OPTIMASH Report Summary

Project ID: 283050
Funded under: FP7-ENERGY
Country: France

Final Report Summary - OPTIMASH (Optimizing gasification of high-ash content coals for electricity generation)

Executive Summary:
Coal is expected to continue to play a major role in the electricity generation of India and Turkey, (as well as in many other countries) and is a key element in their energy security. In spite of their high ash content, Indian and Turkish coals are widely used today for the generation of power and industrial steam. With respect to the efficiency of conversion, high ash coal does pose a problem and hence demands alternate means of conversion.

The overall objective of the OPTIMASH project is precisely to optimize the operating conditions of IGCC technology (Integrated Gasification Combined Cycle) based on high-ash coals. Gasification being the main conversion (and energy loss) step in the IGCC line, most R&D challenges are indeed focused around the gasification technology.

The OPTIMASH project aimed to optimize the efficiency and reliability of gasifiers fueled with high-ash content coals. Several specific objectives have been achieved. The optimum gasification technology compatible with the targeted high ash coals has been selected. The selected technology has been assessed using laboratory scale gasifiers. The targeted coals have been fully characterized in terms of their physico-chemical parameters and their washability. The gasification chemical kinetics of the selected coals has been determined and modeled. Using all these information and data a 1MWth pilot gasification facility has been modeled, numerically simulated, designed in detail, constructed, commissioned and successfully tested. A coal washing plant capable of feeding the pilot gasifier has also been designed. Operation data from the pilot gasifier plant has been used to model commercially relevant up-scaled versions of the developed gasification technology.

Project Context and Objectives:
In India and Turkey a significant part of the available coal has a high ash content (>35 wt%). At present high ash coals are washed, to reduce the ash content and fired in boilers to produce electricity. Gasification offers the possibility to convert high ash coals in a combustible gas that can be combusted in Gas Turbines. The hot flue gases are utilized to produce steam for a steam turbine (Combined Cycle). Integrated gasification combined cycle (IGCC) power generation systems are considered as prospective next-generation technology for power generation from coal. IGCC can provide several operating possibilities and increases the chances of reducing the gaseous and solid emissions from power systems. In addition pre-combustion capture technologies become possible.

The overall objective of the OPTIMASH (Optimizing gasification for high-ash content coals for electricity generation) project is to optimize the operating conditions of IGCC technology based on high-ash coals. Gasification being the main conversion step (and energy loss) in the IGCC line, most R&D challenges are indeed focused around the gasification technology. The OPTIMASH project aims to optimize the efficiency and reliability of gasifiers fueled with high-ash content coals.

There are various designs of gasifiers available in the market, such as, fixed/moving bed (Lurgi), entrained flow (GE, Shell), and fluidized bed (U-Gas, SES) etc. However, currently no proven and reliable IGCC technology and no gasification technology exists that use high-ash coals. Practically all of the world wide IGCC technologies are based on entrained flow gasification. However, for high-ash coal these types of slagging gasifiers do not seem suitable. No commercial companies such as Shell,
Siemens and General Electric supply entrained flow gasifiers for coal with these high ash contents. The main problem is the high content of ash which results in a very large amount of molten slag. Additionally, the entrained flow gasifier is not a very efficient way of high-ash coal conversion since also the ash needs to be heated to a temperature of typically 1500°C which consumes a large amount of oxygen. Other types of, preferably non slagging, gasification technologies need to be developed for the conversion of high ash coals. Moving bed technology could be an option, but this type of gasifier produces a high amount of tar, requires extensive gas cleaning and only pure oxygen can be used as oxidant.

Coal remains a major stay in India’s electricity generation and key element in its energy security. In spite of its high ash content Indian coals have been widely used for the generation of power and industrial steam. The high ash coal is primarily sub-bituminous in nature and is quite benign in terms of sulphur content. In terms of efficiency of conversion, high ash coal does pose a problem in terms of the process of combustion and hence demand alternate means of conversion. With a total reserve of 195 billion tonnes, coal currently accounts for more than 50% of total primary commercial energy supply in India and for about 58.3% of total electricity generation. Coal is likely to remain a key energy source for India, for at least the next few decades as India has a significant amount of domestic coal reserves (relative to other fossil fuels) and a large installed-capacity for coal-based electricity production. This situation in many ways is also very similar in Turkey, and also for example in Greece.

The present method of Power generation via Rankine cycle and high-ash coals are used through direct combustion processes. While extensive technology developmental work is being carried out to make the Rankine cycle more efficient via super critical power generation cycle, this is prone to issues of high temperature challenges accentuated by high ash content especially the alpha quartz in high ash coal. Coal gasification obviates many of these issues and has much contemporary importance because of the fact that it is considered as the technology for the future in terms of efficiency and cleaner environment. Integrated gasification combined cycle (IGCC) power generation systems are considered as prospective next-generation technology for power generation from coal. IGCC can provide several operating possibilities and increases the chances of reducing the gaseous and solid emissions from power systems. In addition pre-combustion capture technologies become possible. The fundamental operation in any IGCC system is the gasification process. Clearly three critical advantages are 1) High efficiency energy conversion without issues of very high temperature steam generation due to use of combined cycle 2) Compact design for large scale generation of electricity due to high pressure systems and 3) Clean environmental parameters due to the very nature of IGCC and provides a very good platform for Carbon Capture and Sequestration (CCS) technology integration in future. However, gasification is largely influenced by the type of coal and operating conditions. It is very important that the characteristics and the conversion behaviour of different types of coals used in these modern gasification technologies are completely understood for their adoption in these technologies. Gasification of Indian and similar coals faces a big problem of reduced gasification efficiency and handling a large amount of inerts (ash), which in turn raises a question on its economic feasibility.

