STAGED OMB FOR MODULAR GASIFIER/BURNER

Final Technical Report

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ABSTRACT: The goal of this final project report is to comprehensively summarize the work conducted on project DE-FE0031506. In accordance with the Statement of Project Objectives (SOPO), the University of Kentucky Center for Applied Energy Research (UK CAER) (Recipient) has developed a staged opposed multi-burner (OMB) gasifier, scaled down from a commercial gasification technology to utilize coal slurry as feed for the high-temperature gasification. The project involved the design, fabrication, commissioning, parametric testing, and performance validation of the entrained gasifier with multiple burners to narrow the major near-term technical gaps that impede the application of small-size gasification by modularizing the system.

Project results verified the UK CAER approach to address the major technical challenges on the gasification modularization for a distributed application at a small scale of 1-5 MWe, while maintaining advantages in cost and flexibility, which include: 1) a cost-effective burner configuration to provide high flexibility in both load and fuel feed; 2) the modularized staged-OMB to provide better gasification performance such as a desired temperature profile, better fuel conversion, better gasification efficiency, and long lifetimes of the refractory wall and burners; and 3) load control simply through changing the number of burners firing. UK CAER's staged gasifier configuration, fuel blend performance, and economic evaluation shows promise, as summarized in this report, as an effective means for improved gasification efficiency with reduced operation cost and process complexity.

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1) EXECUTIVE SUMMARY

1.1 Overview

To meet the US Department of Energy (DOE) strategic goal on the modularization of gasification technology for a distributed application at a small scale of 1-5 MWe, while maintaining advantages in cost and flexibility, UK-CAER has developed a staged-OMB gasifier with a scaled-down commercially available OMB gasification technology to utilize coal water slurry (CWS) as feed for high-temperature gasification. This staged-OMB arrangement aims at reaching a high flexibility of fuel feed and load by varying the number of burners in service, improving fuel conversion and gasification efficiency by providing a better flow pattern and mixing because of the opposed burner arrangement, and prolonged burner service life by controlling temperature distribution along the gasifier to avoid hot spots. This staged-OMB arrangement provides for staged-firing of standardized opposed burners to obtain a wide range of fuel feed and advances application of modularization to small-scale gasification.

The UK CAER 1 ton per day (TPD) (dry basis) OMB gasifier was modified to allow for staged gasification with a five-burner configuration and operated to demonstrate the flexibility in fuel feed and load while maintaining operational stability and reliability, through parametric experiments. The staged-OMB gasifier is able to provide an expanded load range of 20%-150% (turn-down ratio of 7.5) compared to 40%-120% (turn-down ratio of 3) of the original design. Additionally, the burner design installation has been standardized to that all five burners are identical and can be easily replaced when needed. Finally, the effect of water quench on the product gas composition was investigated and found to promote the water gas shift (WGS) to enrich the H_2 content and H_2/CO ratio to a certain extent.

The innovative aspects of the staged-OMB gasifier include: 1) the ability for quick startup or shutdown: it takes ~4 hours to switch between configurations; 2) a high-capacity factor: there are five burners in the gasifier which can be treated as three independent pairs for material feed, which ensure the high reliability and availability of the gasification unit; 3) high load flexibility: the gasifier can be operated with the load range of 20%-150% of design capacity.

To reach the cost reduction goal and to enable the opportunity for lifecycle greenhouse gas reductions by locating distributed generation and/or fuel production closer to the energy source, a scaled-down gasification technology is required, where the modularized gasifier needs to have high flexibility in both load and fuel for wide application by the end user at different locations with different fuel, especially in remote areas. The major obstacle to wide market penetration is the high capital cost required for such an operation at small scale. With the advancement delivered upon the success of the UK staged-OMB gasification technology, the effect of this hurdle has been reduced. This process has three major competitive advantages that will drive market penetration. First, a cost-effective modularized burner approach to provide high flexibility in load and fuel. Even though the COE (Cost of Energy) for a 5 MWe staged-OMB gasifier is high, the fuel and variable O&M (Operation and Maintenance) are low compared to other reference cases. Fixed O&M and capital costs are the main contributors to the high COE. Second, the staged-OMB gasifier outperforms the comparison gasifiers on total syngas production, syngas heating value, and H_2/CO ratio. Differences in CO_2 content in the product syngas and oxygen demand of the gasifier are marginal. Third, while the staged-OMB gasifier does provide moderate cost savings in the gasification process area, the other process areas account for nearly 77% of the total plant cost. Significant capital savings in other process areas, specifically power production, air separation, and acid gas removal, would have the biggest impact on the economic feasibility of this process. Demonstration of the technical feasibility of this staged-OMB gasifier for syngas production and/or power generation, shows the commercial potential for modularization of the gasifier at small scale with multiple burners.

