OPTIMASH

Optimizing Gasification of High-Ash Content Coals for Electricity Generation

THIRD PERIODIC REPORT

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Project objectives for the period

WP3 Design, manufacturing and testing of the pilot gasification system

The work package 3 is the most critical package in this entire programme of OPTIMASH gasifier. All the work packages were oriented to ensure that the 1 MWth plant built at Thermax captures all the complexities of the high ash coal in India and EU zone more particularly in Turkey. During the period under consideration, Thermax completed the installation and pre-commissioning of the OPTIMASH pilot gasification pilot facility. The next steps were to conduct various experiments and carry out campaigns of 'runs' for collection of data with the ultimate objective that this will enable recommendations for building IGCC (Integrated Gasification Combined Cycle) power plant a key technology in clean coal. High pressure gasification for high ash coal being a 'first time' experience, a thorough testing of the gasifier system for design & rated pressure has been carried out for leakage control. Subsequent to its integration, all the subsystems were tested for their performance and tuned up as required. Gasification experiments were carried out in two phases wherein phase-1 was performed in the month of March and Phase-2 was performed in April 2016 to demonstrate the system performance.

In parallel a small scale (200 KW) lab-scale gasifier for operating at near atmospheric pressure was also built during this period of the project to get insight for high ash coal gasification. This gasifier provided valuable insights and hands-on experience. The trials conducted during the test campaigns helped to demonstrate and understand the fluidization behavior of high ash coal, tar generation, syngas composition, flame stability in the burner and the effects of steam gasification. It also helped to establish the startup procedures as well as guidelines for operation and maintenance of the plant.

During this period, Thermax also built a state of the art lab facility for gas & tar analysis. This was yet another step which enabled to reap benefits in getting to understand the gasification kinetics and products of gasification process.

WP4. Process model development of the gasifier for upscaling to the commercial scale

WP4 aims to build-up robust conceptual processes using technically feasible models and equipment that have been demonstrated at pilot scale in WP3, in order to prepare a design requirements document to upscale the high-ash content lignite gasification plant to a commercial scale. Setting up of the OPTIMASH 1 MW High Pressure Gasification demonstration plant in WP3 has provided confidence on the feasibility of the gasification of high ash coals at elevated pressures for electricity generation. During the period under consideration, different process models developed in WP2 and equipment that have been demonstrated at pilot scale in WP3 are put together in this Task to provide a design requirements document to upgrade the high-ash content lignite gasification demonstration plant to a commercial scale. Coal gasification processes are modeled using the test results from the OPTIMASH demonstration plant and also additional results from laboratory scale and pilot scale facilities obtained by the OPTIMASH partners. AspenPlus V8.3 software is used for the modelling and simulation of the coal gasification processes with Gibbs free energy minimization approach. The key operating parameters including the feed steam temperature, feed air temperature, steam to coal ratio, and the heat loss are introduced into the model based on the input operating conditions from the Thermax 200 kW pilot scale gasifier and the 1MW OPTIMASH demonstration plant. AspenPlus simulation results are also compared to the ECN's Vergass22 model. The effects of changing the gasification operation parameters on the output syngas composition, HHV of the syngas, char split fraction and the gasification efficiency are investigated. The application of the models for scale-up to commercial-size IGCC plants at high pressures are also examined using GTPRO software which is used to predict the performances of a complete Integrated Gasification Combined Cycle (IGCC) plant. It is shown that the net power and efficiency of IGCC power plants are higher than pulverized coal fired power plants, considering the possible application of gas turbine/steam turbine combined cycle in the IGCC plant.

Work progress and achievements during the period

WP3 Design, manufacturing, testing of the pilot gasification system

The tasks 3.1 to 3.5 have been completed during the previous period. In the Third period, the remaining two sub-tasks have been completed.

Task 3.6. Installation and commissioning

This task concerned the plant erection, piping, electrical and instrumentation installation and commissioning. This sub task has been fully completed so that testing of the pilot gasification facility was possible during this same period.

3.7 Testing

OPTIMASH partners met on 5th and 6th November 2015 at Thermax Pune campus and provided the directions to conduct the test protocols on the gasifier. 9 trials were conducted on the Pilot gasifier from 1.5 pressure to 4 bar pressure and temperature ranging from 850 to 940^{o}C. The original design of the Optimash 1 MW plant at 10 bar was first interpolated for arriving at expected results at 4 bar and then the actual data collected at 4 bar was compared to evaluate the performance of the gasifier. Cold gas efficiency, carbon conversion and higher heating values are taken as three key parameters.

