Improved Biomass Firing with New Grate System and Vision Sensor with Control

EUDP Project no. 64012-0142

Project manager:	FORCE Technology
Project partners:	Euro Therm A/S Burmeister & Wain Scandinavian Contractor A/S (BWSC has taken over the activities after bankruptcy of BWE)

1. Project details

Project title	Improved Biomass Firing with New Grate System and Vision Sensor with Control
Project identification (program abbrev. and file)	Project no. 64012-0142
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	FORCE Technology, Park Allé 345, 2605 Brøndby, Denmark
Project partners	Euro Therm A/S Burmeister & Wain Scandinavian Contractor A/S (BWSC has taken over the activities after bankruptcy of BWE)
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Table of Contents

2. Short description of project objective and results

2.1 Short description of the project objectives and results in English

The aim of the project was to develop reliable and efficient combustion systems based on integration of an advanced vision-based sensor and extended grate controllability with an adequate intelligent control scheme for optimisation of operating parameters and ensure complete burnout of biomass fuels with lower quality and greater variations in the fuel properties.

A basic premise for development and test of a control scheme is that the camera can provide a "good picture" in an acceptable period for the online picture analyses and that the vision system is able of tracking the start of the combustion zone as an early signal to the control scheme.

Therefore, the basic objective of the project has been to adapt and further develop the vision system developed for waste-to-energy boilers to biomass fired boilers.

The project aims at developing a flexible biomass grate that allows optimum combustion and contributes to low emissions.

Through installations and trials at three different biomass boilers (two district heating and one combined heat and power) - firing three different biomass fuels, the project has developed a compact and robust vision system (GrateVision®) that can be installed at any biomass and grate fired plant. The original purge air system from waste-to-energy plants could not be applied and a new system was designed and tested at the straw fired boiler.

Having the right field of view the vision system can track both the start and the end of the combustion zone and transmit the digital signals to the SCADA system of the boiler.

The development of a control scheme was not possible or feasible at the two wood fired boilers and development of a scheme for the straw fired CHP plant was excluded as BWE went bankruptcy.

Euro Therm has developed and successfully tested the first version of the improved grate and continues working on how the obtained experiences together with results from CFD calculations (separate project) and the GrateVision® picture analyses can form the basis of an improved biomass combustion.

2.2 Kort beskrivelse af projektets formål og resultater på dansk (short description of the project objectives and results in Danish)

Projektets formål var at udvikle driftssikre og effektive fyringssystemer baseret på integration af en avanceret vision-baseret sensor og en rist med udvidede reguleringsmuligheder med et tilpas intelligent reguleringskoncept til at optimere driftsparametre og sikre fuldstændig udbrænding af biomasse brændsler af lavere kvalitet og med større variationer i brændselsegenskaberne.

En grundlæggende forudsætning for udvikling og afprøvning af et reguleringskoncept, som kan optimere procesparametrene og forbedre styringen, er, at kameraet kan give et "godt billede" i et acceptabelt tidsrum, så billedanalysen og visionssystemet er i stand til at identificere og følge starten af forbrændingszonen, som er det tidligste og bedste signal for et reguleringssystem.

Projektets primære formål har derfor været at tilpasse og videreudvikle visionssystemet udviklet til affaldsenergianlæg til biomassefyrede kedler.

Målsætningen er desuden at udvikle en forbedret rist, som kan medvirke til optimal forbrænding og bidrage til lavere emissioner.

Projektet har igennem installationer og forsøg på tre forskellige kedler (to fjernvarme- og en CHP-kedel), som fyrer med forskellige biobrændsler, udviklet et kompakt og robust visions-system (GrateVision®), som kan installeres på alle ristefyrede biomassekedler. Det originale spulesystem udviklet til affaldsenergianlæg kunne ikke overføres til biomassefyrede anlæg, og et nyt system blev designet og afprøvet på det halmfyrede anlæg.

Med det rette synsfelt kan visionssystemet identificere og følge både starten og slutningen af forbrændingszonen – og sende de digitale signaler til kedlens SRO-anlæg.

Udviklingen af et reguleringskoncept var ikke mulig eller gennemførlig på de to træbrænd-selsfyrede kedler, og udviklingen af et koncept på den halmfyrede CHP-kedel blev umulig-gjort med BWE's konkurs og efterfølgende afbrydelse af denne del af projektet.

Euro Therm har udviklet og med succes installeret og afprøvet den første udgave af en for-bedret rist og fortsætter arbejdet med at samle erfaringer fra CFD-beregninger (uden for dette projekt) og fra videoer fra GrateVision® systemets billedanalyse til den videre udvikling af risten.

3. Executive summary

The aim of the project was to develop reliable and efficient combustion systems based on integration of an advanced vision-based sensor and extended grate controllability ensuring complete burnout of biomass fuels with lower quality and greater variations in the fuel properties. Euro Therm wants to improve their stepped grate by using new compositions of the alloys and new design of the grate slats of the grate giving better air distribution.
FORCE Technologys GrateVision® system for Waste-to-Energy boilers was the start of the adaption and development of a vision system for biomass and grate fired boilers.

Preliminary investigations concluded the position of the start of the combustion zone is the best/earliest input for the combustion control system. It is important that the vision system can recognise and track this phenomenon. To achieve a robust and fast picture analysis the camera(s) must see the entire combustion zone, the field of view must be free and the uptime of the entire system must be high.

At Hinnerup Fjernvarme the camera housing hardware was adapted and further developed to the wood fuel and the dimensions of the boiler, but it did not function satisfactorily for the cameras in the side wall of the boiler. The purge system functioned well for the camera at the end of the boiler. The GrateVision® software was further developed and optimised using video recordings from different operational situations and boiler loads. The GrateVision® software easily identified the end of the combustion zone – but not the start. The cameras in the side walls could not see the start of the combustion zone and the end of the zone was difficult to track because of flames.

Based on the picture analyses of the combustion on the grate at Hinnerup Fjernvarme, Euro Therm has developed a new design of the slats of their grate. The trials at another DH plant have shown that by placing these slats in the middle of the grate a good distribution of the fuel was obtained whereby the wear on the slat became less.
Because the system could not track the start of the combustion zone – and because the improved grate was not installed at Hinnerup Fjernvarme, we decided not to start the development of a control scheme there.

The project manufactured one camera housing fitting the existing guide tubes in the wall of the wood pellets fired boiler at Halsnæs Forsyning. The combustion of wood pellets is very clean which is an advantage when the task is to identify the start of the combustion zone. An improved purge air system and camera housing were designed and mounted in the middle guide tube covering almost the entire grate.
The GrateVision® software developed during the trials at Hinnerup was used with small modifications. The software easily identified both the start and the end of the combustion zone in different operational loads/situations.
The purge system was not working properly and could not keep the camera lens clean for more than 12 hours. Because of the too short uptime, it was not realistic to connect the system to the SCADA system and start the development of a control scheme.

The implementation of the vision system at the straw fired Maribo-Sakskøbing CHP plant (MSK) became delayed because the installation should be during the annual planned downtime and because of illness and busyness at BWE. A compact vision camera system including an automatic extraction system and an improved purge air system were installed at MSK.
The camera hardware and online picture analysis operated successfully, but due to sticky ash particles the peephole of the camera was covered within few hours. BWE decided to reprogramme the boiler cleaning system at MSK to cover the area of the camera. We managed to record some hours of video of the very narrow combustion zone. The vision software easily identified and kept track of the end of the combustion zone.

After months of inactivity due to busyness and illness at BWE, we decided that the vision system should be moved to the new straw fired BWE plant at Lisbjerg (Århus) and the rest of the project work finished there. When the Lisbjerg plant was ready for moving and installation of the vision system, BWE went bankruptcy and the project branch was closed.

Missing a long-term test, the project did not have the possibility to develop a control scheme using the input signal from the vision system.

The vision of FORCE Technology is to offer the vision system as an advanced sensor in consultancy assignments. FORCE Technology has produced marketing material for marketing staff introducing this service together with our other services aimed at biomass fired boilers.

The system is installed at Halsnæs Forsyning as a part of project including trials with co-firing of wood chips and garden/park waste.

Euro Therm continues working on how the obtained experiences together with results from CFD calculations (separate project) and the GrateVision® picture analyses can form the basis for an improved biomass combustion.

BWSC has not shown interest in utilising the results from the project.

4. Project objectives

The objectives of the project were

1) To investigate, develop and adjust a waste combustion sensor to fit biomass firing.
2) To develop a flexible biomass grate that allows optimum combustion and contributes to low emissions. The grate should be designed with the aim of achieving a simple and optimised grate regarding manufacturing, with lower costs for service and maintenance. Furthermore, the grate shall be designed with extended control properties, to be able to eliminate the variations in the fuel properties and the lower quality of the biomass.
3) To develop a control scheme for optimisation of operating parameters and enhanced control of straw and wood chip co-combustion.
4) Installation, initialisation and demonstration at four heat and CHP plants of varying sizes. The vision sensor should first be installed at two plants for short term tests and after adjustments, installed at two plants for long-term test.
5) Preparation of guidelines for market introduction and quantification of benefits of the technology including a vision for marketing and material for marketing staff will be made.

The project activities were conducted in two branches:

a) Activities aimed at medium-sized wood chip and wood pellets district heating plants (Euro Therm and FORCE Technology)
b) Activities aimed at large straw fired CHP plants (BWE and FORCE Technology)

A basic premise for development and test of a control scheme for optimisation of operating parameters and enhanced control is that the camera can provide a "good picture" in an acceptable period for the online picture analyses. This includes the right location and field of view of the camera, a functioning camera cooling and purge air system and in some cases a functioning boiler wall cleaning system. If the hardware of the GrateVision® system developed for large waste-to-energy plants cannot be adapted and developed to the wood or straw fuels and boilers the system cannot provide a "good picture" and reliable input signals for development of a control scheme. Another basic premise is that the vision system is able of tracking the start of the combustion zone as an early signal to the control scheme.

4.1 Implementation, activities for biomass fired DH plants

4.1.1 Preliminary investigations

To get the best/fastest combustion control, it is important that the system can recognise the start of the combustion zone because this phenomenon is the first visible impact from variations in the fuel composition (moisture content).
Prior to this project, the GrateVision® software was able of tracking the end of the combustion zone - but not the start. Previous tests have shown that the start of the combustion zone could not be tracked from a camera looking from the end of the grate and that the preferable position would be in a side wall well above the grate.
Getting a "good picture" is crucial for the picture analyses and requires that basic but not trivial conditions are fulfilled: The camera(s) must see the entire combustion zone, the peephole of the camera must be kept free of ash/slag, the lens of the camera must be kept clean, the uptime of the entire system must be high - and the picture analysis algorithms must be robust and fast.