The specific objectives of the OPTIMASH project were structured around 5 work packages:

WP 1 Assessment of the suitability / adaptability of the indirect gasification concept to high ash coals

Objectives: Assessment and selection of the most promising gasification technology in an IGCC system for high-ash content coals. The main candidate is fluidized bed gasification. In this category, indirect gasification and circulating bed (CFB) gasification are the most important options.

Task 1.1 High-ash coal gasification review (ECN, IITM, CNRS)
Task 1.2 SWOT analysis (ECN)
Task 1.3 Test performance on the ECN’s lab scale MILENA gasifier (ECN)
Task 1.4 Feasibility of proposed gasification technologies (ECN, THERMAX)

WP 2 Characterization / preparation of high-ash coals and the optimization of their gasification

Objectives: Characterization of physico-chemical properties of high-ash content coals and assessment of optimized
beneficiation-preparation routes for coals from different sources
Development of pressurized drop tube furnace for generation of gasification kinetic data and modelling of chemical kinetics. Development of laboratory scale gasification system with optical access for diagnostics. Development of physico-chemical models of gasification and CFD simulation of lab-scale and pilot-scale gasifier. Enhancement of global performances of gasifier by investigating and integrating
- upstream processes such as coal beneficiation
- downstream processes such as gas cooling, cleaning, flyash removal and ash disposal
- improved design measures such as avoiding agglomeration and corrosion, evolving fuel flexibility

Task 2.1 Fuel characterization and assessment of optimized beneficiation-preparation routes for high-ash content coals (TKI, HUN, IITM)
Subtask 2.1.1 Characterization studies on the samples taken from different Indian and Turkish high-ash pits (TKI, HUN, IITM)
Subtask 2.1.2. Determination of specifications and washability characteristics of the coal in the laboratory (TKI, HUN)
Subtask 2.1.3. Determination of different quality products to the gasification unit by modelling and simulation (TKI, HUN)
Subtask 2.1.4. Designing a pilot washing plant for high-ash content coals (TKI, HUN, THERMAX)

Task 2.2 Generation of gasification kinetics data and development of kinetics model (IITM, CNRS)
Subtask 2.2.1 Experiments on determination of coal reaction kinetics
Subtask 2.2.2 Development of coal gasification kinetics model

Task 2.3 Setting up of instrumented laboratory-scale gasification system with optical access for laser diagnostics (IITM)

Task 2.4 Gasification model development/improvement, CFD simulation, validation and scale-up studies (IITM, THERMAX, CNRS)
Subtask 2.4.1. Kinetic modelling
Subtask 2.4.2. Fluid dynamic modelling

Task 2.5 Global performance improvement of high ash coal gasification (ECN, IITM, CNRS, THERMAX)

WP 3 Design, manufacturing, testing of the pilot gasification system
Objectives: Set up a 1 MWth pilot-scale plant based on the improved design as a result of the efforts made in WP1 and WP2, and operate it up to 10 bar at THERMAX. Operate the plant and generate data so that gasification models for geometric modifications and scale-up can be refined further.

Using validated models, make design improvements and test the system performances.

Task 3.1. Process design (THERMAX, ECN, IITM, CNRS)
Task 3.2. Basic engineering (THERMAX)
Subtask 3.2.1 System level basic engineering
Subtask 3.2.2 Component level engineering
Task 3.3. Detailed engineering (THERMAX)
Task 3.4. Manufacturing (THERMAX)
Task 3.5. Procurement (THERMAX)
Task 3.6. Installation and commissioning (THERMAX)
Task 3.7. Trials, data collection and analysis (THERMAX, ECN, CNRS)
Task 3.8. Operation and maintenance (THERMAX)

WP 4 Up scaling to the commercial scale
Objectives: Build-up robust conceptual processes, which are technically feasible using models and equipment that have been demonstrated at pilot scale in WP3, in order to prepare a design requirements document to upgrade the high-ash content lignite gasification plant to a commercial scale. Experimental and simulated results will be compared to validate both data and the models. The application of the latter in the scale-up of commercial-size IGCC plants at high pressures will be also dealt in WP4. Cost and CO2 foot-print evaluations will also be examined. Literature survey on scale-up will be carried out and geometrical, pressure and hydrodynamic scale-up strategy will be hypothesized.