1.2 Key Results

Task 2.0 – Construction of the Staged-OMB Gasifier

UK CAER modified the existing 1 TPD pilot-scale gasifier with the addition of one vertical burner to the top of the gasifier to allow for staged-firing. An existing port was utilized. This modified staged-OMB gasifier has five burners controlled independently by a set of slurry feed pumps and mass flow controllers (MFCs). The available operation modes for this two-row configuration can be in an ascending load, with firing of either one burner (vertical), two burners (one pair), three burners (vertical + one pair), four burners (two pairs), and five burners (vertical + two pairs). The staged-OMB gasifier has provided a wide load range of 20%-150% of design capacity.

The existing top port, designed for an endoscope, included a 2” flange while the horizontally oriented ports for the burners include 4” flanges. A spare horizontally mounted burner assembly was modified by machining the 4” flange off and welding a 2” flange on. The results of this work are shown in **Exhibit 1**. The burner length was not modified.

Exhibit 1. Original Burner (left) and Fifth Burner with Smaller Flange (right).

Burner Atomization Optimization: To reduce the residual carbon in the coal ash/slag, atomization optimization experiments were performed. The burner configuration is shown in **Exhibit 2** and test rig data collected with the original configuration is shown in **Exhibit 3**. Atomization was evaluated in a test rig, external to the gasifier, with water blown with N_2, not CWS blown with O_2 as used during gasification. It was found that each burner tip and jacket diameter was slightly different, but when matching the components to get as close as possible to a 1 mm anulus around the burner tip, the difference in feed velocities was minimized.

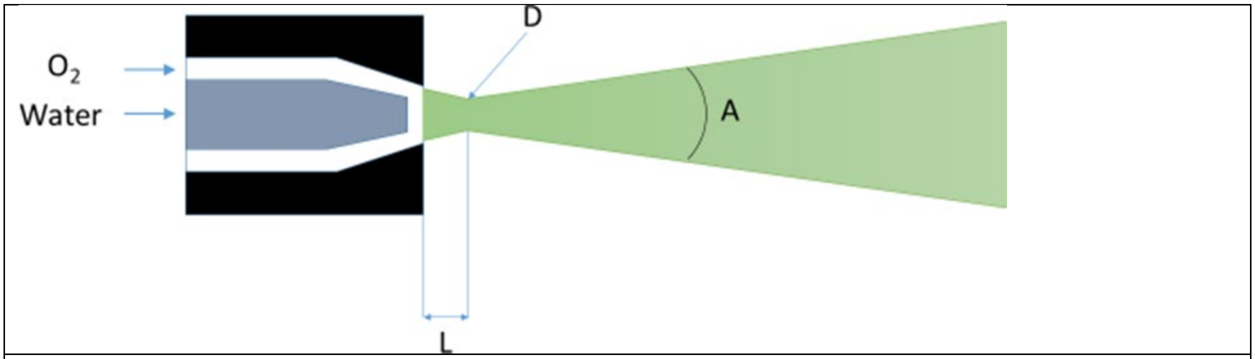

Exhibit 2. Atomization of CWS Burner.

Exhibit 3. Burner parameters affecting operation, after anulus around the burn tip adjusted.

Burner	Tip Diameter (mm)	Jacket Diameter (mm)	Velocity Before annular adjustment (m/s)	Velocity after annular adjustment (m/s)
C	7.0	7.54	85	99
A	6.9	7.47	85	98
D	6.8	7.34	87	99
B	6.7	7.21	90	99

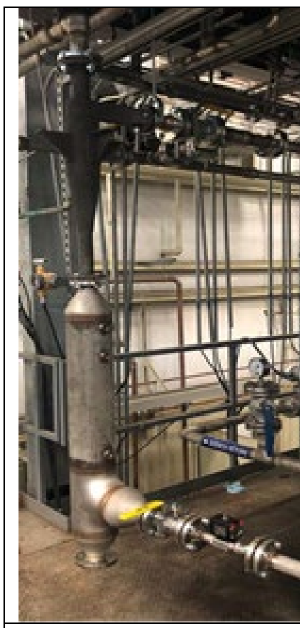

Exhibit 4. Cyclone separator installed with sump level control.

A new cyclone separator was installed between the quench chamber and the water scrubber, as shown in **Exhibit 4**. This new cyclone separator is designed to remove approximately 50% of the total particulates from the product syngas line exiting the gasifier. The addition of the cyclone separator allows for longer operational periods and helps prevent downstream clogs in the water scrubber.

Task 3.0 – Parametric Study of Staged-OMB

Performance with and without burner staging was compared by collecting and analyzing experimental data to determine the impact of fluid dynamics on mixing, gasification, and controllability of the gasifier temperature profile which has a direct effect on the burner and refractory service life. Varied process parameters included: the number of CWS-loaded burners, the operating temperature and pressure, the oxygen to carbon (O/C) atomic ratio, and the coal concentration of the CWS.

