GrateCFD

Enabling optimum Grate fired woody biomass and waste to energy plant operation through Computational Fluid Dynamics

SINTEF NTNU

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Editorial staff at SINTEF Energi AS (SINTEF Energy Research):
Øyvind Skreiberg (GrateCFD project manager)
Mette Bugge (GrateCFD sub-project manager)
Nils Erland L. Haugen (GrateCFD sub-project manager)

Editorial staff at NTNU (Norwegian University of Science and Technology):
Terese Løvås (GrateCFD sub-project manager)
Corinna Netzer (GrateCFD PostDoc candidate)

Dr. Øyvind Skreiberg,
Chief Scientist at SINTEF
and GrateCFD project manager
Oyvind.Skreiberg@sintef.no

Background

This handbook is prepared by SINTEF Energy Research and the Norwegian University of Science and Technology (NTNU) with the purpose to provide both partners in the GrateCFD project, relevant research projects and centres, policy makers and others with a simple and easy to read guide on woody biomass and waste to energy plant operation.

The information in this handbook is based on studies performed throughout a 4-and-a-half-year period in the competence building project entitled "GrateCFD – Enabling optimum Grate fired woody biomass and waste to energy plant operation through Computational Fluid Dynamics".

GrateCFD has run from 2017 to 2021 with a total cash budget of 24 million NOK, whereof 80% financed by the Research Council of Norway through the ENERGIX program and 20% financed by the industrial partners Statkraft Varme AS, Oslo EGE (now REG Oslo), Returkraft AS, Vattenfall AB and Hitachi Zosen Inova AG. In addition, LOGE AB and NTNU contributed with in-kind.

The overall objective of GrateCFD has been development of CFD aided design tools and operational guidelines for optimum grate fired BtE and WtE plant operation through:

- Model development: improved fuel/fuel bed and gas release models, heat-exchanger deposition models and reduced kinetics models (NOx); and validation of these
- Simulations: transient and steady state CFD simulations of BtE and WtE plants; and validation
- Concept improvements: BtE and WtE plant case studies selection, setup, simulations and analysis, giving design and operational guidelines

The sub-objectives were:

- Develop improved fuel, gas and particle sub-models to be included in the CFD simulations
- Develop numerical tools that are tailored to study concept improvements for grate fired BtE and WtE plants, with focus on emission reduction, combustion performance, energy efficiency and availability
- Obtain operational and retrofitting guidelines for optimum operation of grate fired BtE and WtE plants through CFD simulation case studies
- Education of highly skilled candidates within this area and training of industry partners
- Monitoring of activities and state-of-the-art within this area and dissemination of knowledge to the industry partners, and other interested parties when applicable

Main anticipated results of the project were guidelines aimed at improving combustion conditions, obtaining optimum operation over a wide range of thermal loads, decreasing emission levels at significant variations in fuel composition and production demand and increasing combustion and plant efficiency and availability.

Introduction

Knowledge needs

At the time of establishing the GrateCFD project, four central documents were defining the current national bioenergy strategy: Klimameldingen, Energi21, Skog22 and Strategy for increased expansion of bioenergy - 2008. The latter states that Norway shall **double the bioenergy production from 14 to 28 TWh by 2020** and that district heating shall contribute with a significant part of this. The doubling of the bioenergy production has however not become reality.

Biomass, including the biogenic fraction of wastes, is an important renewable energy source and important as a part of **security of supply** in Norway, where we today rely heavily on the electricity grid to deliver the needed heating for e.g. our houses. Close to 80% of the domestic heating is by electricity and 15-20% by wood log combustion, while district heating accounts for a low but continuously increasing and important amount (about 3%) and heating with gas is close to zero. This **makes Norway quite different** when compared to other European countries, with a dispersed population and low population density together with a challenging topography. Hence, small- to medium scale (<20 MW) biomass combustion plants are preferred for district heating, unless connected to larger industries needing process heat, often with a larger municipal solid waste (MSW) combustion plant as base load plant in the larger district heating networks.

However, biomass to energy (BtE) and waste to energy (WtE) plants in Norway need to comply with stricter emission limits and/or adjust to **tighter profit margins**, and EU have implemented a further reduction of emission limits from medium (scale) combustion plants. Tighter profit margins mean that **poorer/cheaper fuel qualities** become interesting, as well as **operational optimization** with respect to **efficiency** and **capacity** maximization. **NOx, particulate** and **CO** emissions are special concerns, as well as the operational challenges following particle deposition on heat **transfer surfaces**. The majority of the operational BtE and WtE plants in Norway are **grate fired plants**, and even though different grate technologies have been developed, they suffer from both **variations in fuel quality** and **changing operating conditions**, resulting in non-optimum operating conditions. The most cost-effective measure to abate the resulting operational challenges, including increased emission levels, are with **primary measures**.

Computational Fluid Dynamics (CFD) is the ultimate design tool for BtE and WtE plant combustion and heat transfer sections, however, cost-effective sub-models need to be developed, implemented and used in an optimum way. Moreover, the CFD simulations need to be carried out for transient conditions, to study the effect of changing operating conditions, and minimize the impact of these through improved plant operation and operational guidelines.

The focus of GrateCFD was therefore on enabling optimum grate fired BtE and WtE plant operation through CFD aided design and operational guidelines. Improved models and modelling approaches, in combination with targeted experiments/measurement campaigns, are keys for future's increased sustainable BtE and WtE plants. This will have a significant impact on two of the most important renewable value chains in Norway today, targeting key bottlenecks, i.e. reducing today's still relatively high and fluctuating emissions from grate fired BtE and WtE plants, ensuring optimum plant capacity utilization and improving their energy efficiency, especially at challenging operating conditions.

GrateCFD was to be executed in close cooperation with Norwegian, Swedish and Swiss grate fired biomass and MSW combustion plant owners and operators, and suppliers, experiencing non-optimum operating conditions frequently and feeling the associated costs.

Background

Grate firing of biomass is typically carried out in relatively small installations (typical thermal power ranging from roughly 1 MW up to about 20 MW). In this operational range the technology is more competitive compared to others, which mainly consists of different variations of fluidized beds (bubbling or circulating). However, because of their thermal range, the furnaces are typically supplied from smaller companies, which cannot support a large R&D department. Stage-wise improvements and modifications to existing designs are performed between each new installation, and significant improvements have been made both to process economy and performance over the years, and a substantial amount of experience has accumulated in the organizations of the furnace and boiler manufacturers. However, there have been few technological leaps, i.e. where performance or emission control has seen major improvement (although some exceptions exist such as the introduction of staged combustion to control NOx emissions). A targeted research effort in collaboration with all branches of development, i.e. academia, institutional and industry, has a potential to create such a leap.

In the WtE segment the grate fired technologies are typically larger compared to the biomass fired ones. In Norway the typical size is around 40 to 60 MW thermal (e.g. the Statkraft Varme Heimdal plant and the Oslo EGE Haraldrud plant) and here the plants are equipped with more advanced NOx reduction systems such as SNCR (Selective Non Catalytic Reduction) or SCR (Selective Catalytic Reduction) and dedicated de-SOx systems. The suppliers of these types of grate fired systems are typically larger than in the biomass segment. However, the increased complexity of WtE systems compared to their biomass fired counterpart require significantly higher levels of process integration, and as a result a more demanding sub-optimization. Although faced with different challenges (market, fuel prices, public opinion, emissions, etc.) the basic underlying technology in grate fired plants is fairly similar for biomass and MSW. They both rely on a moving grate, a topic which was one of the focus points in GrateCFD. More specifically, computational fluid dynamics models which can be used to improve the performance of grate fired processes.

One of the harshest simplifications typically employed in industrial grate fired boiler simulations is to treat the grate and the fuel bed as a steady state wall/inlet. The gas composition, and mass flow rate of gas released from the bed, can be pre-defined but lacks coupling to phenomena above the bed, such as mixing, heat transfer etc. This description by itself does not necessarily have to be a poor one. If the pre-defined values have been validated with relevant experimental data, the model can be used to study for example the position of air injection points above the bed (freeboard). However, the predictive qualities are highly limited, at least when it comes to near bed/grate behaviour. Furthermore, since the primary air supply beneath the grate is completely omitted in this type of formulations, the important coupling between the primary and secondary air and corresponding pressure drop and air distribution on the grate remains underdetermined, or rather highly averaged. Probably the most common mathematical formulation in grate fired applications is the porous media description where the grate or sections of the grate and bed are treated as porous zones. From a computational cost perspective this is an attractive compromise that can provide sufficient information whilst keeping computational cost down. However, the different zones are, again, geometrically pre-defined by the user and hence behaviours such as blow-through and local extinction cannot be predicted. Hence, a technological leap in grate fired processes when considering retrofitting is a model that can take the dominating phenomena into account but which still remains affordable to the industrial community. GrateCFD aimed to identify and further develop these types of models in a dedicated subproject.

