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CLEAN TECHNOLOGIES FOR WOOD COMBUSTION FROM 500 KW TO 50 MW

SCHADSTOFFARME HOLZFEUERUNGEN (500 KW – 50 MW)

Final report

Schlussbericht

Thomas Nussbaumer

Lucerne University of Applied Sciences and Arts, 6048 Horw, www.hslu.ch
Hochschule Luzern – Technik & Architektur, 6048 Horw, www.hslu.ch

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Author

Prof. Dr. Thomas Nussbaumer, Lucerne University of Applied Sciences and Arts, 6048 Horw

Collaboration

Scientific collaborators in the project, Lucerne University of Applied Sciences and Arts, 6048 Horw

Dr. Gabriel Barroso
Dr. Jürgen Good
Martin Kiener (until 2014)
Adrian Lauber
Patrick Schwingruber (until April 2015)
Dr. Jorge Martinez Garcia (until 2014)
Simon Roth

Industry partner

Schmid AG energy solutions, 8360 Eschlikon

Supervision

Dr. Sandra Hermle, Swiss Federal Office for Energy, Bundesamt für Energie, 3003 Berne

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Im Auftrag des Bundesamts für Energie, Forschungsprogramm Biomasse
Mühlestrasse 4, CH-3063 Ittigen, Postadresse: CH-3003 Bern
Tel. +41 31 322 56 11, Fax +41 31 323 25 00, www.bfe.admin.ch

BFE-Projektleiteung: Dr. Sandra Hermle, sandra.hermle@bfe.admin.ch

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Content

Abstract

The present project supplements the work of the NRP 66-Project „Clean Technologies for Wood Combustion from 500 kW to 50 MW“ conducted for the Swiss National Research Foundation (SNRF). In particular, the theoretical outcomes are applied for the design and operation of a prototype boiler in cooperation with Schmid AG energy solutions. The boiler design exhibits the following features:

- a multi-sector grate with four independent zones for primary air injection and grate movement,
- staged combustion with late secondary air injection,
- flue gas recirculation into the four grate sections.

In the project, the influence of the air distribution and the grate movement was investigated experimentally. In addition, a fuel bed model was developed enabling to perform a sensitivity analysis of the operation parameter. Further, numerical investigations by CFD were performed to optimise the secondary air injection and aerodynamic experiments on a scaled model were performed to validate the phenomena related to the jet expansion of the secondary air injected into the main gas flow to optimise the mixing in the combustion chamber.

The investigation reveals that the multi-sector grate offers additional operating parameters which can potentially be applied to adopt the boiler operation to varying load and to varying fuel properties such as the moisture content. The fuel bed model predicts a strong influence of the primary air distribution. Although the predicted trends are validated by experiments in the boiler, the operation of the multi-sector combustions reveals that the grate movement is related to an even more pronounced influence on the fuel conversion on the grate.

Zusammenfassung

Das vorliegende Projekt ergänzt die Grundlagenforschung im Rahmen des NFP 66-Projekts „Clean Technologies for Wood Combustion from 500 kW to 50 MW“ des Schweizerischen Nationalfonds (SNF) durch Umsetzung der Erkenntnisse an einer für Versuchszwecke realisierten Prototypfeuerung. Der Bau der Versuchsanlage erfolgt in Zusammenarbeit mit der Firma Schmid AG energy solutions.

Ziel der Entwicklung ist eine Optimierung der Vorschubrosttechnik, die im Vergleich zu heutigen Anlagen folgende Vorteile aufweist:

- Breiter Lastbereich (30% bis 100% Nennlast).
- Eignung für aschereiche und zur Verschlackung neigende Brennstoffe durch Temperaturkontrolle in einzelnen Rostzonen.
- Hoher Wirkungsgrad durch Betrieb bei tiefem Luftüberschuss.
- Reduktion der Stickoxide aus dem Brennstoffstickstoff durch gestufte Verbrennung.

Diese Ziele sollen durch folgende konstruktive Massnahmen erreicht werden:

- Multi-Zonen Rost mit unabhängiger Luftzufuhr in insgesamt vier Zonen und unabhängiger Rostbewegung aller Zonen.
- Möglichkeit der unabhängigen Abgasrezirkulation in vier Rostzonen mit einer von 0% bis 100% variablen Abgasmenge.
- Luftstufung in der Gasphase.

Im ersten Projektjahr wurde das Konzept der Feuerungsanlage festgelegt und die Dimensionierung der Prototypfeuerung durchgeführt. Dabei wurde unter anderem eine Methode zum Up- und Downscaling von Feuerungen entwickelt und für die Dimensionierung der Versuchsanlage angewendet. Parallel dazu wurden die Messtechnik zur Erfolgskontrolle evaluiert und bestellt. Nebst der konventionellen Abgasanalytik wurde eine Messeinrichtung mit einer gekühlten Lanze zur Probenahme von Pyrolysegas über dem Brennstoffbett realisiert und die Analytik zur Pyrolysegasmessung evaluiert. Im zweiten Projektjahr erfolgten der Bau der Versuchsanlage, der Aufbau der Pyrolysegasmessung und die Realisierung einer gekühlten Probeentnahmesonde. Parallel dazu wurden ein mathematisches Modell der Brennstoffumwandlung auf dem Rost (‚Rostmodell' oder ‚one-dimensional fuel bed model') entwickelt und die Fluiddynamik der Anlage mit numerischen Methoden optimiert. Die fluiddynamischen Berechnungen wurden mit Experimenten an skalierten Modellen validiert, während zur Validierung des Rostmodells Messungen der Pyrolysegaszusammensetzung über dem Rost erfolgten. Im dritten Jahr wurde eine Erfolgskontrolle mit Messungen der Versuchsanlage bei unterschiedlichen Betriebsarten durchgeführt.

Die Resultate zeigen, dass unabhängige Steuerung der Rostzonen, die durch den Multizonen-Rost ermöglicht wird, eine zusätzliche Eingriffsmöglichkeit zur Betriebsoptimierung bietet und der Einsatzbereich der Rostfeuerungstechnik damit erweitert werden kann. Eine mit dem ‚Rostmodell' durchgeführte Sensitivitätsanalyse zum Einfluss der Betriebsparameter weist auf eine starke Eingriffsmöglichkeit der Primärluftverteilung in die einzelnen Zonen hin. Dieser zeigt auf, dass zur Verbrennung von nassem Holz die Primärluftzufuhr in den ersten Rostzonen erhöht werden muss. Dieser Trend konnte an der Versuchsanlage bestätigt werden. Die Untersuchungen an der Feuerung zeigen aber, dass die Bewegung der Rostelemente einen noch deutlich stärkeren Einfluss auf die Brennstoffumwandlung auf dem Rost hat. Für die weitere Anwendung entscheidend ist dabei, dass mit Zunahme der Frequenz

der Rostbewegung das Brennstoffbett nicht in die Länge gezogen wird, sondern im Gegenteil kürzer wird. Dies wird dadurch erklärt, dass die Brennstoffumwandlung durch die Rostbewegung unterstützt und dadurch beschleunigt wird. Da nebst der Länge des Brennstoffbetts auch dessen Höhe und Beschaffenheit für die Durchströmung und Brennstoffumwandlung von Bedeutung ist, wurde als Basis zur Beschreibung des Brennstoffbetts dessen Energieinhalt ermittelt. Dies erfolgte durch Messung der Wärmemenge, die nach Abschalten der Brennstoffzuführung im Kessel bei isothermen Bedingungen an den Wärmezähler abgegeben wurde. Für die untersuchte Basiseinstellung wurde gezeigt, dass eine Reduktion der Rostbewegung durch Verlängerung des Intervalls zwischen zwei Eingriffen zu einer Vergrösserung des Brennstoffbetts um bis zu einem Faktor drei führt und dass dadurch eine Reduktion der CO-Emissionen um bis zu 80% erzielt werden kann. Die Untersuchungen zeigen damit, dass die Beschaffenheit des Brennstoffbetts die Verbrennung massgeblich beeinflusst und dass das Brennstoffbett durch die Rostbewegung stark beeinflusst werden kann. Im Weiteren ist die Luftzufuhr in den einzelnen Zonen von Bedeutung, ermöglicht aber allein keine ausreichende Eingriffsmöglichkeit zur Steuerung der Verbrennung. Für die Entwicklung der Feuerungstechnik und insbesondere der Regelung wird deshalb ein Schwerpunkt auf die Eingriffsmöglichkeiten der Rostbewegung gesetzt und die Aufteilung der Luft auf einzelne Zonen als untergeordnete Steuerungsgrösse verwendet.

Nebst der Brennstoffumwandlung auf dem Rost wurden im Projekt Ansätze zur Optimierung der Aerodynamik im Feuerraum mit numerischen Strömungsberechnungen (CFD) analysiert und teilweise experimentell validiert. Dabei wurden die Einflüsse von Anordnung, Anzahl und Durchmesser der Lufteindüsung auf die Mischung der Gase mit der Sekundärluft untersucht. Insbesondere für den Teillastbetrieb wurden Varianten für eine optimierte Lufteindüsung entwickelt und auf der Versuchsanlage untersucht. Die Auswertungen zeigen, dass mit der Optimierung der Gehalt an Kohlenmonoxid im stationären Teillastbetrieb gegenüber dem Referenzfall um bis zu über 50% reduziert werden kann.