Therefore, from the beginning, the focus of the project was to further develop and optimise the camera housing hardware to get the "good picture" of the entire combustion zone and to adapt the system developed for waste-to-energy plants to straw and wood chip/pellets boilers. Having the "good picture", the GrateVision® software must be adapted to a camera position in the side wall and the algorithms for pre-processing, elimination of optical distortion from the fish-eye lens and the perspective and tracking both the start and end of the combustion zone must be optimised.

4.1.2 Activities at Hinnerup Fjernvarme

At Hinnerup Fjernvarme the camera housing hardware has been adapted and further developed to the wood fuel and the dimensions of the boiler, but it did not function satisfactorily for the cameras in the side wall of the boiler. The purge system functioned well for the camera at the end of the boiler. The GrateVision® software was further developed and optimised using video recordings from different operational situations and boiler loads. Among other things, the algorithms for detection and tracking of the combustion zone were redesigned to be more robust, i.e. independent of the shape and splitting of the combustion zone.

Using videos from the camera at the end of the boiler, the GrateVision® software easily identified the end of the combustion zone – but not the start.

The view of the two cameras in the walls of the boiler was not as estimated because of the height of the fuel layer. The cameras could not see the start of the combustion zone and the end of the zone was difficult to track because of flames along the walls and from the combustion zone itself. Even the improved GrateVision® analysis could not detect and track neither the end nor the start of the combustion zone.

Because of the system could not track the start of the combustion zone and because the improved grate was not installed at Hinnerup Fjernvarme, we decided not to start the development of a control scheme there.

Based on the picture analyses of the combustion on the grate at Hinnerup Fjernvarme, Euro Therm has developed a new design of the slats of their grate. The trials at another DH plant have shown that by placing these slats in the middle of the grate, a good distribution of the fuel was obtained whereby the wear on the slat became less. Euro Therm continues working on how the obtained experiences together with results from CFD calculations (separate project) and the GrateVision® picture analyses can form the basis for an improved biomass combustion.

4.1.3 Activities at Halsnæs Forsyning

Based on the experiences from the installation and trials at Hinnerup Fjernvarme, we decided to test the GrateVision® system at a wood pellet fired boiler. The combustion of wood pellets is very clean which is an advantage when the task is to identify the start of the combustion zone. This project manufactured one camera housing fitting the three existing guide tubes. An improved purge air system ("shower head") and camera housing were designed and mounted in the middle guide tube covering almost the entire grate.

The GrateVision® software developed during the trials at Hinnerup was used with small modifications. The software easily identified both the start and the end of the combustion zone in different operational loads/situations. This was the first time during many years of development that the software managed to identify the start of the combustion zone.

The "shower head" was not working properly and could not keep the camera lens clean for more than 12 hours.

Because of the too short uptime of the vision system and the travelling grate, we decided not to connect the system to the SCADA system and start the development of a control scheme.

4.2 Implementation, activities for straw fired CHP plants

During the first years, the implementation of the vision system at MSK became delayed partly because the installation of the camera should be done during the annual planned downtime of MSK and partly because of illness and busyness at BWE. Later the activities in this project branch were stopped due to the bankruptcy of BWE. BWSC taking over BWE did not present a plan covering their activities in the rest of the project and FORCE Technology and EUDP decided to stop this project branch.

Before the project branch was stopped a compact vision camera system including an automatic extraction system and an improved camera purge system were installed at MSK straw fired CHP plant. The camera, purge and cooling air systems, the extraction system and online picture analysis operated successfully but due to sticky ash particles the peephole of the camera was covered. Based on experiences of FORCE Technology, BWE decided to reprogramme the boiler cleaning system at MSK to cover the area of the camera.
Missing a cleaning system at MSK, the camera had a good view only for few hours before the peephole was covered – and a manual cleaning was required. We managed to record some hours of video of the very narrow combustion zone on the vibrating grate. The vision software analysing the videos easily identified and kept track of the end of the combustion zone.

After months of inactivity due to busyness and illness at BWE, we decided to move the vision system to the new straw fired BWE plant at Lisbjerg (Århus) and that the cleaning system for the boiler walls should be programmed based on the experiences at MSK.

When the Lisbjerg plant was ready for moving and installation of the vision system, BWE went bankruptcy and the project branch was closed later as described above.

Missing a long-term test, the project did not have the possibility to develop a control scheme using the input signal from the vision system.

4.2.1 Marketing plan

The vision of FORCE Technology is to offer the vision system as an advanced sensor in consultancy assignments i.e. trouble shooting, balancing of boilers with new fuels, balancing of new boilers, etc. Several plant owners have shown interest in this service and Halsnæs Forsyning has requested that the test system installed at their Weiss boiler is upgraded and restarted as a part of co-firing wood chips with a new cheaper fuel – park & garden waste.

FORCE Technology has produced marketing material for marketing staff introducing this service together with our other services aimed at biomass fired boilers.

5. Project results and dissemination of results

5.1 Preliminary investigations

5.1.1 The "good picture"

To get the best/fastest combustion control, it is important that the system can recognise the start of the combustion zone. The position of the start of the combustion zone is an "early" signal because the first visible impact of variations in the fuel composition (moisture content) is the position of the ignition of the fuel. This type of changes will impact the position of the end of the combustion zone several minutes later (~15-30 min.). An early signal gives a control system the possibility to react earlier and faster.
Prior to this project the GrateVision® software was able of tracking the end of the combustion zone - but not the start. Previous tests have shown that the start of the combustion zone could not be tracked from a camera looking from the end of the grate (because of the flames from the combustion zone) and that the preferable position would be in a side wall well above the grate.
Getting a "good picture" is crucial for the picture analyses and requires that basic but not trivial conditions are fulfilled: The camera(s) must see the entire combustion zone, the peep-hole of the camera must be kept free of ash/slag, the lens of the camera must be kept clean, the uptime of the entire system must be high - and the picture analysis algorithms must be robust and fast.

All previous GrateVision® systems have used a NIR camera (Near InfraRed). It was decided that the test installation at Halsnæs Forsyning should test if more information could be retrieved using a cheaper RGB camera (Red Green Blue colour camera).

Therefore, from the beginning, the focus of the project was to further develop and optimise the camera housing hardware to get the "good picture" of the entire combustion zone and to adapt the system developed for waste-to-energy plants to straw and wood chip/pellets boilers. Having the "good picture" the GrateVision® software must be adapted to a RGB camera position in the side wall and the algorithms for pre-processing, elimination of optical distortion from the fish-eye lens and the perspective and tracking both the start and end of the combustion zone must be optimised.

5.1.2 Optimisation of the grate

It is important that the grate of the boiler can distribute the primary air properly to the combustion.
BWE is marketing a proven vibrating grate with holes of different sizes and significant pressure drop distributing the primary air well to the combustion zones. The Maribo-Sakskøbing plant has this grate installed.
The Euro Therm stepped grate for wood chips must be optimised regarding manufacturing, reliability and lower costs for service/maintenance. Furthermore, the improved design of the grate must enable good air distribution and proper handling of low quality fuels. The improved design of the grate requires detailed information about the performance of the existing grate – information which only the GrateVision® system can supply. Therefore, the development of the new grate design must follow the installation and trials with the vision system at Hinnerup Fjernvarme.

5.1.3 Control concepts

In the PSO project "Online optimising of waste fired boilers" FORCE Technology has tested an advanced control concept based on input signals from GrateVision®. The output of the control concept was changes in the grate speed and primary air flow to each of the four combustion zones.

5.1.3.1 Wood chip fired district heat boiler

The Euro Therm district heat boilers have manual dampers distributing the primary (and secondary) combustion air to furnaces. Automation of these dampers is not economic. The grate speed is the same for the entire grate. Therefore, the output from a control concept must be changes in the grate speed and the total flow of combustion air. The input for the control concept is the position of the start of the combustion zone. The control concept will probably be simpler than the advanced concept developed for waste fired boilers.

5.1.3.2 BWE straw fired CHP boiler

In the design of the BWE straw fired CHP boiler the grate has one zone only. Therefore, the output from a control concept must be changes in the vibration cycle and the total flow of primary air. The input for the control concept is the position of the start of the combustion zone. The control concept will probably be simpler than the advanced concept developed for waste fired boilers.

5.2 Project results – Euro Therm branch

5.2.1 System for wood chip fired plant at Hinnerup Fj.v.v.

5.2.1.1 Location selection

The wood chip fired district heat boiler (5 MW) at Hinnerup Fjernvarmeværk supplied by Euro Therm A/S was chosen because it has the type of grate that Euro Therm must optimise. Hinnerup Fjernvarmeværk was interested in the project and the results of the trials and therefore willing to do the boiler work for the installation of the cameras. More over Hinnerup Fjernvarme is close to the address of Euro Therm in Tranbjerg making it easy for the employees to follow the trials.

The dimensions of the freeboard above the grate prevent one camera to see both sides of the grate (Figure 1). Therefore, we decided to install one guide tube in each side of the boiler. The position of the start of the combustion zone was unknown by operational staff of the boiler. Experiences from previous trials show that the position of the camera should be in the first half of the grate, but not too close to the start of the grate because of the risk of soot formation from the sub-stoichiometric combustion processes, in order to be able to see the start of the combustion zone. A position to the right of the bearing pillars in the boiler (Figure 3) was chosen because the cameras would cover almost the entire grate (Figure 3 and Figure 2). In addition, one guide tube was installed at the end of the grate for a camera covering the entire grate (Figure 4).

