Annual Report 2008-2009

Nordic Graduate School of

Biofuel Science and Technology

BiofuelsGS-2

**Chalmers University of Technology, Sweden**

**Technical University of Denmark, Denmark**

**Norwegian University of Science and Technology, Norway**

**Åbo Akademi University, Finland**

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Cover design and layout: Anne-Leena Gröning
ISSN 1459-6407
Karhukopio Oy

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## Preface

The Nordic Graduate School in Biofuels Science and Technology – Phase 2 (BiofuelsGS-2) is a postgraduate programme operated jointly by the four universities Chalmers University of Technology (CTU), Sweden, Technical University of Denmark DTU), Denmark, Norwegian University of Science and Technology (NTNU), Norway, and Åbo Akademi University (ÅAU), Finland. BiofuelsGS-2 is a direct continuation to the former Nordic graduate school "biofuelsGS", which was established in 2003. BiofuelsGS-2 is funded by the Nordic Energy Research for the period of four years, starting the 1 st of January 2007, ending the 31 st of December 2010.

The members of the school board are Professors Bo Leckner (CTU), Kim Dam-Johansen (DTU), Johan Hustad (NTNU) and Mikko Hupa (ÅAU), who is also acting as chairman. The coordinator of the school is Dr. Maria Zevenhoven (ÅAU). The coordination office is located at Åbo Akademi University in Turku, Finland and the coordinating assistant is MSc. AnneLeena Gröning (ÅAU).

A team of senior researchers is additionally tightly cooperating with the coordination to organize the program, planned to be performed in BiofuelsGS2. The team consists of Prof. Peter Glarborg, Dr. Flemming Frandsen, Dr. Jytte Boll Illerup, (DTU), Dr. Henrik Thunman, Dr Lars-Erik Åmand (CTU), and Dr. Øyvind Skreiberg, Dr Morten Grønli (NTNU) and Dr. Anders Brink (ÅAU).

This 2008-2009 BiofuelsGS-2 annual report reviews the progress of and plans for students in the school. The students report their progress. Furthermore, the annual report provides general information about the BiofuelsGS-2 as well as of the participating universities.

We wish all students, supervisors and board members of the BiofuelGS-2 a pleasant, intensive and fruitful collaboration during the coming active years of the school.

## 1. About BiofuelsGS-2

The goal of the new Graduate School, the BiofuelsGS-2, is to continue to raise the esteem and quality of the doctoral training within the Nordic universities in the area of biomass and waste conversion to fuels, heat and power. The graduate school aims also at providing the basic scientific and technical knowledge to solve problems related to conversion of biofuels. This is achieved by collaboration in post-graduate course arrangements, shared student supervision by student and supervisor visits between the base universities, and intensive industry-academia networking.

The BiofuelsGS-2 consists of 16 students (partly funded directly by the school, partly funded by other sources) and their supervisors. Also, additional students from the four partners are given the possibility to participate with funding from other sources.

The individual courses of biofuelsGS-2 are advertised broadly and are open to students at all participating Nordic universities.

In summary, the School activities include:

- Tailor-made study and research plans for all participating students, including study and research visits at other Nordic universities.
- Intensive courses organized directly by the school: 1 per year in key topics of biofuel conversion science and technology, provided by the senior researchers and professors within the participating universities or by invited lecturers from industry.
- Intensive courses organized by others: Additional 1-4 per year provided by cooperating partners to BiofuelsGS-2 such as the Danish Graduate School of Chemical Engineering, "Molecular Product and Process Technology (MP2T)", the Finnish Graduate School in

Chemical Engineering (GSCE) and the Swedish post-graduate training program CeCost.

- Annual seminars where the students present their work and discuss with each other.
- An Annual Book published at the annual seminars, consisting of progress reports by the students of the School.

## 2. Activities 2008-2009

The BiofuelsGS-2 was initiated the 1st of January 2007.
At the moment of writing the school counts 16 participating students.

Information was spread through the website of BiofuelsGS-2, http://web.abo.fi/instut/biofuelsGS2/New%20web/index.html and a 3rd newsletter was sent to participants and their supervisors in March 2009.
Through the website information about the program such as courses, meetings and seminars is delivered.
The site also provides a description of the school and a list of contact addresses of all participants.

In 2008 the graduate school started its largest effort - A course in 4 parts on "Analytical Techniques In Combustion" was organised This course aims to give students a critical view on analytical tools available for studying combustion processes.
Part 1 of the Nordic course was held at CTH in October 2008. Students were able to join a measurement campaign and were introduced in the secrets of on-line analyses and solid sampling. During the campaign wood and straw were co-fired and different techniques were used to minimise alkali-chloride formation. The measurement campaign formed and will form a red thread through the other 3 parts of the course, the second held at DTU in February 2009 and the third held at NTNU in May 2009. The last part is planned to take place at ÅA in September 2009. Samples taken during the campaign were analysed with analytical techniques available and combustion experiments were carried out in lab scale facilities.

After the course all groups of students will write a scientific report on different subjects encountered during the course such as "Mass- and specie balances", "Fuel nitrogen conversion in the CFB", "Fuel nitrogen conversion in oxyfuel combustion", "Deposit formation", "Influence of the addition of straw and ammonium sulphate on bed material and fly ash composition", etc. Results will be presented at the annual seminar and the annual report in 2010.

During the last year Daniel Stanghelle, Robert Johansson and Kim Hougaard Pedersen defended their doctoral theses.

An important part of the activities in the school is the annual seminar. In 2008 this seminar was held in Visby on 14$^{th}$-16th of September. CTH acted as host for the seminar. Almost all students and supervisors attending the school were present.

## 3. Participating universities:

### Åbo Akademi University (ÅAU), Finland

### Process Chemistry Centre

The Process Chemistry Centre at Åbo Akademi (PCC) is a research centre active in the field of chemical engineering. It has four major focus areas of which one is combustion and materials chemistry research. The PCC was granted the status of "Center of Excellence" by the Academy of Finland the first time in the year 2000 and has renewed this status in 2006. The status of "Center of Excellence" will continue until 2011. The PCC studies physico-chemical processes at the molecular level in environments of industrial importance, in order to meet the needs of tomorrow's process and product development. This mission statement is realized in the combustion and materials chemistry research in two subdivided themes:

- Combustion
    - Modelling
    - Experimental
- Materials
    - Biomaterials
    - Conventional

Åbo Akademi University has been active in the area of combustion and materials chemistry since 1974. Work performed has included both basic research and trouble-shooting cases. At present some 40 people are actively involved in the combustion and materials chemistry research. 6 of these are post-doc level full time researchers. Presently there are 15 research projects dealing with various aspects of chemistry in combustion and/or gasification. In all, the PCC consists of some 130 researchers.

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## Chalmers University of Technology (CTU), Sweden

Department of Energy and Environment

The department consists of several sections, among them a research group dealing with energy conversion. The research group which is of interest for the present activity, the division of Energy Conversion, works with combustion devices and conversion (drying, devolatilization, combustion and gasification) of solid fuels, biofuels and wastes with respect to efficiency, reliability and environmental performance. The combustion technologies of primary interest are fixed and fluidized bed. The department operates one of the largest research plants available in Europe (in the world, except China), a $12MW_{th}$ circulating fluidized bed boiler. The academic staff of the division of Energy Conversion consists of 3 professors, 3 associate professor, 1 assistant professor, lecturers and doctoral students.

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## Technical University of Denmark (DTU), Denmark, Combustion and Harmful Emission Control (CHEC) Research Center

The CHEC (Combustion and Harmful Emission Control) Research Centre, at the Department of Chemical Engineering of the Technical University of Denmark, carries out research in fields related to chemical reaction engineering and combustion, focusing on high-temperature processes, formation and control of harmful emissions, and particle technology. CHEC has achieved international recognition through a combination of experimental techniques and modelling. Laboratory experiments provide detailed and accurate data on chemical and physical processes in the systems studied. The data is subsequently interpreted by mathematical modelling based on chemical kinetics, chemical reaction engineering, multi-phase and component thermodynamics, and fluid dynamics.

The CHEC laboratories are well equipped and include equipment for gas adsorption and mercury porosimetry, particle size distribution, simultaneous thermogravimetric and differential scanning calorimetric, Fourier transform IR, high-temperature light microscopy, and ash viscosity measurements. The laboratories also include a lab-scale wet flue gas desulphurization column, a SCR test-rig, and a number of reactors from lab to pilot-scale, used to characterize and investigate fixed-bed, entrained flow and fluid bed combustion processes, emissions, ash formation, deposition and corrosion.

The CHEC Research Centre has staff personnel of about 40, including 7 professors/associate professors, and about 20 PhD students.

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## Norwegian University of Science and Technology (NTNU), Norway

## Department of Energy and Process Engineering

The Department of Energy and Process Engineering has a total of 150 employees, including approximately 80 PhD students. We have an extensive contact net, and our Master students are employed by both industry and public administration. Our research is applied by offshore and onshore industry, by consulting companies, for energy advisory services, by engineering companies and public administration.

The Department of Energy and Process Engineering at the Norwegian University of Science and Technology is an international know-how organization. The Department aims at being a driving force within education and research comprising the total energy chain - from electricity/heat production to end-use in industry and buildings. Our activities include systems based both on natural gas and renewable energy. Pollution problems connected to the general environment and to the indoor/residential environment is an important part of this work. We also perform research on industrial process technology in a wider sense, including refining of Norwegian raw materials into superior and competitive products.

Our business concept is to develop and communicate knowledge, thus contributing to added value and improvement of society. Our target is to be a premise provider to the authorities and an innovation resource unit for the Norwegian industry within our fields of science. By ensuring that Norwegian industry and the public authorities have access to knowledge of a high international level, we contribute to the solution of important issues in the society.

The Department has four specialist groups:

- Thermal Energy
- Industrial Process Technology
- Energy and Indoor Environment
- Fluids Engineering

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# 4. Organisation of biofuelsGS

## 4.1 Board


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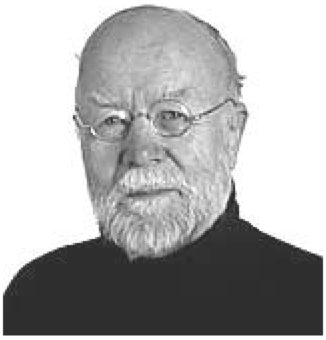
I am Professor in Inorganic Chemistry at the Åbo Akademi Process Chemistry Centre. My team's research activities deal with detailed laboratory studies and advanced modeling of the chemical aspects in various types of combustion systems, such as fluidized bed boilers, pulping industry spent liquor recovery boilers etc.
I also have an interest in ceramic materials for various applications. Since 2006 I am also the Dean of our Technical Faculty at Åbo Akademi.



**Professor Bo Leckner**

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I am professor in energy conversion technology at Chalmers University of Technology. I have mostly been working with questions related to combustion of solid fuels, combustion devices, and a number of different subjects ranging from reduction of emissions to heat and mass transfer. Much work has been connected to fluidized bed combustion.

**Professor Kim Dam-Johansen**
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Professor in Combustion and Chemical Reaction Engineering. Head of Department of Chemical Engineering, Technical University of Denmark, Director of the CHEC (Combustion and Harmful Emission Control) research centre dealing with:

- High-temperature processes
- The formation and control of harmful emissions
- Particle technology
- Chemical product design

**Professor Johan E. Hustad**
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My main research area is thermal conversion of solid, fluid and gaseous fuels to heat and electricity with focus on energy, economy, safety and the environment:

- Combustion and gasification technologies for biomass fuels and solid refuse-derived fuels in several different types of equipments.
- Combustion in diffusion flames, diluted flames, partially premixed flames and premixed combustion for boilers, Stirling Engines, gas turbines and in burners for off-gases from fuel cells (mainly catalytic burners).
- Fluidized bed technology
- Gas cleaning equipment
- Formation mechanisms for different pollutants in combustion
- Prediction, modelling and reduction of pollutants from several combustion technology processes both for land-based and off-shore plants and equipment.