Im Rahmen des SNF-Projekts sind derzeit die Untersuchungen zum Einsatz der Abgasrezirkulation und der Luftstufung im Gang.

1 Introduction

1.1 Motivation

Basis for a sustainable wood supply chain with respect to economy and ecology is to follow the cascade principle by utilising high quality wood for industrial applications prior to direct conversion to energy. If this requirement is met, currently close to 50% of the wood mass (contributing to less than 50% of the economic value) is directly converted to low quality wood residues during harvesting and wood processing. An important target to improve the valorisation of the wood chain is to increase the share of wood mass used for products. However, this share will remain significantly lower than 100% resulting in considerable amounts of wood residues from forestry and industry. In addition, all wood products are finally found as urban waste wood (UWW, “Altholz”) at the end of the life cycle. Due to its inhomogeneous character and due to specific (but often unknown) contaminations with halogenes (Cl, F) and heavy metals, there is only a limited potential for recycling of UWW. Consequently, a conversion of both, wood residues and UWW to energy is the dedicated final step in a cascade of the wood chain to maximize the economical and ecological benefit. Hence combustion systems for wood resources are needed, which

1. achieve high conversion efficiencies into useful energy as heat and power,
2. are specifically suited for wood residues and (with additional measures) for UWW, and
3. which can safely not only meet the environmental standards, but which can also ensure environmentally friendly operation under practical circumstances (which is not guaranteed by meeting the environmental standards, since practical operation can strongly vary from acceptance control conditions). This is important with respect to
   a) pollutant emissions into the ambient, and
   b) with the additional target to recover incombustible materials (grate ash, cyclone ash, filter ash, sludge and condensables) in different specific fractions and as inert materials to enable further utilisation in the future (depending on fuel type e.g. for agricultural and forestry applications or as building material) instead of waste disposal as applied today.

Wood combustion, however, contributes to the air pollution. Most relevant are emissions of organic compounds, particulate matter (PM), and nitric oxide emissions (NO_X). To increase the share of wood energy and to meet more stringent standards, combustion systems enabling the use of low quality wood fuels at low emissions are needed. With respect to potential pollutant abatement, the following groups of emissions need to be considered:

1. Products from incomplete combustion (PIC), i.e.
   – carbon monoxide (CO)
   – volatile organic compounds (VOC)
   – condensable organic compounds (COC)
   – polycyclic aromatic hydrocarbons (PAH)
   – solid elemental and carbonaceous compounds (elemental carbon EC, “soot”)
   PIC are emitted in gaseous (CO, VOC), liquid (COC) and solid phase (EC) with PAH being emitted both, as vapours and particle-bound. Thus PIC contribute to primary PM. In addition, PIC emitted

in the vapour phase as VOC can cause secondary PM by photochemical formation of secondary organic aerosol (SOA) in the atmosphere.

2. Inorganic particulate matter smaller than 10 micrometres (PM_{10}), smaller than 2.5 microns ($PM_{2.5}$) and ultrafine particles (UFP) smaller than 100 nm including inorganic compounds (alkali metals, salts, and carbonate carbon (CC)).
3. Nitric oxide emissions (NO_X).
4. Specifically in case of contaminated fuels such as UWW, halogen organic acids such as HCl and HF as well as polychlorinated-*p*-dibenzo dioxines and furanes (PCDD/F) need to be additionally considered and avoided by primary measures or removed by secondary measures.

The pollutant emissions from biomass combustion are crucial due to the following reasons:

1. As life cycle analyses show, the environmental impact of wood energy origins to more than 80% from direct combustion emissions with app. 40% from PM_{10} and 40% from NO_X [1].
2. Biomass combustion is identified as dominant source of black carbon (BC) [2], which according to IPCC exhibits a global warming potential (GWP) for 100 years of 460 times the one of CO_2.
3. In Switzerland (as in many other countries), wood combustion is the major source of organic carbon in PM_{10} [3].
4. The strongest health relevance in air pollution is associated with PM_{10} [4] .
5. Airborne pollutants are identified as an important drawback for a further propagation of biomass as renewable energy source by the International Energy Agency (IEA), which identifies an important need of R&D with respect to basic knowledge and technology development for the reduction of PM_{10} and NO_X [5].

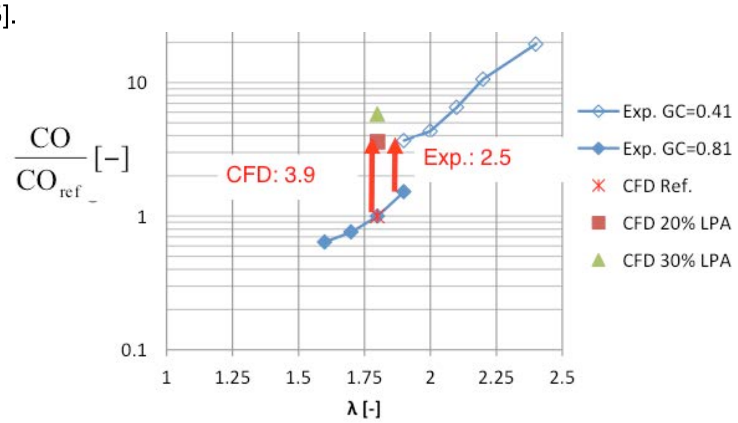


Figure 1.1 CO emission factor (i.e. CO normalised to the CO emissions in the reference case) as function of the excess air ratio. GC = Grate coverage [6]. LPA = leaking primary air.

Concerning grate combustion, initial tests on the influence of the distribution of wood fuels on a 1.2 MW grate boiler showed that the grate coverage can play a relevant role for the combustion process. In particular, an uncovered section on the last part of the grate can lead to undesired air flows through the grate thus resulting in non-ideal flow conditions. As a consequence, the boilers are often operated at increased excess air ratio leading to a significant efficiency reduction. In addition, increased CO concentrations can occur in the flue gas. As shown in Figure 1.1, an increase of the CO emissions by a factor of 3.9 is predicted by CFD calculations, while the experiments reveal an increase by a factor of 2.5. Although the simplified mechanisms in the CFD result in an over-estimation of the effect, the experiments confirm the significant influence of uncovered grate sections.

1.2 Target

The objective of the project is to develop basic knowledge and concepts for clean wood combustion technologies for the size range from 500 kW to 50 MW to fulfil the specific needs of wood industry. The main focus is a combustion design based on grate boilers as most relevant and economic technology, but with new standards of primary measures to safely reduce PIC including COC and VOC contributing to PM_{10} as primary and secondary aerosol and NO_X, which is a contradiction in nowadays technologies, but which can be achieved by a multi-stage concept and to guarantee high practical availability. Therefore the project wants to improve the understanding of the fuel conversion on a grate and in the gas-phase, to develop a numerical model for boiler optimisation, and to validate the design requirements experimentally. Specific attention is given on the influence of different combustion sections on the grate and on multi-stage combustion conditions such as air staging conditions. Based on these findings, an improved design and control strategy for grate boilers is developed.

1.3 Research plan

To reach the above mentioned targets, the following three tasks are conducted:

1. In cooperation with Schmid AG as industry partner, a modularly designed grate boiler with several sections for independent primary air injection, flue gas recirculation, and grate movement shall be designed. The boiler shall enable an operation at different combustion modes for primary measures to increase the load range and maintain an optimum grate operation at varying load and moisture content of the fuel. Besides, gas analysis for raw gas above the grate and for flue gas in the stack was evaluated and purchased.

2. A fuel bed model (FBM) shall be developed to predict the solid fuel conversion on the grate as function of the operation parameter such as load and moisture content. The model shall be connected to CFD calculations in the gas phase, enabling the prediction of the pollutant emissions. Further, CFD modelling shall be applied to optimise the secondary air injection into the boiler and the geometry of the combustion chamber.

3. To validate the CFD calculations, an experimental setup is planned to investigate the gas flows and the gas mixing in scaled model experiments by means of image analysis and Particle Image Velocimetry (PIV).

2 Results

2.1 Multi-sector grate boiler

To investigate the influence of different grate sections in the combustion laboratory, a semi-industrial demonstration plant of 150 kW was designed in cooperation with Schmid AG energy solutions. During the project, the laboratory was re-arranged to enable the implementation of the semi-industrial grate boiler. Further, the boiler was installed and put into operation in the laboratory. Figure 2.1 shows a cross section of the boiler, while Table 2.1 illustrates the operation parameters for the experiments and the CFD calculations.

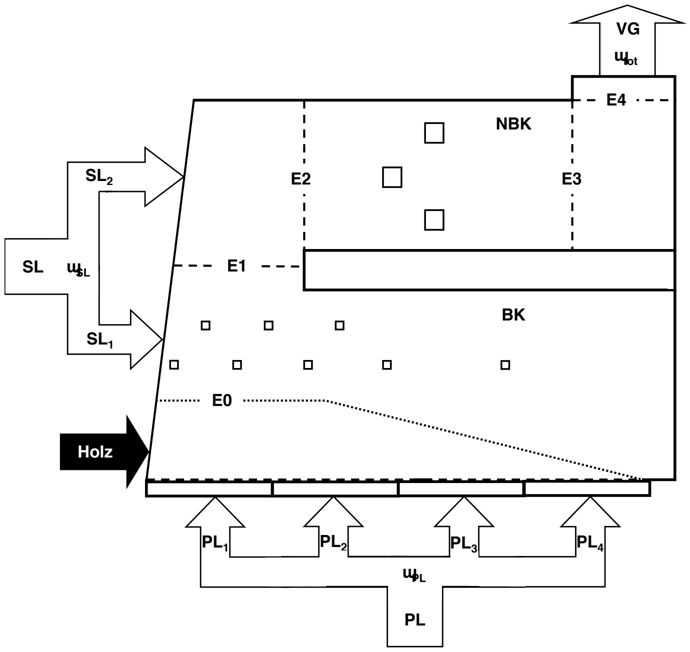


Figure 2.1 Cross section of the multi-sector prototype grate boiler with four independent primary air zones and two secondary air injection zones.

