

Two possibilities exist to realize air staging. The first option is to supply the primary air for a substoichiometric combustion with a secondary air supply to complete the combustion. The second possibility was realized in this project, in which the secondary air is mixed to the cool flame product before entering the surface burner. Figure 5 depicts the setup for air-staged vaporization. The layout of the secondary air addition to the cool flame product is supported by flow simulations in CFD. With ANSYS 10.0, different geometries for the secondary air nozzle are investigated, looking at fluid flows, mixture area, and mass flow distribution on and in the downstream-positioned surface burner. The simulation investigated the

FIG. 4: Test bench with glass vaporizer for atomization evaluation
mixture of cool flame product and secondary air in coaxial flow and crossing flow at a 45 deg angle. In Fig. 5, the version with a 45 deg cross flow is illustrated.

B. Exhaust Gas Recirculation

In order to further reduce nitrogen oxide emissions, the use of exhaust gas recirculation is possible. By increasing the inert mass flow through the combustion zone, the heat transport out of the reaction zone is higher and the flame temperature will drop. According to the thermal nitrogen oxide formation mechanism, the nitrogen oxide emissions will decrease with reduced flame temperature.

The exhaust gas recirculation was simulated by adding air or nitrogen to the process, reducing the fuel-air ratio. The additions were calculated to rates corresponding 18, 28, and 36% of exhaust gas recirculation.

VI. RESULTS

A. Evaluation of Atomization Techniques

The ultrasonic atomizer shows a high demand of electrical energy. In order to vaporize 100 ml/h of fuel oil, 70 W_{el} are necessary. Related to the fuel demand of up to 1900 ml/h, an electrical power demand of 1330 W_{el} arises. With a maximum electrical power output of 2000 W_{el}, the electrical efficiency would drop drastically. Due to this result, no further investigations into combining the ultrasonic atomization with the burner were carried out.

The test configurations for the atomization technique evaluation are displayed in Table 1. Results of the emission analysis for the evaluated atomization techniques

FIG. 5: Setup for secondary air addition to the cool flame flow; the secondary air is redirected by 45 deg to improve mixture with the cool flame products while entering the surface burner
TABLE 1: Evaluated test configurations, analyzed within the glass vaporizer

<table>
<thead>
<tr>
<th>Test</th>
<th>Power output (kW)</th>
<th>Pump</th>
<th>Nozzle type</th>
<th>Pressure valve</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPIV</td>
<td>3–11</td>
<td>Danfoss gear pump</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LPIV</td>
<td>7</td>
<td>Danfoss gear pump</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MCP 1</td>
<td>6–9</td>
<td>Microdosage pump MCP 20/50</td>
<td>Danfoss 0.40 gph 60 deg S</td>
<td>Antidrip valve Hago Ecovalve HC</td>
</tr>
<tr>
<td>MCP 2</td>
<td>3–14</td>
<td>Microdosage pump MCP 20/50</td>
<td>Danfoss 0.40 gph 60 deg S</td>
<td>Antidrip valve Hago Ecovalve HC</td>
</tr>
<tr>
<td>MCP 3</td>
<td>3–16</td>
<td>Microdosage pump MCP 20/50</td>
<td>Danfoss 0.50 gph 60 deg S</td>
<td>Antidrip valve Danfoss LE</td>
</tr>
<tr>
<td>MCP 4</td>
<td>3–16</td>
<td>Microdosage pump MCP 20/50</td>
<td>Danfoss 0.40 gph 45 deg SR</td>
<td>Antidrip valve Hago Ecovalve HC</td>
</tr>
</tbody>
</table>

are given in Fig. 6. Herein, the emissions in milligrams per kilowatt hour are plotted against the power output in kilowatts, showing the carbon monoxide emissions on the left with bold symbols and nitrogen oxide emissions on the right with outlined symbols. The nitrogen oxide emissions were calculated for 140 ppm fuel nitrogen at a fuel-air ratio of $\Phi = 0.87$. Nitrogen oxide emissions rise with increasing power output because the surface load of the burner increases. Hereby,

FIG. 6: Emissions (CO and NO$_x$) of the evaluated atomization techniques with total air supply, fuel-air ratio $\Phi = 0.87$, and corrected nitrogen oxide emissions for 140 ppm fuel nitrogen
surface load is defined as thermal power output divided by surface area of the burner. In the case of the atomization technique evaluation, the nitrogen oxide emissions are in nearly all cases above the limit of 110 mg/kW-h of the RAL-UZ 46. Taken that the certification for micro-CHP units RAL-UZ 109 (oil-fired micro-CHP units), the emission is well below the desired level, since the limit for RAL-UZ 109 is 2500 mg/Nm$^2$ (~2500 mg/kW-h). Carbon monoxide emissions tend to be critical at low power outputs, especially below 5 kW. At high power rates, the carbon monoxide emissions decrease to very low levels. The corresponding emission limits of the German RAL-UZ 46, being 110 mg/kW-h for nitrogen oxide and 60 mg/kW-h for carbon monoxide, are plotted as limits inside the figure.