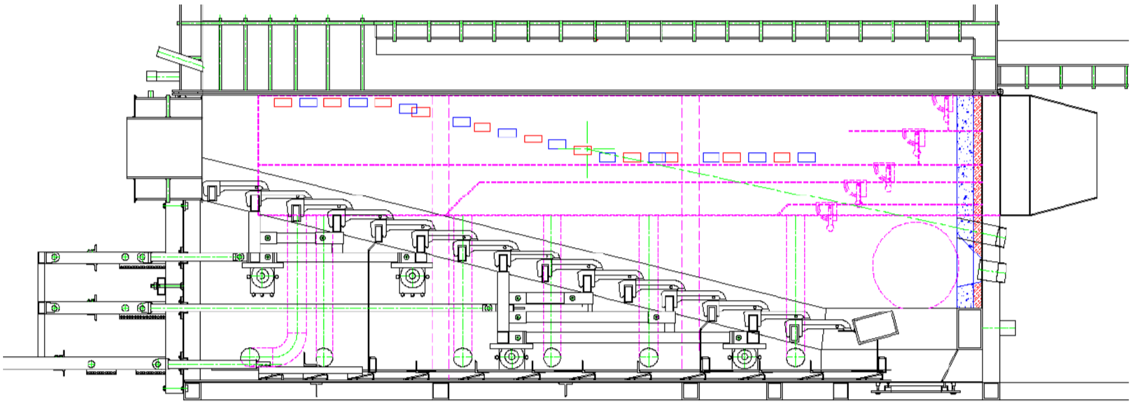

Figure 1. Drawing of furnace of Hinnerup Fjernvarmeværk wood chip fired district heat boiler (5 MW).

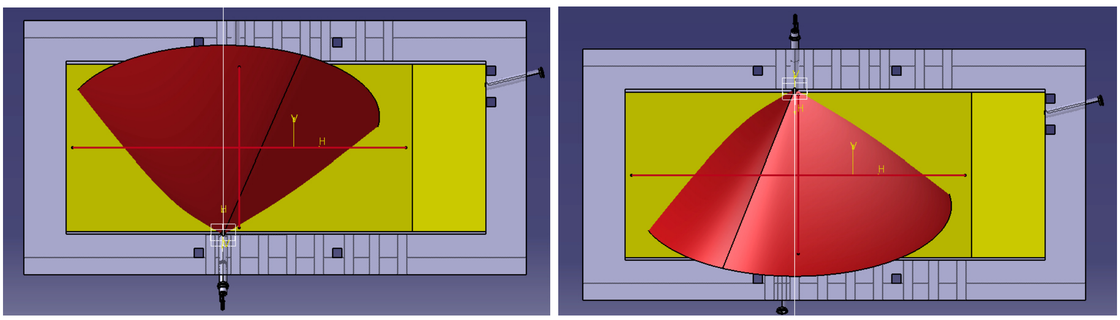

Figure 2. Drawing showing the line and field of view of the left and right cameras (red cone 100°). The effective view angle of the camera is 75-80°. The grate is illustrated with a dark yellow colour.

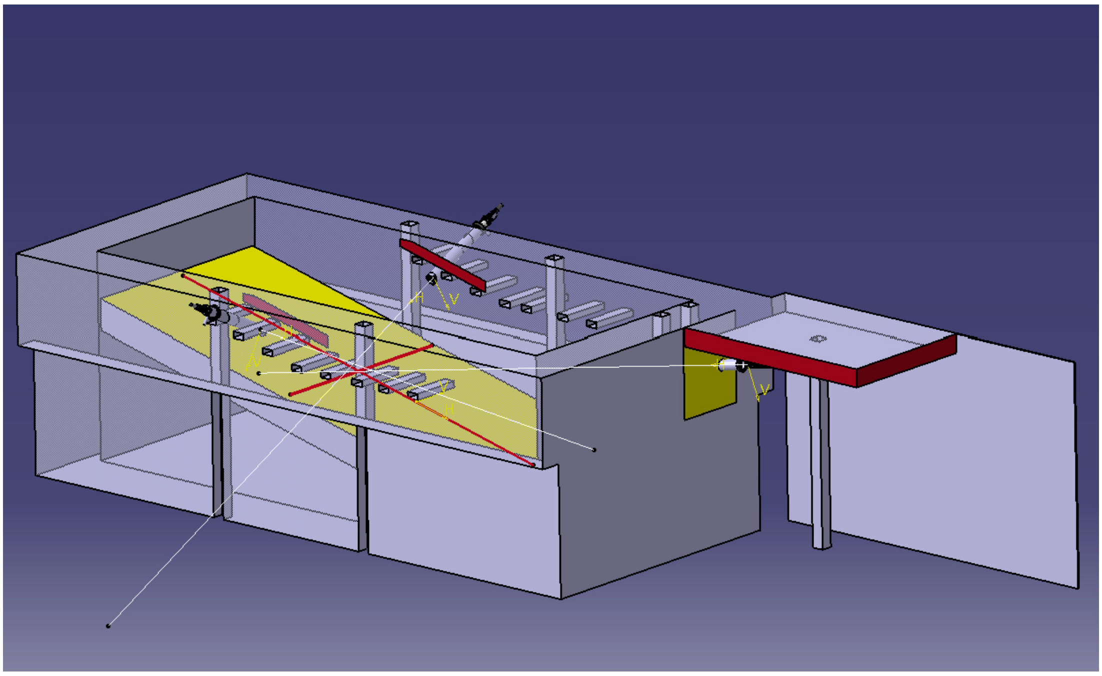

Figure 3. Drawing showing the lines of view of the three cameras placed in the furnace of Hinnerup Fjernvarmeværk. The grate is illustrated with yellow colour.

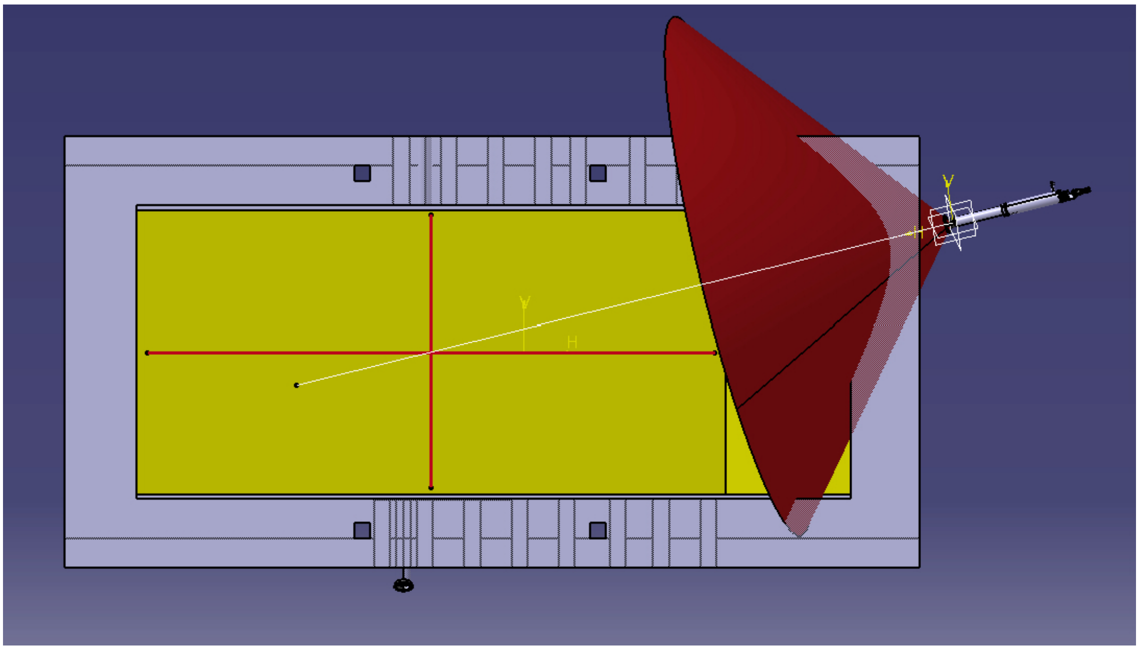

Figure 4. Drawing showing the line and field of view of the camera at the end of the grate (red cone 100°). The grate is illustrated with a dark yellow colour.

5.2.1.2 System design, manufacturing and mounting at Hinnerup Fjernvarme

Previous experiences from camera installations at Reno Nord (Waste-to-Energy) were that a "shower head" with cooling and purge air cold prevents ash particles and dust from sticking to the camera lens. A camera housing was designed and two pieces were manufactured to fit all the three guide tubes (Figure 5).

Figure 5. Left: Drawing of camera housing placed in guide tube in boiler wall.
Right: Picture of camera housing.

During a planned stop for maintenance in September 2014, the three guide tubes were installed. The GrateVision® system was installed 2015-01-07 with a NIR camera at the right side and a RGB camera at the end of the boiler (Figure 6).

Figure 6. Left: NIR camera installed in the right side of the Hinnerup boiler.
Right: RGB camera installed at the end of the boiler.

The control box was in the room behind the boiler (Figure 6, right) and connected with the FORCE PC in the control room of Hinnerup Fjernvarme by an ethernet cable installed by this project. The PC could be controlled from FORCE Technology through the internet. The functions of the control/interface box were:

- Supply of clean compressed cooling and purge air for the cameras
- Supply of 5.5 VDC for the cameras
- Transmittion of video streams from cameras to the FORCE PC in the control room at Hinnerup Fjernvarme.

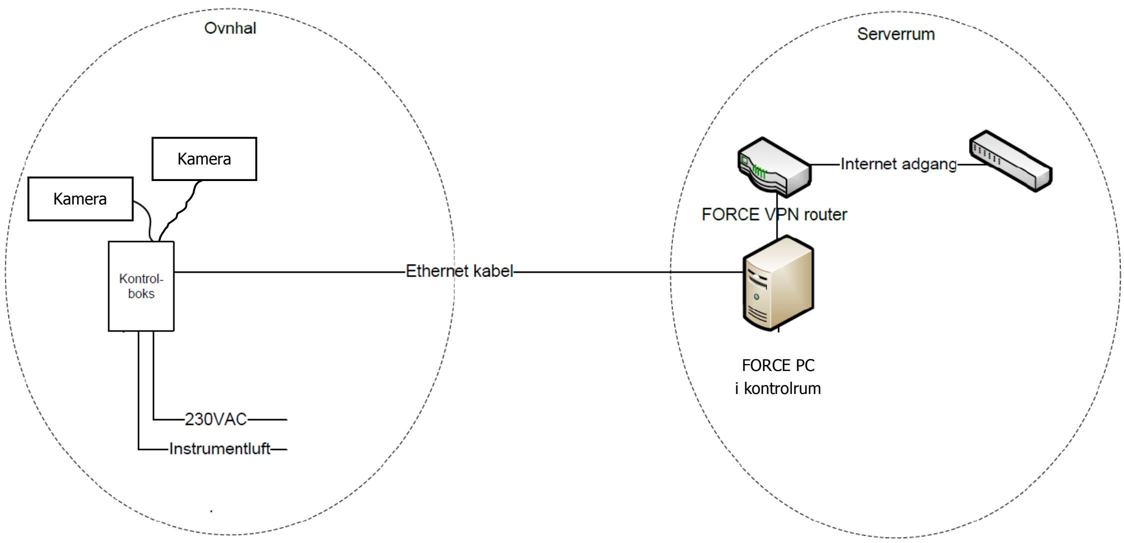

Figure 7. Architecture of the camera control and transmission system including control/interface box, ethernet cable, PC, routers, etc.