Table 2.1 Operation parameter of the 150 kW prototype boiler at 30% load and at nominal load.

Parameter	Load 30% / 100%	Dimension
Combustion capacity	59 / 176	[kW]
Boiler efficiency	85	[%]
Heat output of the boiler	50 / 150	[kW]
Primary excess air λ_P	0.70	[-]
Excess air at first secondary air λ_{S1}	0.88	[-]
Excess air at second secondary air λ_{S2}	0.22	[-]
Excess air ratio $\lambda_{tot} = \lambda_P + \lambda_{S1} + \lambda_{S2}$	1.8	[-]
Moisture content w	30	[%]
Temperature of the primary air	25	[°C]
Temperature of the first secondary air	130 / 65	[°C]
Temperature of the second secondary air	220 / 120	[°C]
Temperature combustion chamber exit	650 / 850	[°C]
Ambient pressure	1.013	[bar]
Pressure drop in combustion chamber	70	[Pa]

Figure 2.2 and Figure 2.3 show the equipment and the setup in the laboratory with an electrostatic precipitator (ESP) for particle removal. The grate consists of four independently operated grate sections. For each grate section, a separate air injection with continuous measurement of the air flow is available. As an option, flue gas can be injected into the four primary zones.
In addition, two gas analysis lines were evaluated and purchased, one for raw gas analysis above the grate and one for flue gas analysis in the stack.
Furthermore, a liquid cooled sampling probe was constructed and built to enable gas sampling above the grate. This sampling will be used to validate the modelling of solid fuel conversion on the grate with experiments in the laboratory grate boiler.

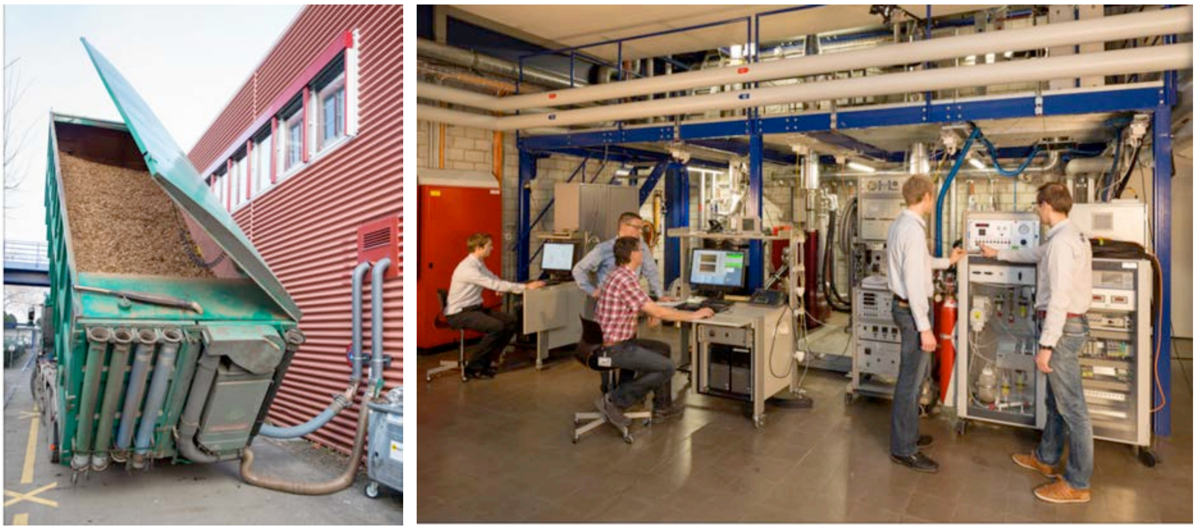


Figure 2.2 Left: Delivery of forestry wood chips.
Right: View on gas analysis equipment in operation.

Figure 2.3 Multi-sector grate boiler and electrostatic precipitator (ESP, left from boiler) in the laboratory.

To validate the effect of the primary air distribution, combustion experiments were performed in the grate boiler. The experiments revealed, that the grate movement strongly influences the solid fuel conversion on the grate. By theoretical considerations, the following effects from the grate movement are expected:

Effect 1: On the one hand, the grate movement results in a fuel transport in grate direction towards the ash disposal at the end of the grate as shown in Figure 2.4. Consequently, a prolongation of the fuel bed can be expected induced by the grate movement.

Effect 2: On the other hand, the experiments described in Figure 2.4 show that the grate movement also results in a relevant mixing of the fuel particles in all three directions, i.e. mainly horizontally but also vertically and less pronounced also perpendicular to the grate.

Figure 2.4 Visualisation of effect of grate movement on fuel distribution and mixing.
Left: Initial situation with four fuel layers. From bottom to top: natural wood chips (brown), white coloured wood chips, green wood chips, red wood chips.
Right: Final situation after fuel bed transport by grate movement.

Investigations starting with standard operation conditions reveal that the fuel bed volume shrinks with increasing grate movement as described in Figure 2.5, which shows the CO content in the flue gas as function of the energy stored in the fuel bed. The heat content of the fuel bed is a measure for the bed volume and the conversion rate of the fuel and it is measured by the heat output of the boiler after shut-down.
Since this observation is in contradiction to the effect 1 described above it is concluded that for the investigated conditions, effect 2 is most relevant and hence the grate movement causes an increased fuel conversion rate on the grate. In addition, the investigation reveals that a short interval period between grate movements has a negative effect on the combustion quality indicated by increased CO emissions. Compared to the standard operation, an increase of the fuel bed volume by a factor of 3 results in an 80% reduction of CO. Increased CO at small fuel bed volumes can be explained by un-

covered sections leading to an inhomogeneous air distribution and air streaks through the grate and thus uncontrolled flow situations.
From these findings it is concluded that a nearly covered grate at high fuel bed volume is a precondition for optimised combustion. Further, the grate movement strongly influences the fuel bed length and volume, however in a complex way, as it may lead to an increase in fuel bed volume due to the fuel transport or in a decrease due to the accelerated conversion as found here.

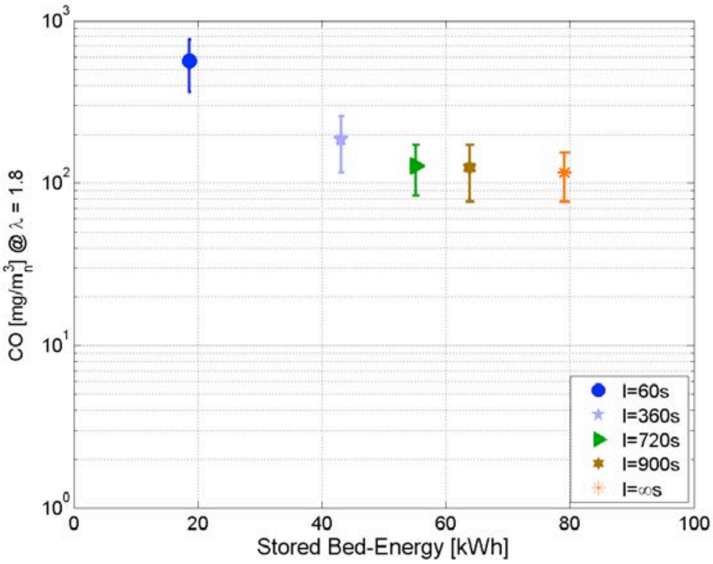


Figure 2.5 CO emissions at 30% load as function of the bed volume indicated by the energy content of the fuel bed on the grate. Parameter I = Interval period of grate movement. Standard case: I = 60 s corresponding to v_R = 0.44 mm/s (if counting forward movement only). The stored bed energy is measured by measuring the heat output from the boiler after shut-down.

2.2 Combustion modelling

2.2.1 Modelling of the solid fuel conversion on a grate

2.2.1.1 Semi-empirical model for CFD calculations

To perform CFD calculations, a semi-empirical approach for the prediction of the gas concentrations and the temperature profile above the fuel bed was applied. This one-dimensional transient model introduced by Baillifard and Nussbaumer [7] and in the style of Klasen [9] is based on the assumption that the mass release from the fuel bed equals zero at the fuel feeding side of the grate and at the end of the grate, while in between a peak occurs. The fuel mass conversion is adopted to experimental findings at typical combustion conditions on the investigated grate boiler. The release of hydrogen and oxygen from the fuel is assumed to be proportional to the carbon release, while the moisture release is calculated according to the evaporation behaviour influenced by the local temperature. Furthermore, a complete consumption of the primary air is assumed and hence the primary excess air is not exceeding the value of 1 above the grate, while as average primary excess air ratio, a value of 0.7 is introduced according to the reference operation parameters. In addition, the gas concentrations are calculated based on the equilibrium concentrations described for wood gasification by Reed [8]. The calculations were performed in MATLAB.