CWS Burners in Service

The UK CAER gasifier was operated in two ways. First, with four opposed burners, two pairs of two burners, all loaded with CWS and with two opposed burners loaded with CWS and second with one set of opposed burners loaded with CWS and the opposite set of burners fed by natural gas for gasification temperature control. The gasification pressure is constant to 0.1 MPaG and the coal used is River View coal (RV) from Western Kentucky. Two CWS burner operation had higher effective syngas content ($CO+H_2$) at both gasification temperatures evaluated than four CWS burner operations; however, the carbon conversion was lower. This may be due to the supplemental natural gas feed. **Exhibit 5** shows that more natural gas was fed during condition 3 than condition 4 to maintain a 1400 ºC gasification temperature compared to 1350 ºC. This shows that operation with four CWS burners can both maintain the gasification temperature and produce a higher content of effective syngas, with a higher carbon conversion, than operation with only two CWS burners.

Exhibit 5. Operating conditions for testing the quantity of burners loaded with CWS.				
Operating Condition	**1**	**2**	**3**	**4**
Type of Coal	RV	RV	RV	RV
Gasifier Chamber Temperature (°C)	1400	1350	1400	1350
Gasification Chamber Pressure (MPaG)	0.1	0.1	0.1	0.1
CWS Solid Content (wt.%)	57	57	57	57
Additive (Coal-based wt.%)	0.3	0.3	0.3	0.3
Limestone (Coal-based wt.%)	1	1	1	1
O/C Atomic Ratio	1.00:1	1.03:1	1.04:1	1.02:1
Number of CWS Burners in Service	4	4	2	2
Number of Natural Gas Burner in Service	0	0	2	2
Heat Value Ratio (NG%:Coal%)	0:100	0:100	20:80	8:92

Operating Temperature

Three temperatures (1300 °C, 1350 °C and 1400 °C) are tested with two CWS burners and two natural gas burners in service. Again, the pressure is constant at 0.1 MPaG and the RV coal is used. The results on the syngas composition, effective syngas content, and carbon conversion are given in **Exhibit 6**. The H_2 content decreased with increasing operating temperature but is higher than the contents of CO and CO_2 for all three conditions. This indicates that part of the natural gas is gasified to produce higher H_2 levels leaving some of the coal in the gasification chamber unreacted. At higher temperatures, the CO content decreases, and the CO_2 content increases due to heat request. The carbon conversion and effective syngas content are given in the right graph of **Exhibit 6**. The effective syngas content reduces while the carbon conversion increases with the increasing operating temperature. Although the higher temperature benefits the gasification of coal, the gasification temperature also needs more heat from the combustion to be maintained.

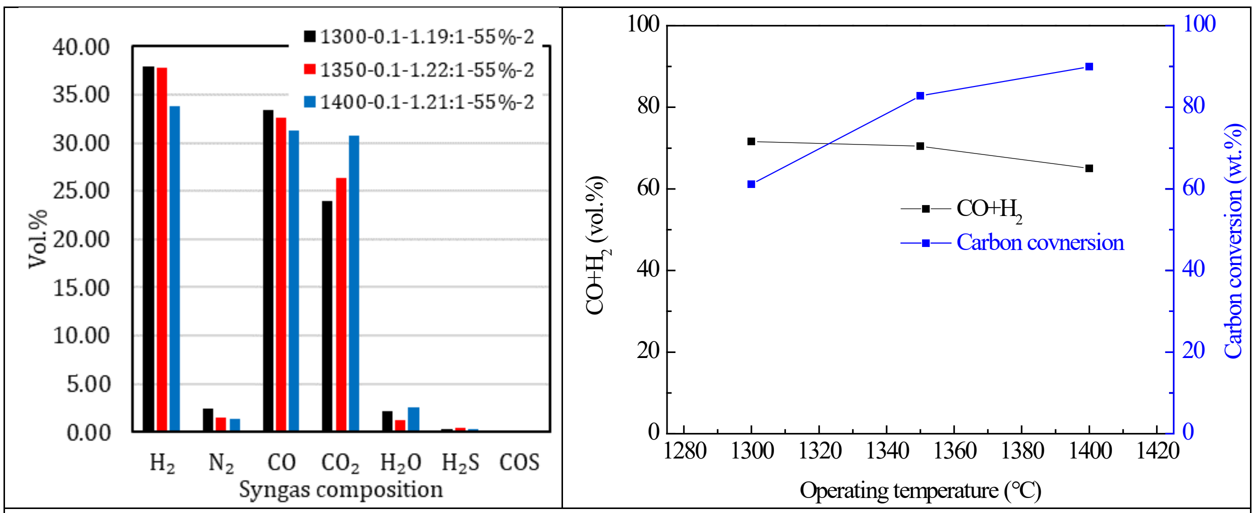

Exhibit 6. Syngas composition and carbon conversion at different operating temperatures.
Note: The operating conditions are denoted with the values given in the legend. These identifying numbers are ordered as: Operating Temperature (°C), Operating Pressure (MPa), O/C Ratio, coal concentration (weight %), and Number of CWS Burners. For example, the condition "1350-0.1-1.1:1-55%-2" means the operating temperature is 1350 °C, the pressure is 0.1 MPaG, the atomic ratio of

oxygen to carbon of the reaction is 1.1:1, the coal concentration in CWS is 55 wt.%, and the number of burners loaded with CWS is 2.