In GrateCFD, two different levels of simulation tools were to be developed to study the fuel bed and the boiler. One tool designed to be faster and more user friendly, while the other more CPU demanding and accurate. The former tool is based on a stochastic reactor model approach, where the fuel bed and furnace are divided into a network of partially stirred stochastic reactors that can contain gas and/or particles and can handle detailed chemical kinetics and exchange heat, mass and momentum. The state variables are described with probability density functions. This tool was to be developed by NTNU in collaboration with LOGE. The other one, the accurate and predictive tool is based on a CFD approach, where the entire boiler, including the fuel bed, is discretized into a fine computational mesh. The main development here was to be on the bed model. In this model, a new approach, which combines the advantages of the porous bed methodology (low computational cost and robust) with that of Lagrangian fuel-particle tracking (transient and high accuracy) was to be used. A so called 1-dimensional layered particle model was to be the heart of the model, which makes this new approach capable of handling transient effects, such as bed collapse and bed blow-through, while still maintaining relatively low CPU costs. This development was to be done by SINTEF and NTNU in close collaboration. The rationale behind developing two different simulation tools is that while the faster tool is also relatively easy to use and immediately useable by the industry, the more accurate one also can be used to tune and validate the faster one for a new boiler geometry, whereafter a larger simulation matrix can be performed.

Perhaps the most significant influence on thermal performance of any boiler is the design of the heat transfer surfaces. And even more important, how those surfaces perform over long periods of continuous operation. **Particle depositions on heat exchanger surfaces**, particularly on high temperature surfaces, are detrimental to the lifetime of the heat exchangers due to corrosion induced by the deposit layer. Thick deposit layers will also significantly reduce the heat transfer and increase the pressure drop, and hence reduce the plant efficiency. It is therefore important to reduce the amount of particle deposits. This can be done by using a detailed understanding of the mechanisms leading to particle deposition to optimize the flow conditions in the boiler. Accurate predictions of the particle impaction efficiency could be obtained if care is taken in order to fully resolve the flow field. However, this is in contrast to most previous works on the topic where relatively coarse grained simulation meshes have been used together with the RANS (Reynolds Averaged Navier Stokes) simulation approach. In such approaches the flow field will not be accurately described, and hence the particle deposition rate will be wrong. However, in several papers by members of the GrateCFD project group, it has recently been shown that with current computer resources, one can use the DNS (Direct Numerical Simulations) approach to resolve all relevant fluid scales (2010, 2013), and thus, accurately reproduce the correct particle deposition rates. The models used in these papers were in GrateCFD to be extended to also include the effects of turbulence from the combustion chamber, thermophoresis and Brownian motions in order to obtain a full description of all simulations were the processes leading to particle deposition on the heat exchanger tube bundles. All DNS simulations were to be performed using the Pencil-Code, which is an open-source multi-physics simulation tool that has been developed by members of the research group for more than a decade.

The above mentioned sub-models were to be transferred to generic furnace and boiler models. These models were to focus on phenomena that can be addressed in a steady state framework, such as gas phase mixing, NOx emissions and CO burnout, as well as more complex phenomena that must be addressed in a time dependent framework (i.e. transient) such as collapse of the bed, and CO peak release from the bed as function of local transient occurrences. One of the key goals with these models is to maintain computational performance and keeping computational time down. This is crucial in order to make the models available to the industrial community, which may have limited computational resources and time.

Improvements and modifications of **existing biomass or MSW grate fired processes** have a potential to significantly improve profitability, availability and reduce operational expenses. However, obtaining this without turning to costly modifications presents several challenges, for example; keeping emission levels below legislated values, and handling of lower grade fuels in the process. It is important to address these challenges in targeted case studies that assess the feasibility in the individual installations and not just on a generic basis. Concerning this topic, several process performance numbers (and governing process parameters) can be identified,

i) **Efficiency**:
Measures and modifications which may be used to reduce the excess air ratio, reduce the carbon content in the ash and improve heat recovery and thus improving overall efficiency,

ii) **Load and fuel flexibility**:
Grate fired processes are typically characterized by a large operational span, meaning that they can operate from approximately 25 % of design capacity (i.e. summer operation) up to full capacity (winter operation). However, there is an interest to increase the heat production beyond the original design capacity, to reduce fossil oil consumption (which is generally used in auxiliary boilers) during periods with high demand. This presents significant challenges since volume flow rates increase in the combustion chamber, which may result in both increased emissions and increased wear on process equipment. In addition, fast changes in production capacity while adapting to consumer demand or fluctuating prices may also influence both emissions and overall efficiency. Hence, studies focusing on load flexibility are motivated to **increase availability**, and increase the use of renewable fuels, i.e. to mitigate use of fossil oil. In conjunction with load flexibility comes fuel flexibility, i.e. an increased need to use a more **diversified feedstock** (e.g. bark, branches and treetops, refuse derived biomass fuels, demolition wood etc.) driven by decreased profit margins and an increasing influence of the circular economy concept. Specifically, inorganic constituents and moisture content will influence deposition on heat transfer surfaces, bed characteristics, emissions and overall thermal efficiency. Achieving increased performance numbers in these areas was in GrateCFD to be obtained by **targeting three key zones** in the combustion process; the primary air delivery and distribution system (beneath the grate), the **grate** and the **secondary air** delivery and distribution system (above the grate). In addition, attention was to be turned towards minimizing ammonia slip and maximising the performance of the **SNCR systems**. Simulations was to be performed on selected **real installations** (case studies) focusing on obtaining effective under-grate wind box design to reduce leakages, prevent primary air blow-through at reduced thermal load, reduce superficial velocities above the bed whilst maintaining good mixing, i.e. turbulence, reduce ash entrainment and preferably also the pressure drop through the grate. The influence of the above mentioned parameters was to be analysed through simulations of the grate and bed where the influence of bed porosity and moisture content were to be investigated to determine guidelines for operation with different fuels and at different production capacity. The most **significant breakthrough in grate firing** of biomass has been made in advanced secondary air supply systems. The design of the secondary air system (and the amount of air to the secondary system compared to the primary system) has a critical influence on NOx and CO emissions, and unburnt carbon in both the fly ash and the bottom ash. The term **air staging** is well established where preferable conditions can be obtained to **minimize emissions** whilst improving performance and reducing unplanned maintenance stops. Simulations were to be performed to determine the optimum size and position of secondary air injection points with the goal to reduce emissions and improve burnout whilst increasing thermal capacity and process flexibility. Additional simulations were to be performed to improve SNCR system performance and focus on measures that reduces ammonia usage and slip. The goal of all these simulations is to attain guidelines on how to carry out low cost retrofitting and improvements of existing boiler installations to reduce/avoid the need for new boiler installations, and to improve the performance of secondary measures to reduce emissions (such as SNCR) when considering production increases. The **guidelines** were to be aimed at; **improving combustion conditions**, obtaining **optimum operation over a wide range of thermal loads**, and how to **decrease emission levels at significant variations in fuel composition and production demand** and to **increase combustion and plant efficiency and availability**.

WtE history and future in Norway

Since the establishment of the first modern MSWI/WtE plants in Norway in the 1980s, many technological, regulatory, and societal changes have taken place and have gradually transformed this sector of the MSW management system that is now well established and uses robust solutions.

WtE is at the center of several key sectors: waste treatment (especially contaminants' destruction/removal and the safe reduction of waste weight and volume before final disposal), environment (gaseous emissions including CO_2, solid residues) and energy production (heat, power). It can with confidence be said that in the near future WtE will have to adapt to circular economy principles, i.e., (1) expand to better integrate processes related to material sorting and recovery/recycling to ensure that only unrecyclable fractions are incinerated, and (2) contribute to climate change mitigation.