Figure 2.6 on the left shows the gas release indicated as total mass flow which describes the assumption of the model. All other graphs show the calculated resulting primary air excess (Figure 2.6 right), the calculated gas profiles (Figure 2.7 left), and the resulting gas temperature (Figure 2.7 right).

Due to the limitation of the primary excess air at 1, the calculated temperature profile exhibits two sharp peaks in an early and in a late section of the grate, which consequently results in a potentially unexpected temperature minimum in an intermediate grate section due to a low excess air in this zone. This situation is probably not resembling the real situation appropriately, which is expected to be less pronounced. However, since the mass flow in the two zones with over-estimated temperatures is small, the simplification exhibits a minor influence on the calculation. Nevertheless, the temperature drop in an intermediate section of the grate as well as the coincident CO_2 peaks have in principle been validated by profile measurements on the grate [6].

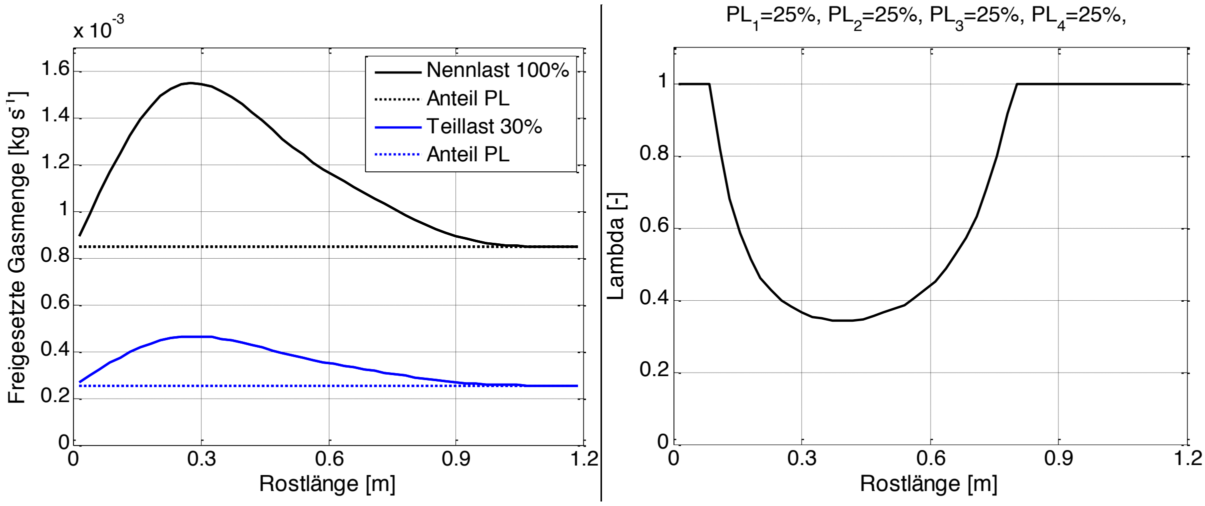


Figure 2.6 Gas release (left) and primary excess air ratio (right) as function of the grate [32].

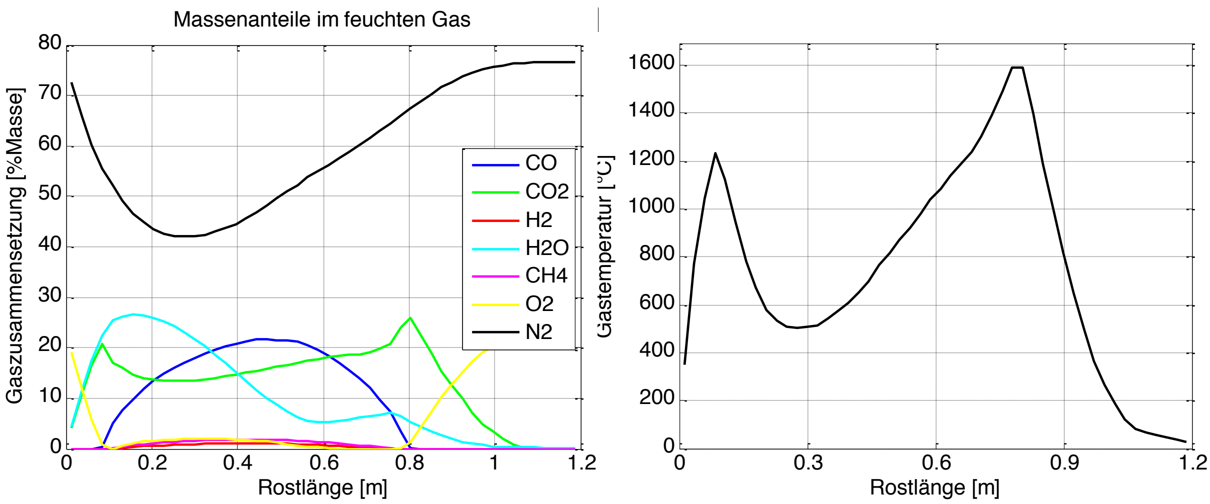


Figure 2.7 Gas release (left) and primary excess air ratio (right) as function of the grate [32].

2.2.1.2 Advanced one dimensional model for parameter variations

To investigate the influence of varying fuel parameters, in particular the moisture content, a more specific one-dimensional transient fuel bed model (FBM) was developed based on the walking column principle (Figure 2.8, Figure 2.9) [12] and calculated in MATHEMATICA.

The model considers drying, pyrolysis, and char oxidation, gas flow through the pore space of the bed, conductive, convective and radiative heat transfer, and reduction of the bed volume. It allows to study the influence of fuel properties (moisture content, ash content, composition, particle size, bed porosity, solid density) and operating parameters (excess air ratio, temperature).

The calculations are based on the physical conversion processes and the chemical reactions during drying, pyrolysis, and char gasification, for which generic information such as kinetic data is available from fundamental research and described in the respective literature. Based on properties of wood fuels, the chemical and physical conversion mechanisms initiated by radiation from the furnace wall are described in an overall model.

The results confirm that variations of fuel humidity and particle size result in significant changes of the fuel conversion history on the grate. The model was initially developed for a single sector grate and further extended to a multi-sector grate divided into four independent consecutive zones.

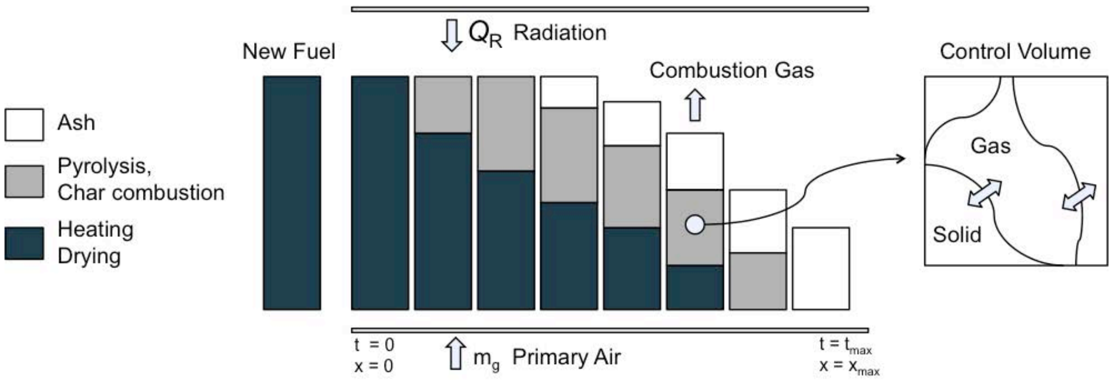


Figure 2.8 Schematic of the model. As a fuel column enters the grate it receives radiation heat from the ceiling of the combustion chamber Q_R and primary air introduced from the bottom of the grate. As a consequence, the solid phase loses mass by drying, pyrolysis and char oxidation processes leading to a reduction of the bed volume.

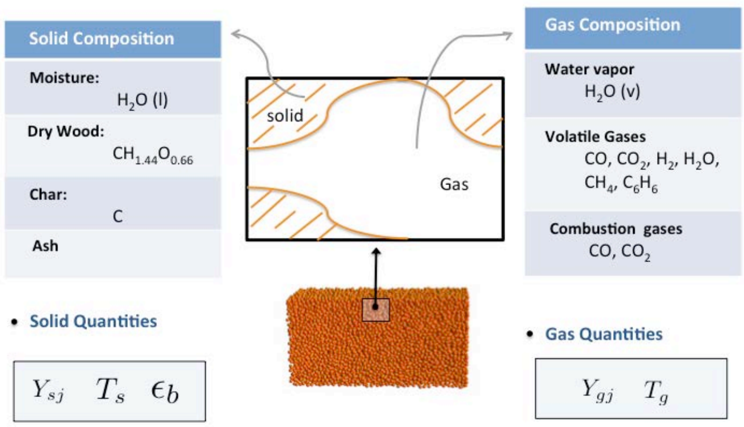


Figure 2.9 Basic description of the fuel bed model.

The applicability of the model is described by a 1.2 MW grate boiler operated at optimised conditions in a reference case. Figure 2.10 shows the results and describes concepts to achieve optimum conditions for solid fuel conversion on the grate by adjusting operation parameters as follows:

With increasing fuel humidity, the original parameter settings result in an undesired combustion regime due to the increase in fuel bed volume and time for fuel drying. Consequently, unburnt carbon is found in the grate ash. Model runs with adopted parameter settings reveal that ideal conditions on the grate can be recovered

- by pre-heating of the primary air, or
- by reducing the boiler capacity, or
- by utilising fuel with smaller particle size.