Figure 8. GrateVision® user interface on FORCE Technology PC in the control room.
The B/W GrateVision window is using NIR camera in the right boiler wall.
The colour picture is livestream from RGB camera at the end of the boiler.

5.2.1.3 Online video analysis software

The GrateVision® online video analysis software implemented was based on the system previously developed by FORCE Technology. The software was adapted to the RGB camera and the new locations of the cameras in the side wall. The algorithms for aperture control, pre-processing, elimination of optical distortion from the fish-eye lens and the perspective were optimised. The algorithms for detecting and following the start and end of the combustion zone were redesigned to be robust and quicker.

The system was not connected to the SCADA system of the boiler. If connected, the GrateVision® software can transmit the position of the start, the end, the area and light intensity of the combustion zone and other information retrieved by the video analysis to the SCADA system of the boiler. Also, the GrateVision® software can automatically import relevant process parameters (i.e. O_2 concentration, etc.) from a SCADA system and show them in graphs together with the parameters from the vision analysis. Figure 13 shows the user interface of the GrateVision® system.

5.2.1.4 Long-term trials at Hinnerup Fjernvarme

The trials started 2015-01-07 and continued with major interruptions until 2016-02-01. The purposes of the trials were to:

- Test the new purge system ("shower head")
- Test if the GrateVision® software could retrieve more information from videos from a RGB camera
- Provide videos at different operational situations for optimisation and further development of the GrateVision® software.

Test of purge system

The air for the new purge system ("shower head") was supplied by a high-pressure blower rented for the trials. At full load the temperature of the air supplied was too high (~50 °C) for the camera and the amount of air supplied was lowered giving an adequate air flow and camera temperature.

On the camera at the end of the boiler, the temperature was suitably low probably because the distance to the combustion area was several meters. The purge system and the cameras installed at the end of the boiler worked satisfactorily during the entire long-term trial (Figure 9, right).

On the cameras sitting in the side of the boiler, the temperature at the front of the lens and the "shower head" itself was still too high probably because of the short distance (< 1 m) to the flames and the burning fuel layer. The temperature of the "shower head" on the cameras at the side wall of the boiler was so high that the borescope was damaged and the trials were stopped until a solution was found. We decided to develop and manufacture a ceramic dummy instead of the "shower head" (Figure 10, left).

Figure 9. Left: Camera front with "shower head" from position in the right side of the boiler after few days of operation.
Right: Camera front with "shower head" from position at the end of the boiler after weeks of operation.

After one month of operation with the ceramic dummy, the temperature at the front of the camera increased rapidly and the camera was taken out. The ceramic dummy was broken probably because of thermal stress (Figure 10, right).

Figure 10. Left: Special designed ceramic dummy installed instead of "shower head" of the side wall camera.
Right: Damaged ceramic dummy.

NIR vs. RGB camera
Comparison between the information about the combustion from an RGB camera and a NIR camera showed that nearly all information was gathered in the signal of the red colour of the RGB camera. The conclusion was that the cheaper RGB camera gives a better picture for the human eye, but not more information for the picture analysis than the NIR camera. The NIR camera has a sensitivity below visible light giving a better look through flames. Figure 19 shows snapshots from videos of NIR and RGB camera.

Videos for optimisation of algorithms
Several months with different operational situations and boiler loads (including stopping) were recorded during the long-term test period.

Figure 11. Simultaneous snapshots of video streams from cameras in side walls.
Left: NIR camera in right side. Fuel travels from left to right.
Right: RGB camera in the left side. Fuel travels from right to left.

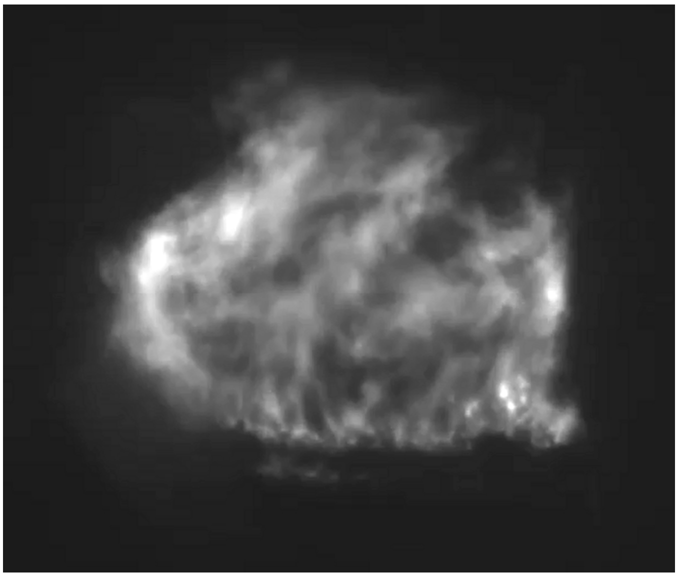

Figure 12. Snapshot of video stream from NIR camera at the end of the boiler.
The fuel travels from top to bottom.

5.2.1.5 Technical results from GrateVision® installation at Hinnerup Fjervarme

The purge system for the cameras did not function satisfactorily for the cameras in the side wall of the boiler. The temperature at the front of the camera was too high probably because of the short distance to the fire. A ceramic dummy insulating the camera lance from the radiation from the flames survived for one month before it broke down. The purge system functioned well for the camera at the end of the boiler.

The air from the "shower head" interfered with combustion because of the short distance to the fuel layer. The interference was identified as a light spot on the surface of the bed in the line of view. The interference was significant at low load only.

The GrateVision® software was further developed and optimised using video recordings from different operational situations and boiler loads. The algorithms for pre-processing, elimination of optical distortion from the fish-eye lens and the perspective were adapted to the position of the camera – and optimised. The algorithms for aperture control, detection and tracking of the combustion zone were redesigned to be more robust, i.e. independent of the shape and splitting of the combustion zone.

Using videos from the camera at the end of the boiler, the GrateVision® software easily identified the end of the combustion zone (Figure 13).

The view of the two cameras in the walls of the boiler was not as estimated. The cameras could not see the start of the combustion zone and the end of the zone was difficult to track because of flames along the walls and from the combustion zone itself. Even the improved GrateVision® analysis could not detect and track the end of the combustion zone.

A RGB camera provides a better picture for the human eye, but not more information for the pictures analysis than the NIR camera. The NIR camera is more expensive but has a sensitivity below visible light giving a better look through flames. More investigations must be done before it can be concluded which camera is the better.

At this stage of the project the practical/mechanical issues e.g. to keep the temperature of the camera lens low and the field of view clear were still the most challenging. The location and field of view of the camera(s) have great significances for the possibility of getting a "good picture".

Missing the tracking of the start of the combustion zone, the development of a control scheme was not possible or feasible at the Hinnerup Boiler.

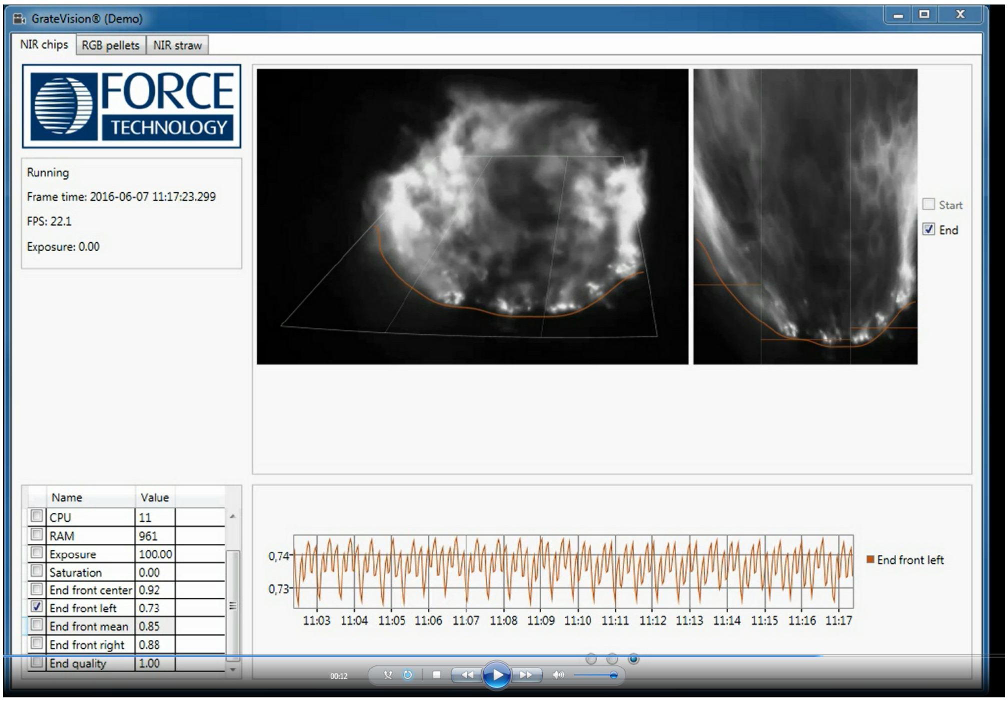

Figure 13. GrateVision® snapshot with video stream from NIR camera at the end of the boiler.
Left picture: Raw video stream from camera with graphical overlay showing grate dimensions (white lines) and the identified end of the combustion (orange curve). Fuel travels from top to bottom.
Right picture: Processed video stream corrected for optical distortion from fish-eye lens and perspective. Fuel travels from top to bottom. Orange curve is the identified end of the combustion zone.
Bottom graph: Average position of the end of the combustion zone (orange line in in central part of grate, right picture). Note the periodic behaviour originating from the movements of the grate.

5.2.2 *Design of new grate (Euro Therm A/S)*

After seeing the GrateVision® pictures analyses of the combustion on the grate of the boiler at Hinnerup Fjernvarme, Euro Therm focused on development of the grate slats. Both the composition of the alloys and design of the grate slats were in focus. Particularly a potential was seen for a better air distribution by changing the design of the slats on the sides of the grate. It was expected that an optimised air distribution could result in a better combustion control and hence a better utilisation of the grate area and lower emissions. The development of new side slats took place on two fronts. Partly in close cooperation with the subcontractor of Euro Therm having expert knowledge within castings, material specifications, etc. and partly through numerous trials at different customers boilers where Euro Therm had "modified" the existing slats. In the development, Euro Therm aimed at a new slat meeting our requirements for durability, handling (weight) and the cost of manufacturing.