From the obtained data, it has been observed that the key performance parameters are deviating less than 10% from the designed values. This could be a result of higher heat loss in actual 1 MW plant versus the assumed heat loss of 5%. Comparatively, for large scale plants of the order of 100-150 MWe, the heat loss value is less than 1.5% (of heat input). The results also showed that the tar levels in pressurized gasifier are higher than the Lab-scale gasifier. This is due to lower temperature in the freeboard in the pressurized 1MW gasifier. Another important result is that the CGE, CC, HHV & tar content are in close range in atmospheric as well as pressurized gasification conditions. The high pressure gasifier has obviously efficiency advantage for power generation via the IGCC route.

<u>Main Conclusions from the tests</u>

The OPTIMASH 1 MWth pilot gasification facility has been tested for two months i. e. March and April 2016, while the 200 kWth lab gasifier was running about a year from May 2015 to April 2016. Following are our main observations:

1. The design objectives are achieved based on the outcome of the trial runs. It has been established that high ash coals can be gasified at high pressure under fluidized bed conditions in a stable manner.
2. The gas produced is of good quality suitable for power generation through combined cycle gas turbine but also using gas engines.
3. This data can be utilized for designing a full scale IGCC project which is a key component in a Clean Coal Technology space.
4. The pilot plant has been operated at 1.1, 2.0 & 4.0 bar pressures but shoved some problems at 6.0 bar mainly due to system issues and not the process issues.
5. The mal-distribution of the fluidisation air caused by the misalignment of the distributor plate is the main problem observed at higher pressures (6 bar). Otherwise the performance at 1.1 & 4.0 bar has shown limited pressure impact.
6. Overall the plant efficiency is definitely the big advantage when operating the gasifier at higher pressures for the integration of the gasifier with the combined cycle (IGCC scheme).

More generally, finalizing the design, setting up the facility, pre-commissioning and testing took enormous efforts and we were able to conduct the tests on the main gasifier for only two months. Good data has however been collected in this short period and the facility will be run on "need basis" and also to address some of the issues limiting the high pressure operations (such as correcting distributor plate).

The OPTIMASH 1 MWth high ash coal gasification pilot plant is now available for all OPTIMASH partners and those that EU will designate for conducting tests within the confidentiality and other commercial aspects to be decided by the EU and the management of Thermax.

WP4. Process model development of the gasifier for upscaling to the commercial scale

Simulation of high ash coal gasification in a fluidized-bed

AspenPlus software is used in industrial chemical processes modeling, simulation, optimization, sensitivity analysis and economic evaluation. It provides comprehensive physical property models, a library of unit operation models and fast and reliable process simulation functions together with advanced calculation methods. With the physical property database and the operation models provided by Aspen Plus, engineers are able to simulate an actual power plant behavior effectively and accurately. In AspenPlus coal can be treated as a mixture composed of a series of stable elementary substances, such as C(s), H, N, Cl, S(s), O and ash forming elements because there is no molecular formula for describing the coal chemical composition due to its natural structural complexity and composition diversity. To model the pyrolysis/devolatilization process in the gasifiers, the coal is converted into a mixture composed of a series of stable simple substances, including C(s), H_2, N_2, Cl_2 , S(s), O_2, H_2O and ash forming elements. As a first step, coal is decomposed into elements by the reactor block of AspenPlus and the steam is also fed into the reactor to provide the heat needed for the process of decomposition. The steam is transported to the Gibbs reactor block as the gasification agent with air. The chemical equilibrium calculations are performed in the RGibbs reactor block based on the Gibbs free energy minimization method. In this process, the un-burnt carbon is burnt in the combustor to increase the air inlet temperature supplied by the compressor. Finally, the product gas from the gasifier emerges from the process and its properties are estimated by the AspenPlus computations.

Scale up analysis by THERMAX using the test results from the high pressure1 MWthOPTIMASH gasification demonstration plant

Setting up of 1 MW High Pressure Gasification plant has provided confidence on the feasibility of the gasification of high ash coal at elevated pressures for electricity generation. The experimental data available from the OPTIMASH 1MWth pilot plant has been used to design a full scale IGCC Plant as a part of clean coal technology (CCT) development strategy. The results and data from 1 MW plant are used and extrapolated using simulation tools (GTPro software) to predict the performances of an Integrated Gasification combined cycle (IGCC) plant.