Based on this example, the model shows to be a useful tool to predict the influence of parameters on the fuel conversion and is applicable for combustion design and development of control strategies.

An ideal combustion situation can be recovered by an increase of the primary air, or by an increase of the primary air ratio, or by a reduction of the fuel particle size as described in the last scientific progress report. The application of these measures is, however, limited and related to undesired side effects. While a variable air preheating is highly complex, an increase of the primary excess air disables the application of mechanisms to reduce fuel-NO_X by air staging and a reduction of the fuel particle size is not applicable as control measure. Therefore a method was introduced to identify ideal operation regimes described in [12].

Consequently, there is an interest in finding additional measures to control the solid fuel conversion at varying fuel moisture by a parameter, which can be varied independently. For this purpose, calculation runs with the extended FBM were performed with variation of the air distribution in the four sectors described in Figure 2.11. For the given example, case (c) with slightly shifted primary air towards the main gasification zone, i.e. the second zone on the grate, achieves a nearly ideal situation on the grate enabling a complete solid fuel conversion at 80% grate length as compared to the reference case. Hence, the process simulation shows that a variable air distribution through the grate in independently operated grate sections is a promising option to enable an improved boiler control at variable fuel properties.

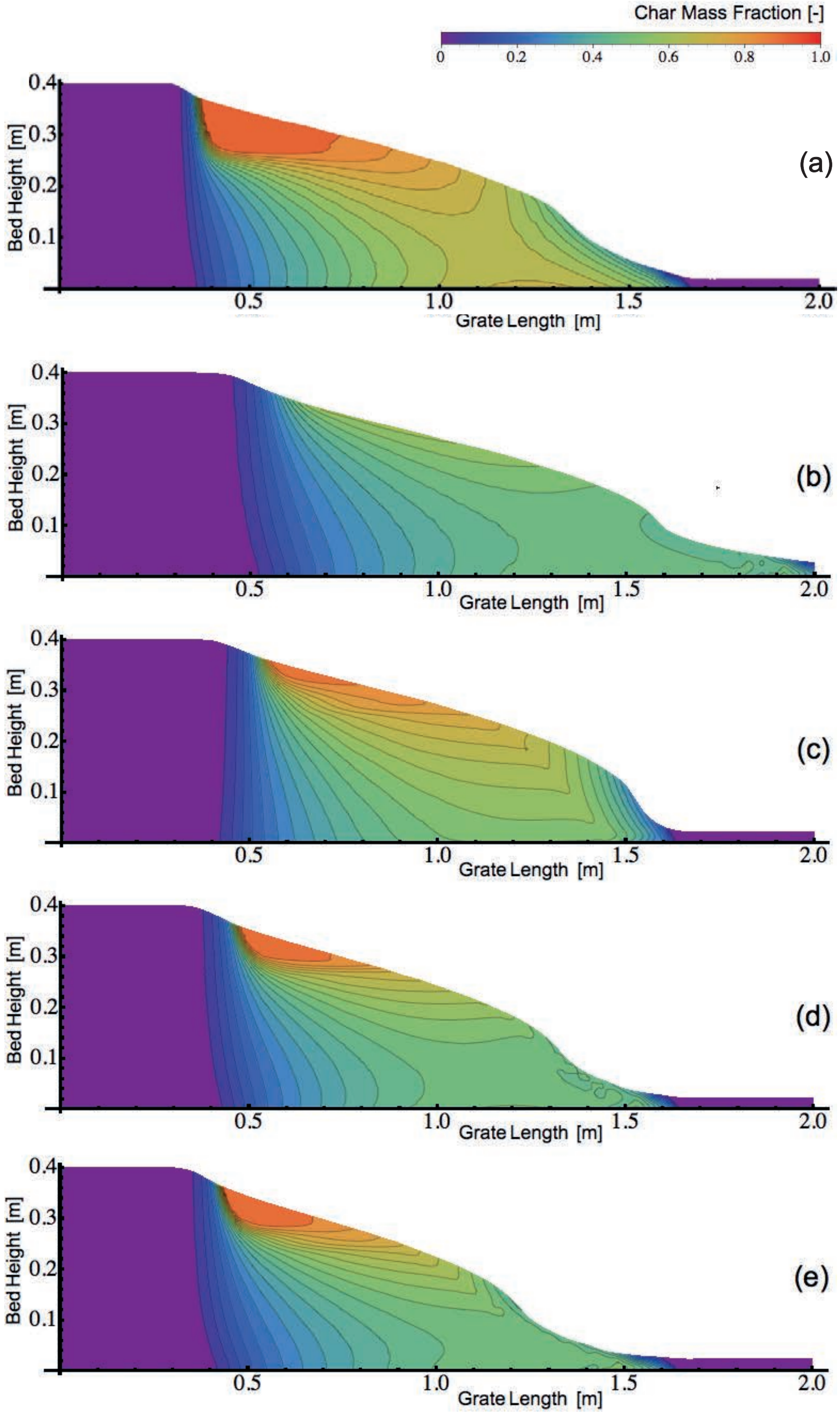
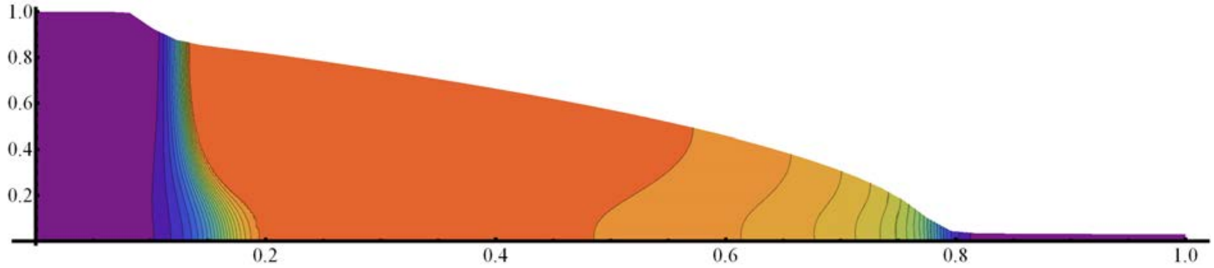
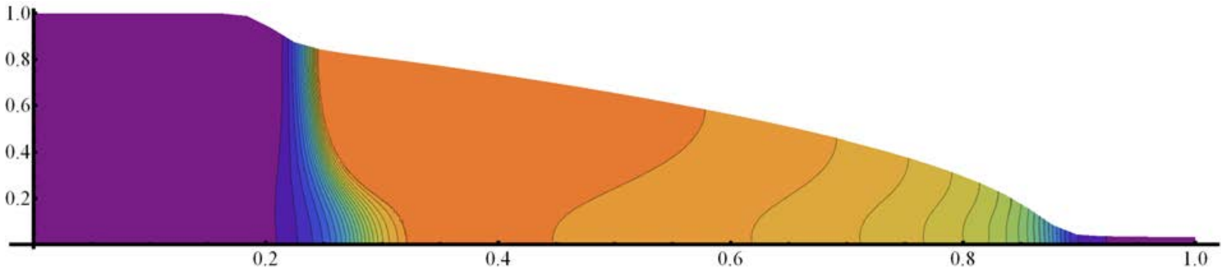


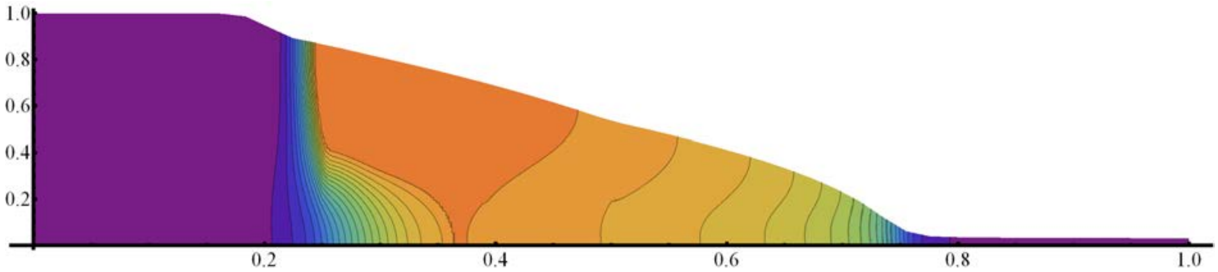
Figure 2.10 Char mass fraction in the fuel bed on the grate calculated with the model.
(a) Char mass fraction obtained with the input parameters listed in Table 3 (reference case).
(b) Same as (a) but with 40% moisture instead of 30%.
(c) Same as (b) but with pre-heated primary air at 420 K instead of 320 K.
(d) Same as (b) but boiler output Q = 1.0 MW instead of 1.2 MW.
(e) Same as (b) but with particle diameters Dp = 36 mm instead of 48 mm.



(a)



(b)



(c)

Figure 2.11 Char mass fraction (char = red, violet = zero char) in the fuel bed calculated with the new bed model for four independent primary air sections of the multi-sector grate.
(a) Reference case: moisture content 30%, primary air temperature 50°C, primary excess air 0.7, homogeneous air inlet of 25%/25%/25%/25%.
(b) Reference case except for moisture content increased to 50%.
(c) Case (b) except for adopted air inlet of 20%/40%/25%/15%.