Task 4.1 Collecting process data and review of gasification models (CNRS, ECN, IITM, THERMAX)
Task 4.2 Development of process modelling and validation (CNRS, ECN, THERMAX, IITM)
Task 4.3 Technico-economic and environmental impact evaluation (CNRS, ECN, THERMAX)

WP 5 Management and dissemination

Objectives: Administrative, contractual and financial management. Coordination of the scientific and technical activities. Internal and external communication. Implementation of the dissemination and exploitation plan

Task 5.1 Administrative management (CNRS)
Task 5.2 Coordination of the project activities (CNRS and partners)
Task 5.3 Implementation of the dissemination and exploitation plan (CNRS and partners)

Project Results:
The main S & T results of the OPTIMASH project are summarized below following the WP structure of the project.

WP1 Assessment of the optimized gasification technology
Task 1.1 High-ash coal gasification review
Task 1.2 SWOT analysis of available technologies

The high-ash coal gasification review study has revealed that there are various designs of coal gasifiers available in the market, such as, fixed/moving bed (Lurgi), entrained flow (GE, Shell), and fluidized bed (U-Gas, SES) etc. However, it was confirmed that no proven and reliable IGCC technology and no gasification technology exists that use high-ash coals. Practically all of the world wide IGCC technologies are based on entrained flow gasification. For high-ash coal these types of slagging gasifiers are not suitable. No commercial companies such as Shell, Siemens and General Electric supply entrained flow gasifiers for coal with high ash contents. The main problem due to the high ash content is the generation of very large amounts of molten slag. Therefore, it appeared clearly that other types of gasification technologies, preferably non-slagging, needed to be developed for the conversion of high ash coals. Moving bed technology could have been an option, but this type of gasifier produces a high amount of tars requires extensive gas cleaning and only pure oxygen can be used as oxidant.

In order to select the best technology for the gasification of high-ash content coals, a detailed survey of the existing literature and technologies has been performed and reported in D1.1. The conclusions of this survey indicated that a fluidized bed gasifier is the optimal choice for the conversion of high-ash coals. The main advantage is a high efficiency, possibly air blown gasification, freedom in particle size, and non-slagging conditions. In addition because the temperature remains relatively low (<1000°C), melting of the ash is prevented, and the required coal pre-treatment is limited. Various companies supply or have supplied fluidized bed gasifiers. The main disadvantage of fluidized bed gasification technologies is the limited carbon conversion, which implies that the ash will contain a significant part of the energetic value of the coal. An additional combustor is required to utilize this heating value. Various concepts have been proposed to utilize the heating value in the char.

Task 1.3 Adaptability tests of the MILENA gasifier to high ash content coals

In this project indirect and direct fluidized bed gasification processes have been evaluated and tested. The ECN lab-scale facility MILENA is used for the tests. In D1.2 a summary is given of the different fluidized bed gasification tests done in the ECN MILENA lab-scale gasifier configured in different ways. The tests have been performed in WP1 for Indian and Turkish coals using both the conventional MILENA, the inverted MILENA (gasification in BFB) and air blown BFB; fluidization tests of coal ashes have also been performed. The tests indicated that gasifying high ash coal in the riser of the MILENA is not feasible. The conversion of coal is too low (~ 30% wt.) due to the low volatile content of the coal and the short residence times of MILENA riser; hence there is an excess of char going to the combustor, and as a consequence, the heat released in the combustor leads to too high temperatures (well above 1000°C). On the contrary, gasification under reverse MILENA conditions (i.e. feeding in BFB), the so-called i-MILENA, has been shown technically possible.
Task 1.4 Feasibility of proposed gasification technologies

The results of Task 1.1 have clearly shown the limited availability of gasification technologies for high ash coals. Strong interactions between the OPTMASH consortium partners and using the results obtained in WP1, the following conclusions have been reached:

* High pressure operation possibilities for i-MILENA system are limited and the benefits of increasing pressure are also limited; in addition, under high pressure conditions, the complexity of the systems will increase.
* High pressure fluidized bed gasification is therefore a preferred solution over low pressure i-MILENA.
* In addition, i-MILENA tests showed tar generation in the produced gases, so tar removal is required.
* On the contrary, THERMAX experience with CFB gasification of coal shows no tar.

Therefore, pressurized fluidized bed gasification is selected for further development of the OPTIMASH project with strong focus on high carbon conversion (in WP3).

WP2 Characterization / preparation of high-ash coals and the optimization of their gasification

Task 2.1 Fuel characterization and assessment of optimized beneficiation – preparation routes for high ash content coals

Coal characterization studies have been conducted on the samples taken from different Indian and Turkish origin high-ash pits. Particle size distribution, proximate analysis, ultimate analysis and heating value of the coal are estimated. Elemental analysis of ash and its fusion temperature are also evaluated. Grindability index of coal and coal blends are also determined. Washability characteristics of the coal are determined using heavy liquid tests. Washability of size fractions and its final products are investigated. Based on these results, samples are prepared for gasification tests with an optimum ash level from washing. Modelling and simulation were carried out to determine the products from the gasification unit. Alternative coal washing plant flow sheets are prepared to produce different quality feed material to the gasification unit by simulation. The applicability of various dry and wet coal cleaning equipment is also examined. A complete pilot washing plant for high-ash content coal is designed.