The (recent) past

The main waste regulatory events have taken place since the 1990s onwards. The EU has been the main driver for this positive evolution (applicable to the EEA countries like Norway) such as:

- the **Waste Hierarchy** that ranks the preferred options for waste treatment (see Figure 1)
- the EU **Waste Framework Directive** translated into Norwegian legislation in *Avfallsforskriften kapittel 10 Forbrenning av Avfall*, the main document regulating the WtE sector
- the **EU Landfill Directive** that regulates the types and amounts of waste that can be landfilled with clear targets to reduce its use. A main consequence has been a significant increase in WtE capacity in the recent years (see also next point concerning organic waste)
- The **EU BREF BAT WI**, the reference document (part of the IED, Industrial Emissions Directive) that compiles important data and knowledge about Best Available Technologies (BAT), practices and typical performance, encompassing almost all aspects of waste incineration (WI)

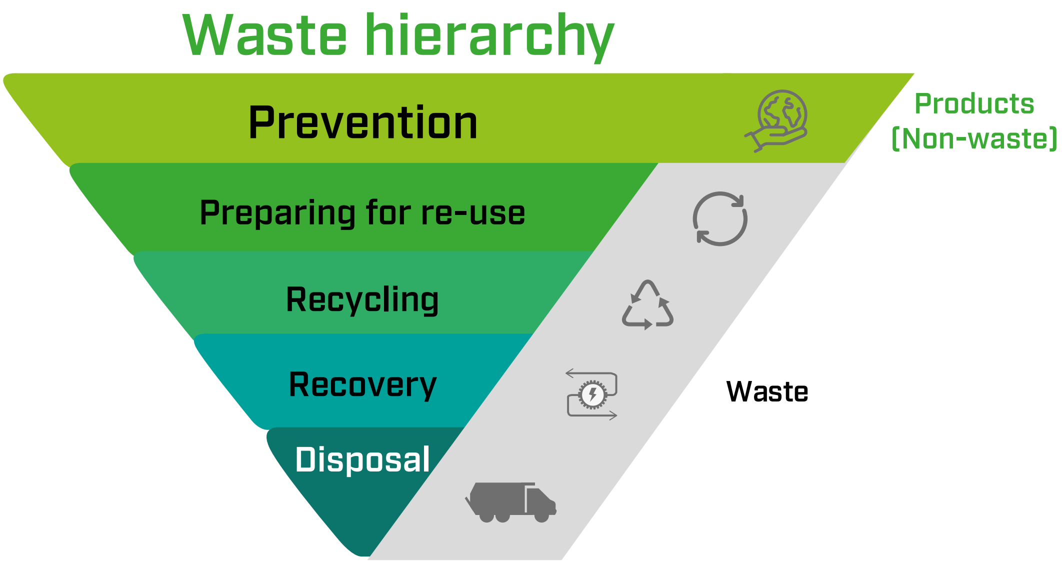


Figure 1.
The Waste hierarchy.
Ref: the European Commission.

Hence, stricter and stricter legislation, especially concerning gaseous emissions limits, has driven technological developments and the implementation of more and more efficient solutions in terms of costs and reduced environmental impact. In 2009, a **national landfill ban for biologically degradable waste** was enforced in Norway and this has led to an increase in MSW combustion capacity from ca. 1.1 million tons in 2008 to 1.6-1.7 million tons today (stable level since 2017-2018). Furthermore, a **support scheme for the development of district heating networks** (funded by the public body Enova) has been in place for some years now and has contributed to the development of WtE (see also next section).

The present

There are currently **18 WtE plants in Norway processing MSW**, with an average size of 50-60 ktons/year. Only 7 WtE plants have a capacity of 100 ktons/year or more. These are located in the main cities, i.e., Oslo (two), Stavanger, Bergen, Trondheim, Kristiansand and Ålesund. This rather low average capacity (from an EU perspective) is explained by

Norway's difficult topography and spread population of just above 5.3 million. According to statistics Norway (SSB), each Norwegian produces about 427 kg household waste per year and even though the decoupling of the waste generation increase from the economic growth is still not a reality, the gap is narrowing.

The WtE plants operate on average at 90+% capacity and process about **1.6-1.7 million tons MSW (household and commercial waste mostly) per year**. WtE produces about **45% of the district heating in Norway** (the largest single contributor) as well as some processed heat to industry, electricity and cooling. Some of the heat is lost due to a lower demand in the summer season. The bottom ashes are landfilled as ordinary waste while the fly ashes are classified as hazardous waste and are currently landfilled at Langøya. Several Scandinavian actors are actively working on improving fly ash valorisation.

The main **income** of most Norwegian WtE plants is the so-called gate fees, the second one being energy sales. However, the **competition** from Swedish WtE plants that can offer lower gate fees (ca. 600 ktons MSW are exported to Swedish WtE each year) and **low energy prices** have led to limited profitability for private actors, even though it should be noted that most WtE plants are owned by municipalities and operate on a full cost principle.

The **revised BREF BAT WI** was finalised in December 2019 and the authorities in EU/EEA countries have 4 years from this date to implement it into their legislations as it is now legally binding (it was not the case for the previous 2006 version). It has not been implemented by the Norwegian Environment Agency (Miljødirektoratet) yet.

The future

For approximately the last 5 years, several important trends have been gaining momentum, especially concerning **climate change** – in short, limit/reduce GHG emissions (NB: Norwegian WtE is not part of the EU ETS system) and **Circular Economy principles** - in short, promote material recovery to replace virgin resources.

The EU has formulated its strategy, goals and targets in several documents, most importantly **EU Green Deal** and the **EU Circular Economy Action Plan** (the Norwegian Sirkulær strategien was launched on June 16th 2021) but also the **EU taxonomy**. The final goal is for the EU to be climate neutral by 2050.

The **Circular Economy principles** will dominate and can briefly be summarised as two main points for waste management:

- Requirement for the **separate collection** of food (from 2023) and plastic waste (from 2025) with specific numbers for 2025, 2030 and 2035 (different for food & plastic). The requirements apply to municipalities; companies generating MSW-like waste have different rules.
- Requirement/targets for **material recovery rates**, 65% by 2035 for MSW (with intermediate numbers in 2025 (55%) and 2030 (60%)). According to SSB, the material recovery rate of household waste has been approx. 40% for the last decade in Norway.

The EU taxonomy is a green classification system that translates the EU's climate and environmental objectives into criteria for specific economic activities for investment purposes. EU taxonomy recognises as green, or "environmentally sustainable", economic activities that make a substantial contribution to at least one of the EU's climate and environmental objectives, while at the same time not significantly harming any of these objectives and meeting minimum social safeguards. EU taxonomy will enable investors to re-orient investments towards more sustainable technologies and businesses. Two out of the six objectives have been reviewed so far, the last four will be by the end of 2021. The role of WtE in the EU taxonomy is still being debated.

There is no doubt that the **implication of these strategies, plans and objectives will be significant** for the development of WtE in the EU but also the amounts and properties of the waste fractions sent to WtE. In addition to challenges, the future may also offer new opportunities to the WtE sector that could proactively redefine and expand its role (both upstream and downstream) by grasping commercial opportunities in terms of material sorting (to be sent to material recovery) and negative CO_2 emissions (CCS and CCUS) as a significant portion of MSW is of biogenic origin.

New business models, more sustainable products' design and production processes, digitalisation, new consumer behaviours and requirements and alternative technologies will greatly impact the whole WtE sector (and society at large) but energy recovery of unrecyclable waste fractions – well integrated into a circular economy – will be an essential part of an efficient waste treatment strategy.

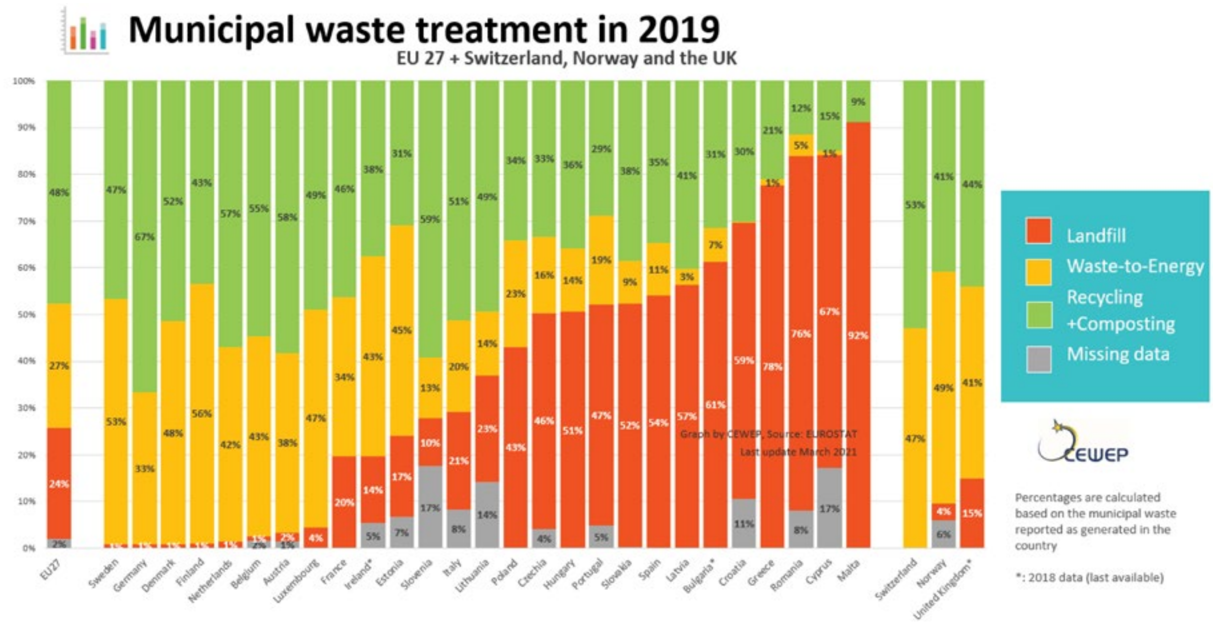


Figure 2.
Municipal waste treatment in 2018 in EU 28 + Switzerland, Norway and Iceland. Ref: CEWEP.