2.2.2 Gas phase modeling

To further optimise the combustion conditions with a specific focus on part-load, the injection of the secondary air into the combustion chamber was investigated in [32]. Figure 2.16 shows the investigated geometry and the mesh for the calculations. CFD calculations were performed in ANSYS CFX with a k-є model for turbulence, an Eddy Dissipation Model (EDM) for the combustion and a Discrete Transfer for radiation.

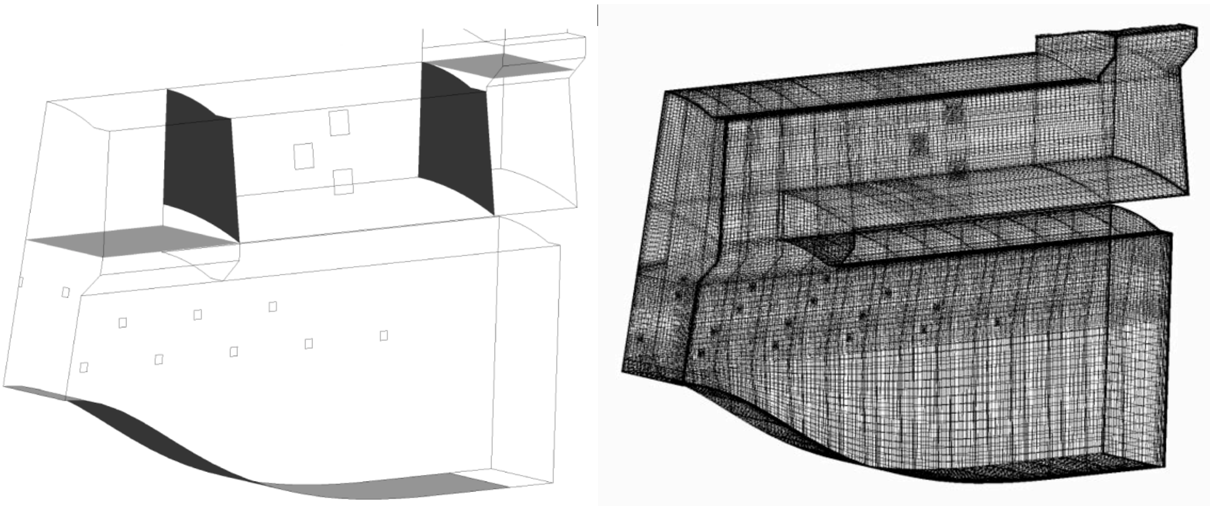


Figure 2.12 Geometry of one symmetrical volume of the investigated boiler (left) and mesh for CFD calculations (right).

For the combustion reactions, hydrogen, methane, and carbon monoxide are considered by the following reactions:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{2-1}$$

$$CH_4 + \frac{3}{2}O_2 \rightarrow CO + 2H_2O \tag{2-2}$$

$$CO + \frac{1}{2}O_2 \rightarrow CO_2 \tag{2-3}$$

In addition, formation of thermal nitric oxide is implemented as a single-step reaction according to [10], [11]:

$$N_2 + O_2 \rightarrow 2NO$$

$$\text{with} \quad R_K = A_K \cdot T^{\beta} \cdot \exp\left(-\frac{T_K}{T}\right) \cdot [N_2] \cdot [O_2]^{0.5} \quad [\text{mol m}^{-3}\,\text{s}^{-1}] \tag{2-4}$$

$A_K = 2.26206 \cdot 10^{15}$ [$m^3 K^{0.5} kmol^{-1.5} m^{-1.5} s^{-1}$], β = -0.5 [-], T_K = 69466 [K]

Figure 2.13 shows the calculated CO concentrations in different planes of the combustion chamber for the reference case. To exemplify the influence of variations in the secondary air injection, Figure 2.14

describes an identical case but with reduced diameter of the secondary air injection. For this example, an increase of the gas velocity and thus the resulting momentum flux ratio leads to an improved mixing and therefore reduced CO emissions. However, as discussed separately, a further reduction of the jet diameter can also lead to an increase in CO [13], [21]. Figure 2.15 demonstrates the effect of an asymmetrical secondary air injection. For the investigated case of part-load operation, this also results in an improvement of the combustion quality.

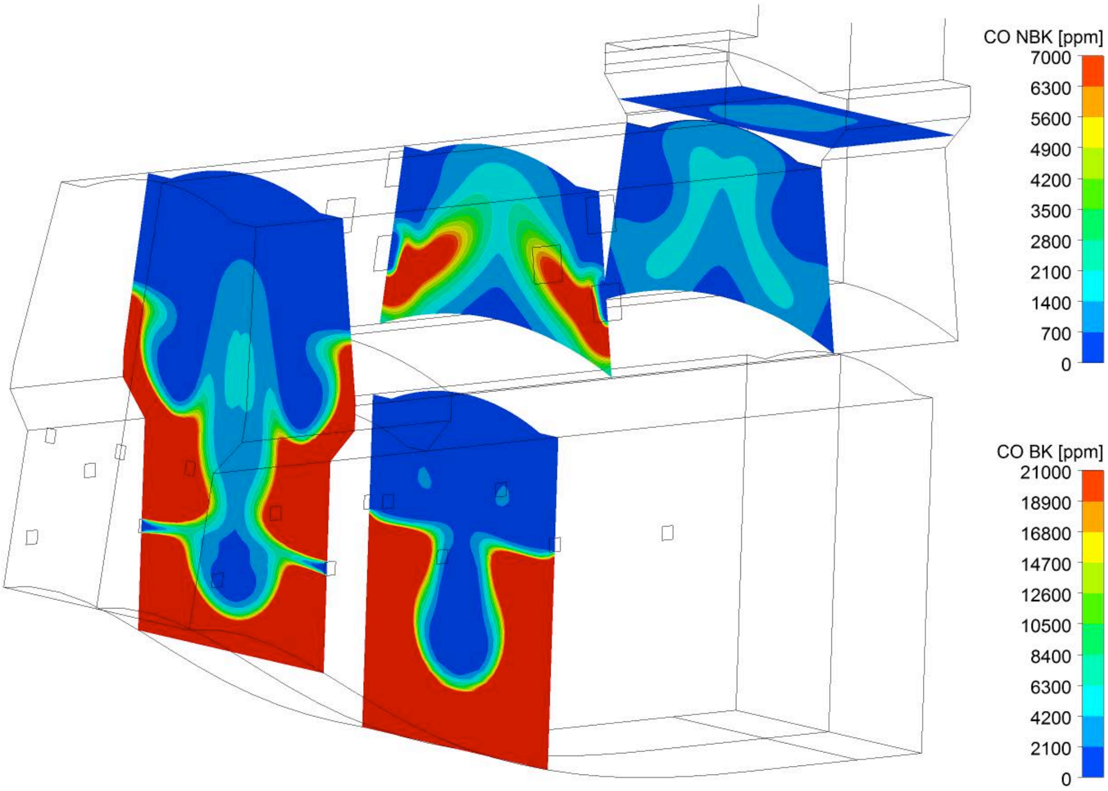


Figure 2.13 CO concentrations at 30% boiler load for the reference case with a jet diameter of 21 mm. The lower legend for CO is valid for the first two planes, the upper for the consecutive planes.

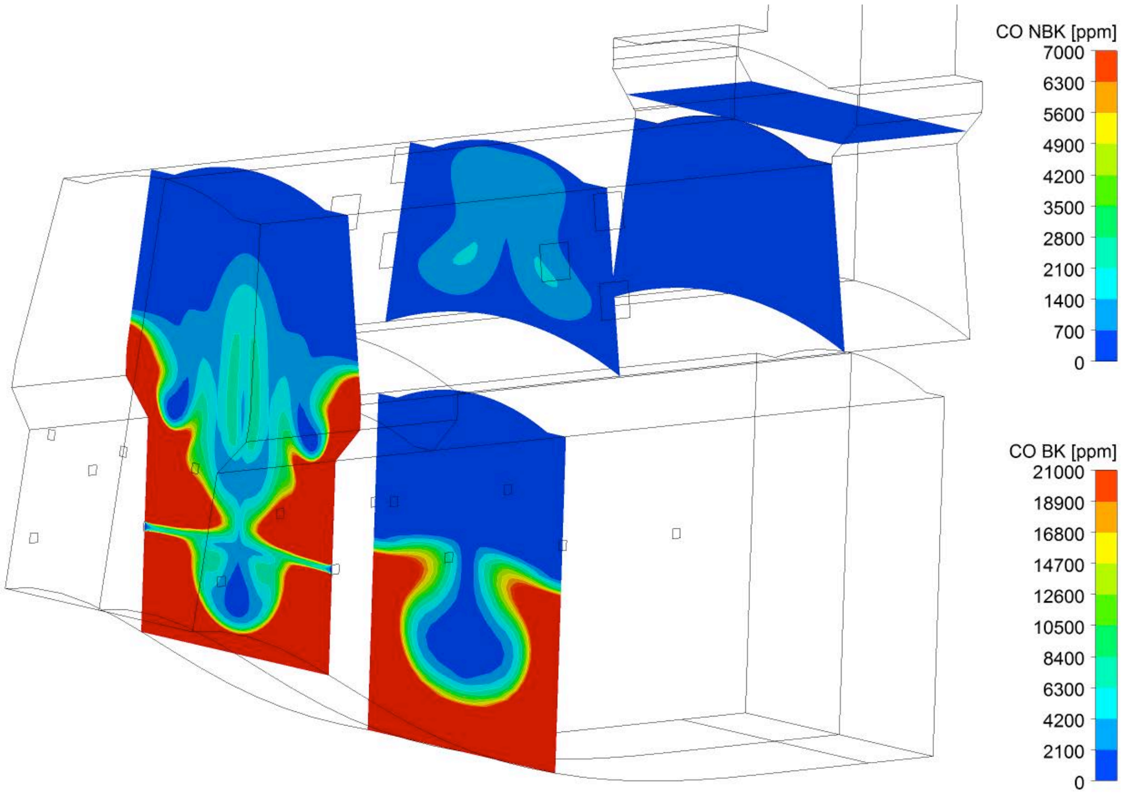


Figure 2.14 CO concentrations at 30% boiler load with a jet diameter of 15 mm.
The lower legend for CO is valid for the first two planes, the upper for the consecutive planes.