CWS Concentration

The gasification performance is related to the coal concentration in CWS because water requires energy to evaporate. During this project, the effect of different CWS concentrations from 55 to 59 wt.% was tested and the detailed parameters are listed in **Exhibit 7**. A higher coal concentration in the CWS will affect the viscosity and thus the pumpability of the slurry, and further will affect the atomization performance of the burner.

Exhibit 7. Parameters for testing the effect of the CWS solid concentration.

Operating Condition	**1**	**2**	**3**
Coal Type	RV	RV	RV
Gasification Temperature (°C)	1350	1350	1350
Gasification Pressure (MPaG)	0.1	0.1	0.1
CWS solid (wt.%)	55	57	59
Additive (Coal-based wt.%)	0.3	0.3	0.3
Limestone (Coal-based wt.%)	1	1	1
O/C atomic ratio	1.01:1	1.02:1	1.02:1
Number of CWS Burners in Service	2	2	2
Number of NG Burners in Service	2	2	2
Heat Value Ratio (NG%:Coal%)	14:86	8:92	12:88

Exhibit 8 shows the syngas composition, the effective syngas ratio, and the carbon conversion with increasing CWS concentration. On the left, the CO_2 concentration decreases with increasing coal content due to less water evaporation. This points to an overall increase in gasification. This is also indicated by the increased amount of effective syngas produced at higher CWS concentrations, as shown on the right.

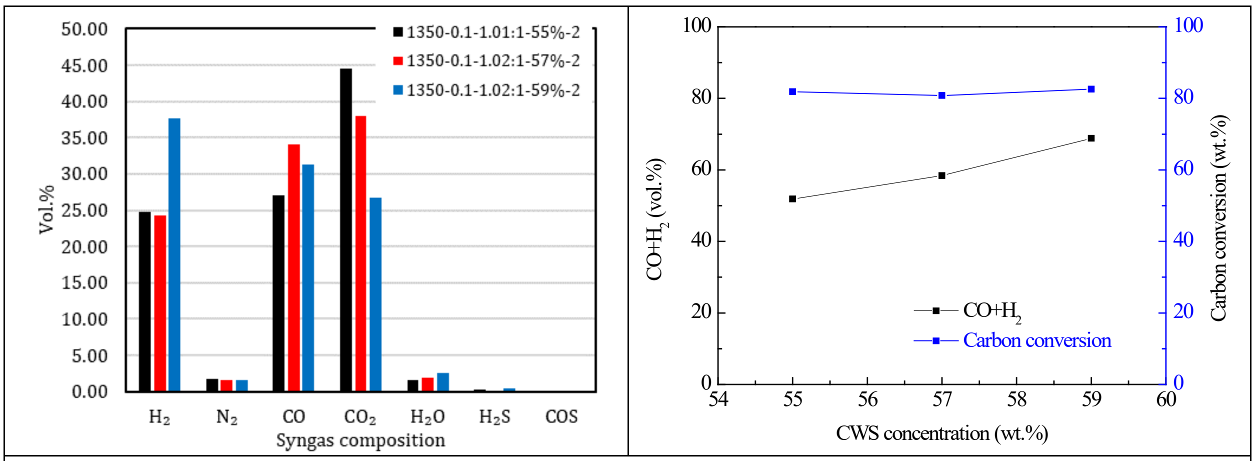

Exhibit 8. Syngas composition and carbon conversion as a function of CWS solid concentration.

O/C Atomic Ratio

The O/C atomic ratio is also used to evaluate gasification performance. The effect of different atomic ratios of O/C in the gasification reaction for the staged-OMB gasifier is investigated and the operating parameters are given in **Exhibit 9**. As shown on the left, both H_2 and CO content are higher than the CO_2 content. However, as shown on the right, the carbon conversion is low compared to the other testing conditions. The increased CO_2 content may be attributed to the increased oxygen flow rate from the increased O/C atomic ratio due to high solid concentration in the CWS. Oxygen will more easily react with the natural gas than with coal, so higher H_2 and CO levels are observed with operating with two CWS burners and two natural gas burners than with four CWS burners.