In the context of this Task, the following results are obtained:

1. The IGCC technology is a comparatively new concept for power generation industries and has yet to be better developed and established like conventional power plants consisting of boilers and steam turbines that have a strong mass manufacturing basis. However, comparison of the performances of IGCC v/s Super Critical (SC) Power Plant show that IGCC provides technical superiority with respect to abatement of pollutants like SOx & NOx as compared to post combustion capture of same in the case of Super Critical Power Plant. It is to be noted that especially in India, there is a large focus on the reduction of SOx & NOx emissions. Post combustion emission control technologies are putting heavy cost penalties on the CAPEX and OPEX of the utility industries. The IGCC technology provides an elegant way to reduce these emissions by capturing H2S, COS and NH3 prior to the combustion of syngas. The pressurized operation of the IGCC units also reduces the overall equipment size and foot print area. Moreover the pollutants are brought down to quite low levels in order to suit the acceptability norms of the gas turbines. Hence the consortium is of the opinion that IGCC is a better route than SC/USC. The detailed analysis will certainly need further and continuous interactions with the technology suppliers for the gas cleaning island. Cost comparisons also require further investigations.

2. The 1 MWth OPTIMASH demonstration plant provides enough data for setting up the design requirements for gasification plants for various other applications relevant to the Indian Scenario, such as small scale power plants based on internal combustion syngas engine and mid-sized plants for conversion to SNG in order to provide it to the end user via grid-connectivity. The low rank high ash coal poses problems in terms of particulates emissions and hence directives from the Indian government have been issued to avoid the local stress on ash management and environment issues. The average ash content is reduced to below 34% level by blending imported coal. The developed and proposed system is suitable for wide variety of coals and hence it does not pose any limitation on ash content. India is deficient in natural gas (NG) resources and hence highly dependent on its import. In the absence of the supply chain for NG, coal has been widely adopted by industries for their various fuel needs (power, heating and cooling). Hence, coal gasification provides the opportunity to explore other usages of the syngas such as conversion to substitute natural gas (SNG). The gasification based small scale power plants of the scale of 0.5- 5.0 MWe are attractive due to the better efficiency of the power generation units like syngas operated gas engines. Thermax Ltd. is already working on these concepts to meet the existing demand.

Comparison of IGCC plant v/s Super Critical Plant

As a part of WP4, the data available from the OPTIMASH high pressure 1 MWth coal gasification demonstration plant is used for scaling up to IGCC power plants at higher capacities. THERMAX performed necessary simulations using the GTPRO software for up-scaling from 1 MW coal gasification plant to 100 MW+ IGCC plants. GE GT 6F.03 turbine is suitable for synthesis gas operation; it has a single cycle (SC) net efficiency of 36% on LHV basis. GT manufacturers are today capable of delivering operational flexibility and performances needed to adapt to a rapidly evolving power generation environment. For example, GE gas turbine products are ranging in the individual output from 22 MW to 519 MW ranges for utility power generators and industrial operators.

There are two options available that can be considered for building the Gasification Island:

1. High pressure gasifier (25-30 bar) based on the gas turbine (GT) requirements
2. Medium pressure gasifier (5-10 bar) and boosting the syngas by a compressor to the GT required pressure

For the Cold Gas Efficiency, we know that small scale plants have higher heat losses than the large plant. Hence the CGE will improve as the plant size increases from 1MW level to 100+ MW scale. We used the following estimated values for the CGE:

1 MW Plant	65.00
100 – 500 MW Plant	69.25

Performance details of 132 MWe IGCC Plant

Simulations on GTPRO software were performed with the design basis inputs from the gasifier modelling output of 132 MW_e high pressure (30 bars) coal gasification units. The summary of the output is given below:

GTPRO upscaling simulation results	**132 MW + IGCC Plant**
Coal Feed Rate (TPH)	69.13
GT Gross Power (kW)	74204
ST Gross Power (kW)	57567
Combined Cycle Gross Power (kW)	131771
Combined Cycle Efficiency (%)	54.7
Gasification - Cold Gas Efficiency (CGE) (%)	69.25
IGCC Gross Efficiency on HHV (%)	38

In total, four cases have been studied, where ash content for the coal has been varied from 26% to 41% and plant power level was changed from 132 MW to 541 MW. The scale up from 132 MW to 541 MW for both coals shows 8% improvement in overall efficiency of the IGCC plant. This is due to improved efficiency of large scale turbines. It is also observed that CO2 emissions can vary between 722-808 kg/MW depending upon the case considered. In terms of pollution control, the major part of S and N will be released in the gasifier itself, and the syngas will be mostly free from it. In addition, when combusted in the char combustor the un-burnts from the gasifier (about 10% of the load), give additional increase in efficiency.