## 4.2 Coordination

**Dr. Tech. (Chem. Eng.) Maria Zevenhoven**

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| TOPIC | **Ash forming matter** |

Besides acting as coordinator for the Nordic Graduate School of Biofuel Science and Technology, Biofuels 2, I am senior researcher in ash forming matter at the Åbo Akademi Process Chemistry Centre.

I wrote my PhD thesis on ash forming matter in biomass fuels in 2001 and since then I have been involved in different projects where ash forming matter, ash or heavy metals played an important role.

I am also involved in teaching at the university and coordinate the course Chemistry in Combustion processes-2

**MSc Anne-Leena Gröning**

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Parallel to my studies in analytical chemistry at the Åbo Akademi University I worked in several projects connected to environmental analysis. After some years of laboratory work in the industry, because of some health problems and the fact that I wanted to have shorter workdays when my children started school, I found my way back to Åbo Akademi.

Today I take part in the administration of the laboratory of analytical chemistry and work as a coordination assistant in three ongoing international projects at the Åbo Akademi Process Chemistry Centre.

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I am a senior researcher at Åbo Akademi University, Process Chemistry, where I mainly is involved activities related to modelling. My modelling topics include:

- CFD modelling of thermal conversion processes
- Emission modelling
- Combustion engine modelling
- Heat and mass transfer modelling

I am also active in the Scandinavian-Nordic Section of the Combustion Institute and in the Finnish Flame Research Committee.

**Dr. Øyvind Skreiberg**
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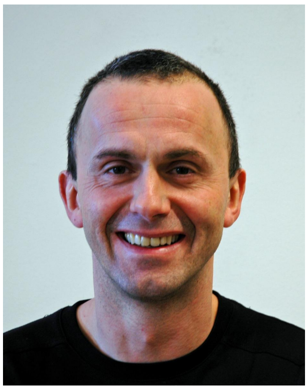
I received my diploma as a mechanical engineer at the Norwegian Institute of Technology (NTH) in Trondheim in 1992, where I finished my PhD thesis on "Theoretical and experimental studies on emissions from wood combustion" in 1997. My work as Research Scientist at the Norwegian University of Science and Technology (NTNU, former NTH) changed in 1998 when I became a Nordic Senior Research Scientist within Nordic Energy Research, on Biomass Combustion. My working background deals with heat engineering and combustion in general, with special emphasis on biomass combustion. Main research topics are emission formation and reduction in combustion (NOx, $N_2O$, CO, hydrocarbons and particles). This includes both experimental work, from single wood particles to wood logs, and modelling work (empirical, chemical kinetics, CFD). Additionally, I am involved as a lecturer in several courses at NTNU. Furthermore, I am a member of the IEA Bioenergy Task 32 where I represent the Norwegian University of Science and Technology since 1998.



**Dr. Ing. Morten G. Grønli**

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TOPIC **Fuel characterization**

**Modeling of pyrolysis, gasification and combustion**

Morten finished his PhD on pyrolysis modelling in 1996 with a scholarship from the Nordic Energy Research Program. After that he worked as a researcher at SINTEF before he became Laboratory Manager at the Department of Energy and Process Engineering at NTNU in 2003. He has been quite actively involved in the Nordic Courses and seminars/workshops that have been given at NTNU over the last 15 years.

At the moment there is not so much time for doing research, but he is giving some lectures related to bioenergy in different courses at NTNU and is co-advisor of a few PhD-students at our department.


**Senior Advisor, PhD Jytte Boll Illerup**

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Since 2008 I have been employed as a Senior Advisor at DTU Chemical Engineering, Technical University of Denmark – attached to the research group CHEC (Combustion and Harmful Emission Control). At the same department I finished my PhD thesis on "Hydrogen Sulfide and Sulfur Dioxide Retention on Limestone at High Temperature and High Pressure" in 1994. I am platform coordinator for the Danish National Advanced Technology Platform 'New Cement Production Technology' and I also participate in various research and public-sector services activities. From 1995 - 2008 I was employed at the Danish National Environmental Research Institute (NERI) where I was head of section for the work concerning international reporting of air emissions inventories to e.g. the UNECE Convention on Long Range Transboundary Air Pollution, the UN Framework Convention on Climate Change and EU. I have participated in many research projects related to air emissions inventory/projection and integrated assessment and been project leader for several projects concerning emissions from heat and power production including residential use of wood for heat.

**Associated Professor Flemming Frandsen**

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Graduated as Chemical Engineer from the Department of Chemical Engineering, Technical University of Denmark (DTU), 1991, and received a PhD degree from the same university on 'Trace Elements from Coal Combustion' in 1995. Has been and is currently involved in several national and international research projects on slagging, fouling and corrosion in utility boilers fired fully or partly by biomass (wood, straw, and others) and waste. He is co-founder of a Nordic Energy Research Program PhD short course on 'Ash and Trace Element Chemistry in Thermal Fuel Conversion Processes'.

List of expertise: Solid fuel ash characterization, biomass and waste, formation of fly ash and combustion aerosols, deposit formation, sintering and agglomeration, high-temperature corrosion, trace element transformations and emissions, deposition probe measurements, and analytical techniques.

**Associate Professor Henrik Thunman**

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My main research topic is modelling the conversion of solid fuels. However, I have also modelled black liquor conversion during my thesis work for the Master of Science degree in 1994. In 1995 I started to investigate the combustion of solid fuels in a fluidised bed combustor, with the main focus on the fragmentation and attrition processes. In 1997 I changed the direction of the research to combustion of biofuels in fixed beds, a work, which is still ongoing.

## 5. Participating students


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|---|---|
| TOPIC | **High temperature gas cleaning with granular bed filter** |

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|---|---|
| MAIN SUBJECT | **High temperature gas cleaning** |
| SUPERVISORS | Prof. Johan E. Hustad<br>Prof. Otto K. Sønju |
| M.Sc. | April 2007 |
| DOCTORAL STUDIES | |
| Started | June 2007 |
| To be completed | January 2012 |

## High temperature gas cleaning with granular bed filter

Kavitha Pathmanathan

### Background

Gas cleaning is an important issue in many technological field namely gasification, biomass combustion and waste incineration. The off-gas from gasification processes can be further utilized in gas engines, gas turbines and high temperature fuel cells to generate electricity and heat. Those utilization processes may require specific upstream gas cleaning steps including the removal of particles, tars or other pollutants to avoid damages to the downstream equipment from particle fouling and erosion effects and to allow the cleaned gas to meet the environmental emission regulations. Furthermore, harmful air emissions can pose a considerable risk to the environmental and human health. Since gas utilization occurs at high temperature, it is energetically advantageous (efficient conversion of fuel to energy) to accomplish gas cleaning those temperatures. Furthermore, reduction of overall efficiency from blockage, clogging and corrosion due to condensation of condensable organic compounds can also be avoided with high temperature gas cleaning. There are a limited range of technologies available for commercial high temperature gas cleaning. The Panel Bed Filter (PBF) is one of the most promising approaches for high temperature gas cleaning.

### Objective

The overall objective of this research is to investigate experimentally the filtration behavior of different panel bed filter designs. The investigation shall lead to the improvement of the performance of the PBF mainly focusing on increasing the filter capacity, increasing filtration velocity, application at high temperature and testing of the filter in a commercial scale.

- **Increase the filter capacity**

  - The filter size can be reduced by increasing the filter capacity. This can be done by increasing the filtration velocity and/or increasing the filtration surface area.

- **High temperature applications**

  - High temperature filtrations are essential for many processes where the off-gas is further utilized for heat and electricity production. Therefore filtration at high operating temperatures can be a new alternative within high temperature gas cleaning technologies.

**Method**

**Task 1**: Laboratory investigations of new louver design namely the filter tray design from room temperature up to 120°C.

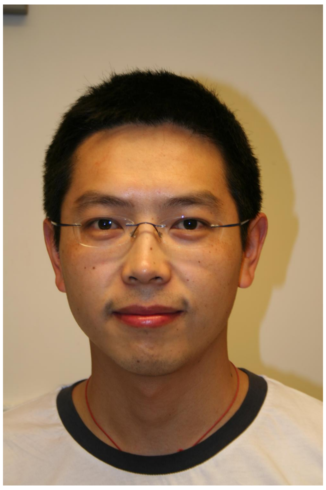
**Task 2**: Laboratory investigation of prototype PBF at temperature of 350°C from a slipstream from a sand-oil extraction process.

**Task 3**: Investigation of up-scaled PBF installed at Bjertnæs Sag AS to reduce the particle emission from the process off-gas.

**Task 4**: Modeling of the puff-back system during the regeneration shall be carried out in order to understand the flow distribution in the cleaned-gas compartment of the filter.

**Presentations and publications**

- K. Pathmanathan, O. K. Sønju, J. E. Hustad,: "A compact granular bed particle filter for high temperature synthesis gases" (2009) Fourth International Conference on Clean Coal Technologies, Dresden, Germany, 19th May 2009.



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| TOPIC | **Effect of additive in reducing fouling and corrosion in biomass combustion and gasification applications** |

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|---|---|
| MAIN SUBJECT | **Inorganic and ash chemistry in biomass combustion** |
| SUPERVISORS | Pro Johan E. Hustad<br>Doc Morten Grønli |
| M.Sc. | July 2005 |
| DOCTORAL STUDIES | |
| Started | September 2006 |
| To be completed | March 2010 |

## Effect of Additive in Reducing the Fouling and Corrosion in Biomass Combustion and Gasification Applications

**Liang Wang**

### Background

One serious operation problem associated with biomass combustion in a boiler is the behaviour of alkali metals (K and Na) and chlorine contained in biomass fuels. The interaction of these alkali metals, chlorine and other ash forming elements may cause severe fouling and corrosion problems in the biomass combustion process. The fouling and corrosion in biomass combustion boiler is closely related to the composition of deposited materials, and in particular the presence of potassium chloride (KCl (g)) and sodium chloride (NaCl (g)) in the flue gas. It is believed that KCl causes the fouling by lowering the ash melting points to 700-800°C and increase the adhesion of ash particles on the heat transfer surfaces. Furthermore, KCl will lead to very high corrosion rate by initiating and accelerating the oxidation of the metal alloys. One promising method to minimize the fouling and corrosion in biomass combustion boilers is to use additives to capture these problematic alkali chlorides and thus change the chemistry and physical properties of the deposits. The additive works by reacting with KCl (g) and NaCl (g) to form K (Na)-additive compounds with relatively high ash melting temperature while HCl (g) is released to the flue gas. In this way, less fouling deposits will be formed and Cl is removed from deposits, which furthermore reduces high temperature corrosion. A number of laboratory and full scale investigations have revealed that different additives such as kaolin, bauxite, dolomite and $(NH_4)_2SO_4$ performed well to eliminate the alkali chlorides problems at specified conditions. However, the use of commercially available additive products such as kaolin, bentonite is not often financially attractive because of their relatively high costs. According to the experience from industry, utilization of additives will increase the price of fuel for relative high level, if a commercial additive is used. It is more interesting to search for alternatives to the commercial products.

**Objective**

- Screening and identifying more high efficiency additives with low cost for reducing ash related problems in biomass combustion
- Investigation of the additives on biomass properties in lab scale
- Study of the additives on biomass fouling deposition tendency with advanced reactor
- Utilization of additives in biomass combustion boiler to test the influences on the biomass ash behaviour

**Method**

- Use of ash melting miscopy, STA, XRF and XRD analysis for ash
- Capture of deposits from reactor and analysis
- Combustion the mixture of additives and biomass in industrial boiler and analysis the ash sample collected from combustion

**Activities 2007-2008**

- Screening the new additive with high efficiency and low cost
  Several new additives were tested in lab with ash fusion microscopy. Based on the results the marble sludge from the paper industry waste with very low cost has high ability to increase the ash melting temperature.
- Simultaneous thermal analysis for influence on biomass ash with presence of additive sewage sludge. The results show that sewage sludge can decrease wheat straw ash melting tendency and release amount of alkali contained species.
- Pelletization of one kind of wood pellet with two kinds of additives sewage sludge and marble sludge. The ash from this

pellet has high agglomeration and sintering tendency. The influence of additives on the wood pellet ash behaviour will be investigated during combustion in boiler and ash samples will be analyzed with more advanced techniques.