Using the total air supply, ~15% of the total energy has to be recuperated to heat the air to the necessary temperature in the vaporizer. Using air-staged vaporization, the necessary heat amount can be reduced to 1.5% of the total energy. In this case, the secondary air will be added after vaporization and before combustion on the surface burner. The mixing of cool flame products and cold secondary air bears the possibility of deposit formation due to condensation of hydrocarbons in the cool flame product, when the temperature of the mixture falls below ~250°C. Raising the temperature of the secondary air reduces the risk of deposit formation. The necessary heat is supplied (in the experimental setup) with an air heater.

Results of the investigation with secondary air supply show a low level of carbon monoxide emissions, fulfilling the emission limits given by the German guideline RAL-UZ 46. The nitrogen oxide emissions are above the emission limit of 110 mg/kW-h. The results shown in Fig. 7 prove that the chosen path to reduce

FIG. 7: Emission analysis for air-staged combustion at $\Phi_{\text{Primary}} = 1.67$ and $\Phi_{\text{Primary}} = 2.5$ at $\Phi_{\text{Total}} = 0.87$; NO$_x$ emissions are calculated for a fuel with 140 ppm nitrogen (injector: pressure-stabilized swirl nozzle)
the nitrogen oxide emissions was successful because the nitrogen oxide emissions could be reduced from over 500 mg/kW⋅h to ~320 mg/kW⋅h with a primary fuel-air ratio of $\Phi_{\text{Primary}} = 2.5$. The results in Fig. 7 were gained with a pressure-stabilized swirl nozzle.

The comparison of fuel atomizer techniques showed no observable differences in the spray quality. All three techniques performed well in the desired power range, showing good spray quality. The emissions were slightly lower using the microdosage pump due to the continuous flow through the pump. The microdosage pump combined with a simplex nozzle and pressure valve were chosen for the realization, because this setup combines excellent atomization with low cost and good accessibility of the components, because they are standard parts used in heating units.

B. Air Staging

Realizing a homogeneous mixture of cool flame product and secondary air is crucial for clean combustion. Different mixer geometries were simulated to predict the flow within the mixers. The simulation returns the fuel mass fraction along the burner surface, as well as the fluid flow rate and direction. The calculation area includes the fluid flow to the mixing area and the whole interior of the surface burner. Figure 8 gives an overview of numerical simulation results at a power output of 9 kW with one of the mixing units. The calculated mixing unit allows a homogeneous mixing of the cool flame products, from the loop-type vaporizer, with the secondary air. The pressure drop can be held at an acceptable level by increasing the width of gap A, shown in Fig. 5.

FIG. 8: Exemplary summary of simulation results using mixing unit III at 9 kW
C. Exhaust Gas Recirculation

The exhaust gas recirculation was simulated by adding air or nitrogen, reducing the fuel-air ratio, corresponding to 18, 28, and 36% exhaust gas being recirculated. The result of the exhaust gas recirculation simulation is depicted in Fig. 9, showing the nitrogen oxide emissions for all variations. Adding 36% of simulated exhaust gas, either by air or by nitrogen, shows the possibility to reduce the nitrogen oxide emissions below the limit of RAL-UZ 46. The results are calculated to a nitrogen concentration of 140 ppm in the fuel and a fuel-air ratio of $\Phi = 0.87$.

The carbon monoxide emissions remain below the limit of 60 mg/kW-h for all exhaust gas recirculation rates (see Fig. 9). For low powers, <5 kW, the carbon monoxide concentrations rise to a maximum of 55 mg/kW-h, while at high powers, >11 kW, the concentration remains at very low levels of ~10 mg/kW-h. For the highest exhaust recirculation level of 36%, the carbon monoxides emissions show higher values of up to 30 mg/kW-h.

VII. CONCLUSIONS

The micro-CHP system developed by OTAG (2008) in Olsberg, Germany, is currently running with natural or liquid gas. A liquid-fuel burner for the existing system is to be developed and tested.
Different atomization techniques for liquid fuels were evaluated by emission analysis and optically using a glass vaporizer. The simplex nozzle with antidrip valve fed by a microdosage pump showed a continuous flow and excellent spray properties combined with easy accessibility and low cost of the components. The burner operated with a cool flame vaporizer using fuel oil no. 2 was tested successfully over the complete power range of 3–19 kW (overall).

The innovative vaporization technique, the cool flame vaporization, is used to create a homogenous fuel-air mixture. The cool flame vaporization allows deposit-free vaporization and homogenous mixture of fuel and combustion air. Using a loop-type vaporizer allows stable operation of the cool flame reactions.

Reducing the nitrogen oxide emission of the combustion process was investigated using air staging and simulated exhaust gas recirculation. The air staging is realized by mixing the secondary air with the cool flame products from the vaporizer within the surface burner, and exhaust gas recirculation was simulated by reducing the fuel-air ratio and by increasing the amount of inert fluid. The results show the combination allows operating the burner with emissions below the limit of the German guideline RAL-UZ 46.

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