The char combustor is of the fluidized bed type which operates below 950 °C that also reduces NOx emissions. Any further control of SOX can be done by in-situ lime addition. Particulate control can be done by Electrostatic precipitator (ESP). The costing details have to be however worked out more.

It is observed in our calculations that coal based IGCC plants have higher efficiencies for large scale MW plants as compared to coal power plants using the super critical technology. We can also add that IGCC plants, as they use gas turbines, do not require water to generate power; this saves nearly 60% of water consumption as compared to a conventional Rankine cycle plant (steam turbine).

We have also performed scaling-up simulations starting from the 1MW base case to 100MW and 500MW and observed that IGCC performs better than conventional power plants. But to achieve reliable operation at high power scales further work is needed leading to technological advances in plant integration, gas clean-up, turbine selection and design & balance of plant. The GTPRO upscaling simulation results agree well with those reported in the literature for low rank coal applications of the IGCC approach. However, adoptability of the IGCC plant depends on many factors like cost, process complexity, suitable gas turbines and overall plant integration. Higher CAPEX is one of the major reasons for the low adoption of this technology. IGCC is a new technology as compared to PC fired units and hence development, design and manufacturing costs are higher. It needs further development work on these areas to optimize the technology.

IGCC provides elegant way for reductions of SOx & NOx

Thermal Power Plants using Advanced Super Critical Technologies are more focused on the enhancement of the efficiency of the system and the reduction of CO2 emissions. But these technologies do not provide easy emission control possibilities for SOx and NOx. Hence additional equipment and utilities are required to capture these emissions which impose cost penalties to the end user. In IGCC plants, H2S and NH3 generated during the process are removed from the syngas before it enters into the gas turbine. Hence selective absorption of H2S and NH3 components in IGCC plants helps to reduce SOx and NOx emissions from the gas turbine. As the gasifier operates at high pressure due to the requirements of the gas turbine, the overall system including gas cleanup becomes quite compact.

Other relevant applications

The OPTIMASH 1 MWth high ash coal gasification pilot plant provides enough data for setting up gasification plants for various applications at different power levels, relevant for the Indian Energy Strategy but also for other countries possessing similar kind of high ash coals such as Turkey. The following two applications are particularly identified where the currently developed high ash coal gasification technology can also be used to address the issue of natural gas substitution (Substitute-Natural Gas-SNG) and also generation of combined heat and power using gas engines for a distributed energy scenario.

<u>Substitute Natural Gas (SNG) Production</u>

The major factors that lead to consider SNG production from coal gasification route are:
- Abundant low rank quality coal in India (and in other countries and regions)
- Poor natural gas grid connectivity issues in India

• Techno-economic viability of gasification plants in the capacity ranges of 10 – 100 MW scale; but obviously the project strict economics will depend on the natural gas market price long term trends. On the other hand, using domestic energy resources obviously increases the energy independency of a country or region.

Small scale plant for combined heating and power applications

Syngas produced from coal gasification can be cleaned and used in gas engines for combined heat and power generation for total power ranges of few MWs compatible with decentralized energy strategies. In addition such small to medium range gasification systems can also be fed by biomass or other organic waste residues in a scheme that can be called co-gasification. This strategy would then contribute to dispose various waste streams otherwise difficult to handle (such as scrap tires or other organic industrial waste and agricultural waste of various origins), following the circular economy concept. In addition, co-gasifying coal with bio/organic-waste would also reduce the greenhouse gas emissions footprint of both from coal conversion but also from waste storage areas (emitting large amounts of methane when landfilled or CO2 if accidentally burned). A right scale of the proposed plant and modularization of the system can make this process economical. It is possible to achieve ~21% power generation efficiency at small to medium scales using syngas to gas engine route where the conventional Rankine cycle efficiencies are quite low. In fact, today's gas engines even approach a power efficiency of 40%. The same plant can also provide additional heat in the form of steam and hot water for other usages like cooling and heating applications, increasing therefore the combined efficiency to 53%. Some other applications can also be considered such as the use of syngas for the replacement of other fossil fuels like the furnace oil or natural gas in furnace applications in industries like Steel, Ceramic, Glass, etc.