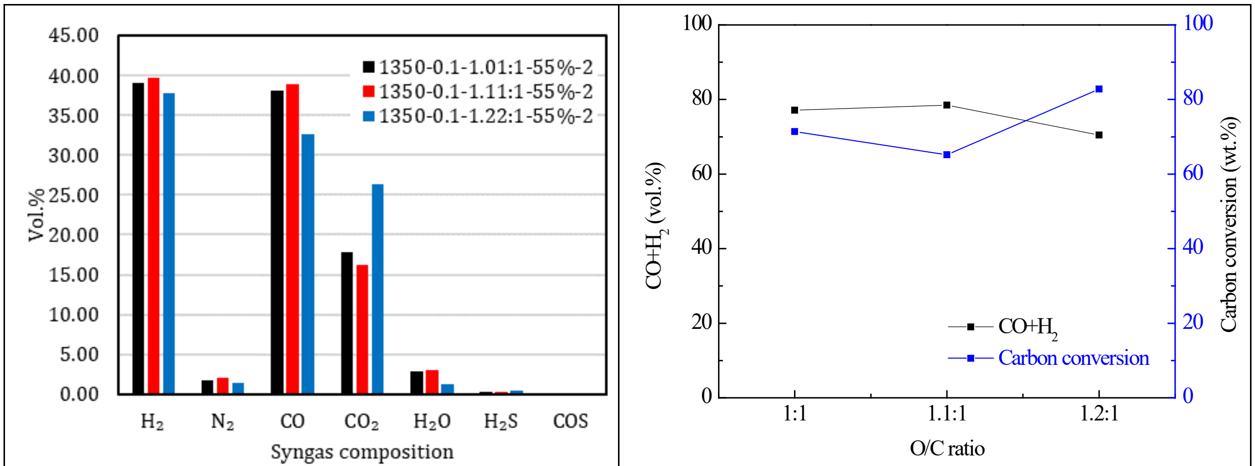

Exhibit 9. Syngas composition and carbon conversion with different O/C atomic ratios.

Operating Pressure

Higher pressure benefits the gasification of coal in entrained flow gasifiers due to reduction of volume of gaseous reactants during the gasification process. Commercial entrained flow gasifiers generally operate at a pressure of 4-6 MPa. The staged-OMB gasifier operation allows lower pressure conditions as shown in **Exhibit 10**. The syngas H_2 content at 0.15 MPaG is lower than that at 0.1 MPaG, but the reverse trend is present for the CO content. Although, the lower operating pressure at both temperatures produces more effective syngas content ($CO+H_2$), the carbon conversion for the higher-pressure conditions is better than at lower pressure conditions. At the lower pressure condition, more natural gas is added to maintain the temperature, possibly causing more gasification of natural gas rather than coal. Additionally, when the pressure increases to 0.15 MPaG, coal gasification increases and the natural gas moves towards combustion for heat support, which is evidenced by the elevated carbon conversion paired with increased CO_2 levels seen at the higher pressure.

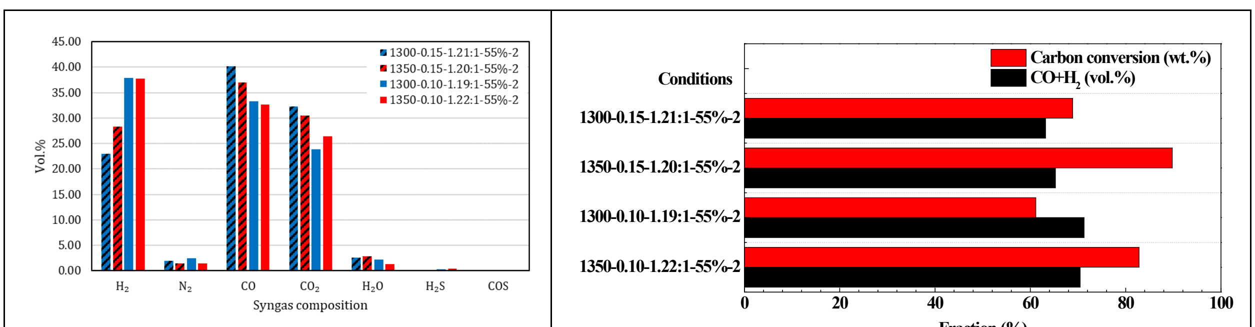

Exhibit 10. Syngas composition and carbon conversion at different operating pressure conditions.

Task 4.0 – Fuel Flexibility with Fuel Blend

Fuels of different rank, ash property, and particle size distribution (PSD) were evaluated to determine the upper and lower limits of staged-OMB application. Blend fuel has been tested to provide thorough information for feeding and burner design. It was determined that fuel blending provides the capability of modifying the ash behavior for gasification. **Exhibit 11** provides details on the five types of coal evaluated.

Exhibit 11. Coal Information Summary.