5.2.3 *Test of new grate*

During 2017 slats with different alloys of the castings were installed in several boilers owned by customers of Euro Therm. The preliminary results observed during inspection in Q2 2018 show that a better durability is obtained.

At Ebeltoft Fjernvarme, a type of slat creating a greater air flow through the grate was tested. The Euro Therm standard got a 1 mm "buffer" welded on each side (Figure 14) providing a ~2 mm gap between the slats.

The trials showed that by placing these slats in the middle of the grate, a good distribution of the fuel was obtained whereby the wear on the slat became less. The disadvantage was that more particles fell through the grate gabs.

Euro Therm continues working on how the obtained experiences together with results from CFD calculations (separate project) and the GrateVision® picture analyses can form the basis for an improved biomass combustion.

Figure 14. Prototype of slat providing a greater air flow through the grate.

5.2.4 System for wood pellet fired plant at Halsnæs Forsyning

5.2.4.1 Location selection

Based on the experiences from the installation and trials at Hinnerup Fjernvarme not providing the desired tracking of the end of the combustion zone, we decided to test the GrateVision® system at a wood pellet fired boiler. The combustion of wood pellets is very clean which is an advantage when the task is to identify the start of the combustion zone. The wood pellets fired district heat boiler (10 MW) supplied by Euro Therm to Halsnæs Forsyning A/S in Frederiksværk was constructed with three guide tubes for GrateVision® cameras. This project took advantage of this opportunity and manufactured one camera housing that could be used in all three guide tubes. Figure 15 shows the field of view of a camera located in the middle guide tube. Depending on the actual – and at the time of construction - unknown position of the combustion zone, the camera can be installed in the appropriate guide tube.

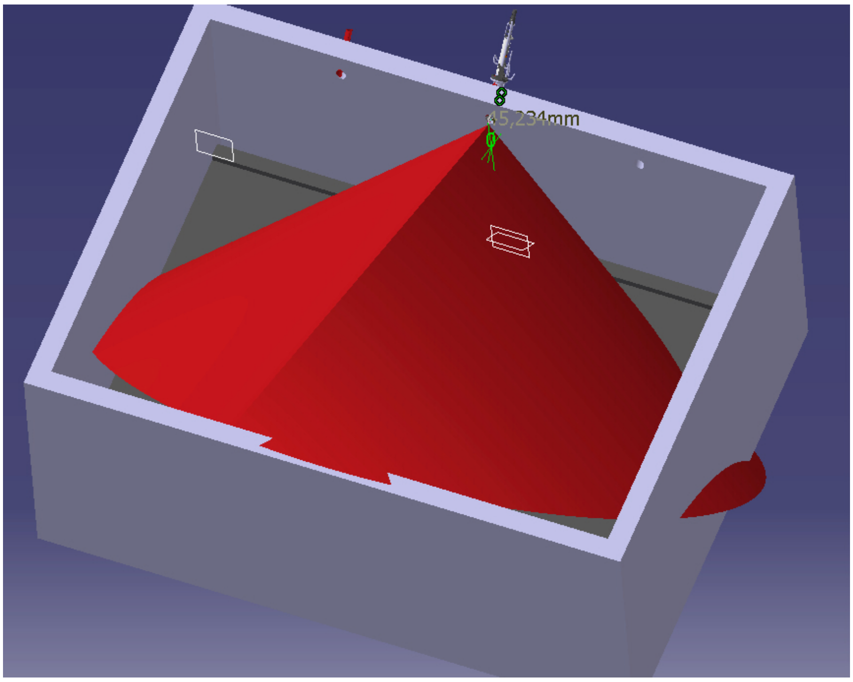

Figure 15. Drawing of field of view (red cone, 100°) of camera located in the middle of the three guide tubes. The effective field of view is smaller - 75-80°. The surface of the travelling grate is grey.

5.2.4.2 System design, manufacturing and mounting at Halsnæs Forsyning

Having a greater distance from the camera to the grate and taking into account the experiences from the camera located at the end of the boiler at Hinnerup Fjernvarme, we decided to use an improved design of the purge system ("the shower head"). An improved "shower head" and camera housing (Figure 16) were designed for this application. Figure 17 shows the camera mounted in the middle guide tube.

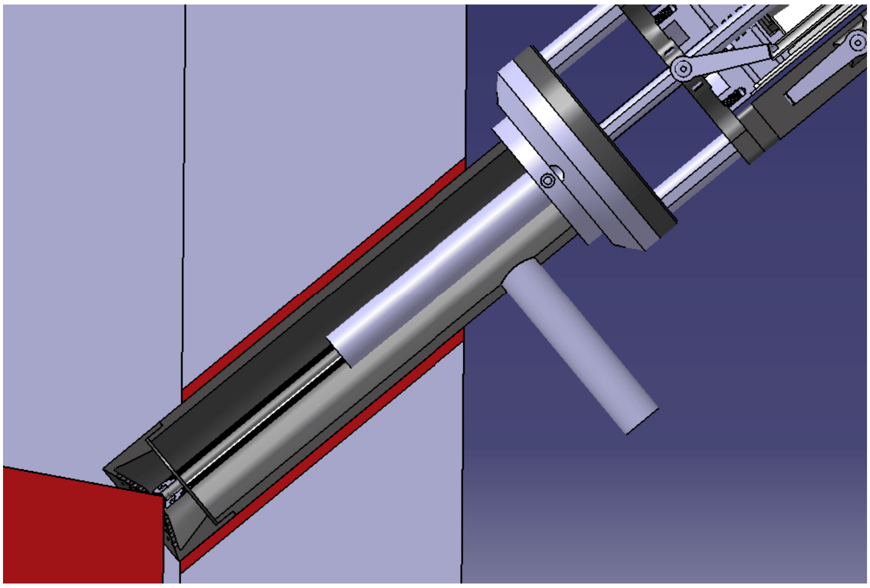

Figure 16. Drawing of guide and camera tubes with "shower head" mounted in the boiler wall. The read cone illustrates the field of view of the camera.

Figure 17. Left: Camera housing mounted in the middle guide tube of pellet boiler of Halsnæs Forsyning.
Right: Camera flange and camera housing.

5.2.4.3 Control/interface system

In the boiler room, the control box was close to the camera. The functions of the control/interface box were:

- Supply of clean compressed cooling and purge air for the camera
- Supply of 5.5 VDC for the camera
- Transmitting of video stream from camera to a FORCE laptop PC

The laptop PC was recording the video stream or/and running the GrateVision® video analysis software. The system was not connected to the control system of the boiler.

5.2.4.4 Development of online video analysis software

In the beginning, this installation was equipped with a RGB camera and later with a NIR camera. The GrateVision® online video analysis software implemented was based on the system developed during the trials at the Euro Therm boiler at Hinnerup. The algorithms for aperture control, pre-processing, elimination of optical distortion from the fish-eye lens and the perspective were further optimised. The system was not connected to the SCADA system of the boiler. Figure 18 shows the user interface of the GrateVision® system.

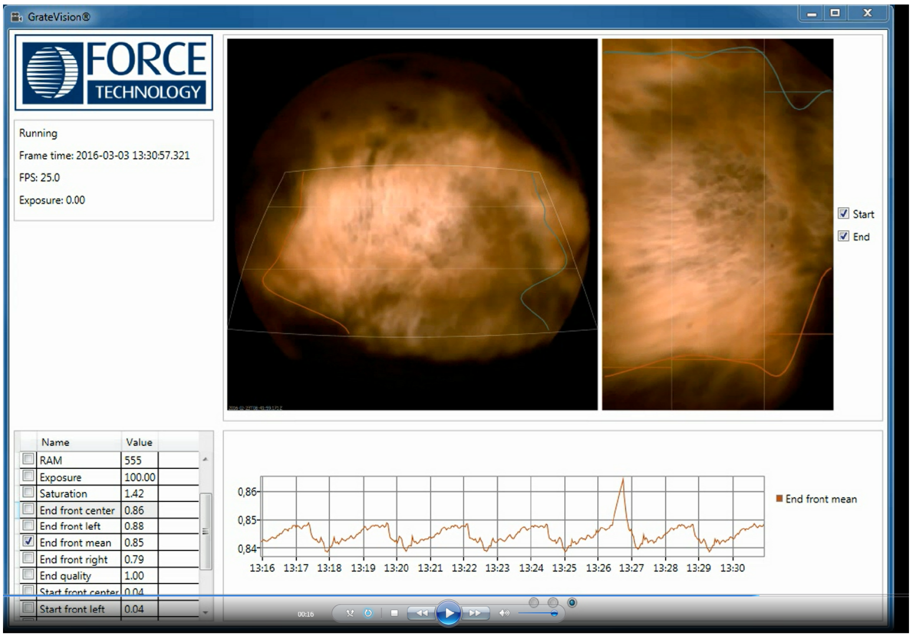

Figure 18. User interface of the GrateVision® online video analysis software.
Left picture: Raw video stream from camera with graphical overlay showing grate dimensions (yellow lines) and the identified start and end of the combustion. Fuel travels from right to left.
Right picture: Processed video stream rotated 90° and corrected for optical distortion from fish-eye lens and perspective. Fuel travels from top to bottom. Blue curve (top) is the identified start of the combustion zone. Orange curve (bottom) is the identified end of the combustion zone.
Bottom graph: Average position of the end of the combustion zone (orange line in right picture). Note the periodic behaviour originating from the movements of the grate.

5.2.4.5 Trials at Halsnæs Forsyning

The GrateVision®-system was installed on 2016-02-08 and the trials were stopped 2016-03-30 when the boiler was taken out of service by Halsnæs Forsyning.
The purposes of the trials were to:

- Provide videos at low and high load for optimising and further development of the GrateVision® software – especially a robust identification of both the start and end of the combustion zone
- Test the improved purge system ("shower head")

- Identify the most common positions of the combustion zone and thus the correct guide tube for the camera
- Test if the GrateVision® software could retrieve more information from videos from a RGB camera.