**Presentations and publications**

1) Liang Wang, Johan E. Hustad, Morten Grønli, (2009), Influence of additives on biomass ash characteristics, Abstract accepted by 17th European Biomass Conference & Exhibition, 2009, Hamburger, Germany

2) L.Wang, J. Hustad, (2008), Alkali chlorides related fouling and corrosion in biomass combustion, 1st NTVA-CAE Joint Seminar on Strategy, Research and Development in Renewable Energy, pp. 225-239.

3) Liang Wang, Johan E. Hustad, Morten Gronli, TG-MS Study the Influence of Additives on Biomass Pyrolysis, to be submitted as a journal paper

4)Liang Wang, (2008), Presentation-Alkali chlorides related fouling and corrosion in biomass combustion, 1st NTVA-CAE Joint Seminar on Strategy, Research and Development in Renewable Energy, Beijing, China

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|---|---|
| TOPIC | **Thermal conversion of biomass with emphasis on product distribution, reaction kinetics and sulfur abatement.** |

| | |
|---|---|
| MAIN SUBJECT | **Thermal conversion** |
| SUPERVISORS | Prof. Johan Hustad<br>Doc. Morten Grønli |
| M.Sc. | Dec 1997 |
| DOCTORAL STUDIES | |
| Started | March 2004 |
| To be completed | May 2009 |

**Thermal conversion of biomass with emphasis on product distribution, reaction kinetics and sulfur abatement**

Roger Khalil

**Background**

Most of the work performed in this study has concentrated on the thermal decomposition of biomass. While the main objective was to study biomass gasification for the purpose of increasing the share of energy to produce more electricity rather than heat, most of the experimental work was performed at inert conditions due to the simple fact that biomass is mainly composed of volatiles that evaporates prior to the gasification stage.

The characteristics of the devolatilized products during pyrolysis are reported in Paper I for several fuels types that have been considered as sources for energy production due to their fast growing abilities. Paper I also reports results for the same biomass types in oxidative atmosphere. An oxidative atmosphere is also important from the gasification point of view because partial combustion is normally used in a gasification process in order to produce the necessary energy for the endothermic gasification reactions. For these studies and the rest of the pyrolysis experiments (papers II and III), the macro-TGA was used which allows the use of large biomass samples (80 g. for most of the experiments).

Another goal of this study was to condition the devolatilized products in order to generate an upgraded gas product with reduced pollutants. Paper II gives a detailed study on the effect of non-thermal plasma on the devolatilized products from pyrolysis of straw pellets, while paper III concentrate on reducing the sulfuric compounds from the gas phase. Two different methods for reducing sulfur emission in pyrolysis of straw were looked upon. The first is an active method that involves hindering the sulfur release with the producer gas through chemical reactions in the char matrix. This was done by introducing calcium based additives to the straw prior to pelletization. The second method was gas product treatment with non-thermal plasma.

Finally the gasification kinetics of two types of wood chars, pine and birch were reported in paper IV. This work was aimed at finding the reaction rates for these types of wood chars.

**Objective**

To study the thermal decomposition of biomass, the retention of sulphur and gasification kinetics

- Macro TGA-Experiments for the study of gas product release during pyrolysis
- The retention of sulphur by the use of calcium based additives
- The gas conditioning of gas pyrolysis products with a non-thermal plasma
- Micro TGA experiments for the study of gasification reaction rates of hard and soft woods

**Method**

- Use of Macro-TGA
- Use of Micro-TGA
- Use of additives for sulphur retention
- Use on non-thermal plasma for gas conditioning
- Detailed gas analysis of the gas products

**Activities 2008-2009**

Writing the introduction of the PhD book

**Presentations and publications**


[1] Khalil R. A., Várhegyi G., Jäschke S., Grønli M. G., Hustad J. E. "CO2 Gasification of Biomass Chars: A Kinetic Study" Energy & Fuels 23 (2009) 94-100.

[2] Khalil R. A., Mészáros E., Grønli M. G., Várhegyi G., Mohai I., Marosvolgyi B., Hustad J. E. "Thermal analysis of energy crops Part I: The applicability of a macro-thermobalance for biomass studies" Journal of Analytical and Applied Pyrolysis 81 (2008) 52-59.

[3] Khalil R. A., Seljeskog M., Hustad J. E. "Straw Pellets Pyrolysis: Effect of Nonthermal Plasma on the Devolatilized Products" Energy & Fuels 22 (2008) 686-692.

[4] Khalil R. A., Seljeskog M., Hustad J. E. "Sulfur Abatement in Pyrolysis of Straw Pellets" Energy & Fuels 22 (2008) 2789-2795.

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| TOPIC | **Improvement in running and maintenance cost of wood-pellets based heating centrals.** |

| | |
|---|---|
| MAIN SUBJECT | **Thermal conversion** |
| SUPERVISORS | Prof. Johan Hustad |
| Cand.Agric. | 1996 |
| DOCTORAL STUDIES | |
| Started | March 2006 |
| To be completed | 2010 |

The Ph.D. studies are done part time combined with a profession as a marketing manager of Bioenergy in Statoil Norge AS.

The studies are financed by Statoil Norge AS.

**Improvement in running and maintenance cost of wood-pellets based heating centrals.**

## Background

Utilisation of bioenergy for heating purposes (not transportation) is increasing in Norway, opposite to traditional use which only has been wood industry, large district heating and heating stoves in households. Nevertheless the government goals are larger, 4 TWh growth in water based heating (mainly bioenergy) before 2010 (NOU 1998:11).
The refining degree woodpellets have achieved a certain level of utilization in Norway with a use of approximately 45 000 tons per year. This is distributed between approximately 5500 units of pellets stoves and 100 medium size heating centrals (below 3 MW). Complement to this is existent woodchips based heating centrals which also can use woodpellets.
Woodpellets are seen as a necessary degree of refined biomass to reach conversion goals from small- and medium size users of oil and electricity in the stationary sector/heating purposes.

The benefits of wood-pellets, which are important when used in new fields, are as follows:

- A relatively homogenous fuel
- An easy fuel to trade
- Quality standards are established
- Very high energy content regarded to volume
- Transportation and handling are done in closed systems with pressure air.
- Wood-pellets are dry, and problems with fungus, air quality in storage-rooms and frozen material is non-existing.
- An easy fuel should increase the possibilities to increase both environmental and economic prestations regarding all conversion technologies.

Woodpellets and biomass in general compete mostly against electricity and to some extent heating oil.

Therefore end-user comfort and perspectives is important to increase use in Norway. Since Norway is a country with a large lack of water-based heating systems, maintenance personnel is not used to both boilers and these heating systems. In addition, many installations are using wood-pellets, but the boilers are designed for wet wood-chips with a weak running performance as a result.

In a holistic view, introduction is not only a technical challenge but also include the operators capability and willingness to use bioenergy.

**Objectives**

- Investigate the system fuel-heating central - personnel introduction and point out potentials for improvement
- What properties should wood-pellets heating plants have to credit a standardized fuel as wood-pellets with higher reliability and lower running costs?
- Investigate and make developments to increase low output and on/off running conditions
- Due to lack of traditional raw materials for pellets productions, investigate new interesting ones like pine pulpwood with bark and lignin residues from 2G-ethanol production

**Method**

Task 1. Through the discipline systems engineering and a questionnaire investigate the system fuel-heating central-personnel and point out potentials for improvement in the whole system.

Task 2. Production of wood-pellets from pine pulpwood with bark; fresh and 6 month aged. Fuel quality and combustion behaviour

Task 3. Production of wood-pellets from pine pulpwood with added pure lignin. Fuel quality and combustion behaviour.

**Publications and presentations**

Articles from task 1 and 2 are to be published in Biomass & Bioenergy journal.

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| TOPIC | **Fluidized bed combustion** |

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|---|---|
| MAIN SUBJECT | **Waste combustion in fluidized beds** |
| SUPERVISORS | PhD David Pallarés<br>Ass.Prof. Henrik Thunman<br>Prof. Filip Johnsson |
| M.Sc. | Nov 2008 |
| DOCTORAL STUDIES | |
| Started | Nov 2008 |
| To be completed | Nov 2013 |

# Waste combustion in fluidized beds

Johanna Olsson

**Background**

With increasing demands for an environmentally sustainable society, waste has become a more frequently used fuel. However, utilization of waste fuels in fluidized bed boilers faces many challenges: uneven fuel and air distributions and corrosive deposits to mention a few. To improve the performance of waste-fired fluidized bed boilers; a greater understanding of both the fuel itself and the technology is needed.

At present, a usual approach is to empirically fit the mixing of solids and the gas in the bed with help of experimental data. The dynamic behavior of the fluidized bed is determined by the interaction between the gas and the solid particles and in the bottom bed this interaction result in a special behavior; the bubble flow pattern, see figure 1 below. Thus, a description of the processes taking place in a fluidized boiler requires detailed knowledge and an accurate model of the dynamics of the bottom bed for conditions corresponding to combustion units based the underlying controlling phenomena to be implemented together with models for the other sections of the boiler.

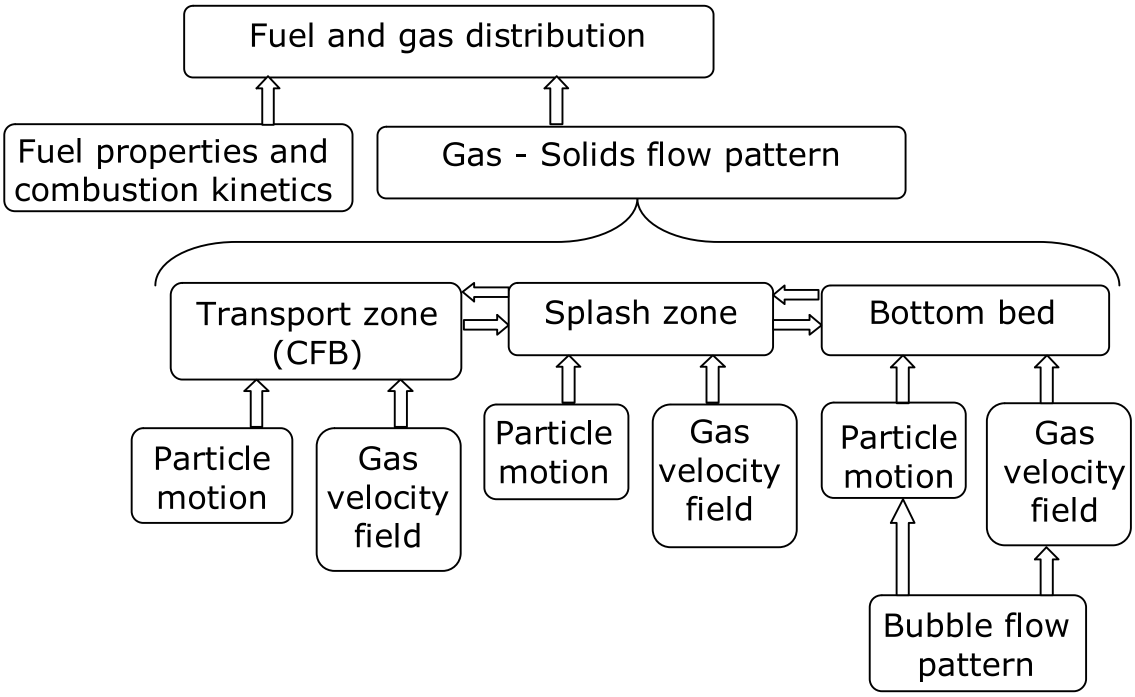


**Figure 1: Outline of the connection between the dynamics of the fluidized bed and the fuel properties and combustion kinetics.**

## Objective

Provide means to:

- evaluate performance of existing FBC units
- improve and optimize the performance of FBC units
- simulate new boiler designs

As well as contribute to an increased knowledge regarding the critical issues related to waste combustion.