Parameter	**Gibson Coal**	**River View Coal**	**Powder River Basin (PRB) Coal**	**PRB Coal SCM**	**PRB Coal CRM**
Moisture Content (%)	14.47	12.14	26.11	24.94	29.64
Volatiles Content (%)	31.15	35.62	31.68	31.53	31.17
Ash Content (%)	6.63	8.19	5.42	4.14	5.17
Fixed C Content (%)	47.75	44.05	37.44	39.54	34.50
S Content (%)	1.20	2.92	0.25	0.33	0.29
C Content (%)	64.26	63.05	51.92	54.05	49.27
H Content (%)	4.52	4.64	3.57	3.78	3.48
O Content (%)	7.47	6.35	12.6	11.51	11.9
N Content (%)	1.45	1.45	0.77	0.65	0.72
High Heating Value (BTU/lb)	11535	11514	8800	9350	8425
Fluid Temp-reducing (°C)	1337	1198	1215	1198	1217
Fluid Temp-oxidizing (°C)	1404	1346	1249	1336	1249
T-250 (°C)	1440	1298	1197	1159	1215

Task 5.0 – In-situ Water Gas Shift (WGS) Development

To promote the H_2/CO ratio, the syngas generated from the gasifier needs to be conditioned by WGS.

UK CAER investigated how to form an optimally staged quench method with an adjustable water flow rate injected at each stage to enhance the WGS. As shown in **Exhibit 12**, the H_2/CO ratio was greatly improved with the addition of red mud. 7.5 to 15 kg of red mud with a particle size of <125 um was added to the quench water over a course of ~15 minutes when operating with two CWS and two natural gas burners in service.

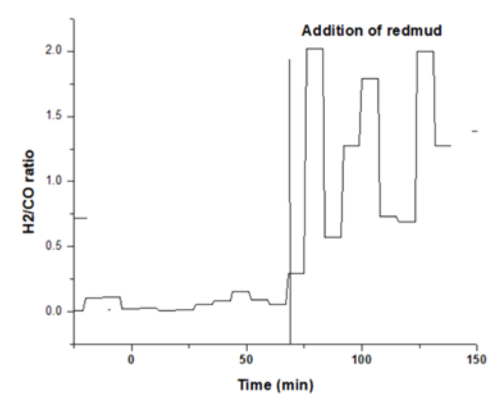

Exhibit 12. Syngas H_2/CO ratio without then with catalytic in-situ WGS.

Simulation was also completed to aid understanding of observed test results. The study shows that the H_2/CO ratio can be promoted and that a 600-800 °C temperature zone can be formed to allow for improved WGS at the exit of the gasification chamber before further quenching to a lower temperature, approximately 70 °F.

Task 6.0 – Burner Testing

The gasifier burner are very important for high fuel conversion and load turn down ratio. Performance improvements were established through oxygen and N_2 (simulating syngas) staging and mixing with fuel to induce hot gas local recirculation around the burner jet, and the intensity of impingement at burner plane for a better ignition, fast fuel heat up, and flame stability.

The burner tests are summarized in **Exhibit 13**.

Exhibit 13. Burner test summary.

Operating Condition	**1**	**2**	**3**	**4, 9**	**5, 16**	**6, 13, 17**	**7**	**8, 11**	**10**	**12**
Type of Coal	RV	RV	RV	RV	RV	RV	RV	RV	RV	RV
Gasification Temperature (°C)	1400	1350	1400	1350	1300	1350	1400	1350	1350	1350
Gasification Pressure (MPaG)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
CWS Solids Concentration (wt%)	57	57	57	57	55	55	55	55	59	55
Additive (coal-based, wt %)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Limestone (coal-based, wt %)	1	1	1	1	1	1	1	1	1	1
Feed O/C Atomic Ratio	1.00:1	1.03:1	1.04:1	1.02:1	1.19:1	1.22:1	1.21:1	1.01:1	1.02:1	1.11:1
Number of CWS Burners in Service	4	4	2	2	2	2	2	2	2	2
Number of Natural Gas Burners in Service	0	0	2	2	2	2	2	2	2	2
Heat Value Ratio (Natural Gas%:Coal%)	0:100	0:100	20:80	8:92	12:88	20:80	20:80	14:86	12:88	20:80
Syngas Content										
H_2 (vol%)	27.86	25.82	39.56	24.25	37.92	37.79	33.77	24.81	37.61	39.67
N_2 (vol%)	1.40	1.54	1.27	1.63.	2.40	1.44	1.3.6	1.79	1.55	2.02
CO (vol%)	34.43	31.52	35.00	34.13	33.34	32.66	31.24	27.07	31.24	38.81
CO_2 (vol%)	32.83	38.22	21.20	37.98	23.90	26.40	30.71	44.45	26.70	16.13
H_2O (vol%)	3.11	2.70	2.57	1.88	2.16	1.28	2.59	1.64	2.49	3.06
H_2S (vol%)	0.34	0.19	0.38	0.12	0.27	0.41	0.31	0.23	0.40	0.29
COS (vol%)	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.02	0.01
$CO+H_2$ (vol%)	62.29	57.34	74.56	58.38	71.26	70.45	65.01	51.87	68.85	78.48
CO/CO_2	1.09	0.86	8.60	0.90	4.25	1.28	1.04	0.85	1.56	5.88
H_2/CO	0.81	0.82	1.13	0.71	1.13	1.16	1.09	0.92	1.21	1.02