Videos for optimisation of algorithms
Several days of different operational situations and boiler loads (including stopping) were recorded during the test period

Test of purge system
The amount of air consumed by the new purge system ("shower head") was quite high compared to the capacity of the compressor at Halsnæs. Therefore, the air was supplied by two high pressure blowers running on low load to keep the air temperature down. The temperature of the "shower head" and the camera lens was satisfactory. The trials showed that the lens became dusty after approx. 12 hours. It was necessary to clean the camera lens on a regular basis. The lens could easily be cleaned with a swab.

Position of camera
Trials at different boiler loads showed that a camera in the middle guide tube could see the combustion zone in all relevant boiler situations.

NIR vs. RGB camera
Comparison between the information about the combustion from a RGB camera and a NIR camera again showed that nearly all information was gathered in the signal of the red colour of the RGB camera. The conclusion was that the cheaper RGB camera gives a better picture for the human eye, but not more information for the pictures analysis than the NIR camera. The NIR camera has a sensitivity below visible light giving a better look through flames. Figure 19 shows snapshots from videos of NIR and RGB camera.

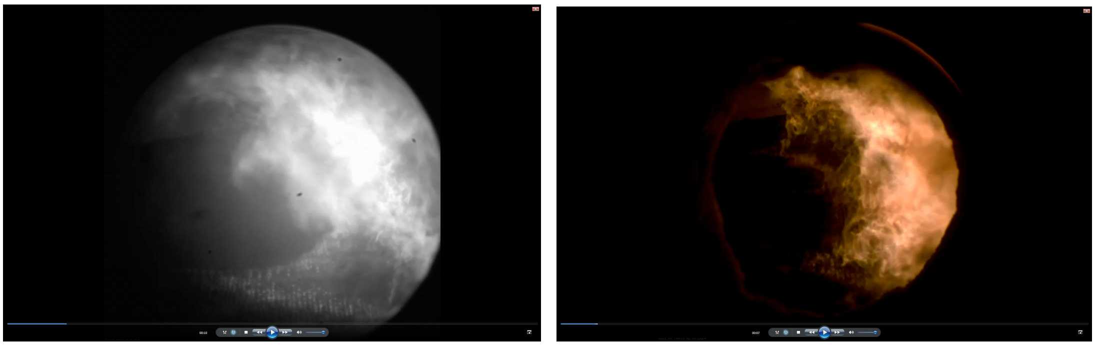

Figure 19. Left: Snapshot from NIR camera. Right: Snapshot from RGB camera. Fuel travels from left to right.

5.2.4.6 Technical results

The GrateVision® software developed during the trials at Hinnerup was used with small modifications of the aperture control algorithm.

The GrateVision® software easily identified both the start and the end of the combustion zone (Figure 18). This was the first time during many years of development that the software managed to identify the start of the combustion zone. If this early signal is transmitted to the SCADA system, it means that a control system can react earlier and faster.

The "shower head" was not working properly and could not keep the camera lens clean for more than 12 hours.

A RGB camera gives a better picture for the human eye, but not more information for the pictures analysis than the NIR camera. The NIR camera is more expensive but has a sensitivity below visible light giving a better look through flames. The choice of camera will probably depend on customer demands.

At this stage of the project, the practical/mechanical issues e.g. to keep the field of view clear is still the most challenging. Moreover, the location and field of view of the camera(s) has great significances for the possibility of getting a "good picture". Having a "good picture", the optimised algorithms can now track both the start and the end of the combustion zone.

The control of the traveling grate of the wood pellet fired boiler at Halsnæs Forsyning has a different geometry and air distribution system than a wood chip fired plant. A control scheme developed for this system would not be usable for at wood chip fired plant.

5.3 Project results – BWE branch

5.3.1 Preliminary investigations

Before the installation at MSK, BWE and FORCE Technology investigated the requirements of an industrial application of the GrateVision® system.

If the system should be installed on an existing boiler the mounting must happen without welding and drilling in or damaging the pressurised water/steam system. A special flange and mounting system were developed for that purpose.

Preliminary investigations revealed that the OPC communication used between the GrateVision® control/interface box and the SCADA system was still the most easy and flexible method.

To supervise and service a test or an industrial GrateVision®, the GrateVision® PC located on the site must be able to be controlled from a (FORCE) PC via the internet.

Because the flames from combustion of straw are more intensive than those from wood pellets and based on the experiences from the installation at Hinnerup Fjernvarme and Halsnæs Forsyning, it was decided to use a NIR camera in the MSK setup.

5.3.2 Location selection

BWE had chosen the straw fired CHP plant at Maribo-Sakskøbing as the first test location. The plant was built by BWE in 1999 and produces 9 MW power and 20 MW district heat firing 40,000 t/y straw and husks. The plant is equipped with a BWE vibrating and sloping grate. Based on experiences with the GrateVision® cameras at the waste-to-energy plant Reno Nord at Aalborg (having a similar geometry and flue gas flow pattern), we expect that the flux of particles directly encountering the camera will be less when the camera is in the side wall of the boiler.
Because of the needed space for the camera extraction system, location of boiler equipment and the platforms of plant, only few locations were usable. Taking into account the effective view angle of the camera (75-80°), it was decided to install one camera to the right of the start-up burner (Figure 20). The NIR camera could see almost the entire grate surface missing only the very beginning and end of the grate at the side of the camera (Figure 21).

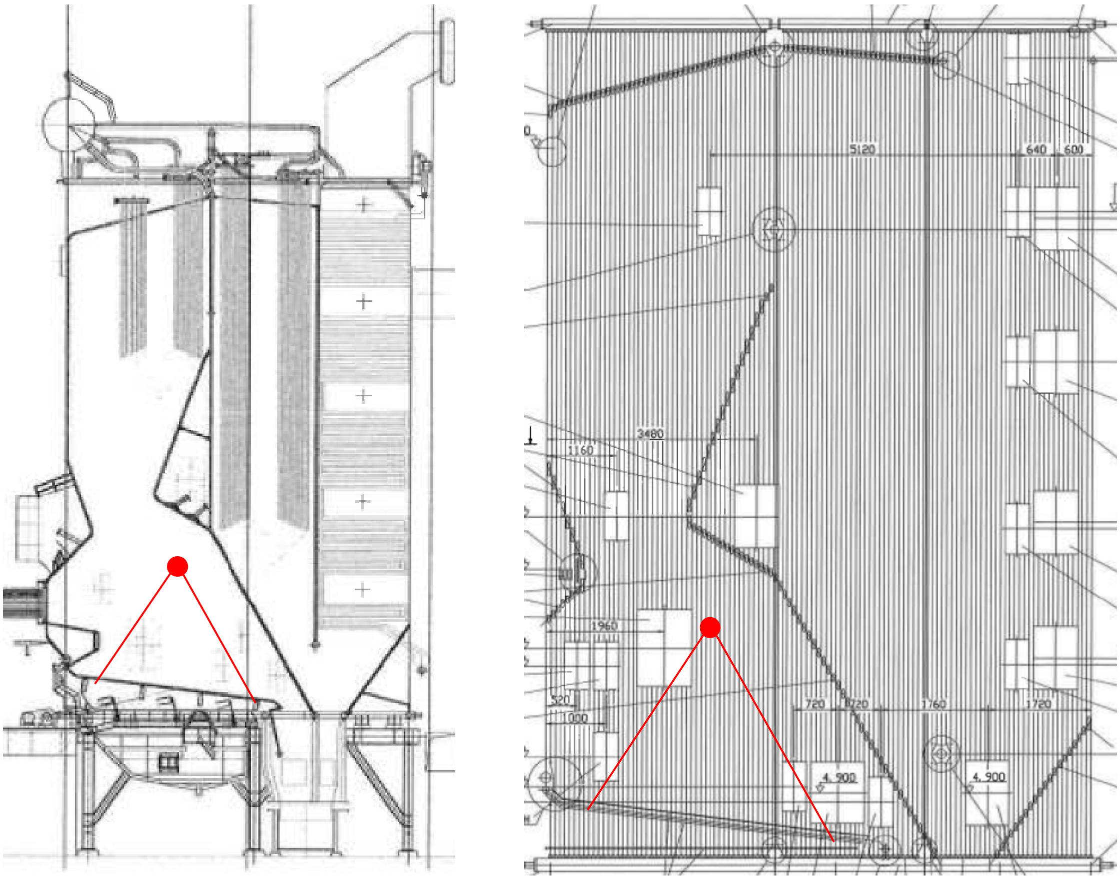

Figure 20. Location of camera in the side wall at MSK straw fired CHP plant. The view angle of the camera is 100° but effectively 75-80°.

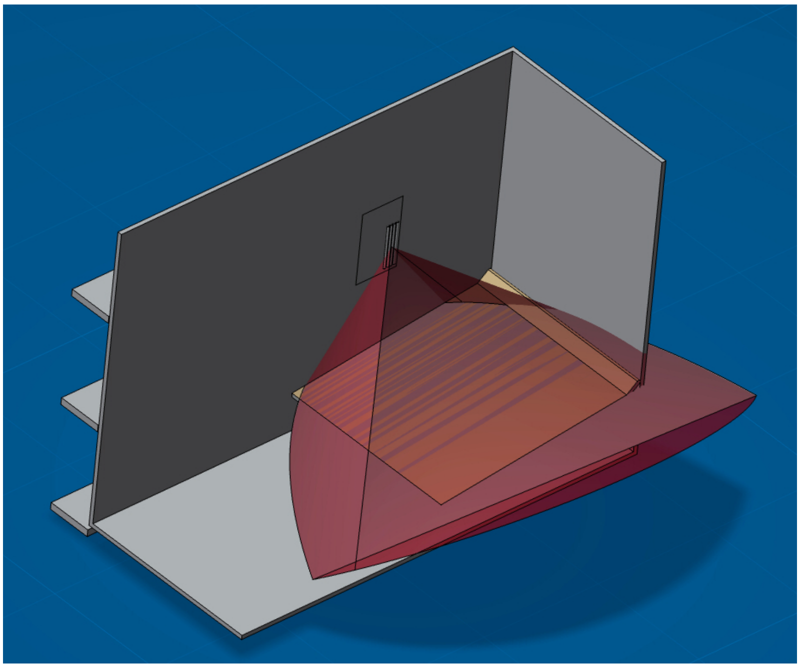

Figure 21. Drawing of field of view (red cone, 100°) of camera located in the side wall of boiler. The surface of the vibrating grate is yellow.

Figure 22. Preparing installation of camera. Cut-out (incorrectly too large) of insulation and cover to the right of the start-up burner.