## Method

- Experimental investigations both in small and large scale units to identify the parameters that influence the bottom bed dynamics.
- Evaluation of existing models for the bottom bed dynamics and properties of the bubble flow pattern
- Development and validation of models for the bottom bed dynamics and the bubble flow pattern to be implemented as a sub model in conjunction with models for the remaining parts of the boiler.

**Activities 2008-2009**

- Experimental investigation of the influence of the bed height, the pressure drop across the distributor plate and the gas velocity on the fluidization regime and bubble flow properties

The bubble flow pattern has been the subject of many studies but the majority of the studies have not been performed under condition corresponding to combustion units. The boiler dimensions, fluidization gas velocity, bed height-to-width ratio and air distributor-to-bed pressure drop ratio between are main parameters that characterize fluidized bed combustion units. The bubble flow pattern is influenced by a variety of parameters and depending on the settings, different types of flow patterns emerge. These patterns, or regimes, are classified depending on the dynamics of the bed. So far only two parameters have been used for mapping of the fluidization regime, the distributor pressure drop and the fluidization gas velocity. In these studies the bed height was not included as a parameter even though several experimental studies have concluded that the bed height influences the dynamics of the bed .

As immediate further work, an attempt to account for the bed pressure drop in the mapping of the fluidization regimes, i.e. and not assuming them as a function of exclusively the distributor pressure drop and gas velocity, shall be made. At the same time a study of the bubble flow properties in the bottom bed will be conducted. Initial experiments will be carried out in a cold 2D bed and data will be collected with both digital images and dynamic pressure recording.

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| TOPIC | **CFD modelling of oxy-fuel combustion** |

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|---|---|
| MAIN SUBJECT | **Combustion characteristics of oxy-fuel flames – Experiments and modelling** |
| SUPERVISORS | Professor Filip Johnsson,<br>Associate Professor Henrik Thunman |
| M.Sc. | February 2005 |
| DOCTORAL STUDIES | |
| Started | May 2005 |
| To be completed | May 2010 |

## Combustion characteristics of oxy-fuel flames

## – Experiments and modelling

Stefan Hjärtstam

### Background

Computational fluid dynamics (CFD) is a popular modelling tool used within industry and research to simulate both non-reacting and reacting flows. Combustion models, incorporated in CFD software are commonly aimed and tuned for traditional combustion using air to oxidize the fuel.

Carbon dioxide is the dominant greenhouse gas in terms of amount of gas emitted, and global warming as a consequence of $CO_2$ emissions is undoubtedly one of the most challenging environmental problems of our time. Capture and storage of $CO_2$ produced by combustion of fossil fuels have a significant potential to contribute to $CO_2$ reduction, allowing for a continuous use of fossil fuels as a bridge towards more sustainable energy systems (ultimately being non-fossil). If the fossil fuel is co-fired with biomass the contribution of the reduction could be even greater. Oxy-fuel combustion (also known as $O_2/CO_2$ combustion) is emerging as a possible carbon-capture technology, due to its comparatively favourable economics, and since it is more or less based on known technology. In oxy-fuel combustion, $N_2$ is separated from the air, and the fuel is burnt in a mixture of $O_2$ and recycled flue gas. The resulting high concentration of $CO_2$ in the flue gas enables direct $CO_2$ recovery. If a mixture of fossil fuel and biofuel is co-fired in a future oxy-fuel power plant, a negative (or zero) contribution of $CO_2$ to the atmosphere is possible, if the emitted $CO_2$ is captured and stored. Resent research has shown that the combustion properties of oxy-fuel flames differ from those of conventional air-firing. Oxy-fuel flames often possess high in flame concentrations of CO, but the emission levels of CO are often comparable with the emissions of conventional combustion.

As mentioned, CFD programs are used as tools for the prediction of the behaviour of various combustion units. Due to the different oxidant composition of oxy-fuel combustion compared to air-fired units, more detailed experimental data are of interest to further develop the present CFD-tools to better predict oxy-fuel combustion environments.

**Objectives**

1. Investigate the influence of different $O_2$ fractions (recycle rates) in the feed gas during oxy-fuel combustion and compare the results with a reference air-fired case. Objective completed in 2007.
2. Examine the effects on the flame structure and the emissions that follow from changing the recycle rate in oxy-fuel combustion. With the aim to gain sufficient data for future modelling of oxy-fuel flames. Objective completed in 2007/2008.
3. Evaluate the existing CFD-models ability to handle oxy-fuel combustion and suggest possible improvements.

**Method**

**Task 1.** In 2007 measurements of temperature and gas composition in Chalmers 100 kW combustion unit for three different oxy-fuel cases, in terms of $O_2$ concentration in the feed gas, were performed and compared with a reference air-fired case.

**Task 2.** Computational fluid dynamics have been used to model propane-fired oxy-fuel combustion in the Chalmers 100 kW unit. The influence of the choice of turbulence model in combination with suitable global reaction mechanisms have been investigated to set up a base line case for future modelling of oxy-fuel flames.

## International co-operation

This work is primarily sponsored by EU within the RFCS programme in the OxyMod project (Contract RFCR-CT-2005-00006) and from EU within the 6th framework programme in the ENCAP project (Contract SES6-CT-2004-502666).

## Publications and Presentations

1. Hjärtstam, S., Andersson, K., Johnsson, F. "Combustion characteristics of lignite-fired oxy-fuel flames", The Proceedings of the 32nd International Technical Conference on Coal Utilization & Fuel Systems, Clearwater, Florida, USA, June 10-15, 2007.
2. Andersson, K., Johansson, R., Hjärtstam, S., Johnsson, F., Leckner, B. Radiation intensity of lignite-fired oxy-fuel flames. Experimental Thermal and Fluid Science, Volume 33, Issue 1, Pages 67-76,2008.

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| TOPIC | **Fixed-bed combustion** |

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| MAIN SUBJECT | **Modeling of combustion of biofuels in grate furnaces** |
| SUPERVISORS | Assistant Professor Henrik Thunman, Professor Filip Johnsson |
| M.Sc. | February 2004 |
| DOCTORAL STUDIES | |
| Started | March 2004 |
| To be completed | November 2009 |

Modeling of combustion of biofuels in grate furnaces

Sven Hermansson

## Background

The use of biofuels for production of heat and power has increased during the last decades. One of the most frequently used techniques for conversion of biofuels into energy is combustion in grate furnaces. Grate furnaces are typically installed in small scale power plants, i.e. plants with production capacity under 20 $MW_{th}$, because of their benefit in simplicity concerning construction and control systems compared to e.g. fluidized bed boilers. In Sweden there exist around 150 grate furnaces for production of 5 $MW_{th}$ and more, and many more at lower capacities.

The design of grate furnaces, especially the small scale ones, is much dependent upon practical experience. Creating combustion models, both for the conversion in the fuel bed and in the gaseous phase, could give the furnace developers a useful tool for improvement of not only the efficiency and emissions of the furnace but also increasing the flexibility in the use of fuels and avoiding grate-material deterioration.

Today, the available bed-combustion models for engineering studies of grate furnaces are very simplified. When visually studying the combustion in a grate furnace it can be seen that there exists a range of effects that differ from the idealized view of the combustion and that need to be taken into account to create a reliable model. Such effects are e.g. channeling inside the fuel bed and at the bounding walls which are suspected to cause elevated emission levels of harmful substances. An increasing problem in grate furnaces that puzzles the uses is, also, grate deterioration. To some extent the disturbances and deterioration can be explained by practical issues like insufficient fuel mixing and air maldistribution through the fuel bed, but there are still a range of uncertainties that need to be further investigated. Therefore it is seen as important to develop models for the combustion that can take these multidimensional effects in the fuel bed into account combustion. The models should thereafter be implemented into engineering CFD-models that describe the real combustion situation in grate furnace.

**Objectives**

1. Development of a fixed-bed model that includes multidimensional combustion effects, and implementation into commercial CFD-software.
2. Analysis of channelling flow inside a fixed fuel-bed and at the presence of a solid wall.
3. Analysis of near-grate conditions as possible causes of grate-material deterioration.
4. Introducing theories of non-linear bed shrinkage and fuel flow due to conversion.

**Method**

Computational fluid dynamics in combination with existing models of thermal conversion of solid fuel and own theories of bed shrinkage and movements.

**Publications and Presentations:**


1. Hermansson, Sven; Brink, Anders; Thunman, Henrik: Structural collapses and inhomogeneous flow conditions in fixed-bed combustion. Proceedings of the American-Japanese Flame Research Committees International Symposium, 2007

2. Frigerio, Simone; Thunman, Henrik; Leckner, Bo; Hermansson, Sven: Estimation of gas phase mixing in packed beds. Combustion and Flame, 153 pp. 137-148, 2007
3. Hermansson, S.: 'Disturbances in Fixed-Bed Combustion', *Thesis for Degree of Licentiate of Engineering*, Chalmers University of Technology, Göteborg, Sweden, 2007.
4. Hermansson, S., Olausson, C., Thunman, H., Rönnbäck, M., Leckner, B.: 'Combustion Disturbances in the Fuel Bed of Grate Furnaces´, *Proceedings of the 7th European Conference on Industrial Furnaces and Boilers*, Porto, Portugal, 18-20 April 2006.
5. Ghirelli, L., Hermansson, S., Thunman, H., Leckner, B.: 'Reactor residence time analysis with CFD', *Progress In Computational Dynamics*, Vol. v 6, n 4-5, 2006, p 241-247.

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| TOPIC | **Gasification** |

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| MAIN SUBJECT | Biomass gasification |
| SUPERVISORS | Associate Professor Henrik Thunman, Dr Martin Seemann, Professor Filip Johnsson |
| M.Sc. | September 2008 |
| DOCTORAL STUDIES | |
| Started | October 2008 |
| To be completed | October 2013 |

Biomass gasification and gas analysis

Fredrik Lind

## Background

Today, when reduction of fossil carbon dioxide is of great importance, biomass has gained a new position as a carbon dioxide neutral fuel for heat and power production. Biomass can also be converted to a fuel for vehicle reducing diffuse emissions of carbon dioxide from transport sectors. One process that can be used is thermal gasification with fuel production. In the gasification operation 70 – 95 % of the dry biomass is devolatilised by heat to a synthesis gas.

In the fuel process the synthesis gas can either be used for production of synthetic natural gas or for production of a liquid fuel such as methanol, dimethyl ether or Fischer-Tropsch diesel. The devolatilisation operation is endothermic and heat has to be transferred to the biomass. After the devolatilisation the char remains, which in turn can be used for heat production. This concept is used in the 2 – 4 $MW_{fuel}$ gasifier at Chalmers University of Technology.

In December of 2007 the gasification unit was taken into operation. The gasification unit is coupled to a circulating fluidized bed boiler for district heat production. The gasifier has high flexibility to different types of biomass. A great advantage of this gasifier, in comparison with units for industrial purposes, is the possibility to supervise the processes with a lot of different parameters.

During 2008 and 2009 the gasification system was enlarged with a gas preparation and analysis system, see picture. A side gas stream, up to 300 kW, is possible to extract from the raw gas line. The water content in the side stream is condensed in two tublar heat exchangers, these heat exchangers also works as a trap for contaminations (e.g. particles and tars). The gas is subsequently transported to peltier cooling device where most of the remaining moisture is taken away. The last remaining moisture is removed in a silica gel filter. After the drying sequence the gas is pumped through a volumetric measuring unit and the composition is finally determined with gas chromatography. Beside the gas chromatography it is possible to connect the dried gas to an additional measuring technique, FTIR (Fourier Transform Infrared Spectroscopy).

Part of the gas analysis system

**Objectives**

4. Literature studies and development of an analysis system for the raw gas from the gasifier.
5. Examine the composition of the raw gas when using different fuel and different operation conditions in the gasifier.
6. Study tar cleaning technologies and develop a method for tar cleaning and tar utilization.