Task 7.0 – 3-D Simulation of Staged-OMB Gasifier and Burner Effect

UK CAER developed an experimentally calibrated, 3-D gasifier model and used it as an analysis tool to simulate the staged-OMB gasifier with different operating conditions and designs. By using this model, UK CAER has performed a systematic and parametric study to understand the impact of fluid dynamics and fuel properties, as well as the arrangement of burners, on the gasifier flow field, impinging, mixing, and resulting temperature profile and performance, including the jet momentum on the impinging of jet streams, on the residence time distribution of fuel particles, and the flame zone temperature and distribution.

Fluid Velocity Distribution

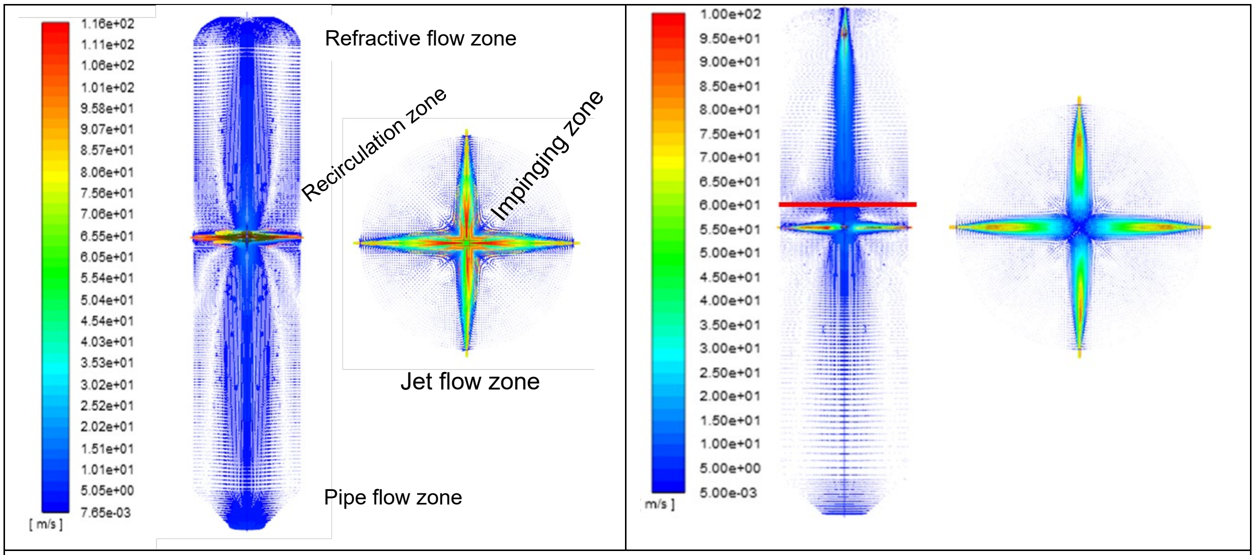

Exhibit 14. Velocity Vector Distribution of the Flow in the OMB four-burner gasifier (left) and staged-OMB five burner gasifier (right).

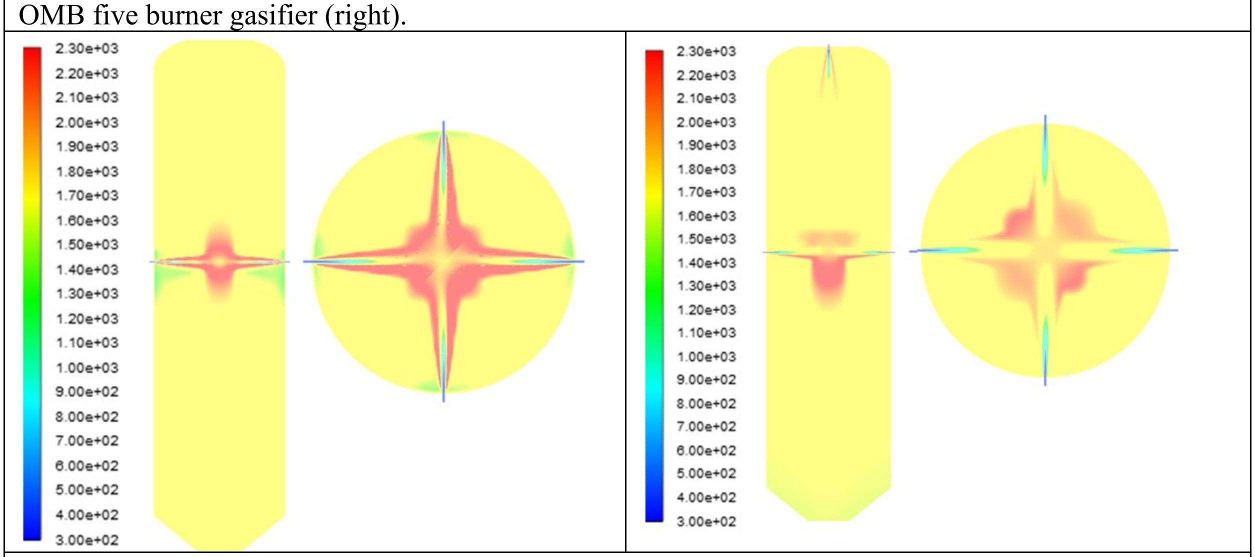

Exhibit 15. Temperature Distribution in the OMB four-burner gasifier (left) and staged-OMB five burner gasifier (right).