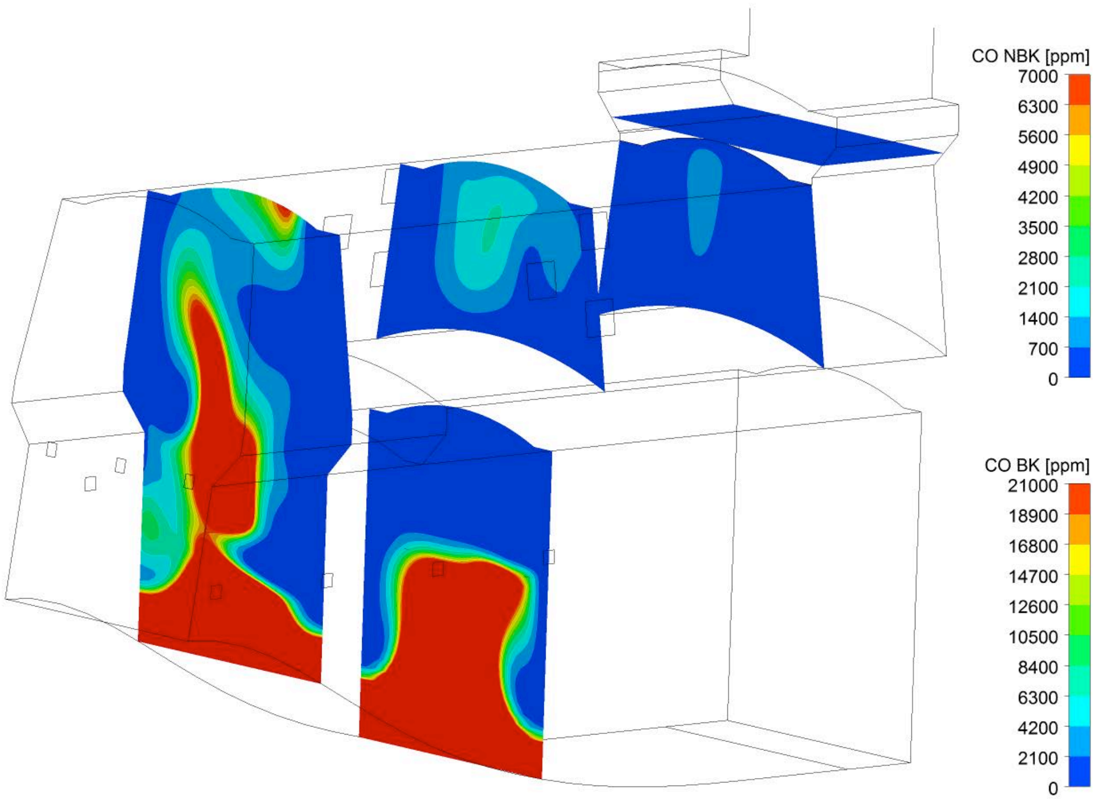


Figure 2.15 CO concentrations at 30% boiler load with a jet diameter of 21 mm and staggered air injection.
The lower legend for CO is valid for the first two planes, the upper for the consecutive planes.

The CFD calculations at part-load and full load for different arrangments reveal the following trends [32]:

For the reference case with symmetrical secondary air injection, the secondary air jets from both sides converge in the middle thus leading to a zone with high oxygen mass flow and increased turbulence. The chemical reactions mainly occur in this regions or at the surface of the secondary air volumes respectively. Due to the concentration of oxygen in the centre of the combustion chamber, a lack of oxygen results at the side walls leading to streaks of carbon monoxide in these sections, which lead to increased CO emissions. Therefor, two concepts for an optimised secondary air injection are investigated:

A first approach is based on a reduced jet diameter. This results in an increased momentum flux ratio as introduced in [13] and in an increased penetration depth as long as the maximum penetration depth is not yet reached. In addition, the the mixing zone with high turbulence is increased in size.

In a second approach, the secondary air injection is implemented asymmetrically with an alternative arrangement on both sides of the combustion chamber thus resulting in a staggered air injection. The main target of this arrangement is to avoid unmixed CO streaks across the side walls, since the penetration depth of the secondary air is not limited in the middle of the combustion chamber.

A comparison of arrangements with identical boundary conditions except the secondary air injection reveal that compared to the reference case, an increase of the momentum flux enables a further CO reduction by approximately 23% at part-load operation, while the staggered air injection did not fulfil this target, but resulted in a CO increase of 24%. These trends are confirmed by experiments in the prototype boiler. With respect to the mixing conditions and the resulting combustion quality, an optimum momentum flux ratio in the order of 1 was found for a coaxial air injection from both sides. Beside this, the investigation revealed that cooling air inlet in the front door of the combustion chamber leads to a significant increase of the excess air ratio and the CO content in the flue gas and hence need to be avoided.

2.3 Experimental investigations on fluid dynamics

2.3.1.1 Fluid dynamics investigation of the combustion chamber

The turbulence and the residence time distribution strongly depend on the flow conditions in the combustion chamber and significantly influence the reaction chemistry. Since three dimensional flow patterns such as vortices are difficult to be safely predicted by CFD, aerodynamic experiments were performed in cold model by image analysis and Particle Image Velocimetry (PIV) to validate the expected flow patterns. Based on the similarity rules of fluid dynamics, a cold model of a grate boiler was designed enabling to investigate different air settings and combustion situations on the grate. In addition, a cold model to investigate the air injection into a main flow was built. Figure 2.16 shows the setup for the experiments and Figure 2.17 an example of the cold model of the boiler. Figure 2.18 shows a comparison of CFD calculations in the combustion chamber and the flow pattern measured by cold model experiments which reveals good agreement. In addition to this, the existence of vortices at the entrance of the post combustion chamber, which was predicted by CFD, was validated by PIV experiments in the cold model.

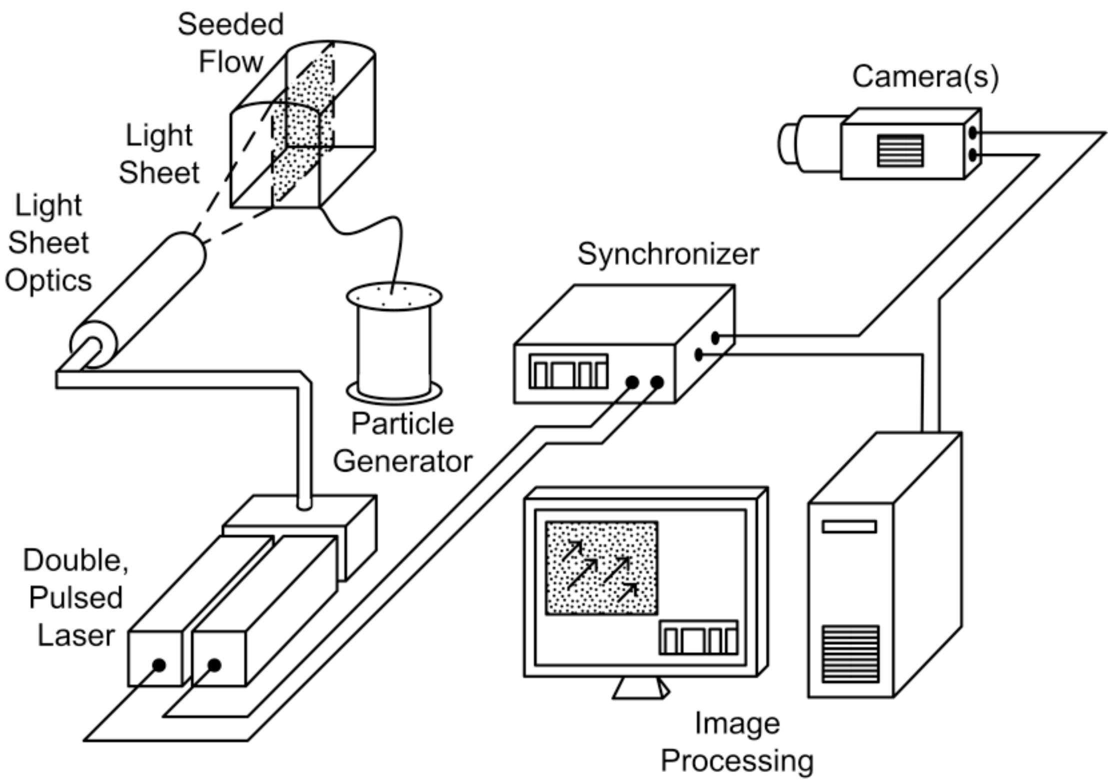


Figure 2.16 Experimental setup for aerodynamic investigations of a combustion model and a jet in cross flow with Particle Image Velocimetry (PIV) [13].