Sub-tasks 2.1.1 - 2.1.3

Among the characterization studies, size-by-size chemical and thermal analysis, petrographic analysis, particle size distribution and heavy liquid tests have been conducted on three coal samples, one from India (IC) and two from two different regions in Turkey (TR-T and TR-S) which were acquired as per high ash target of the OPTIMASH project. The results of coal characterization are detailed in deliverable D2.1.

The analysis results showed that, in dry basis, the LHVs of the samples are in the range 3050-3350 kcal/kg where the ash content of TR-S coal is slightly lower. The results indicate also that TR-S sample contains high amount of sulfur (3.75%) compared to that of TR-T and IC samples (1.78% and 0.42% respectively). The volatile matter content of TR-S sample is also higher than other two samples. The petrographic analysis indicated that TR-T and TR-S coal samples are of sub-bituminous type whereas IC sample exhibits features of two different coal types and therefore indicates a mixture (or a blend) of two different coals of different origin.

In the characterization studies, heavy liquid tests and flotation tests were also conducted on coal samples from India and Turkey. The heavy liquid test results show that, low density and hence low ash containing fraction of the IC sample is very low. Therefore, any attempt towards coal washing would result in considerable loss of combustibles in the tailings. Flotation of IC sample following grinding to fine sizes (-300 microns) did not help reduce the coal loss to rejects. As a result, it appears more appropriate to use the Indian coal as-is and without washing in gasification tests. TR-T coal sample responds very well to
density based separations. However, even at very high densities, the ash content of the clean coal obtained from TR-T sample is very low (< 20%) and does not meet the “high ash” requirements of OPTIMASH project. TR-S sample, similar to IC sample, although enables lower ash content products, significant amount of coal would be lost to rejects. At any separation density, the calorific value of the rejects would be higher than 1000 kcal/kg. On the other hand, the ash content of the run-of-mine coal suggests that TR-S coal does not require any further ash removal and already meets the high ash requirements of OPTIMASH project.

Sub-Task 2.1.4 Design of a pilot coal washing plant

The objective of the coal washing pilot plant was to supply clean coal to the 1 MWth OPTIMASH pilot gasifier. In order to design a safe plant in terms of capacity, the thermal efficiency of the gasifier was assumed to be 35%. Using the data obtained in coal characterization studies (D2.1) and simulation tools, several coal washing alternatives have been evaluated. The size distributions and washabilities of the samples were used as input in LAVE software developed by the partner HU. Various alternative flowsheets were evaluated by using simulations. The main processes evaluated were: FGX dry beneficiation, Jig, Heavy medium separation, Teetered bed separation and spirals for fine fraction. The simulation results revealed that heavy medium separation is the only method suitable for IC coal. FGX and Jig were found to be inefficient and would result in serious coal losses.

Data obtained from Indian coal samples (IC) supplied by THERMAX are used as basis for the design of the pilot plant (Deliverable D2.2 should be consulted for the details of the design procedure and the design results). The plant is designed to produce both 35% and 45% ash containing coal. The required capacity of the plant is calculated as 5000 kg/h for -50 mm feed material which provides 3500 kg/h and 1500 kg/h of coal having 45 % and 35 % ash, respectively. The same flow sheet can be used for both 35% ash and 45% ash products by changing only the separation density of the medium in HMD. Coal samples from Turkey, TR-T and TR-S, will be used without further processing. TR-T is the middling product of TKI’s existing Tunçbilek washing plant and TR-S is suitable for using as run of mine. The optimum particle size for the gasification process will be determined in the later stage of the project. Therefore, a size reduction stage may also be added to the pilot plant flow sheet.

As a conclusion for the coal beneficiation activities, these results re-confirm also that the efficient separation at higher sizes by density based separation does not necessarily mean that the separation would be as successful by flotation. Flotation characteristics of coal depend not only on the liberation of the coal but also on the hydrophobicity of coal sample which is determined by the rank of the coal. Practically, the increasing rank improves coal’s hydrophobicity and hence flotation characteristics. Therefore, in general the “older coal reserves have better flotation characteristics than that of younger coals such as sub-bituminous coal and lignites.

Task 2.2 Generation gasification kinetics data and development of high-ash coal gasification kinetics models

The pyrolysis, combustion and gasification behaviors of high ash Indian and Turkish coals and chars have been investigated by the coupled TG–MS method (see Deliverable 5). The results indicate that the ignition temperature and the temperature of maximum mass loss rate are identical for both coals, but the burn out temperature of Indian coal is higher. During thermal decomposition and devolatilization of the coals, CO, CO2, H2 and CH4 are the major gaseous products. The ignition temperature, the temperature of maximum mass loss rate and the burn out temperatures of char particles are higher compared to coal particles of similar size. As the size of the particle is increased, the burn out temperature is also increased. Particle size effects are not significant during the pyrolysis stage of the coal. The particle size does not have a significant effect on the activation energy within the range of parameters investigated. The gasification process of the investigated coals starts above 800 °C in water vapour ambience. The gasification process of the coal starts around 700 °C in blended mixtures of water vapor, air and oxygen. The gasification reaction of char particles commences around 850 °C for both water vapor and blended mixtures of water vapor and air/oxygen. The complete burn out of both coal and char samples occurs at 950 °C which indicates the suitable gasification temperature with high carbon conversion rate and gas efficiencies for high ash coals in the
conditions of fluidized bed gasifiers. The activation energies are comparatively higher for the Indian coal under various reducing ambient conditions compared to values for the Turkish coals. The activation energy of the char particles is higher than the coal particles under oxygen ambience. The heating rate influences coal devolatilisation rates and the pore structure of the generated char particles. The char produced during pyrolysis at high heating rates shows higher gasification rates in most of the cases. These results were helpful to understand the high ash coal gasification process and its kinetic parameters and to properly design the OPTIMASH pilot gasification system in WP3.