5.3.3 System design

5.3.3.1 Camera housing

The design of the camera housing was based on the design developed previously by FORCE Technology and the experiences from the camera trials at Hinnerup Fjernvarme and Halsnæs Forsyning. The "shower head" purge system – using a substantial amount of air – was not implemented at MSK, but a simpler and less air consuming purge system was developed. The camera was equipped with a longer borescope (480 mm) necessary due to the sharp angle of the line of view.

5.3.3.2 Mounting flange

The idea of the compact mounting system is that the camera including the automatic extraction system must be able to be mounted

- without welding
- without drilling in or damaging the pressurised water/steam system.

Figure 23. Mounting flange mounted on the boiler wall.

The mounting requires only eight 8 mm holes in the fin for the mounting flange and one 12x26 mm hole for the borescope to look through. All holes are drilled in safe distance to the steam pipes.

5.3.3.3 Automatic extraction system

The boiler at MSK has a cleaning system programmed to cover the wall with the camera too but not the zone close to the start-up burner where the camera was located. To protect the lens from the water spray during cleaning sessions, the camera is extracted automatically before the cleaning process begins. The extraction system receives a signal from the cleaning system when it is initiated.

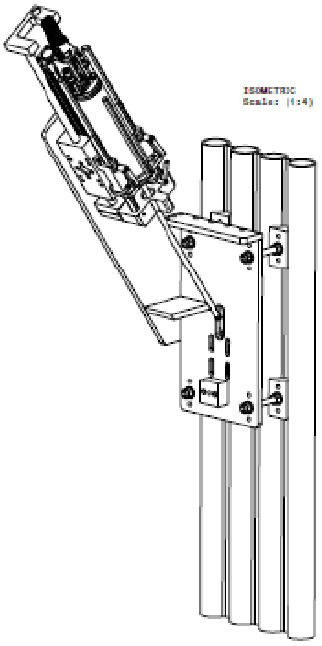

Figure 24. Mounting flange and extraction system mounted on the boiler wall.

5.3.3.4 Control/interface system

The control box and the camera system were in the boiler room and connected with FORCE PC in the server room of MSK by an ethernet cable installed by this project. The PC could be controlled from FORCE Technology through the internet. The functions of the control/interface box were:

- Supply of clean compressed cooling and purge air for the camera
- Supply of 5.5 VDC for the camera
- Transmitting of video stream from camera to FORCE PC in the server room at MSK
- Receiving start signal from the boiler cleaning system
- Control of extraction and insertion of the camera.

5.3.3.5 Online video analysis software

The GrateVision® online video analysis software developed for the installations at Hinnerup Fjernvarme and Halsnæs Forsyning was implemented and configurated to the geometry of MSK. The position of the start, the end, the area and light intensity of the combustion zone and other information retrieved by the video analysis were transmitted to the SCADA system of MSK. The GrateVision® software automatically imported relevant process parameters (i.e. O_2 concentration, etc.) from the SCADA system at MSK and showed them in graphs together with the parameters from then vision analysis. Figure 26 shows the user interface of the GrateVision® system.

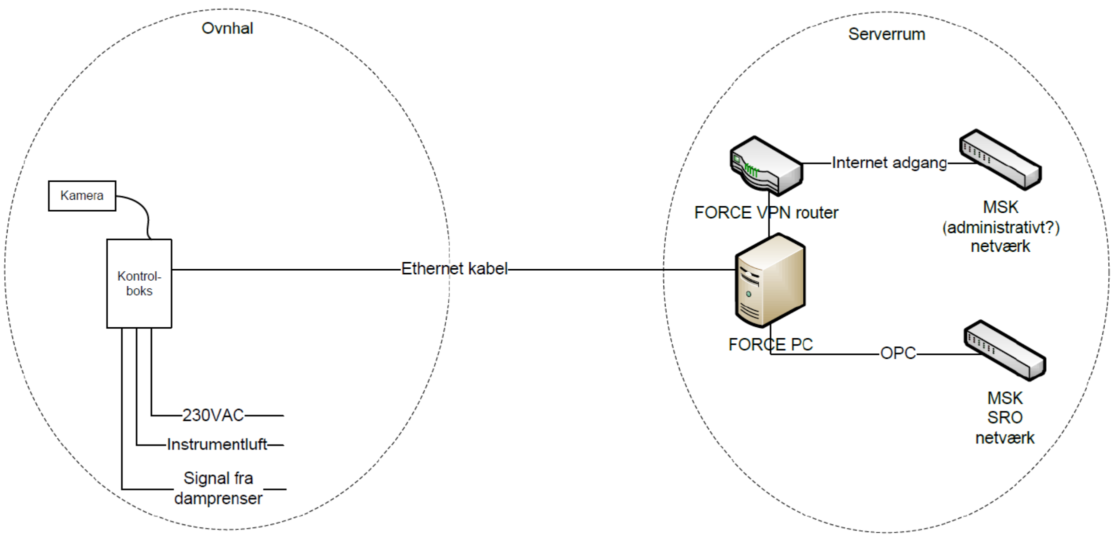

Figure 25. Architecture of the camera control and transmission system including control/interface box, ethernet cable, PC, routers, etc.

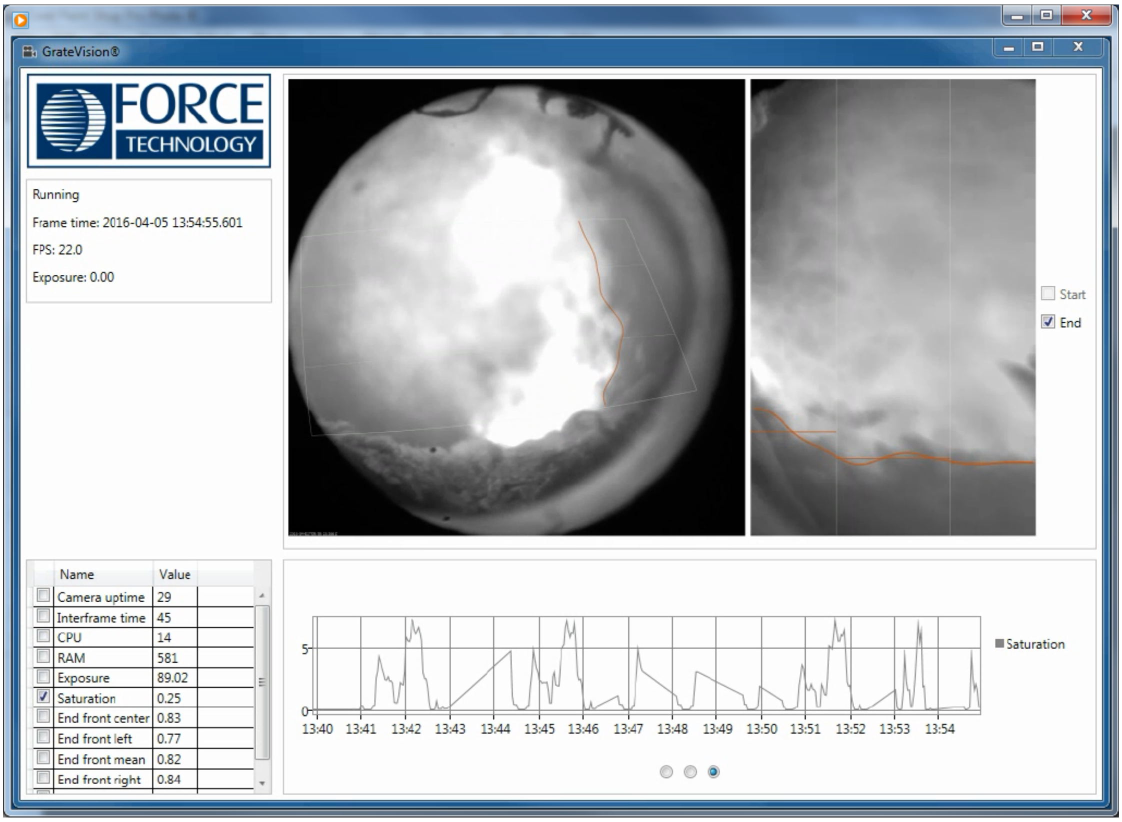

Figure 26. User interface of the GrateVision® online video analysis software.
Left picture: Raw video stream from camera with graphical overlay showing grate dimensions (white lines) and the identified end of the combustion. Fuel travels from left to right. Orange curve (right) is the identified end of the combustion zone.
Right picture: Processed video stream rotated 90° and corrected for optical distortion from fish-eye lens and perspective. Fuel travels from top to bottom. Orange curve (bottom) is the identified end of the combustion zone.
Bottom graph: Average position of the end of the combustion zone (orange line in right picture).

5.3.4 Manufacturing and mounting at MSK

The systems were manufactured by FORCE Technology and installed at MSK 2015-09-29.

Figure 27. Left: Camera (in steel cylinder) mounted in extraction system mounted on the boiler wall at MSK.
Right: Control/interface box mounted close to the camera.
The black hose contains connections between the camera and the control/interface box. The blue hose is supplying compressed air for the extraction system.

The installation was quick and successful. The camera cooling and the new purge air system, the camera extraction system and control/interface box functioned well after minor adjustments.

5.3.5 Tests at MSK

Immediately after the installation of the camera and vision system, the recording of videos began. The videos were intended for optimising the vision analysis – specially to identify the start and end of the combustion zone. Several days of operation were recorded but soft slag/ash-deposits sticked to the inner surface of the boiler wall and slowly blocked the peep-hole of the camera. The new purge air system was not designed to remove the deposits on the inner wall and could not keep the field of view open.

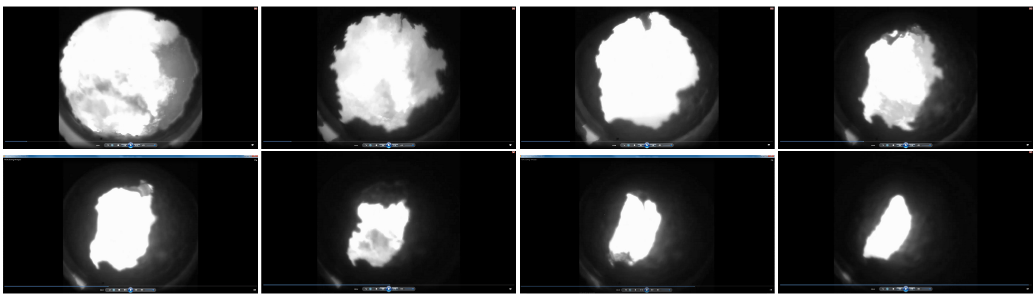

Figure 28. Snapshots of video showing blocking of field of view within few hours due to sticky ash.