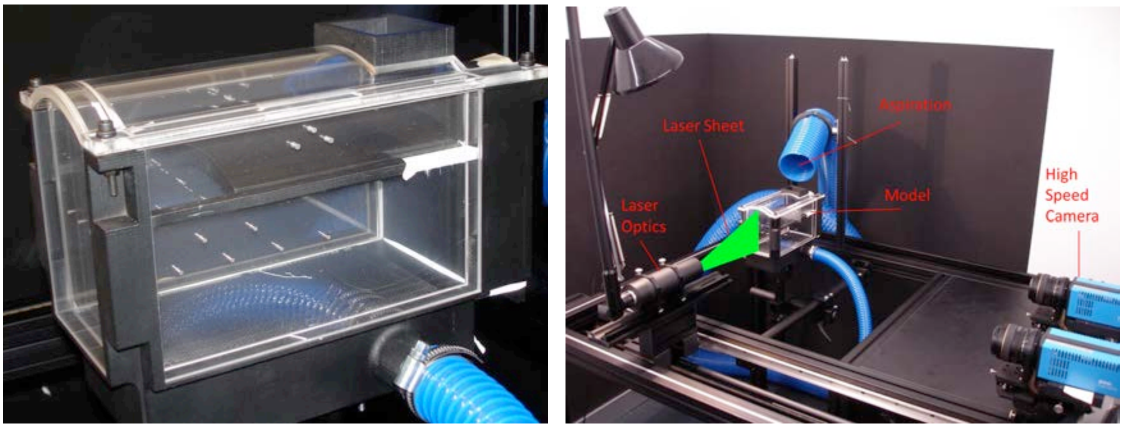


Figure 2.17 Scaled cold flow model of a grate boiler for PIV investigations (left) and experimental setup (right).

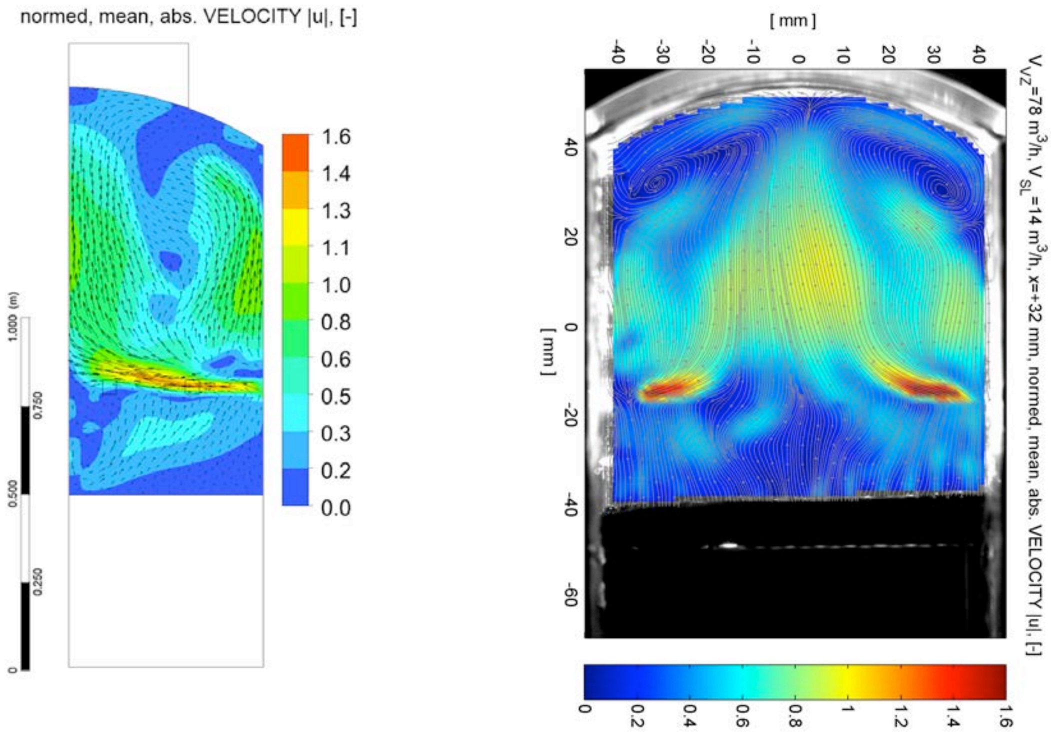


Figure 2.18 Comparison of CFD-calculations (left) with PIV-measurements on the model (right). The pictures show the normed mean velocity in plane P5 for the reference case. For the CFD-calculation (left) only the right half of the combustion chamber is shown as a symmetric flow is assumed [19].

2.3.1.2 Fluid dynamics investigation of a jet in cross flow

A separate setup of a scaled model for aerodynamic measurements on the secondary air injection was designed and constructed . Measurements were performed to investigate the influence of the main design parameters on the mixture of the jet flow representing secondary air with the main flow representing the combustible gases in the combustion chamber.

The air injection is considered as a jet in cross flow (JICF), where the cross flow is assumed to be a turbulent channel flow with the maximum penetration depth being limited by the opposite wall. In the literature for a jet in cross flow without spatially limited penetration depth, the product of nozzle diameter and momentum flux ratio between jet and main flow is introduced as a characteristic flow parameter. The own measurements show that this parameter can also be used for a jet in cross flow with opposite wall. The product of nozzle diameter and momentum flux ratio is used as a design parameter for the penetration depth and the cross-sectional area of the jet, which determines the mixing performance between secondary air and combustible gases. The investigation shows that in order to maximise the mixing performance for a single-sided air injection, the jet diameters need to be dimensioned to enable a penetration depth into the main flow of 50 % as shown in Figure 2.19. This can be achieved if the product of the nozzle diameter normalised by the channel height and momentum flux ratio is designed to a value of 0.1 to 0.2 as illustrated by the PIV measurements in Figure 2.20. In case of opposite secondary air injection of two jets which impact in the middle of the cross section, higher momentum flux ratios are applicable, since the penetration depth is limited in the middle of the combustion chamber.

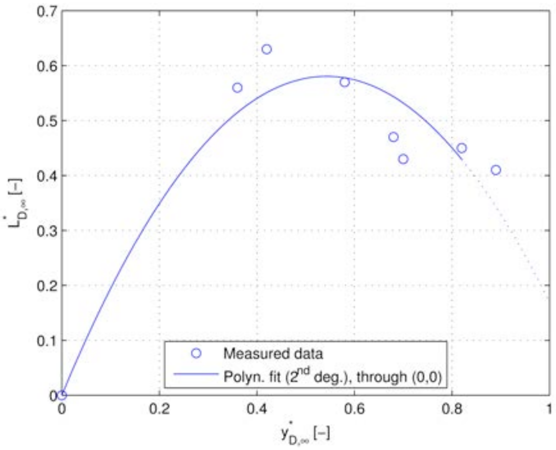


Figure 2.19 Jet expansion in the far field as function of the penetration depth of the jet [15].

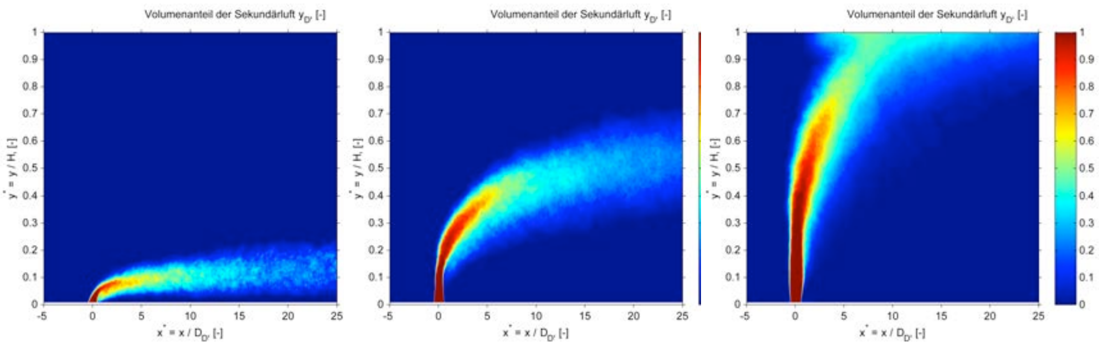


Figure 2.20 Jet expansion for effective impulse ratios of 0.04, 0.16, and 0.63 (from left) [15].

3 Outlook

Due to the progress within the ongoing NRP 66 project, it is expected that the targets of a multi-sector grate for combustion improvement and expansion of the load range can be met. Based on this, the application of biomass combustion will potentially be improved with respect to load variability, combustion efficiency, and organic pollutant reduction. Beside this and due to regular summer smog situations, measures to reduce NO_X emissions from biomass combustion will become more important. This is underlined by the announcement of more stringent emission limits for biomass boilers on NO_X in the European Union, which cannot be met by today's technology. Consequently, primary measures for NO_X reduction are crucial. Since fuel NO_X are most relevant in biomass combustion, the potential of air-staging combined with flue gas recirculation and a multi-zone primary air inlet will be investigated. Further needs for research in biomass combustion will be related to secondary measures for NO_X reduction in automatic boilers. Consequently, air-staging and flue gas recirculation are being investigated in the second phase of the ongoing NRP 66 project.

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