Intensive TGA and mass spectrometry experiments of Indian and Turkish coal samples have been performed under various conditions. Mass losses of the coal and the mole fractions of evolved species have been measured during pyrolysis under various heating rates using a thermo-gravimetric analyzer (TGA) and a mass spectrometric analyzer. The properties of the produced char such as the pore surface area (BET) obtained by N2 adsorption method and SEM analysis have been evaluated. The kinetic parameters, activation energies (E) and Arrhenius constant (A) of gasification for different sized coal particles at various conversion levels have been determined from the thermogravimetric data. The dependencies of kinetic parameters on particle size and conversion levels during coal gasification have been estimated. The activation energy of the gasification is found depending on the char generation conditions and particle sizes. A mathematical model is proposed for char reactivity dependency based on instantaneous mass loss rate under chemically-controlled conditions (Regime-I), which is a function of temperature (T), CO2 concentration in the bulk gas (pCO2) and system operating pressure (p_total). This model has been used for the gasification reactor design in WP3. The data have also been used for the reacting flow simulations of the fluidized bed gasifier in WP2 and WP3 (see also Deliverables 7 and 9).

Task 2.3 Setting up of an instrumented laboratory-scale gasification system

The high-ash content coal gasification technology adopted in OPTIMASH is Circulating Fluidized Bed Gasification (CFBG). The advantages of this technology are a compact gasifier, higher carbon conversion and easiness for scaling up. A detailed design of a 0.1 MWth Lab scale CFBG system has been carried out and installed at IITM (see Deliverable 6). This task pertains to the setting up and testing of a gasifier for optimization of high-ash coal gasification. The design task also comprised numerical simulations of the facility using the CFD code Barracuda for flow analysis in the CFBG; the simulation results were also compared with computations using the Fluent CFD code. Cold flow studies on critical components such as cyclone separator and loop seal have also been performed. ASPENPlus simulations were also performed for process optimization purposes.

The operating pressure of the facility is chosen as 10 bar (similar to the pressure level in the pilot gasification facility developed in WP3 and the operating temperatures are chosen between 900 °C - 1100 °C. Coal samples having ash content of around 40% are used as the base case for designing and sizing of the CFBG gasifier operated with air as oxidant at a nominal power of 100 kWth.

The following design assumptions and calculation approaches have been used:
1. The flow rate and caloric value of the product gas (syngas) are obtained using ASPEN PLUS simulations, following the thermodynamic equilibrium approach.
2. The heat loss from the gasifier is assumed equal to 20 kW, around 20% of output thermal power.
3. The steam to coal ratio is selected as 0.2 for air based system.
4. The solids are recycled back to the gasifier with a drop in temperature of 50 °C to consider the heat loss in the recycle loop (that is, in the cyclone, standpipe, loop-seal and down comer).
5. The Solid Circulation Ratio (SCR) is estimated based upon heat and mass balance to satisfy the syngas caloric value, CGE and hydrodynamic (chocking limit) requirements.
6. Hydrodynamic calculations are performed based upon standard correlations
7. The sphericity of coal particle is assumed equal to 0.65.
8. Superficial velocity at the lower section of the gasifier is determined based on air flow rates from the distributor of the gasifier at specified temperature and pressure.
9. Superficial velocity for the upper section is determined using syngas flow rate produced in the gasifier.
10. Static bed height is calculated for residence times of 35 minutes and 70 minutes based on the steady ash flow rate and bulk density of the coal, assumed as 800 kg/m³.
11. Bend effects at the riser exit are neglected.
12. The total height of the gasifier is taken as 8 m based on the pressure drop calculations and required allowances.
13. The operational regimes of the fluidize bed are estimated using the existing literature knowledge of pressure drop and superficial velocity.

The gasifier built has a riser inner diameter of 90 mm and 8 m height and is made of inconel. The riser is connected to the cyclone through a duct of rectangular cross section (40 mm × 70 mm). The stand pipe of inner diameter 50 mm is connected from the bottom of cyclone to the top of the loop-seal. The loop-seal connects back to the riser through a return leg of diameter 50 mm. The whole system is insulated with a ceramic material. The distributor plate is made of stainless steel of 310 grade. It has a thickness of 30 mm and contains 246 holes of 2 mm diameter separated by a pitch of 4 mm. The loop-seal is made of stainless steel. It has a size of 135 mm × 135 mm × 210 mm and contains a small distributor plate with 1 mm holes and 2 mm pitch.