BtE history and future in Norway

Compared to WtE history, the BtE history is longer and the application area and size range of BtE plants are much wider. Different kinds of grate firing principles are applied, from the very smallest scales like wood stoves and boilers with fixed grates to much larger scale industrial and district heating plants with moving grates. In GrateCFD the focus has been on medium to large scale grate fired BtE plants, with similar grate firing principles as for WtE plants, even though tougher restrictions with respect to emission control, through secondary measures, are enforced for WtE plants.

In Norway, BtE plants are mainly found connected to 1) wood processing industries covering own heat demands by combustion of own wood processing residues and 2) smaller or larger district heating networks. In larger district heating networks, a WtE plant typically covers the base load together with waste heat from industrial processes while a BtE plant contributes with additional load. To cover peak load needs, e.g. electricity or biooil is used.

The fuels used in Norwegian grate fired BtE plants are typically wood processing residues, including bark, or wood chips from sustainable forest management, and sometimes wood briquettes or pellets made from sawdust from wood processing industries.

Through the last few decades district heating has been increasingly developed in Norway, with BtE plants as important contributors. Additionally, many smaller BtE plants have been erected to cover local heating needs. The use of biomass to provide heat for industrial purposes is not developing in the same pace, partly due to the shutdown of pulp and paper industries and limited new BtE plants erected at existing and new industrial sites.

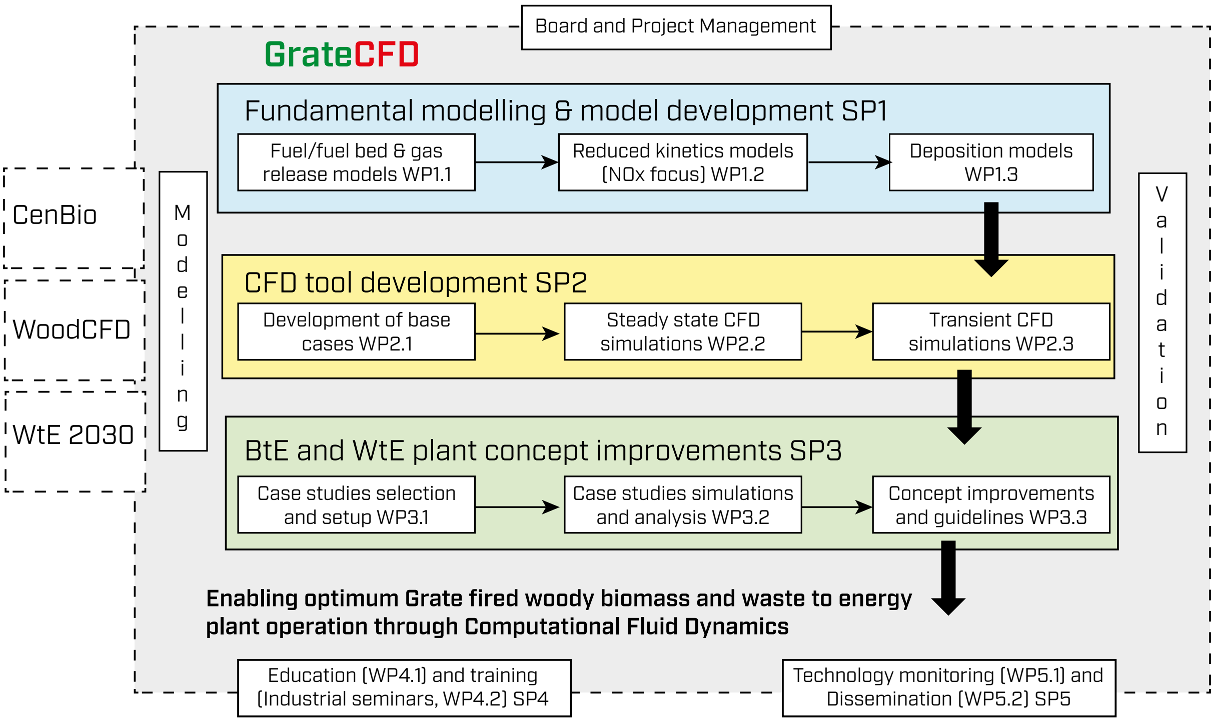
BtE plants needs to comply with emission regulations, concerning particulates, CO, SO_2 and NOx, according to Chapter 27 in the Norwegian pollution control act. Particle separation technologies are typically applied to comply with the particle emission limits, while CO is controlled by controlling the combustion process. Secondary NOx abatement technologies are typically not installed, and NOx reduction by staged air combustion is seldom optimised. I.e., the fuel-N content is mostly influencing the NOx emission level. EU have implemented a further reduction of emission limits from medium (scale) combustion plants, which also affects BtE plants of this category in Norway, as can be seen in Chapter 27 in the Norwegian pollution control act regarding upcoming emission limits. In addition, also sustainability criteria could be introduced for larger BtE plants in Norway in the future.

Even though grate firing technologies for BtE plants are far developed, significant improvements can be made connected to their operation to arrive at improved performance and reduced emission levels by applying primary measures. In this respect there are many similarities with WtE plants, connected to the grate and the freeboard above it, even though the fuel composition can be very different.

As such, modelling of this and using the models in simulations tools can significantly further improve performance and reduce emission levels.

Project structure

The Work Breakdown Structure of GrateCFD has been:
GrateCFD management and work break down structure and project links and information flow.



WoodCFD: Clean and efficient wood stoves through improved batch combustion models and CFD modelling approaches

CenBio: The Norwegian Bioenergy Innovation Centre

WtE 2030: Waste-to-Energy 2030

The project consortium covered all the necessary aspects, and included large and central industrial players in the biomass to energy (BtE) and waste to energy (WtE) areas in Norway, Sweden and Switzerland.

SINTEF Energy Research led the project and focused on both modelling and experimental activities. NTNU (Norwegian University of Science and Technology) supervised the PhD, the PostDoc and Master candidates, and led specific modelling activities. The industrial partners contributed with finances as well as access to plants and their extensive industrial knowledge generated through their commercial activities within the BtE and WtE areas: Statkraft Varme AS, Oslo EGE, Returkraft AS, Vattenfall AB, Hitachi Zosen Inova AG. The constellation of project partners was very strong, bringing together leading research organisations within the field and major industrial players.

The project was divided into 5 subprojects (SP), each subproject was itself divided into several work packages (WP).

Fundamental modelling & model development - SP1: The major objective of SP1 was to develop improved fuel, gas and particle sub-models to be included in the CFD simulations in SP2 and SP3. SP1 leader: Senior Research Scientist Nils Erland Haugen, SINTEF Energy Research.

CFD tool development - SP2: The major objective of SP2 was to develop numerical tools that are tailored to study concept improvements for grate fired BtE and WtE plants, with focus on emission reduction, combustion performance, energy efficiency and availability. SP2 leader: Research Scientist Mette Bugge, SINTEF Energy Research.

BtE and WtE plant concept improvements - SP3: The major objective of SP3 was to obtain operational and retrofitting guidelines of grate fired BtE and WtE plants through CFD simulation case studies. SP3 leader: Senior Business Developer Per Carlsson, SINTEF Energy Research.

Education and training - SP4: The major objective of SP4 was to strengthen the education within this field through MSc and PhD students, and a PostDoc candidate. The objective was also to increase the competence level in the industry. The long-term goal was competence building and strengthening of the education within combustion of biomass and biomass residues in BtE plants and MSW in WtE plants. SP4 leader: Professor Terese Løvås, NTNU.

Technology monitoring and dissemination - SP5: The major objectives of SP5 were to monitor the latest research and technological developments and to disseminate research results. SP5 leader: Chief Scientist Øyvind Skreiberg, SINTEF Energy Research, who also was the GrateCFD project leader.