**Method**

1. Building up a gas analysis system by using chemical- and mechanical engineering. The system should include gas cooling and cleaning as well as the analysing equipment, e.g. gas chromatography.
2. The components in the raw gas are determined in the gas analysis system.
3. Building up a tar cleaning/utilisation system with catalysts in interconnecting fluidised beds.

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| TOPIC | **Waste combustion** |

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| MAIN SUBJECT | **Inorganic reactions in waste combustion** |
| SUPERVISORS | Docent Bengt-Johan Skrifvars,<br>Docent Bengt-Åke Andersson<br>Doktor AnnaLena Elled |
| M.Sc. | June 2007 |
| DOCTORAL STUDIES | |
| Started | September 2007 |
| To be completed | August 2012 |

Inorganic reactions in waste combustion

Frida Claesson

## Background

Modern Energy-from-Waste (EfW) plants often combust several different waste fractions, including household waste and various fractions of industrial waste. Even though household waste is heterogeneous, it constitutes similar amounts and types of paper, plastics, metals etc. Industrial fractions originating from specific sources can, on the other hand, be rather homogenous although; there is a great variety of sources and the reciprocal variation is vast. Identifying the composition of the major fractions combusted in a plant can, together with an enhanced knowledge of the impact of joint fraction, facilitate proactive selection of fractions to be co-combusted and a raised possibility of limiting fouling, corrosion and agglomeration.

This project considers two cases; the fluidized-bed waste combustors in Borås and the grate furnaces burning waste at Renova in Gothenburg. It concerns the characterization of the composition of the major waste fractions (in terms of yearly basis average values as well as seasonal fluctuations) and the impacts from selected components such as K and Na. Based on this information, thermodynamic equilibrium calculations will be performed to simulate the levels of certain inorganic combination. The specific inorganic combination that will be focused on depends on the fuel characteristics and the requirements of the involved companies. In-situ measurement of gases, deposits and particles in the gas suspension will thereafter be performed, together with chemical analysis of fuels, deposits, ashes and flue gases. This constitutes the verification data for the thermodynamic equilibrium calculations. The verification of the calculations indicates the degree of reliability of the simulations and is a key parameter. The simulations aim to evaluate the potential of adding different waste fractions or chemical elements in order to reduce the impact of certain challenging components, such as Na, K and Cl (parameter study). This will be compared to full-scale experiments in both the grate furnace and the fluidized bed furnace.

In brief: the project focuses on mapping of current waste compositions and generic understanding of the reactions of inorganic components occurring when firing different waste fuels in a power boiler. An underlying aim is to be able to follow and understand the pathway of the inorganic element through the boiler, *i.e.* from fuel composition, through evaporation and creation of aerosol to deposits and ash contents. Apart from thermodynamic equilibrium calculations, mass balances need to be formulated from the fuel characteristics as well as from the composition of the deposits and the ashes. Data generated from experiments in the waste combustors in Borås and Gothenburg will be used as input to the mass balances. Such data includes information on operating conditions, fuel, deposits and ash composition as well as characterization of vaporized elements in the suspension and emissions. The scientific challenge of this project is to understand and predict the governing phenomena of fouling, corrosion and agglomeration. The industrial benefits are raised awareness of the fuel composition, which facilitates an active selection of co-combusted fractions and fault detection of sources to unwanted chemical elements. The effect targets are increased boiler availability, boiler efficiency and power production.

**Objectives**

7. Give enhanced cognizance on the composition and seasonal variation of waste fuels.
8. Give enhanced knowledge on inorganic reactions and inorganic element behaviour in waste combustion.
9. Knowledge on how to give less boiler shut downs and increase the boiler life time.
10. Reduce the annual maintenance cost.
11. Possibility to increase the steam temperature (50-100ºC).
12. Give raised possibilities of locating sources of unwanted waste fractions.

**Method**

1. Mapping of current waste composition for the fluidized bed in Borås and the grate furnace in Gothenburg.
2. Thermodynamic equilibrium calculations of fuel components will be compared with In-situ measurements from the boilers.
3. Lab-scale and full scale tests of the effects of lowered bed temperature in BFB boilers (performed in Borås)
4. Full scale test of sulphur recycling in a grate furnace (performed in Gothenburg)

**Publications and Presentations:**

During 2009 two conference articles will be presented, the first one *"Chemical Characterization of Waste Fuel for Fluidized Bed Combustion"* at FBC20 in Xi'an, China in May. The second one *"Annual Variation in Elemental, Dioxin and PCB Content within Swedish Waste Fuels - Results from Two Plants"* on the Twelfth International Waste Management and Landfill Symposium in Sardinia, Italy in October.


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| TOPIC | **CFD based modeling of black liquor char beds** |

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|---|---|
| MAIN SUBJECT | **Inorganic Chemistry** |
| SUPERVISORS | Prof. Mikko Hupa<br>Doc. Christian Mueller |
| M.Sc. | June 2005 |
| DOCTORAL STUDIES | |
| Started | January 2006 |
| To be completed | January 2010 |

## CFD based modeling of black liquor recovery boiler char beds

Markus Engblom

### Background

With the development of more sophisticated models, computational fluid dynamics (CFD) is today considered a valuable research and engineering tool for studying industrial scale combustion processes. The increase in the unit size of black liquor recovery boilers is largely contributed to better understanding of the furnace processes. CFD has had a central role in this development.

Black liquor combustion modeling requires sub-models for droplet conversion, gas phase combustion and char bed combustion. Although the char bed models have become more detailed and refined, the shape of the char bed has been presumed in these models. The presumed bed shape has been sufficient for overall numerical studies of black liquor combustion, but for more detailed studies of the char bed processes, the bed shape should be determined by the combustion process. Description of relevant physical and chemical bed processes is a requirement for a model to predict correctly the behavior of a char bed, including burning rates and shape.

### Objective

To continue development of a char bed model by

- Developing a model for describing change in bed shape during simulation
- Identifying and including description of relevant physical and chemical char bed processes
- Validating model by comparing to observations from real furnaces
- Use of model to gain insight into char bed processes

**Method**

- Use of commercial CFD software
- Development of sub-models
- Comparison of simulation results against observations from real furnaces

**Activities 2008-2009**

- Participation in a measurement campaign aimed at obtaining data for CFD model validation

CFD-based models of today consider the main characteristics of black liquor combustion, namely droplet conversion, gas phase combustion, and char bed burning. These models are based on fundamental concepts and empirical data. The models consider the influence of the local environment on the processes they describe and the models are coupled, meaning that the modelled processes happen simultaneously and affect each other. Based on this, the models could be expected to describe black liquor combustion relatively well. However, their exact prediction capability is not well established. This is due to the lack of quantified in-furnace data for model validation.

Preparation of a comprehensive black liquor recovery boiler measurement campaign started in 2008, and the campaign was carried out in the beginning of 2009. The campaign involved several persons from universities and companies. The objective was to obtain in-furnace data for validation of CFD-based models. Measurements were carried out to obtain data on temperatures, radiation intensities, and gas phase species concentrations inside the furnace. In addition process data was obtained, liquor samples collected, and video footage from the furnace recorded using several cameras. What is especially interesting in the context of char bed modeling is that the boiler was operated in two different modes: with a low and a high char bed. Pictures of the char bed during these operational modes are shown in Figure 1. Time resolved process data and video footage are now available for situations where the char bed is growing and depleting. The analysis of the data will continue, but already now some interesting char bed shape influencing phenomena have been identified from the video footage. In addition, simulation of the two operational modes will be carried out in order to test the char bed shape calculation model.

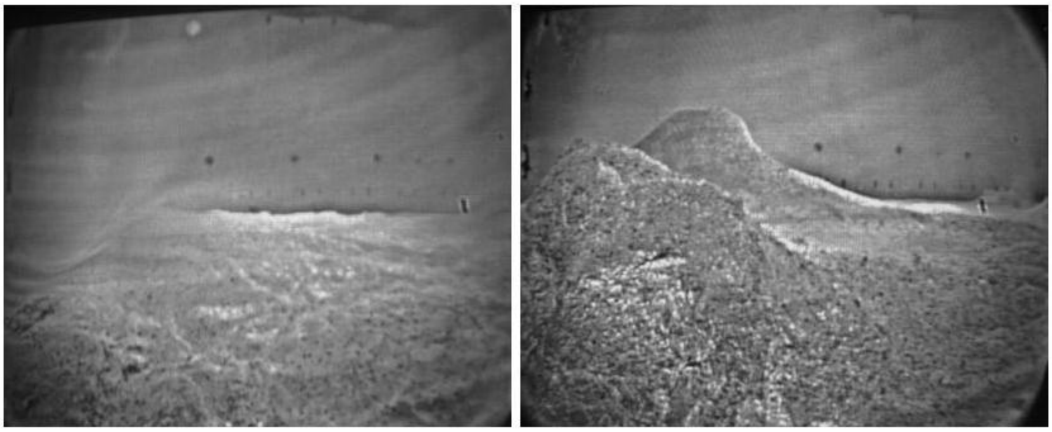

Figure 1. Pictures of the char bed during two operational modes: "low bed" (left) and "high bed" (right).

### International co-operation in addition to BiofuelsGS-2

- External supervisor: Andrew Jones, International Paper Inc.

### Presentations and publications


1 Engblom, M., Bergroth, N., Mueller, C., Jones, A., Brink, A., Hupa, M.,"Impact of droplet size and bed shape on Kraft char bed processes – A CFD study", submitted to TAPPI JOURNAL, 2009.

2 Hupa, M., Engblom, M., Brink, A., Mueller, C.,"How well do we understand recovery furnace processes?", to be presented at the Finnish Recovery Boiler Committee 45th Anniversary International Recovery Boiler Conference, Lahti, Finland, June 3-5, 2009.


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|---|---|
| TOPIC | **Modeling biomass combustion** |

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|---|---|
| MAIN SUBJECT | **Inorganic Chemistry** |
| SUPERVISORS | Dr. Anders Brink,<br>Professor Mikko Hupa |
| M.Sc. | March 2008 |
| DOCTORAL STUDIES | |
| Started | June 2008 |
| To be completed | May 2012 |

Characterizing biomass fuel samples for particle combustion modeling

Oskar Karlström

## Background

Energy production from combustion of solid fuels is extremely important around the world. Most of the solid fuel combustion concerns combustion of coal, but combustion of other solid fuels, such as solid biomass, is becoming more and more important. In EU, the energy production from solid biomass is expected to increase by 25 % between 2006 and 2010. For predicting the behavior of large-scale combustion boilers, the modeling technique CFD can be used. One limitation in CFD-modeling of solid fuel combustion is the use of simplified single particle models for drying, devolatilization and char combustion. There are significant differences in various kinds of solid fuels and, therefore, single particle models require fuel specific input parameters (e.g. kinetic parameters and parameters describing the shrinkage). Experimental techniques for characterizing solid fuel particles in order to model the combustion history of single particles are among others: TGA-, shock tube-, heated grid-, drop tube-, single particle furnace- and laboratory scale fluidized bed experiments. However, when determining fuel specific parameters it is important to note that the parameters are often both model- and fuel specific. Consequently, it might be inappropriate to use parameters from literature when modeling the combustion history of single particles.

**Objectives**

Develop simple and fast methods that find necessary information for modelling the thermal conversion of biomass particles in models that can be included as sub-models into CFD-codes.

**Methods**

- Use a single particle furnace for characterizing large biomass particles (>1mm) for single particle modelling. The idea is to determine parameters that describe the simultaneous drying and devolatilization into a CFD-applicable model. Furthermore, shrinkage parameters will be determined.
- Use combustion history data from a drop tube reactor in order to characterize pulverized fuel particles (>1mm) for single particle modelling. The combustion data is unpublished and available in the IFRF solid fuel data base. Drop tube experiments have been performed on more than 130 different fuels.

**Activities 2008-2009**

A method has been developed for determining parameters describing the simultaneous drying and devolaitlization for large, spherical wood particles. The work is still under progress.