Several tests have been performed with this facility under various gasification conditions. Also, the CFBG was operated under design conditions in non-reactive cold mode up to a pressure of 6 bar. The pressure data were analyzed to ensure proper circulation of the solid material at different pressure conditions. For reacting tests the carbon conversion for 100 kWth runs was found around 74% and for 80 kWth runs around 84%. The cold gas efficiency improved from around 60% (average) to around 75% (average). As far as the gas composition is concerned, CO was in the range of 15% and it increased to around 20% with steam addition. The hydrogen yield increased from around 6.5% to 15% with steam addition.

Task 2.4 Gasification model development/improvement, CFD simulation, validation and scale-up studies

As a part of Optimash work packages, mathematical modeling of the gasification system has been taken up by IITM. Particle laden flows, in general and reactive flows with particles, in particular, are quite complex in their physical as well as mathematical descriptions. The governing equations for the transport phenomena, in general include the conservations of mass, momentum, species and energy equations for both the gas and solid phases. Based on the regimes of flow, the particles may be coarsely spaced or they can be transported as a dense (bulk) phase. Due to the density differences between the phases, the modeling aspects become complex and there are complex coupling terms between the phases. The problem becomes increasingly complex due to the involvement of several time scales. Both oxidation as well as reduction reactions occur simultaneously. Since gasification system involves charring fuels, the processes of release of moisture and volatiles, surface oxidation of char and penetration of oxygen through the ash layer becomes extremely difficult to model. Researchers have carried out mathematical and numerical modeling of reactive particle laden flows by incorporating several assumptions and simplifications to the processes involved. Therefore, a thorough understanding of the studies from literature is highly important. Such a detailed literature review has been presented in this task.

Subsequently, cold flow computation studies on the IITM CFBG system have been carried out using the commercial software Barracuda. Barracuda is custom built software, based on CFD, used more specifically to simulate solid laden gas flows. Physically valid results have been obtained using the Barracuda runs and the results have been systematically analyzed. Further, the cold flow model of CFBG is validated with in-house experiments at atmospheric as well as elevated pressures. One of the complex parts in CFBG is the cyclone and its performance on solid particle separation is much important for the stable operation of the CFBG. Therefore, cold flow simulations of the cyclone separator have been performed. There are a set of standard sub-models used to simulate reacting gas-solid flows. As an initial attempt, the reactive flow in the IITM CFBG has been simulated and the results are analyzed in detail. Then, simulations of BFBG with both Barracuda and the more generic software FLUENT, have been carried out and the validation of reactive flow results against the experimental results from the literature has been performed. Further, the results of reactive flow model of BFBG are compared with in-house experiments at...
IITM. Subsequently reactive flow simulations are carried out corresponding to the experiments with the CFBG of 1 MWth capacity designed by Thermax using a simplified model consisting only of the riser as well as CFBG as a whole.

The main results from this Task are the following:

1. A detailed literature review on modeling approaches of gas-solid flow has been performed, essentially focusing on two fluid models or so-called mathematical models and computational fluid dynamics simulations. Though the mathematical models are able to predict the main features of fluidized beds, its application is limited to the specific operating conditions because the hydrodynamics is calculated using empirical correlations. The governing equations used in CFD are derived from the first principles and can be used to simulate complex multiphase flows in fluidized bed reactors; this approach has been preferred in this Task.

2. The computations showed that the static pressure decreases with height in the riser of the CFBG and the minimum is observed in the cyclone separator. Then the pressure increases as moving down in the stand-pipe and reaches the maximum in the loop-seal. The full loop model for cold flow in CFBG, developed within Barracuda, has been validated with in-house experiments. Further, the validated model is used to predict the hydrodynamics of CFBG operating at elevated pressures. It is noted that the drag model is critical for predicting the gas-solid flows in fluidized bed reactors and should be adjusted properly with the experimental data. It is also shown that a simplified model of CFBG consisting only of riser can be used to predict the hydrodynamics in the riser of the CFBG system.

3. Numerical simulations have revealed that the designed cyclone separator is very efficient. Also the erosion prone areas of the cyclone separator are identified.

4. Implementation of suitable reaction kinetics is critical for the successful modeling of reactive flows in fluidized beds.

5. Modeling full loop CFB gasifiers in a reactive environment is computationally very expensive. In CFB gasifiers, fuel conversion occur predominantly in the riser, therefore, it is suggested to simulate only the riser part of the CFBG. This can be achieved by the use of recycle boundary conditions. Recycle boundary conditions are used to feed back the particles exiting the riser, thereby eliminating the need to model complex solid recycle system.

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. Enormous efforts have gone to build this plant (see Figures in the Appendices) and in February 2016, Thermax completed the installation and pre-commissioning of OPTIMASH. 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.

A parallel small scale (200 KW) lab-scale gasifier for operating at near atmospheric pressure was also built during the course of the project to get insight for high ash coal gasification. This gasifier provided valuable insights and hands-on experience. If we could commission and successfully collect data in the 1 MW system the credit should go for this lab gasifier. 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 course, 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.