Project achievements

The research activities in GrateCFD have been centred around the three scientific sub-projects:

1) **Fundamental modelling & model development**, led by Dr. Nils Erland L. Haugen, Senior Research Scientist at SINTEF

2) **CFD tool development**, led by Mette Bugge, Research Scientist at SINTEF

3) **BtE and WtE plant concept improvements**, led by Dr. Per Carlsson, Senior Business Developer



From left: Nils Erland L. Haugen, Mette Bugge and Per Carlsson

Methods

The following main methods have been applied:

1. A comprehensive review of numerical models for thermochemical degradation of thermally thick woody biomass, and their application in grate furnaces [1]
2. Evaluation of effects of a) operational parameters [2] and b) fuel parameters and flue gas recirculation [3] on NOx emissions through detailed chemical kinetics simulations
3. Development of skeletal mechanisms for prediction of NOx emission in solid fuel combustion - suitable for inclusion in CFD simulations [4], and an experimental and kinetic study on the transformation of fuel nitrogen [5]
4. Investigating grid-independent Eulerian-Lagrangian approaches for simulations of solid fuel particle combustion - for inclusion in CFD simulations [6, 7]
5. A detailed experimental study on the thermal decomposition behaviour of wood pellets under inert and oxidative conditions in a fixed bed reactor [8] and experimental campaigns in full-scale biomass and MSW grate combustion plants
6. Validation of a numerical approach for simulation of the thermal decomposition behaviour of biomass in grate combustion plants [9]
7. Development of a stochastic reactor-based fuel bed model for grate furnaces [10]
8. Development of a surrogate reaction mechanism for waste incineration and pollutant formation - for inclusion in stochastic reactor network simulations [11]
9. Nitrogen oxide prediction within a woody biomass fuel bed using detailed chemistry through the surrogate reaction mechanism [12]
10. Modelling inertial particle impaction on a cylinder in turbulent cross-flow at modest Reynolds numbers - to include heat transfer tube bundle studies [13, 14], using a developed high-order overset grid method for detecting particle impaction [15, 16]
11. CFD and stochastic reactor network simulations of lab- and full-scale grate combustion plants, with focus on NOx reduction in the latter approach [17, 18, 19]

[1] I. Haberle, Ø. Skreiberg, J. Lazar, N.E.L. Haugen (2017). Progress in Energy and Combustion Science 63:204-252.
[2] Ø. Skreiberg, T. Li, E. Vantaggiato, L. Wang, M. Bugge, T. Løvås (2019). Energy Procedia 158:103-110.
[3] Ø. Skreiberg, T. Li, L. Wang, M. Bugge, T. Løvås (2019). Chemical Engineering Transactions 74:217-222.
[4] T. Li, Ø. Skreiberg, T. Løvås, P. Glarborg (2019). Fuel 254, 15 October 2019, 115569.
[5] S. Wang, Y. Niu, T. Li, D. Wang, S. Hui (2020). Fuel 275, 117924.
[6] J. Zhang, T. Li, H. Ström, T. Løvås (2020). Chemical Engineering Journal 387, 1 May 2020, 123964.
[7] J. Zhang (2021). PhD thesis 2021:177, NTNU.
[8] Ø. Skreiberg, M. Bugge, J. Sandquist, F. Buvarp, N.E.L. Haugen. Chemical Engineering Transactions 86:67-72.
[9] M. Bugge, N.E.L. Haugen, T. Li, J. Zhang, Ø. Skreiberg. Chemical Engineering Transactions 86:73-78.
[10] C. Netzer, T. Li, L. Seidel, F. Mauß, T. Løvås (2020). Energy & Fuels 34(12):16599-16612.
[11] C. Netzer, T. Li, T. Løvås. Energy & Fuels 35(9):7030-7049.
[12] C. Netzer, T. Li, T. Løvås. Proceedings of 10th European Combustion Meeting, April 14-15, 2021.
[13] N.E.L. Haugen, J. Krüger, J.R. Aarnes, Ewa Karchniwy, Adam Klimanek. Thermophoresis and its effect on particle impaction on a cylinder for low and moderate Reynolds numbers. Accepted for publication in International Journal of Heat and Mass Transfer.
[14] J.R. Aarnes, N.E.L. Haugen, H.I. Andersson (2019). International Journal of Multiphase Flow 111:53-61.
[15] J.R. Aarnes, T. Jin, C. Mao, N.E.L. Haugen, K. Luo, H.I. Andersson (2020). Geophysical & Astrophysical Fluid Dynamics 114(1-2):35-57.
[16] J.R. Aarnes, N.E.L. Haugen, H.I. Andersson (2019). Int. Journal of Computational Fluid Dynamics 33(1-2):43-58.
[17] N.E.L. Haugen, M. Bugge, A. Mack., T. Li, Ø. Skreiberg. A bed model for grate fired furnaces: theory and comparison with experiments. To be submitted to an international journal.
[18] C. Netzer, T. Li, T. Løvås. Numerical Analysis of Nitrogen-Oxide Formation in WtE Plants using Detailed Chemistry Part 1: Fuel Conversion in the Waste Bed. To be submitted to an international journal.
[19] C. Netzer, M.T., Lewandowski, T. Li, T. Løvås. Numerical Analysis of Nitrogen-Oxide Formation in WtE Plants using Detailed Chemistry Part 2: Emissions in the Freeboard. To be submitted to an international journal.

CFD tool

Experimental campaigns have been conducted to investigate the influence of final pyrolysis temperature, heating rate and purge gas composition (none, 100% N2 and slightly oxidizing atmosphere) on pyrolysis of spruce wood pellets in a fixed bed reactor. A flexible detailed transient fuel-bed model taking into account drying, pyrolysis, and char combustion/gasification, for different fuels (biomass and MSW fractions) have been developed and validated. The fuel-bed model has been implemented in a CFD tool, ANSYS Fluent. The fuel bed model is made up of representative particles, and the motion of every representative particle is individually tracked (Lagrangian tracking through Fluent's Discrete Phase Model). Thermochemical degradation and conversion of the representative particles are calculated by a thermally thick single particle model (SPM), with boundary conditions obtained from the solutions of the gas phase equations. The SPM model then provides sources to the gas-phase equations.

Stochastic reactor network tool

A stochastic reactor network and a newly developed reaction mechanism are used to analyse the emission formation within woody biomass and MSW fuel beds. The individual stochastic reactors in the network account for local inhomogeneity in the fuel bed and provide probability density functions of local conditions and species. The solid fuel is represented using a surrogate approach. The surrogate approach enables a flexible definition of the fuel in the simulation and hence, captures phenomena such as the release of fuel-NO and its precursors and corrosive species. The stochastic reactor network is able to predict major combustion products (CO_2, CO), small hydrocarbons and nitrogen species in close agreement with experimental data. Further, the approach evaluates species and emission formation sensitive to local conditions such as fuel-air ratio and temperature and allows to predict changes in species profiles for load changes.

Kinetics development

Three skeletal mechanisms with varying degrees of reduction were developed based on a detailed kinetics model proposed recently, to be used for CFD simulations including NOx kinetics.

The representation of the solid fuel by surrogate species is adopted from liquid fuel and biomass combustion to be applied to solid waste devolatilization and combustion modelling using stochastic reactors. The surrogate formulation includes biomass components, protein, inorganics, and plastic species, and a comprehensive description of the heterogeneous and homogeneous reactions. Emission pathways for NOx and corrosive species (sulphur, chlorine) are accounted for.

Simulations

Kinetics studies have been carried out on NOx formation and reduction. The CFD tool based on Fluent is used to study the influence of fuel and operational parameters on grate combustion performance. The stochastic approach is used to study emission formation within the fuel bed, to be coupled with freeboard simulations (stochastic reactor network or CFD using OpenFOAM). Grid-independent Eulerian-Lagrangian CFD simulations of solid fuel particle combustion using developed coarse graining algorithms and a layer-based SPM have been carried out. Simulations of particle impaction on tubes in heat transfer tube bundles have been carried out.

Conclusions and further work

CFD and stochastic reactor network tool-boxes have been developed for simulation of BtE and WtE plant operation and design. Kinetics have been both reduced and developed to fit the developed modelling approaches while accounting for the relevant reactions taking place using both biomass and MSW in such grate combustion plants. Simulations have been carried out enabling detailed studies on changing fuel and operational conditions on the behaviour of the fuel bed and the interaction with the freeboard. The GrateCFD project has developed models and tool-boxes useful for giving plant operational and design guidelines through simulations. However, the tools will benefit from further refinement, with the aim of enabling cost-effective simulations of grate fired BtE and WtE plants to improve operation and design.

Sub-project 4: Education and training

Education and training are an important part of a competence building project, involving both knowledge transfer to the industry and education of Master students and PhD and PostDoc candidates. In GrateCFD, the PhD candidate Jingyuan Zhang from China contributed extensively to the work in sub-project 1, while the PostDoc candidate Corinna Netzer from Germany similarly contributed to sub-project 1 and 2. Both candidates were supervised by Professor Terese Løvås, who led SP4. Jingyuan Zhang successfully defended his PhD thesis ”Computational fluid dynamics (CFD) modeling for biomass and waste to energy production” in June 2021, as well as gave a trial lecture on the topic ”Physics informed machine learning for multiphase flow”. Both candidates are now continuing their professional career at NTNU. Several Master students have also been connected to GrateCFD, contributing to different topics through a specialisation project or a Master thesis. In addition, a summer job student has been financed by GrateCFD, through the annual SINTEF summer job project. The combined contribution from the students has been invaluable for the project, making it possible to achieve more within the given budget. Finally, annual workshops targeting the GrateCFD industry partners were arranged, with the purpose of dissemination as well as discussions, benefitting all parties in the project.