Kinetic oxidation parameters have been determined for 130 chars in the IFRF solid fuel data base. The parameters were derived from drop tube experiments. The method that was developed for determining the parameters are based on a method suggested by Ballester and Santiago (2007).

## Presentations and publications

1. Karlström O., Brink A., Hercog J., Hupa M., Tognotti, L., ”Kinetic combustion parameters for chars using the IFRF solid fuel data base”. $16^{th}$ IFRF Members Conference, Boston, 2009.
2. Brink A., Karlström O., Hupa M., ” A simplified model for the behaviour of large biomass particles in the splashing zone of a bubbling bed”, The $20^{th}$ Internation Conference On Fluidized Bed Combustion, Xianyuang

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| TOPIC | **Experimental testing of new flame retardants in polymers** |

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| MAIN SUBJECT | **Inorganic chemistry** |
| SUPERVISORS | Dr Anders Brink,<br>Professor Mikko Hupa |
| M.Sc. | March 2004 |
| LICENTIATE STUDIES | |
| Started | January 2007 |
| To be completed | December 2009 |

**Experimental testing of new flame retardants in polymers**

Johan Lindholm

## Background

Flame retardants are additives in products to reduce the risk of fire. These additives inhibit and prevent fires in different ways. For our safety, the use of flame retardants has increased during the last decades to finally be present almost everywhere, from electronic equipment to furniture, and the need is growing. Halogenated flame retardants have been widely used because of their high efficiency and low cost. Recently it has been proven that several of the halogenated flame retardants are carcinogenic bio-accumulative substances, and have then been banned by the EU.

In Finland 40 900 tons of electronic waste were produced in 2006. One third of this was hazardous waste. This waste cannot be incinerated as municipal solid waste. It has to be handled with special treatment in order to recover the harmful chemicals. The decisions by the EU and these problems have forced the polymer industry to find new alternatives and develop environmentally friendly non-hazardous flame retardants. Regulations and laws on flame retardancy and allowed flame retardants can differ from one country to the other. The new EU legislation for Registration, Evaluation, and Authorization of Chemicals (REACH) requires industry to provide data to establish the safety of new and existing chemicals.

When developing efficient new environmentally friendly flame retardants testing is needed. Many countries have different testing standards. One of the aims of this work is to develop a useful toolbox for testing new flame retardants in polymers using different techniques. To do this, existing equipment will be used and new equipment will be installed, tested and used.

**Objectives**

13. To develop test methods for evaluating the flammability of polymers.
14. To apply the methods to support the development of new fire retardants.
15. To study the physico-chemical mechanisms responsible for the effects of fire retardants.

**Methods**

- UL 94 standard testing
- Cone Calorimeter
- Video combustion
- Pyro-GCMS
- DSC-TGA
- Hot stage microscope

**2008-2009 activities**

A Cone calorimeter (Figure 1) has been successfully installed and used for testing of polymer samples containing different types of flame retardants. One of the main outputs of the Cone calorimeter is heat release rate, which is based on oxygen consumption measurement during combustion. Some results can be seen in Figures 2 and 3. Different types of flame retardants behave in different ways in these two polymers, as can be seen from the figure. The three flame retardant combinations used were ATH (aluminium trihydroxide, 30 wt %), a brominated flame retardant (0,5 wt %) and a new azo compound (0,5 wt %). In polypropylene the three tested flame retardant combinations all decreased the peak heat release rate radically, while in polyethylene clear peaks are still present, but lower than in the pure polyethylene case. Figure 3 shows the total heat release. In the case for polypropylene flame retarded with ATH, it can be seen that a long burning time but with a low peak heat release rate generates almost the same amount of energy as the pure PP. Thus, a low peak HRR and short burning time would be the optimum case for the desired flame retarded polymer.

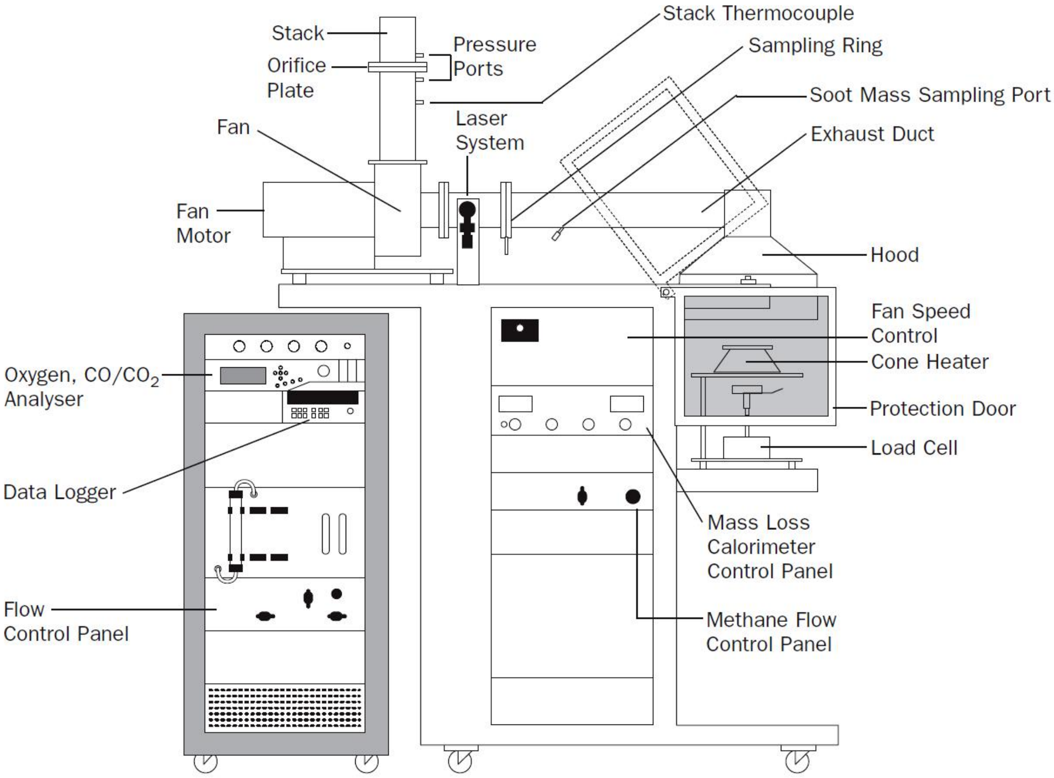


**Figure 1.** Schematic picture of a Cone calorimeter.

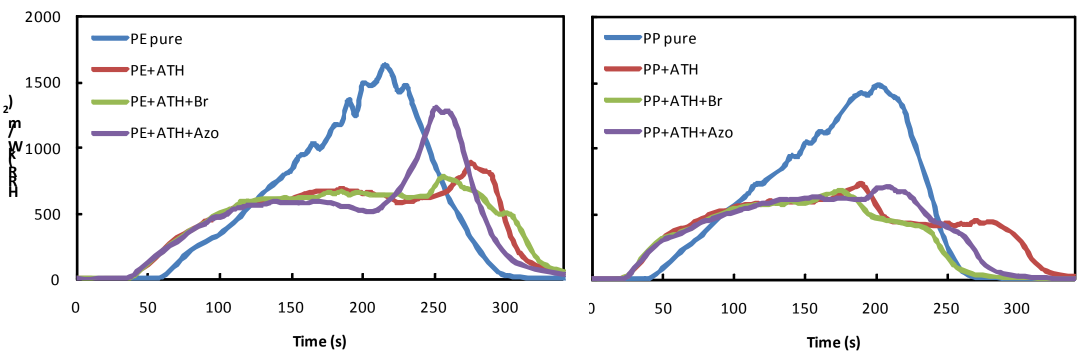


**Figure 2.** Comparison of the HRR behavior of different types of flame retardants in polyethylene and polypropylene.

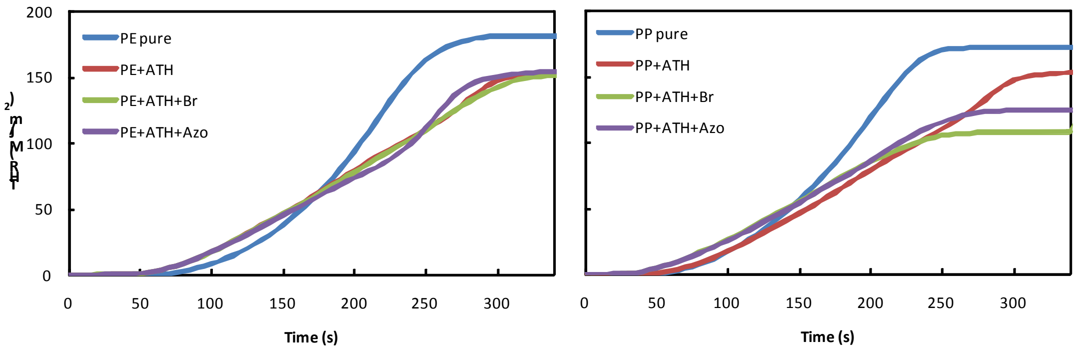


**Figure 3.** Comparison of the THR behavior of different types of flame retardants in polyethylene and polypropylene.

**Publications and Presentations:**

Johan Lindholm: Cone Calorimeter – A tool for measuring heat release rate. Scandinavian-Nordic Section of the Combustion Institute, Topical Meeting 2008, Measuring Techniques in Combustion, October 23-24 2008, Gothenburg, Sweden.

Johan Lindholm, Anders Brink, Mikko Hupa: Cone Calorimeter – A tool for measuring heat release rate. IFRF Finnish-Swedish Flame Days, January 28-29 2009, Nådendal, Finland.

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| TOPIC | **Fuel flexible burners for cement and mineral industry** |

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| MAIN SUBJECT | **Combustion of alternative fuels** |
| SUPERVISORS | Prof., Head of Department Kim Dam-Johansen<br>Prof. Peter Glarborg<br>PhD Klaus Hjuler<br>PhD Morten Boberg Larsen |
| M.Sc. | June 2006 |
| DOCTORAL STUDIES | Industrial PhD |
| Started | 1st January 2009 |
| To be completed | 31st December 2011 |

## Fuel flexible burners for cement and mineral industry

Linda Nørskov

### Background

5% of the global $CO_2$ emissions come from the cement industry [1], of which 54% is from the limestone calcination, 34% is from fossil fuel combustion, and the remaining 12% is from the electricity consumption [2].

During the last decades an increasingly share of the fossil fuels have been substituted with alternative fuels, i.e. biofuel or waste. The substitution is mainly motivated by the following reasons:

- Low fuel cost or possible negative costs opposed to the increasing prices of fossil fuels.
- The fossil fuel resources are saved.
- The alternative fuels may be partly or fully $CO_2$-neutral.
- The cement production is a suitable process for solving waste disposal problems as the waste is effectively utilised as energy and the ash residue is incorporated into the cement product, thus no by-products are formed.

Alternative fuels cover a large range of fuels with different chemical and physical properties. The combustion process of alternative fuels may differ significant from the combustion of fossil fuel mainly due to the alternative fuels generally have larger particle sizes. Also, the alternative fuels often have a lower specific heating value due to a higher ash and moisture content. An additional challenge concerning alternative fuels is the varying and inhomogeneous physical and chemical properties resulting in a fluctuating thermal energy input.

In the typical cement plant, fuel is combusted in the calciner and in the main burner of the rotary kiln, see figure 1. At present, substitution with alternative fuels is mainly done in the calciner where larger fuel particle sizes can be accepted, hereby reducing the cost of fuel comminution.