Elements for a techno-economic evaluation for commercial scale IGCC systems

In order to reduce emissions from coal fired power plants, integrated gasification combined cycle (IGCC) is currently evaluated as a promising technology for its eco-friendliness and high performance. In this approach, pulverized coal is converted into syngas (H2/CO mainly) via the gasification process and the ash and acid gases such as CO2/H2S/COS are removed from syngas. Literature results indicate that, the net power and efficiency of IGCC power plants are higher than pulverized coal fired power plants, considering the possible application of gas turbine/steam turbine combined cycle in the IGCC plant. Quantitative economic analysis is usually performed on individual IGCC power plant to calculate Levelized Cost of Electricity (LCOE) which is a very useful measure to compare different power plants. In the recent detailed studies on the economics of the gasification of low rank coal for electricity generation in an IGCC power plant, such as those of the National Energy Technology Laboratory (NETL) of the U.S. Department of Energy, Total Revenue Requirement (TRR) method is applied to calculate the LCOE. The total equipment cost (TEC) and capital cost scaling methodology of energy systems for IGCC power plants are then estimated. This methodology when applied to estimate the equipment cost of an IGCC power plant of 300 MW class, estimates that the LCOE for an AFC (Ash Free Coal) fueled IGCC power plant without CO2 capture is $ 0.08/kWh, which is smaller by 12% compared to that for RC (Raw Coal) feed IGCC power plant without CO2 capture conditions.

In a similar vein we used GTPRO software for a similar preliminary financial analysis of the 132 MW IGCC plant that we used as a basis for our simulations for scaling-up. The final financial estimates of the GTPRO results show that the needed total investment for a 132 MW

IGCC plant is 244 million US $, the specific investment of the plant is 21844 USD per kW and the break-even electricity price is 0.0809 USD/kWhr. It is important to not to consider those financial figures at face value but rather as showing that such financial estimates can be doable today with existing softwares. The details of the calculations are not given here but can be provided if requested.

Conclusions of WP4

We conclude that the circulating high-pressure fluidized-bed gasification technology for combined heat and power is particularly suitable for high ash coals. The 1 MWth OPTIMASH gasification demonstration plant provides enough data for scaling up gasification plants for various power levels and applications. The simulation results showed that the modeling is successful and qualified for analyzing the effects of the key operation parameters on the gasification results. The validation of model analyses indicated that AspenPlus software accomplishes good performances. The supply of steam has positive effects on increasing the hydrogen yield and the proportion of hydrogen content in the produced syngas. The upscaling results from 10 MW to 120 MW using AspenPlus showed positive effects on the HHV of the syngas and the gasification efficiency, due to the decreasing of the gasification temperature and the increase of the hydrogen and CO yields. The scale up from 132 MW to 541 MW for two different ash contents showed 8% improvement in the overall efficiency of the IGCC plant. This is due to the improved efficiency of large scale turbines. It is observed that CO2 emissions /MW can vary from 722-808 depending upon the case considered. The selective absorption of H2S and NH3 components in IGCC plants helps to reduce SOx and NOx emissions from the gas turbine. The specific investment of the 132 MWth plant is estimated 2184.4 USD per kW using GTPRO software. The break-even electricity price is estimated to be 0.0809 USD/kWh, equivalent to that reported in the literature for commercial scale-up IGCC systems using low rank coals. Additional studies such as scaling-up the plant to 30-50 MW moderate output levels should be carried out. This will reduce the risk factors and associated challenges with higher power levels. Additional detailed studies on aspects such as the detailed design of the gasifier, the heat transfer equipment, and the syngas clean-up system, choice of the gas turbine, and the plant operation and control etc. are needed to take up the technology development forward. Experience gained from 30-50 MW plant operation will be useful for further scale-up to 300-500 MW level plants.

Project management during the period

OPTIMASH consortium management is conducted by the Co-ordinator, Dr Iskender Gökalp and his team at the ICARE-CNRS and at the Delegation Régionale of the CNRS in Orléans. The management tasks during this period consisted mainly in the following:

Organization of the project meetings and participation to other meetings

During the period under consideration, OPTIMASH partners have decided to request a 6 months extension period for the project to properly perform the gasification tests with the pilot gasifier. This extension request was caused by the delay in completing the WP3 of the project. The following are the primary detailed reasons:

1. The critical decisions and inputs for the process and equipment design of the high-pressure 1 MWth pilot plant were obtained in WP1 and WP2 with some delay because of the

complexity of the process. The lab scale circulating fluidized bed gasifier design needed to be completed, therefore additional time was required when compare to the initial Work Plan
2. Since the pilot plant installation is inside the THERMAX industrial site in Pune, India, the strict legal compliances and approvals from appropriate Government agencies were mandatory for the plant erection which needed additional work and induced some delay.
3. The project also encountered challenges related to manufacturing, especially during refractory laying due to smaller cross-section of the gasifier. This has also increased the work content and induced a corresponding delay.
4. Sourcing of critical components like the lock-hopper fuel feeding system, high-temperature and high pressure valves and ash extraction screw & vessel required more effort and consumed more time as compared to the initial plan.