Sub-project 5: Technology monitoring and dissemination

Technology monitoring and dissemination are default activities in a competence building project, and in addition to the default state-of-the-art scientific monitoring within the core areas of the project, also more general monitoring in a broader area is carried out, and is also disseminated where appropriate. Dissemination to the general public has been carried out through the GrateCFD website and through two newsletters per year, as well as through popular science publications. Dissemination to the scientific community has been carried out through scientific presentations at workshops, seminars and conferences, as well as publications in conference proceedings and in international scientific journals. The GrateCFD industry partners have continuously through the project period been kept informed about project progress and achievements. All in all, extensive dissemination of project results has been carried out, in line with the expectations from the Research Council of Norway for a competence building project.

Collaboration with other projects

During the four years of the GrateCFD project, several parallel projects have been running on connected topics, with direct mutual beneficial collaboration or only information exchange. WoodCFD, WtE 2030 and the basic research project ”Particle transport and clustering in stratified turbulent flows” have been the three direct collaborating projects in GrateCFD. Especially WoodCFD, another SINTEF Energy Research competence building project on the development of clean and efficient wood stoves through improved batch combustion models and CFD modelling approaches, has contributed significantly to the initial GrateCFD output, through a joint review paper published in Progress in Energy and Combustion Science. The basic research project ”Particle transport and clustering in stratified turbulent flows” contributed through the collaborative work of the PhD candidate Jørgen R. Aarnes. WtE 2030 (Waste-to-Energy 2030, another SINTEF Energy Research competence building project focusing on contributing to keeping the WtE sector competitive and performant, run in parallel with GrateCFD in the period 2018-20, whereof several of its industrial partners also participated in GrateCFD. Project events were therefore aligned and co-organised, to maximise outputs and being efficient.

Internationalisation

GrateCFD has been an international project, having two international industry partners and as well both an international PhD candidate and PostDoc candidate. Extensive dissemination of project results internationally has been carried out, as well as dissemination of international activities to the project partners. Especially interesting international activities have been those of IEA Task 32 - Biomass combustion and cofiring, RHC-ETIP (Renewable Heating and Cooling - Energy Technology and Innovation Platform) and EERA (European Energy Research Alliance) Bioenergy - Stationary Bioenergy. Norwegian participation in such international forums ensures information flow and influence.

All in all, the combined research and development efforts on BtE and WtE plants ensures a strengthening of competence and research capacity, benefitting the plant operators and connected industries while ensuring a continuous focus on energetic and environmental performance.

Recommendations

GrateCFD has been successful in progressing the knowledge and modelling tools significantly. However, more work is still needed to reach the final target, i.e. to be able to use CFD as a cost-effective design tool for WtE and BtE plants.
Regarding model development and validation work, the project has to a great extent achieved the project objectives, while the objectives connected to simulations and case studies have been reached to a lesser extent. The latter is due to more time and resources needed for model development and validation, and less time and resources being available for simulations and case studies.

Regarding the CFD modelling and simulation approach, the main outcome of the work became the developed and validated (for pellets and wood chips) transient bed model, ready for use in simulations of full scale BtE plants, and WtE plants (given that the actual MSW composition is known). The bed model is both comprehensive and flexible. Instead of treating the bed (and grate) as an inlet, which does not allow for a feedback to the bed, the model provides a proper coupling between the solid fuel and the rest of the furnace. Even though the bed-model is much more comprehensive than previous bed-models, simplifications are still made in order to make it numerically tractable. In particular, collisions between the individual particles in the bed are not considered. Instead, analytical models are used to describe the physical motion of the bed particles. This is a justified assumption, since the exact motion of the bed particles is not significant, it is the average motion of the bed that matters. Furthermore, an accurate numerical prediction of the motion of the individual particles would require extensive knowledge of all physical aspects of the particles, such as: exact size, shape, composition and stiffness, in addition to how the structural integrity of the particle changes with temperature. There is no way such knowledge can be obtained for all particles of a WtE plant. Describing the motions of the bed through analytical functions is therefore considered to be by far the best approach for numerical simulations of full-scale plants.

One of the main realizations made in GrateCFD was the significance of the thermal properties of the grate on the combustion process. Up to now, the common practice has been to consider the bed as divided into three distinct zones along the grate, where the first zone corresponds to drying, followed by the devolatilization zone and the char conversion zone. We now understand that due to the high conductivity of the grate, heat travels also upwards through the grate, which means that the grate acts as an igniter of bed combustion from below. In this way, the lower parts of the bed may be burning, both the gas and the char, all the way along the bed towards what is typically considered the drying zone.

In fact, one of the original objectives was to study how the grate bars and wind boxes influence the behaviour of the fuel on the bed and the further behaviour above the bed, and the project has shown that this is a crucial task. Due to the need for prioritizing in the project, it was not possible to study this aspect further in the GrateCFD project, but its detailed investigation is recommended in a future project. Further work should also include further validation of the model implementation and applying the model/tool to full scale plant studies, e.g.

1. Further refine the validation case by:
    - Use more accurate residence times (awaiting better estimates from experiments)
    - Use better combustion model: Eddy Dissipation Concept (EDC) instead of Eddy Dissipation Model (EDM) + finite rate
    - Extend from 2D to 3D to obtain representative secondary air inlets (and include wall effects) and to be able to simulate thermal transport (and radiation) in grate elements (appropriate inlet temperature to wind-boxes)
    - Include effect of the fuel bed on turbulence (k and epsilon)

2. Perform simulations of full-scale plants:
    - Use different waste fractions in addition to wood
    - Investigate both oxyfuel and air-fired combustion

Regarding the stochastic reactor network modelling and simulation approach, the main contribution was the representation of municipal solid waste using the surrogate methodology and a comprehensive reaction mechanism. The combination of reactor network and detailed chemistry allows formulation and analysis of different waste compositions and their impact on emissions and corrosive species. This is a significant improvement since the waste's elemental composition dominates the species release and hence emission formation. Further, using a stochastic approach allows describing the heterogeneous character of a fuel bed and its local conditions for air supply and temperature. The model is validated against species and temperature measurements of BtE and WtE plants available from the open literature. Besides the insight of chemical processes within the fuel bed, the model can be used to create advanced boundary conditions for CFD simulations, focusing on NOx and corrosive species formation and distribution in the combustion chamber. Knowledge of the occurrence and lifetime of these species can help to develop advanced primary measures.

Further work regarding the surrogate and chemistry model is anticipated to:

- Extend the applicability to other waste fractions
- Refine and validate the introduced assumptions
- Extend the capabilities of the gas phase chemistry, e.g., by dioxin formation

The stochastic reactor fuel bed model is ready to use in combination with full-scale gas phase CFD simulations to find optimal air supply strategies to minimize targeted emissions and increase the plant's thermal and electric efficiency taking into account varying fuel quality, amount, and composition. To extend the stochastic reactor network modelling capacities and enable efficient computational optimization, the model can be updated with:

- Combined use of stochastic reactors for the freeboard and the fuel bed
- Introduction of an advanced solid particle model to gain more information on the solid phase

In the end, WtE and BtE plants are an important part of the Norwegian renewable and sustainable energy system. They will continue to be that in the foreseeable future, however, meeting the increasing demands from stakeholders and authorities are necessary, i.e. adaption and continuous improvements are needed.

The industry partners

Statkraft Varme

Statkraft, annually delivers over 1 TWh of district heating to its customers. It's headquartered in Trondheim, Norway where it also operates its single largest district heating network providing about 30% of the city of Trondheim's need of heating. The company's operations began in 1982 and has since expanded to cover multiple municipalities in Norway and Sweden, and is currently comprising 130 employees. The company's vision is to continuously strengthen its role as a profitable and innovative player in the district heating industry by actively contributing to research, development and innovation activities, and by utilizing smart, new solutions to foster energy efficient buildings and district heating solutions for its customers. Energy to district heating is primarily based on either biofuel or municipal solid waste incinerated in grate fired boilers ranging from small to medium sizes. Additionally adhering to best available technologies for its district heating operations, the company is currently investigating feasibility for CCS deployment at its largest waste-to-energy plant at Heimdal in Trondheim.