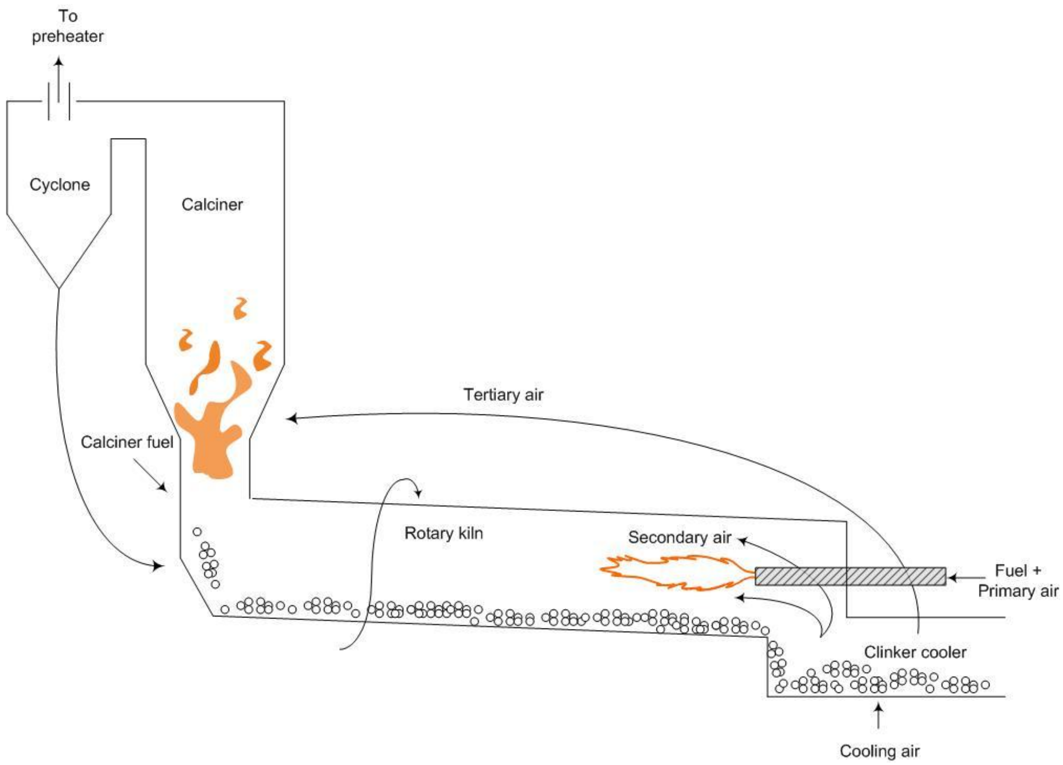


*Figure 1. The pyroprocess of a cement production plant. The raw materials are preheated in a cyclone preheater tower (not shown) by combustion gasses traveling countercurrent, before the calcination in the calciner unit. From the calciner the material enters the rotary kiln where it is further heated and clinkerisation reactions occur before the cement clinkers drop into the cooler unit. Hot air from the clinker cooling is used as combustion air in the rotary kiln (secondary air) and in the calciner (tertiary air).*

The thermal energy for the rotary kiln is provided by a burner, introducing fuel and primary air, generating a flame into the kiln. A typical flame operating on fossil fuels has a temperature of around 2000°C to ensure proper heat transfer for the clinker formation requiring a material temperature of 1450°C [3]. The desired flame properties are generally a relative short, narrow, stable, and centred flame with a high radiation at minimum primary air consumption and minimum formation of thermal $NO_x$ [3]. Proper control of the combustion process and flame properties is vital for ensuring complete fuel burnout in the flame and efficient heat transfer to the clinkers to maintain process stability and clinker quality.

**Objective**

The main objective of this project is to develop a novel scientific framework for effective utilisation of alternative fuels in the main burner of cement and mineral rotary kilns. This will be achieved through studies of physical and chemical phenomena in the combustion process of alternative fuels in the rotary kiln and kiln burner.

The increased understanding of the combustion processes of alternative fuels will be used for optimising and redesigning fuel flexible burners and burner process settings. The goal is to develop a kiln burner that allow for complete substitution of fossil fuels without compromising the clinker quality, production stability, and pollutant emissions.

**Method**

The studies involve literature studies, experimental investigations in laboratories and/or pilot plants, full scale measurements at operating industrial sites, coupled with mathematical modelling including CFD and chemical kinetics calculations.

[1] Mahasenan, N. et al., The cement industry and global climate change: current and potential future cement industry CO2 emissions, Presented at the 6th international conference on greenhouse gas control technologies (GHGT-6), Japan, 2002

[2] Smith, I.M., Potential for economic greenhouse gas reduction in coal-fired power generation. CCC/49, UK, IEA Coal Research, 2001

[3] Bhatty, J.I. et al. eds., Innovations in portland Cement Manufacturing. Portland Cement Association, 2004.

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|---|---|
| TOPIC | **Flash Pyrolysis** |

| | |
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| MAIN SUBJECT | **Flash Pyrolysis of Agricultural Residues for Bio-oil Production** |
| SUPERVISORS | Professor Kim Dam-Johansen<br>Associate Professor Peter Arendt Jensen<br>Niels Bech |
| DOCTORAL STUDIES | |
| Started | July 2007 |
| To be completed | June 2010 |

# Flash Pyrolysis of Agricultural Residues for Bio-oil Production

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## Background

The flash pyrolysis process has been the subject of intense research in the last decades mainly with the objective to maximizing the liquid yields. A high heating rate of the biomass particles and a short gas residence time at temperature of 450 - 600°C is required to obtain the highest possible liquid yield. Depending on the feedstock and operating conditions, flash pyrolysis process of wood produce 50-75 wt % of liquid bio-oil (including water), 15-25 wt % of solid char and 10-20 wt % of non-condensable gases. The flash pyrolysis process is a promising solid biomass thermal conversion route to producing a nearly ash-free liquid fuel with a high volumetric energy density. During pyrolysis, biomass is thermally decomposed without an oxidizing agent to produce a solid charcoal, liquid oil and gases. The char contain most of the inorganic components and it can be used as an energy carrier or as a soil fertilizer. The pyrolysis gas can be used to generate electricity or to provide heat for the pyrolysis process. The pyrolysis gas consists mainly of carbon monoxide, carbon dioxide and light hydrocarbons.

Also, the liquid oil can be directly used without any upgrading as a fuel oil in many combustion applications such as boilers. Upgrading is needed if the bio-oil shall be applied to a vehicle or petrol engine. The liquid oil is composed of a large variety of higher molecular weight species, organic acids, aldehydes, alcohols, phenols and other oxygenates. This oil is also known as a pyrolysis liquid, bio-oil or tar and has a lower heating value of about half that of conventional fuel oil. The heat value of approximately 17 MJ/kg is due to the high oxygen content and the presence of water in the bio-oil. The pyrolysis oil can undergo secondary reactions to be further broken down into gas, refractory tar and water. The distribution and the yield of the pyrolysis products depend on several operating parameters including temperature, heating rate, types of biomass, particle size, reaction condition, and reactor configuration, as well as the extraneous addition of catalysts.

**Objectives**

The aim of this project is to treat the bench scale pyrolysis centrifuge reactor (PCR) with various feedstocks for their compatibility with flash pyrolysis. The operational parameters will be selected based on the literatures. The results from the investigation will be used for optimizing the flash pyrolysis process combined with the mathematical modeling work, with the objective to maximizing the bio-oil yield.

**Method**

- A bench scale Pyrolysis Centrifuge Reactor is used
- Analyze the experimental data and results comparison

**Activities 2008-2009**

- Perform the pyrolyzer experiments using different feedstocks
- Study the bio-oil storage stability
- Investigate the bio-oil combustion properties

## Articles and Presentations

Ibrahim, N. Flash pyrolysis of Agricultural Residues for Bio-oil Production and Utilisation. In: Dam-Johansen, K., Bøjer, M.(eds), M.S. Graduate Schools Yearbook 2007, Dept. of Chemical and Biochemical Engineering, DTU, Kgs. Lyngby, 2007, pp. 97-98.

Ibrahim, N. Flash pyrolysis of Agricultural Residues for Bio-oil Production: The influence of feedstock moisture content on the product yields, In: Dam-Johansen, K., Bøjer, M.(eds), M.S. Graduate Schools Yearbook 2008, Dept. of Chemical and Biochemical Engineering, DTU, Kgs. Lyngby, 2007, pp. 65-68.

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| TOPIC | **Characterization and Quantification of Deposits Buildup and Removal in Straw Suspension-Fired Boilers** |

| | |
|---|---|
| MAIN SUBJECT | **Chemical Engineering** |
| SUPERVISORS | Prof. Kim Dam-Johansen<br>Asso. Prof. Peter Arendt Jensen<br>Asso. Prof. Flemming Frandsen<br>Asso. Prof. Stig Wedel |
| M.Sc. | April 2008 |
| DOCTORAL STUDIES | |
| Started | September 2008 |
| To be completed | August 2011 |

## Graduate school aspirant student

## Characterization and Quantification of Deposits Buildup and Removal in Straw Suspension-Fired Boilers

Muhammad Shafique Bashir

### Background

One of the main sources for sustainable energy now and in the near future is biomass. In Denmark, straw and wood chips are the most abundant biomass sources used for power production. A fairly large surplus of wheat straw exists in certain parts of Denmark, and it can be a better substitute for coal [1]. Use of straw may cause severe operational problems i.e. when 100% straw fuel is applied in large suspension-fired boilers the heat transfer surfaces may be covered by severe ash deposits impeding the plant operation. The reason is that when straw is burned, potassium vapors, salts and silicates with relatively low melting temperatures are formed. These potassium components play a significant role in the deposit formation because they act as glue bonding the individual fly ash particles together [1]. In order to make the operation of 100% straw-fired suspension boilers more efficient, improved technologies for deposit removal are needed.

The deposit formation and removal in biomass-fired boilers has been the objectives for several studies; however some biomass deposit related processes are still not well described. Most studies have been based on measurements in grate boilers, while only limited data are available from biomass suspension-firing where improved knowledge on the transient deposit formation process, the influence of fuel characteristics and mechanisms of ash deposits removal are needed.

**Objective**

The objective of this project is to provide recommendations for the optimal operation strategy of suspension-fired straw boilers with respect to minimization of deposit related problems. The specific objectives of the project are:

- Understanding removal behavior of deposits in the boiler chamber and superheater region (convective pass) of biomass- fired boilers.
- The influence of load, operation conditions and fuel changes (straw, wood or coal firing) on boiler deposits.
- A transient model based description of fuel changes on ash deposition and shedding. The model is intended to describe the deposit related processes as a function of the local parameters as gas velocity, ash particle size distribution, ash particle composition and gas and surface temperature.
- Provide measuring data that can support activities on fuel characterization and CFD modeling.

Based on the obtained knowledge, innovative ideas for deposit removal will be provided and tested. The practical probe measurements will form basis for the transient mathematical model for ash deposition and shedding.

**Method**

- Full scale measurements in suspension-fired boilers to investigate characterisation and shedding of ash deposits for different fuels, using air and water cooled horizontal and vertical deposition/shedding probe.
- Development of sub-models for ash deposition and shedding in the boiler furnace region.

- Comparison of simulation results against observations from real furnaces.

### Activities 2008-2009

Using an advanced horizontal water and air cooled deposition/shedding probe, a series of full scale measurements were performed. The intention of the study was to identify the ash deposition/shedding rate for changed fuel composition and boiler operation in the superheater and convective pass region. The measurements were conducted at Amager Power Plant unit II (suspension-fired boiler) utilizing different shares of Russian wood and Danish straw.