Task 3.1 Process design

WP3 aimed to develop and optimize a 1MWth pilot scale gasification plant for high ash content coals. During the process design phase i) overall plant process simulation has been carried out using engineering tools such as ASPEN Plus and various scenarios for the optimum system have bee assessed; ii) system as well as component level basic engineering was performed. The conceptual design of the pilot gasification facility has provided a system with a capacity of 250 kg/hr of high ash coal (corresponding to 1000 kWth) and operating at 10 bars and 950-1000 °C.

Task 3.2. Basic engineering

In order to complete this task, about 26 engineers from Thermax R&D department worked on this project. 3 different divisions in Thermax (heating, enviro and water) contributed to these efforts. 3 manufacturers and satellite manufacturers worked on several components in addition to 9 sub system suppliers. The total weight of the system is around 80 tons and the area being occupied is 60 x 20 m² (see also Deliverable 9).

Subtask 3.2.1 System level basic engineering

The gasifier and gas cleanup sizing, refractory layouts, equipment sizing, feeding ports and their locations, ash handling, gas outlet, hydrodynamic behaviour, syngas composition and its heating value were designed in this phase. The pilot gasifier design (size and process conditions) mainly incorporated the results from characterization studies of high ash coal (WP 2.1) gasification kinetics (WP 2.2) lab scale gasifier (WP 2.3) and CFD simulation and scale-up studies (WP 2.4). In addition, a comprehensive process-flow-diagram (PFD) and piping and instrumentation-diagram (P&ID) and data sheets for the equipment and a typical layout and instrumentation and control logic diagram has been determined.

Subtask 3.2.2 Component level engineering

Each subsystem of the gasification plant has been discussed with the chosen providers. Design specifications of each component have been finalized based on the process design and on provider inputs and their proper integration has been assessed. Process control of each unit has been finalized. The availability and reliability of the sub components for various scales have also been evaluated within this Task.

Task 3.3. Detailed engineering

Within this Task, detailed specifications of the fabricated equipment and subsystems have been generated and detailed drawings/documents prepared. The following sub-tasks have been completed: Detailed engineering (includes mechanical, electrical, structural engineering and instrumentation), preparation of plant general assembly (GA) drawing in 2D/3D, equipment general assembly drawing in 2D/3D, civil and structural drawings, approvals and finalization of GA, preparation of fabrication drawings, detailed drawings and documents for electrical and instrumentation, purchase specifications and quality assurance plan (QAP).

Task 3.4. Manufacturing

The main components manufacturing has been completed in this Task. They concern the following elements: the gasifier, cyclones, coal feeder, char combustor, air compressor, filter press, rolled shells and dished ends for gasifier, cyclone cones, support rings, different type of flanges, gasifier freeboard and nozzles, freeboard, loop seal flange.
Task 3.5. Procurement

Standard commercial systems have been procured from standard vendors. They concern the main air compressor, N2 pressure swing adsorption (PSA) system, coal conveying and feeding system, Venturi Scrubber & Droplet Separator, Filter Press, accessories for syngas Combustor and Air Preheater, mainly.

Task 3.6. Installation and commissioning

This task concerned the plant erection, piping, electrical and instrumentation and commissioning.

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°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.

Main Conclusions from the tests

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 showed 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

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. 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.

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), H2, N2, Cl2, S(s), O2, H2O 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 MWth OPTIMASH 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:

<table>
<thead>
<tr>
<th>Plant Size</th>
<th>CGE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MW Plant</td>
<td>65.00</td>
</tr>
<tr>
<td>100 – 500 MW Plant</td>
<td>69.25</td>
</tr>
</tbody>
</table>
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 MWe high pressure (30 bars) coal gasification units. The summary of the output is given below:

<table>
<thead>
<tr>
<th>GTPRO upscaling simulation results</th>
<th>132 MW + IGCC Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal Feed Rate (TPH)</td>
<td>69.13</td>
</tr>
<tr>
<td>GT Gross Power (kW)</td>
<td>74204</td>
</tr>
<tr>
<td>ST Gross Power (kW)</td>
<td>57567</td>
</tr>
<tr>
<td>Combined Cycle Gross Power (kW)</td>
<td>131771</td>
</tr>
<tr>
<td>Combined Cycle Efficiency (%)</td>
<td>54.7</td>
</tr>
<tr>
<td>Gasification - Cold Gas Efficiency (CGE) (%)</td>
<td>69.25</td>
</tr>
<tr>
<td>IGCC Gross Efficiency on HHV (%)</td>
<td>38</td>
</tr>
</tbody>
</table>

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-burnt 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.

1. Substitute Natural Gas (SNG) Production

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.

2. 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

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.

Potential Impact:

POTENTIAL IMPACT AND SOCIO ECONOMIC ANALYSIS OF UPSCALING TO A COMMERCIAL IGCC POWER 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 is now available which can be 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 work, the following results are obtained:

a) 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 strong mass manufacturing base. 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
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b) 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

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; 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.