Oslo EGE

Renovasjons- og gjenvinningsetaten (REG) in Oslo translates to Waste Management Agency in Oslo. REG is responsible for collection, treatment and disposal of municipal waste in the City of Oslo. This means a complete responsibility for all communication to the public about waste and waste management, physical collection of the waste, operations and development of the solutions for sorting and treatment of the waste and responsibility for the climate footprint of the waste and the methods used. REG employs approximately 720 people. The industrial activities in REG are 1) receiving and sorting household waste from the city, separating food waste and plastic packaging from residual waste, 2) energy recovery of residual waste, delivering all energy to district heating, and 3) biological treatment of biomass/food waste – producing biogas for transport and bio fertilizer for agriculture.

Returkraft

Returkraft is a Waste-to-Energy plant in Kristiansand, Norway. The facility was put into operation in 2010 and receives approximately 130 000 tons of municipal (60%) and industrial (40%) waste annually. The waste is burned inside a 30 meter high incinerator, and the energy of the waste is then used to produce steam to run a steam turbine and produce hot water to the district heat network. Hence, the energy in the waste is recycled into 95 GWh electric power and 250 GWh heat to the district heating network in Kristiansand. The hazardous substances released to the smoke during the combustion process are cleaned in advanced cleaning systems, and the emissions are far below the Norwegian authorities' requirements. The plant has 44 employees and is also designed to facilitate visitors - 3000 each year. The ownership is public trough the municipal waste companies in the Agder region.

Vattenfall

Vattenfall is one of Europe's largest producers and retailers of electricity and heat. Our value chain goes all the way from production to electricity distribution, sales of electricity, heat and gas, district heating and energy services & decentralised generation. Our main markets are Sweden, Germany, the Netherlands, Denmark, and the UK. The Vattenfall Group has approximately 20,000 employees. Net sales FY2020 was 159 bn SEK, electricity generation 113 TWh, customer sales; electricity 118 TWh, customer sales; heat 14 TWh and customer sales; gas 57 TWh. The parent company, Vattenfall AB, is 100% owned by the Swedish state, and its headquarters are in Solna, Sweden. For more than 100 years we have electrified industries, supplied energy to people's homes and modernised our way of living through innovation and cooperation. We now want to make fossil-free living possible within one generation. Therefore we are driving the transition to a more sustainable energy system through growth in renewable production and climate smart energy solutions for our customers. To succeed we are actively phasing out fossil based production. But that's not enough. We are looking beyond our own industry to see where we can really make a difference. Together with our partners, we are taking on the responsibility to find new and sustainable ways to electrify transportation, industries and heating. For example, Vattenfall considers indirect electrification through fossil-free hydrogen as an important solution to decarbonise the value chains of heavy-emitting industries. One major partnership with Vattenfall participation is HYBRIT – our most advanced industry decarbonisation project. It is the fossil-free sponge iron project for producing fossil-free steel. It is run together with our Swedish partners, steel company SSAB and mining company LKAB. Our district heating area, set to increase significantly in several of our core markets, drives the transformation towards fossil free heating and cooling solutions together with partners, cities and regions. Vattenfall Heat Sweden operates a number of major district heating plants which include ten grate-fired units, both waste incinerators and biomass-firing units. The fuels utilized in these plants are expected to change significantly in the future. To enable a continued optimum grate fired BtE and WtE plant operation, tools are needed to analyse the effects of such fuel changes. This was our prime motive for participating in the GrateCFD project.

Hitachi Zosen Inova

Zurich-based Hitachi Zosen Inova (HZI) is a global leader in energy from waste (EfW), operating as part of the Hitachi Zosen Corporation Group. HZI acts as an engineering, procurement and construction (EPC) contractor and project developer delivering complete turnkey plants and system solutions for thermal and biological EfW recovery. HZI's innovative and reliable waste and flue gas treatment as well as gas upgrading and power-to-gas solutions have been part of over 700 reference projects delivered since 1933.

The research partners

LOGE

LOGE AB is headquartered at Ideon Science Park in Lund, Sweden with additional offices in Cottbus, Germany and in Częstochowa, Poland. LOGE develops and markets state-of-the-art software for chemical processes and our consultants offer Computational Fluid Dynamics-model development and chemical mechanism calculations to the exact specification of your business needs. Together with our partners and the industry, we help reduce harmful emissions from combustion and increase internal combustion efficiency through the development of next-generation technologies and innovative solutions.

NTNU

NTNU is a university with an international focus, with headquarters in Trondheim and campuses in Ålesund and Gjøvik. NTNU has a main profile in science and technology, a variety of programmes of professional study, and great academic breadth that also includes the humanities, social sciences, economics, medicine, health sciences, educational science, architecture, entrepreneurship, art disciplines and artistic activities.

SINTEF

SINTEF is one of Europe's largest independent research organisations. Every year we carry out several thousand projects for customers large and small. For more than 70 years, SINTEF has developed solutions and innovation for society and customers all over the world. This is how we have become a world-leading research institute. We deliver innovation by developing knowledge and technologies that are brought into practical use. SINTEF is a broad, multidisciplinary research organisation with international top-level expertise in the fields of technology, the natural sciences, medicine and the social sciences. We conduct contract R&D as a partner for the private and public sectors, and we are one of the largest contract research institutions in Europe. Our vision is Technology for a better society.

The Research Council of Norway

The Research Council works to promote renewal and innovation in the public sector, competitiveness and growth in Norwegian trade and industry, through a variety of research funding instruments.

Publications

Journal publications

Thermophoresis and its effect on particle impaction on a cylinder for low and moderate Reynolds numbers.
Nils Erland L. Haugen, Jonas Krüger, Jørgen R. Aarnes, Ewa Karchniwy, Adam Klimanek. International Journal of Heat and Mass Transfer 181, 121996.

A detailed experimental study on the thermal decomposition behaviour of wood pellets under inert and oxidative conditions in a fixed bed reactor.
Øyvind Skreiberg, Mette Bugge, Judit Sandquist, Fredrik Buvarp, Nils E. L. Haugen (2021). Chemical Engineering Transactions 86:67-72.

Validation of a numerical approach for simulation of the thermal decomposition behaviour of biomass in grate combustion plants.
Mette Bugge, Nils E. L. Haugen, Tian Li, Jingyuan Zhang, Øyvind Skreiberg (2021). Chemical Engineering Transactions 86:73-78.

Surrogate Reaction Mechanism for Waste Incineration and Pollutant Formation.
Corinna Netzer, Tian Li, Terese Løvås (2021). Energy & Fuels 35(9):7030-7049.

Stochastic Reactor-Based Fuel Bed Model for Grate Furnaces.
Corinna Netzer, Tian Li, Lars Seidel, Fabian Mauß, Terese Løvås (2020). Energy & Fuels 34(12):16599-16612.

Experimental and kinetic study on the transformation of coal nitrogen in the preheating stage of preheating-combustion coupling process.
Shuai Wang, Yanqing Niu, Tian Li, Denghui Wang, Shi'en Hui (2020). Fuel 275, 117924.

Grid-independent Eulerian-Lagrangian approaches for simulations of solid fuel particle combustion.
Jingyuan Zhang, Tian Li, Henrik Ström, Terese Løvås (2020). Chemical Engineering Journal 387, 123964.

Skeletal mechanisms for prediction of NOx emission in solid fuel combustion.
Tian Li, Øyvind Skreiberg, Terese Løvås, Peter Glarborg (2019). Fuel 254, 115569.

An evaluation of effects of fuel parameters and flue gas recirculation on NOx emissions through detailed chemical kinetics simulations.
Øyvind Skreiberg, Tian Li, Liang Wang, Mette Bugge, Terese Løvås (2019). Chemical Engineering Transactions 74:217-222.

Inertial particle impaction on a cylinder in turbulent cross-flow at modest Reynolds numbers.
Jørgen R. Aarnes, Nils E. L. Haugen, Helge I. Andersson (2019). International Journal of Multiphase Flow 111:53-61.

High-order overset grid method for detecting particle impaction on a cylinder in a cross flow.
Jørgen R. Aarnes, Nils E. L. Haugen, Helge I. Andersson (2019). International Journal of Computational Fluid Dynamics 33(1-2):43-58.

An evaluation of effects of operational parameters on NOx emissions through detailed chemical kinetics simulations.
Øyvind Skreiberg, Tian Li, Elettra Vantaggiato, Liang Wang, Mette Bugge, Terese Løvås (2019). Energy Procedia 158:103-110.

Treatment of solid objects in the Pencil Code using an immersed boundary method and overset grids.
Jørgen R. Aarnes, Tai Jin, Chaoli Mao, Nils E. L. Haugen, Kun Luo, Helge I. Andersson (2020). Geophysical & Astrophysical Fluid Dynamics 114(1-2):35-57.