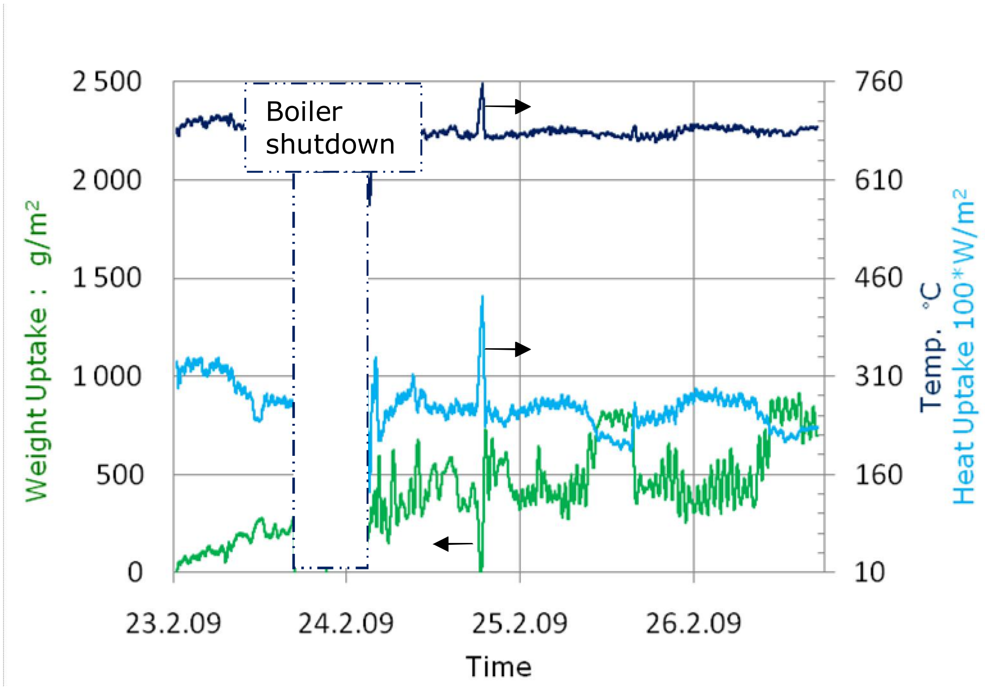
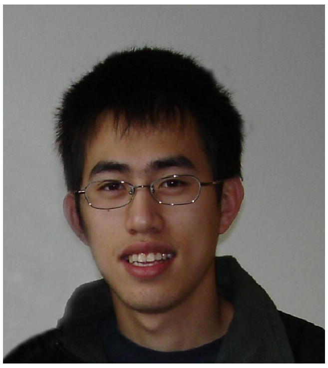



Figure 1: Weight uptake, flue gas temperature and heat uptake for water and air cooled deposition/shedding probe in biomass suspension-fired boiler.

The flue gas temperature near the probe was continuously measured, using a simple thermocouple in a protective shell. Suction pyrometer was used to confirm the accuracy of the flue gas temperature obtained by the thermocouple. A typical difference of 150-160°C between the flue gas measurements with the thermocouple and the suction pyrometer was observed. This temperature difference is due to radiation in a suspension-fired boiler. The first deposit formation was primarily due to condensation of alkali salts, indicated by whitish layer. While, for the second stage of deposit formation is described as solid deposit formation. It is clear from Figure 1, that a peak flue gas temperature; there is sharp decrease in weight uptake and increase in heat uptake, primarily due to surface melting (actual peak flue gas temperature ≥ 930$^{o}$C, temperature for ash melting [4]. It was observed that for increase in straw share, the rate of ash deposition increases and the deposits become more sintered in the windward direction and whitish in the leanward direction.

Transient model accounting for ash deposit formation and removal with changed temperature, ash composition and flow conditions is in the development phase. A vertical deposition and shedding probe is also in the development phase which will provide online information about deposit weight and heat uptake with video monitoring and local flue gas measurement. This probe will be used for full scale measurements at Amager Power Plant unit I (suspension-fired boiler).



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|---|---|
| TOPIC | **Co-combustion of fossil fuels and waste** |

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| MAIN SUBJECT | **Ash chemistry and other related problems** |
| SUPERVISORS | Prof. Peter Glarborg<br>Prof. Kim Dam-Johansen<br>Assoc. Prof. Flemming J. Frandsen |
| M.Sc. | August 2007 |
| DOCTORAL STUDIES | |
| Started | November 2007 |
| To be completed | November 2010 |

**Co-combustion of coal and waste in pulverized coal-fired power stations**

Hao Wu

## Background

Co-combustion of coal and waste offers a short-term and low-cost opportunity to reduce the net $CO_2$-emissions from dedicated coal combustion, and at the same time to get rid of a certain amount of waste produced from industry, agriculture and household. In comparison with a conventional waste incineration plant, co-combustion of coal and waste in a pulverized coal-fired plant offers advantages such as improved electrical efficiency and higher value of usable ash products. In Denmark, the Danish government launched in February 2008 a new long term energy plan in which co-combustion of coal and waste is pointed out to give an important contribution to reduce fossil fuel consumption.

To promote co-combustion of coal and waste in Denmark, there is a need to investigate and understand the impacts of the co-combustion process and related parameters (such as coal quality, waste type and quality, waste energy fraction, particle size and injection mode) on the fuel burnout, flame stability, deposit formation and corrosion, fly ash quality, gaseous emissions, and trace element partitions in a pulverized coal-fired plant. The results from this investigation will show whether co-combustion of coal and waste is a feasible option for pulverized coal-fired plants, and provide use information on the selection of waste materials and operational parameters for the co-combustion process.

## Objective

- Identify suitable waste types, energy fraction and particle size that can be co-combusted in pulverized coal-fired power stations

- Investigate the influences of co-combustion on deposit formation, fly ash qualities, gaseous emission, aerosol formation, and trace element partitions
- Evaluate the co-firing process through kinetic/equilibrium modelling

**Method**

- Performing co-firing experiments in laboratory-, pilot- and full-scale facilities
- Using global equilibrium model and reaction model to analyze the transformation of major inorganic elements and the partition of trace elements during co-combustion

**Activities 2008-2009**

- Performed co-combustion experiments in an entrained flow reactor. The influences of coal types, waste types, waste fractions, different additives on the co-combustion process were investigated.
- Participated in full-scale co-combustion tests on coal and solid-recovered fuel (SRF) in Esbjerg power station. The effects of co-combustion on the aerosol emissions were studied by impactor measurements.
- Involved in a project focusing on characterizing the co-prolysis process of coal and different waste fractions through TGA experiments

**Presentations and publications**

1 H. Wu, P. Glarborg, F.J. Frandsen, K. Dam-Johansen, P.A. Jensen, B. Sander, "Co-combustion of coal and SRF in an entrained flow reactor: a preliminary study", 4th European Combustion Meeting, Vienna, Austria, 2009

2 F.J. Frandsen, A.J. Pedersen, H. Wu, P. Glarborg, P.A. Jensen, O.H. Madsen, K. Lundtorp, B. Sander, "Danish experiences on waste incineration on grates vs. coal-SRF co-firing in suspension", 34th International Technical Conference on Clean Coal & Fuel Systems, Florida, USA, 2009


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| TOPIC | **Fuel flexible rotary kilns for cement production** |

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| MAIN SUBJECT | **Combustion Chemistry** |
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| Started | April 2008 |
| To be completed | March 2011 |

## Fuel flexible rotary kilns for cement production

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### Background

Cement production is highly energy intensive. The energy consumption by the cement industry is about 2% of the global primary energy consumption [1]. Coal and coke have traditionally been the primary fuels in the industry, but increasing fossil fuel prices and environmental concerns make other fuels attractive. Since energy costs accounts for at least 30-40% of the total costs of cement production, there is a great potential to reduce the overall production costs by replacing fossil fuels with alternative fuels[1]. Alternative fuels are typically cheaper than fossil fuels and in some cases the cement producer may even be paid to receive the alternative fuels.

Substitution of fossil fuels with alternative fuels offers the following major advantages:

1. Fossil fuel reserves are saved.
2. Landfill problems are solved.
3. Alternative fuels may be $CO_2$ neutral.
4. Solid residues from the alternative fuels are incorporated into the cement clinker.
5. High flame temperatures and residence times provide good conditions for destruction of organic compounds.

In the recent years the use of alternative fuels has increased. In Germany, for example, the share of alternative fuels is today higher than 50%, while it was only 4% in 1987 [2]. It is expected that the share of alternative fuels will continue to increase in the coming years, which will create a need for new technology to handle, treat and combust these fuel types [3].

Many types of alternative fuels are applied in the cement industry. The majority of the alternative fuels are on solid form, while liquids and gasses are less common. Some of the most common alternative fuels are refuse derived fuels (RDF), tyre derived fuels (TDF), meat and bone meal (MBM) and waste wood [4]. Price and availability are typically the determining parameters for the type of alternative fuel that will be utilised at a specific cement plant.

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[1] In this context ”alternative fuels” refers to all non-fossil fuels and waste from other industries. Secondary, waste or replacement fuels are often used as synonyms for alternative fuels.

The main challenges by changing from traditional fuels to alternative fuels are to:

1. Maintain a stable kiln operation.
2. Ensure a good cement clinker quality.

A key to control these challenges may be to avoid reducing conditions in the material charge in the kiln system and ensure complete alternative fuel burnout. However, this requires a solid knowledge about the combustion behavior of the specific fuel in the kiln system.

## Objective

The overall objective with this project is to improve the knowledge about combustion of solid, alternative fuels in cement rotary kilns. More specific, the project will focus on feeding of alternative fuels through the inlet to the rotary kiln, see figure 1.

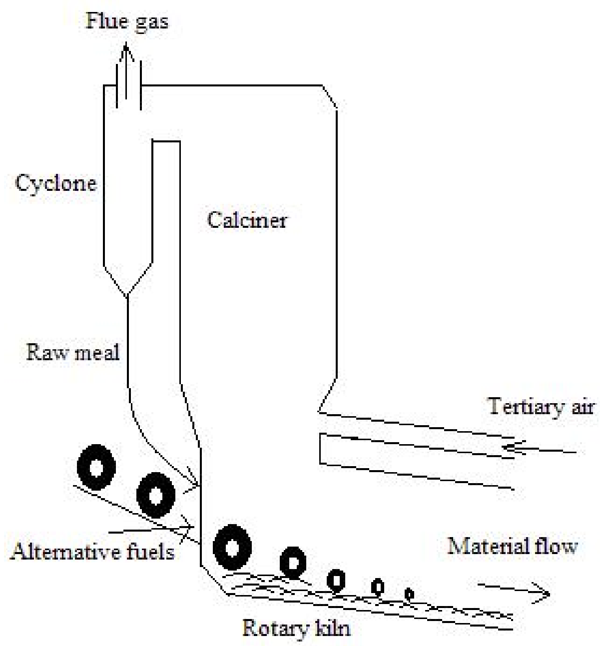


*Figure 2:* ***Calciner and rotary kiln inlet.***

An important advantage with this feeding point is that the need for shredding of the solid fuel can be minimized, thereby saving this expense.

The project shall clarify how local reducing conditions may be minimized. Furthermore, it is desired to study the release of inorganic volatiles, in particular sulphur, when alternative fuels are combusted. Finally, it is desired to investigate if a shift to alternative fuels has any effect on the $NO_x$ emission level.

The alternative fuel types of interest in this project will be waste wood, tyre derived fuel and poly propylene plastic.

The parameters that will be systematically investigated are:

- Kiln atmosphere
- Mixing efficiency (rotational speed and kiln filling degree)
- Fuel particle type/size/shape
- Amount of alternative fuel (substitution degree)

The investigations will be performed via a mix of literature study, laboratory/pilot scale experiments, mathematical modeling and full scale measurements.

**Activities 2008-2009**

Until now, laboratory scale experiments have been made in a fixed bed reactor, where mixtures of tyre char and calcined cement raw materials have been exposed to an atmosphere similar to the atmosphere in a cement rotary kiln. The purpose with these experiments is to investigate the relationship between the mixing efficiency and a) the fuel burnout behavior, and b) the release of sulphur. In these experiments, the measured $SO_2$-signal is taken as a measure for the sulphur release.

Visits to three European cement plants have also been performed in order to learn about practical challenges associated with combustion of alternative fuels. The purpose was also to investigate the possibility for a future corporation with one or more of these cement plants.

**International co-operation in addition to BiofuelsGS-2**

- Corporation with relevant cement plants.

**Acknowledgements**

This project is part of a research platform on future cement technology financed by The Danish National Advanced Technology Foundation, DTU and FLSmidth A/S.