Basic data considered for scale up to 100 MW + IGCC plants

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 % and 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 MWe high pressure (30 bars) coal gasification units. The summary of the output is given in the table below:

Coal Feed Rate (TPH): 69.13
GT Gross Power (kW): 74204
The results of the scale up to 500 MW+ power and the effect of ash content in coal can be summarized as follows. Four cases have been studied, where ash content for the coal was 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 from 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.

When combusted in the char combustor, the un-burnts from the gasifier of (about 10% of the load) will give additional increase in efficiency. The char combustor will be of the fluidized bed type which will operate below 950°C that will also reduce NOx emissions. Any further control of SOX can be done by in-situ lime addition. Particulate control will be done by Electrostatic precipitator (ESP). The costing details have to be however worked out more.

It is observed that coal based IGCC plants have higher efficiencies for large scale MW plants as compared to coal power plants using super critical technology. We should 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 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.

**IGCC provides elegant way for reductions of SOx & NOx**

Thermal Power Plants using Advanced Super Critical Technologies are more focused on the enhancement of 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. Recent studies from low rank coal gasification are reported by Park et al [1] for 300 MW (coal input based) IGCC plant. without CO2 capture. The calculated net power is reflected in the gas turbine and steam turbine block. 58.6% of the total coal input higher heating value was converted into electrical energy with gross efficiency of 52.3%. The gas turbine and steam turbine accounted for 36% and 16.3% of the total coal inlet heating value, respectively. 42.4% of the total coal inlet heating value is converted into net power with 9.9% of the gross power lost. Besides, they have reported that the CO2 emissions are around 753.15 kg/MW. Hence, 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.
The OPTIMASH 1 MWth high ash coal gasification 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.

a. Substitute Natural Gas (SNG) Production
The major factors which 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.

b. 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 system can make this process economical.

As presented in the Table below, the above cases show that 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.

<table>
<thead>
<tr>
<th>IGCC operating conditions for small to medium scale up models</th>
<th>Parameters</th>
<th>Plant Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal 1270 [kg/hr]</td>
<td>1 MWe</td>
<td></td>
</tr>
<tr>
<td>Air 2515 [kg/hr]</td>
<td>5 MWe</td>
<td></td>
</tr>
<tr>
<td>Steam 223.5 [kg/hr]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Syngas 3465 [kg/hr]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel heat in, LHV 4.885 [MW]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Syngas heat to engine, LHV 3.037 [MW]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engine Electrical Efficiency 33.3%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power generated 1.011 [MW]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engine exhaust Temp. 450 [oC]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WHR exit Temp. 140 [oC]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Additional heat available 0.805 [MW]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Additional hot water@85oC 0.80 [MW]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total electrical efficiency 20.7%</td>
<td></td>
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</tbody>
</table>
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 [2]. Data in the literature 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 [3-5]. Quantitative economic analysis is performed on individual IGCC power plant to calculate Levelized Cost of Electricity (LCOE) which is a very useful measure to compare different power plants [5].

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. In Ref. 1, this methodology is applied to estimate the equipment cost of an IGCC power plant of 300 MW class [1]. It was estimated that the LCOE for an AFC (Ash Free Coal) fuelled IGCC power plant without CO2 capture was $ 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 are represented in the Table below. It can be observed 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/kWh. It is important to not consider those financial figures at face value but rather as showing that such financial estimates can be doable today with existing software. The details of the calculations are not given here but can be provided if requested [6].

Financial summary of 132 MWth IGCC plant
Annual electricity generation 810 10^6 kWh
Annual steam generation -962.1 10^9 kJ
Annual fuel consumption 5773 10^9 kJ LHV
Annual water consumption 573.4 10^6 l
Annual CO2 emissions 742.8 ktonne
Total investment 244049 k USD
Specific investment 2184 USD per kW
Initial Equity 73215 k USD
Cumulative net cash flow -15003 k USD
Net Present Value -97829 k USD
Break-even electricity price @ input fuel price 0.0809 USD/kWh
Break-even fuel LHV price @ input electricity price 14.45 USD/Gcal

Some Conclusions

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 demonstration plant provides enough data for scaling up gasification plants for various power levels and applications. The simulation results show 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 indicates 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 show 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 shows 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 MWt 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 will 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.

References

DISSEMINATION ACTIVITIES

The main dissemination activities of the OPTIMASH project concern publications in peer reviewed journals and presentation of the project results in various conferences. These activities are listed below:

OPTIMASH PUBLICATIONS

Journal publications


Some conferences

Gökalp, I., Ersoy, M., OPTIMASH Project: A Technological Option for Electricity Generation from Turkish Lignites”, Proceedings of 12. Turkish Energy Congress, 14-16 November 2012, Ankara, Turkey


K. Jayaraman, E. Bonifaci, N. Merlo and I. Gökalp, High ash Indian and Turkish coal pyrolysis and gasification studies in various ambiences. Mediterranean Combustion Symposium, September 8-13, 2013, Çeşme, İzmir, Turkey

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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

List of Websites:
www.optimash.eu
Contact: Dr. Iskender Gökalp, ICARE-CNRS
iskender.gokalp@cnrs-orleans.fr

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