Investigation on Ash Slagging Characteristics during Combustion of Biomass Pellets and Effect of Additives.
Liang Wang, Geir Skjevrak, Øyvind Skreiberg, Hongwei Wu, Henrik Kofoed Nielsen, Johan E. Hustad (2018). Energy & Fuels 32(4):4442-4452.

Numerical models for thermochemical degradation of thermally thick woody biomass, and their application in domestic wood heating appliances and grate furnaces.
Inge Haberle, Øyvind Skreiberg, Joanna Lazar, Nils Erland L. Haugen (2017). Progress in Energy and Combustion Science 63:204-252.

Conference publications/presentations

Numerical investigation on the release of chlorine and sulfur species from the fuel bed within a Waste-to-Energy plant.
Corinna Netzer, Maurice H. Waldner, Tian Li, Terese Løvås. 30. Deutscher Flammentag, 28-29 September 2021, Hannover, Germany, with paper included in proceedings.

A detailed experimental study on the thermal decomposition behaviour of wood pellets under inert and oxidative conditions in a fixed bed reactor.
Øyvind Skreiberg, Mette Bugge, Judit Sandquist, Fredrik Buvarp, Nils E. L. Haugen. ICheaP15, 23-26 May 2021, e-conference.

Validation of a numerical code for modelling of the thermal decomposition behaviour of biomass in grate combustion plants.
Mette Bugge, Nils E. L. Haugen, Tian Li, Jingyuan Zhang, Øyvind Skreiberg. ICheaP15, 23-26 May 2021, e-conference.

Modelling of grate fired woody biomass and waste to energy plants - Status and further needs.
Øyvind Skreiberg, Nils E. L. Haugen, Mette Bugge, Per Carlsson, Corinna Netzer, Tian Li, Terese Løvås (2021). 29th European Biomass Conference and Exhibition (EUBCE), 26-29 April 2021, e-conference.

Nitrogen Oxide Prediction within a Woody Biomass Fuel Bed Using Detailed Chemistry.
Corinna Netzer, Tian Li, Terese Løvås. 10th European Combustion Meeting, April 14-15, 2021, Virtual Meeting, with paper included in proceedings.

Numerical Analysis of Nitrogen Oxide Formation in Municipal Solid Waste Incineration.
Corinna Netzer, Tian Li, Terese Løvås (2021). 38th International Symposium on Combustion, 24-29 January 2021, Adelaide, Australia.

CFD-DEM modeling of biomass pyrolysis in a fixed bed reactor.
Boyao Wang, Jingyuan Zhang, Terese Løvås, Tian Li (2021). 38th International Symposium on Combustion, January 24-29, Adelaide, Australia.

A Reactor Network Approach for Grate Fired Plants using Detailed Chemistry.
Corinna Netzer, Tian Li, Terese Løvås, Lars Seidel, Fabian Mauß (2019). 29. Deutscher Flammentag, 17-18 September 2019, Bochum, Germany, with paper included in proceedings.

A two-grid formulation for simulation of fixed-bed biomass combustion.
Jingyuan Zhang, Tian Li, Henrik Ström, Terese Løvås (2019). Nordic Flame Days, 28-29 August 2019, Turku, Finland.

Reduced mechanisms for emission control in solid fuel combustion with SNCR.
Tian Li, Øyvind Skreiberg, Terese Løvås, Peter Glarborg (2019). 7th International Workshop on Model Reduction in Reactive Flow (IWMRRF), 18-21 June 2019, Trondheim, Norway.

An evaluation of effects of fuel parameters and flue gas recirculation on NOx emissions through detailed chemical kinetics simulations.
Øyvind Skreiberg, Tian Li, Liang Wang, Mette Bugge, Terese Løvås (2019). ICheaP14, 26-29 May 2019, Bologna, Italy.

A Reactor Network Approach for Grate Combustion Plants based on Detailed Chemistry.
Corinna Netzer, Tian Li, Terese Løvås, Lars Seidel, Fabian Mauß (2019). 17th International Conference on Numerical Combustion, 6-8 May 2019, Aachen, Germany.

Simulation of thermally thick wood particles combustion with an Eulerian–Lagrangian method.
Jingyuan Zhang, Tian Li, Henrik Ström, Terese Løvås (2019). 17th International Conference on Numerical Combustion, 6-8 May 2019, Aachen, Germany.

An evaluation of effects of operational parameters on NOx emissions through detailed chemical kinetics simulations.
Øyvind Skreiberg, Tian Li, Elettra Vantaggiato, Liang Wang, Mette Bugge, Terese Løvås (2018). 10th International Conference on Applied Energy, 22-25 August 2018, Hong Kong, China.

Simulating thermochemical conversion of thermally thick wood particles with an Eulerian-Lagrangian method.
Jingyuan Zhang, Tian Li, Terese Løvås (2018). 37th International Symposium on Combustion, 29 July - 3 August, Dublin, Ireland.

Effects of Fuel Additives on Quality of Agricultural Wastes Pellets.
Geir Skjevrak, Liang Wang, Tore Filbakk, Øyvind Skreiberg, Henrik Kofoed Nielsen, Johan E. Hustad (2018). 26th EUBCE, 14-17 May 2018, Copenhagen, Denmark.

Investigation on Ash Slagging Characteristics during Combustion of Biomass Pellets and Effect of Additives.
Liang Wang, Geir Skjevrak, Øyvind Skreiberg, Hongwei Wu, Henrik Kofoed Nielsen, Johan E. Hustad (2017). 6th Sino-Australian Symposium on Advanced Coal and Biomass Utilisation Technologies, 4-8 December 2017, Perth, Australia.

Student reports

Physics informed machine learning for multiphase flow.
Jingyuan Zhang (2021). Trial lecture.

Computational fluid dynamics (CFD) modeling for biomass and
waste to energy production.
Jingyuan Zhang. PhD thesis 2021:177, NTNU. Main supervisor: Terese Løvås, Co-supervisor: Tian Li

Development of a low-dissipation solver for large eddy simulation based on OpenFOAM.
Sondre Relling (2019). NTNU Master thesis. Main supervisor: Terese Løvås, Co-supervisor: Tian Li

Experimental development of combustion models.
Fredrik Buvarp (2018). SINTEF Summer Job
Project report. Main supervisor: Per Carlsson, Co-supervisors: Mette Bugge, Judit Sandquist

A thermogravimetric and kinetic study on devolatilization of biomass.
Nguyen Cong Thanh (2018). NTNU Master thesis. Main supervisor: Terese Løvås, Co-supervisor: Liang Wang

Reduced chemical model development for grate fired biomass application.
Elettra Vantaggiato (2018). NTNU Project thesis. Main supervisor: Terese Løvås, Co-supervisor: Tian Li

GrateCFD in the media

Circular economy and value chain thinking - The future of Waste-to-Energy.
Øyvind Skreiberg, Michael Becidan (2020). EERA Bioenergy News 13:8-9.

Computational Fluid Dynamics for improving large-scale woody biomass and Municipal Solid Waste combustion units.
Øyvind Skreiberg (2020). IEA Bioenergy Task 36 June 2020 newsletter.

Computational Fluid Dynamics for improving micro- to large-scale woody biomass and municipal solid waste combustion units.
Øyvind Skreiberg (2017). EERA Bioenergy News 2017 (7), p. 5.

Modellering og numeriske simuleringer for økt bærekraft (in Norwegian).
Øyvind Skreiberg (2017). SINTEF blog article.

Publications in progress

Computationally efficient coarse-graining XDEM/CFD modeling of fixed-bed combustion of biomass.
Jingyuan Zhang, Tian Li, Henrik Ström, Terese Løvås. Submitted to an international journal.

A novel coupling method for unresolved CFD-DEM modeling.
Jingyuan Zhang, Boyao Wang, Tian Li, Henrik Ström, Terese Løvås. Submitted to an international journal.

A bed model for grate fired furnaces: theory and comparison with experiments.
Nils E.L. Haugen, Mette Bugge, Alexander Mack, Tian Li, Øyvind Skreiberg. To be submitted to an international journal.

Numerical Analysis of Nitrogen-Oxide Formation in WtE Plants using Detailed Chemistry Part 1: Fuel Conversion in the Waste Bed.
Corinna Netzer, Tian Li, Terese Løvås. To be submitted to an international journal.

Numerical Analysis of Nitrogen-Oxide Formation in WtE Plants using Detailed Chemistry Part 2: Emissions in the Freeboard.
Corinna Netzer, Michal T. Lewandowski, Tian Li, Terese Løvås. To be submitted to an international journal.

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Research partners:
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Contact: Øyvind Skreiberg • Oyvind.Skreiberg@sintef.no
SINTEF Energi AS (SINTEF Energy Research) Trondheim, Norway • www.sintef.no/energy

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