The deposits on the inner surface of the boiler wall could easily be removed by a manual flusher with special angled nozzle designed and manufactured by FORCE Technology for the project, but the field of view blocked in a few hours after each cleaning. The uptime of the GrateVision® system was too short to give a stable input to the SCADA system of the plant.

Therefore, it was decided that BWE should re-programme the boiler wall cleaning system to cover the zone around the camera. Because of busyness and internal challenges in BWE the re-programming was not completed. In the meantime, BWE was finishing a new similar but larger straw fired plant at Lisbjerg, Aarhus and we decided to move the entire camera installation to this plant as soon as it was ready. The boiler wall cleaning system at Lisbjerg should be programmed to cover the area with camera. The plan was to integrate the signals from the GrateVision® system in the control concept of the new plant. Before the Lisbjerg plant was ready for the camera installation, BWE went bankruptcy and the project was halted until the future of BWE was clarified.

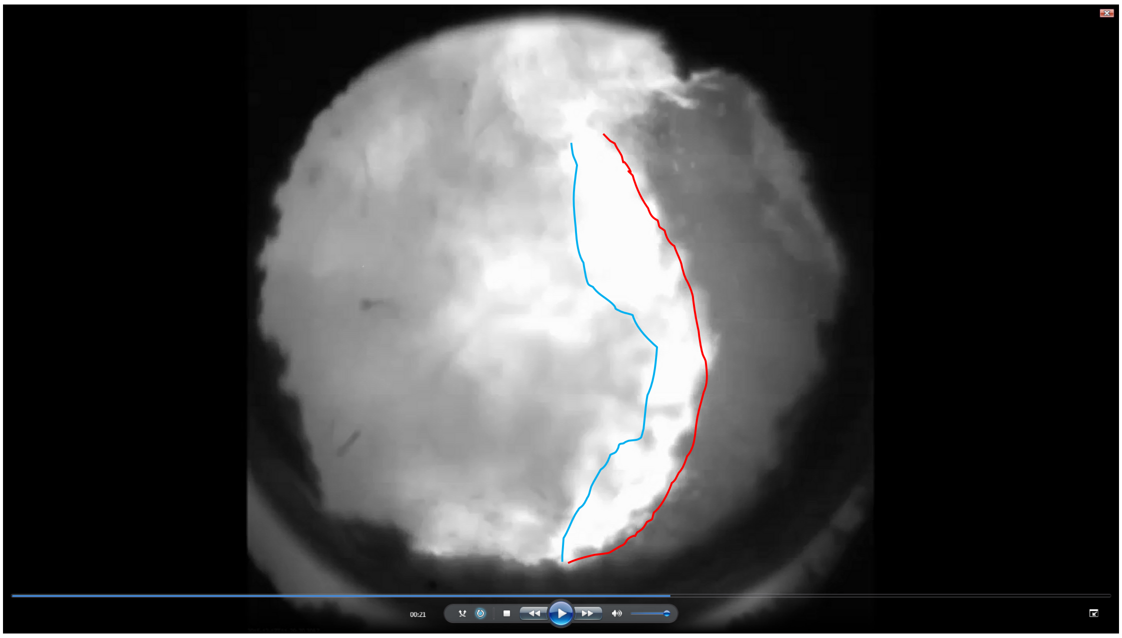

Figure 29. Snapshots of raw video showing the start (illustrated by blue curve) and the end of the combustion zone (illustrated by red curve).

During periods with good and open field of view, we managed to record short videos showing the combustion zone (Figure 29 and Figure 26). The GrateVision® software could easily track the position of the end of the narrow combustion zone. The combustion zone was so narrow that the position of the end of the zone would be appropriate for a control concept. Periods when the grate was vibrating were easily identified because of increased dust and straw particles flowing in the furnace and shadowing the view to the grate. The GrateVision® system raises a "flag" transmitted to the SCADA system when the field of view has this "white out".

5.3.6 Technical results

The NIR camera, the improved air purge system for the camera, the extraction system and the improved online video analysis algorithms were well functioning and met the expectations. The new purge system was not designed to keep the inner boiler wall.

The GrateVision® system could easily identify the start of the narrow combustion zone. Based on experiences from previous projects, the information about the position of end of the combustion zone can contribute significantly to the optimisation of the control of the combustion process. Because of deposits on the inner wall the uptime of the system was too short to supply a usable input signal to a control system.

If the system had been installed at the Lisbjerg plant the GrateVision® software would have been configured to track the start of the combustion zone. The GrateVision® system was not moved to the Lisbjerg plant because BWE went bankruptcy forcing this project branch to close before time.

The main challenge is to keep the peephole of camera free of deposits. We believe that an automatic boiler cleaning system can do the job, but we did not have the opportunity to perform tests.

5.4 Commercial results and expectations of the project

This project has developed a compact camera, cooling and purge system and a robust vision system. The vision of FORCE Technology is to offer the GrateVision® system as an advanced sensor in consultancy assignments i.e. trouble shooting, balancing of boilers with new fuels, balancing of new boilers, etc. Several plant owners have shown interest in this service and Halsnæs Forsyning has requested that the test system installed at their Weiss-boiler is upgraded and restarted as a part of co-firing wood chips with a new cheaper fuel – park & garden waste.

FORCE Technology has produced marketing material for marketing staff introducing this service together with our other services aimed at biomass fired boilers.

5.5 Dissemination of results

The status and preliminary results of the project were presented at the IDA conference, "Challenges in Biomass Combustion" 2016-06-16.

FORCE Technology will disseminate the results of the project in an article in FiB, Forskning i Bioenergi, Brint & Brændselsceller ("Research in Bioenergy, Hydrogen & Fuel Cells").

6. Utilization of project results

FORCE Technology

FORCE Technology has considered to take out a patent on the GrateVision® technology but the preliminary investigations showed that the patent would be very narrow and the risk of rejection of the application high. FORCE Technology believes that the comprehensive know-how is a sufficient barrier for competitors.

The vision of FORCE Technology is to offer the vision system as an advanced sensor in consultancy assignments i.e. trouble shooting, balancing of boilers with new fuels, balancing of new boilers, etc. FORCE Technology has produced marketing material for marketing staff introducing this service together with our other services aimed at biomass fired boilers.

The system is installed at Halsnæs Forsyning as a part of project including trials with co-firing of wood chips and garden/park waste.

Euro Therm

Euro Therm continues working on how the obtained experiences together with results from CFD-calculations (separate project) and the GrateVision® picture analyses can form the basis for an improved biomass combustion. An improved grate makes Euro Them more competitive on the international boiler market.

BWSC

BWSC has not shown any interest in utilising the results from the project.

7. Project conclusion and perspective

Through installations and trials at three different biomass boilers (two DH and one CHP) firing three different biomass fuels, the project has developed a compact and robust vision system (GrateVision®) that can be installed at any biomass and grate fired plant.

Camera housing

The purge system previously working at waste-to-energy plants could not successfully be adapted to the biomass fired boilers. The redesigned air purge system for the camera and the optional automatic extraction system keep the camera lens cold and clean. The new purge system was tested at MSK straw fired CHP plant and kept the lens cold and free of dust. The purge system was not designed to keep the inner boiler wall clean. A vison-system installed at a CHP plant with floating or sticky slag/ash requires a plant and fuel specific cleaning system.
An installation in a membrane wall of a CHP plant requires only small holes drilled in the fins. Installations in a district heat boiler require thin guide tube through the water filled wall.

Vision algorithms

The improved GrateVision® system is working with both NIR and/or RGB cameras and can be configurated to any boiler geometry. The project has further developed and optimised the algorithms for aperture control, pre-processing, elimination of optical distortion from the fish-eye lens and the perspective and tracking both the start and end of the combustion zone.

Trials at three biomass fired boilers

The GrateVision® system was installed at three biomass fired boilers with following results.

Hinnerup, wood chips

- Using the camera installed at the end of the boiler, the vision system easily tracked the end of the combustion zone
- The field of view of the NIR and RGB cameras in side wall of the boiler and the intense flames prevented the vision system in tracking both the start and the end of the combustion zone.

Halsnæs Forsyning (DTB), wood pellets

The vision system tracked both the start and the end of the combustion zone.

Maribo-Sakskøbing, straw

The vision system tracked the end of the combustion zone. Based on the video recordings we expect that the vision system would be able of tracking the start of the combustion zone. Because the project was stopped, we did not have the opportunity to configurate the vision system to track the start of the combustion zone. The combustion zone is so narrow that we expect that the end of the zone can be used as input to the control system.

Control scheme

The project did not have the opportunity to develop a control scheme using the position of the start of the combustion zone. At Hinnerup the vision system could track the end of the combustion zone only, and the improved grate was not installed in the boiler. The control of the traveling grate of the wood pellet fired boiler at Halsnæs Forsyning has a different geometry and air distribution system than a wood chip fired plant. A control scheme developed for this system would not be usable for at wood chip fired plant. At straw fired CHP plant at Maribo-Sakskøbing or Lisbjerg a control scheme could probably have been developed, if the project had not been closed.

Development of improved grate

Euro Therm has developed an improved stepped grate with a better composition of the alloys and design of the grate slats. Trials (outside this project) showed that by placing these slats in the middle of the grate a good distribution of the fuel was obtained whereby the wear on the slat became less. The disadvantage was that more particles fall through the grate gabs.

Perspectives
The compact and robust vision system (GrateVision®) still needs a long-term test to reach proof-of concept. During a long-term test the first steps towards development of a control scheme could be taken. International customers are interested in the GrateVision® system for straw fired CHP plants. To be competitive and interesting for medium sized district heat boilers, the GrateVision® system must be downscaled and the components used cheaper.

The vision of FORCE Technology is to offer the vision system as an advanced sensor in consultancy assignments i.e. trouble shooting, balancing of boilers with new fuels, balancing of new boilers, etc.

Several plant owners have shown interest in this service and Halsnæs Forsyning has requested that the test system installed at their Weiss-boiler is upgraded and restarted as a part of co-firing wood chips with a new cheaper fuel – park & garden waste.

Euro Therm continues working on how the obtained experiences together with results from CFD calculations (separate project) and the GrateVision® picture analyses can form the basis for an improved biomass combustion.