This extension has been obtained and the project continued until 30 April 2016. The Fifth Progress Meeting has been organized at Thermax in Pune, India in 5-6 November 2015, to which all OPTIMASH partners have participated. This was the occasion for all partners and the Commission to see and review the erected OPTIMASH 1MWth high ash gasification pilot plant and to agree on the commissioning and testing plans for the final months of the project. The OPTIMASH project Final Meeting was successfully organized in Brussels on 18 July 2016.

In addition to these meetings, several other meetings were organized by the co-ordinator in Turkey with the Turkish partners and also the Turkish coal energy sector to disseminate the results from the OPTIMASH project. In parallel to face to face meetings, intensive email coordination has been maintained between the partners to discuss project development and progress issues.

Several international conferences and seminars were attended by the OPTIMASH consortium partners to meet and discuss with other groups active in the coal gasification area and to disseminate the results of the OPTIMASH project.

Some of these meetings are the following:

Christiaan van der Meijden, Bram van der Drift, Berend Vreugdenhil, Sander Grootjes, Herman Bodenstaff, Guadalupe Aranda Almansa. Allothermal gasification of high-ash coals. New Horizons in Gasification, 10-13 March 2014, Rotterdam, The Netherlands

K. Jayaraman, I. Gokalp, Steam and CO2 gasification kinetics of high ash coal chars produced under different heating rates. 31st Annual International Pittsburgh Coal Conference, 6-9 October 2014, Pittsburgh, USA.

R.R. Sonde et al., Breaking the Shackles and Building IGCC as a Credible Clean Coal Technology Option for India. Conference on Coal Resurgence from Energy-Secure Society (2014) IICT, Hydrabad, India

Orhan, E.C., Gulcan, E., Gulsoy, Ö., Ergun, L., Can, M., Aghlmandi, A., Ersoy, M., (2015), "Strategies for modeling and simulation aided design of a coal washing plant for gasifier feed operation", 32nd Annual International Pittsburgh Coal Conference, October 5-8 2015, Pittsburgh, USA

R.R.Sonde et al., Experiences on Establishment of Gasification plants in India. CAE-INAE workshop on clean coal technology (2016) Ryerson University, Toronto, Canada

R.R. Sonde, India's foray in clean coal technology: coal still remains the mainstay. Optimash project on high ash coal gasification. Seminar on clean coal by India energy alliance. September 2016, New Delhi

Research articles published based on the results of the OPTIMASH projectare listed below:

K. Jayaraman, I. Gokalp, Thermal characterization, gasification and kinetic studies of different sized Indian coal and char particles. **International Journal of Advances in Engineering Sciences and Applied Mathematics** 6: 31-40 (2014)

K. Jayaraman, I. Gokalp, Effect of high ash coal-char generation method on steam, CO2 and blended mixture gasification. **Fuel** 153: 320-327 (2015)

K. Jayaraman, I. Gokalp, E. Bonifaci and N. Merlo, Thermogravimetric and evolved gas analysis of high ash Indian and Turkish coal pyrolysis and gasification, **Fuel** 154: 370-379 (2015)

K. Jayaraman, I. Gokalp, Thermogravimetric and evolved gas analyse of high ash Indian and Turkish coal pyrolysis and gasification. **Journal of Thermal Analysis and Calorimetry** 121: 919-927 (2015)

K. Jayaraman, I. Gokalp and S. Bostyn, High ash coal pyrolysis studies at different heating rates to analyze its char structure, kinetics and evolved species. **Journal of Analytical and Applied Pyrolysis** 113: 426 – 433 (2015)

G. Aranda, A.J. Grootjes, C.M. van der Meijden, A. van der Drift, D.F. Gupta, R.R. Sonde, S. Poojari, C.B.Mitra. Conversion of high-ash coal under steam and CO2 gasification conditions. **Fuel Processing Technology** 141: 16–30 (2016)

K. Jayaraman, I. Gokalp, S. Jeyakumar, Estimation of synergetic effects of CO2 in high ash coal-char steam gasification, **Appl. Thermal Eng.**, 110: 91-998 (2017)

Project status

The project has been successfully completed. All the financial reports have been submitted to the Commission.