The feed slurry entering the gasifier from four opposed nozzles collides in the furnace and is impinged in the center. Five fluid zones are defined and labeled in **Exhibit 14,** including jet flow zone, impinging zone, refractive flow zone, recirculation zone, and pipe flow zone. For five burner configuration (Exhibit 14-right), due to the blocking effect of the impinging, the turbulence intensity in this impinging zone is very high. Moreover, the five-burner gasifier adds an impact area in the upper part of the chamber that also enhances the turbulence intensity on the upper part. Comparing the velocity vector diagram of four burner configuration with that with five burners, the difference is mainly that the upper flow field of the staged-

OMB (five-burner) gasifier is more intensified, and the backflow position of the staged-OMB gasifier is located around the upper impinging zone. The fluid velocity in these two gasifiers both can reach 100 m/s.

Temperature Distribution

On the burner plane, as shown the cross-section area in **Exhibit 15**, the temperature in the impinging zone is similar for the OMB (four burner) gasifier and staged-OMB (five burner) gasifier. It can be seen from the temperature distribution graph that the high temperature area of the gasifier is mainly concentrated near the jet boundary and around the impact area of the flow stream. The temperature distribution near the wall of the gasifier is relatively low and uniform, indicating that the temperature distribution in the multi-burner gasifier is reasonable.

Moreover, the temperature of slag hole zone in OMB gasifier is about 1200 ℃, lower than the temperature value of the staged-OMB gasifier, nearly 1400 ℃. This proves that the addition of the fifth burner can push the high-temperature zone down and closer to the slag hole zone which benefits the slag discharge.

Syngas Component & Concentration Distribution

Exhibit 16 shows the contour plots of the volume fraction of CO, H_2, H_2O, CO_2 and O_2 in the gasifier. The concentrations of CO and H_2 are high for the operation of staged-OMB gasifier, due to the high mixing efficiency from five burners. CO_2 in the four-nozzle gasifier is concentrated in the jet boundary area, mainly generated by swirling and recirculated combustion. There is a large amount of H_2O in the outer boundary area of the jet around the plane nozzle outlet of the staged gasifiers, which mainly comes from two aspects: one is generated by entrapment of H_2 combustion; the other is generated by evaporation of water from coal slurry in the inner boundary layer due to a large amount of heat generated by combustion. However, in the staged-OMB gasifier with five burners, due to the addition of an impinging zone in the upper flow field, the backflow stream in the upper furnace will carry H_2O to disperse in the upper furnace. Therefore, with the development of refraction flow, the secondary reaction is enhanced, and the concentration of H_2O decreases and reaches equilibrium in the pipe flow area. The carbon dioxide concentration in the staged-OMB gasifier concentrates on the border near the burner. There is less O_2 and only located on the core jet flow of the burner.

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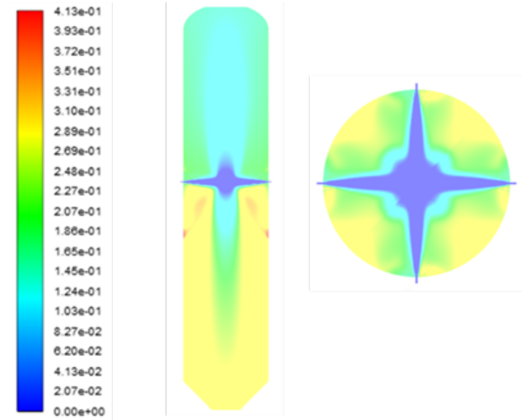
CO



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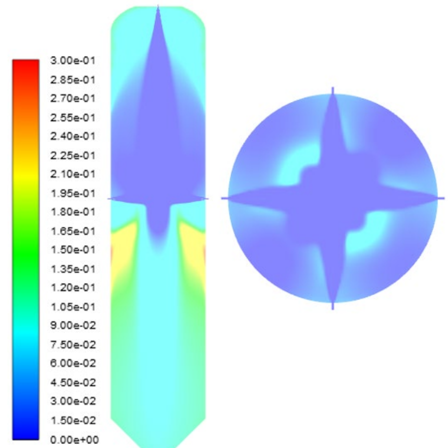
CO



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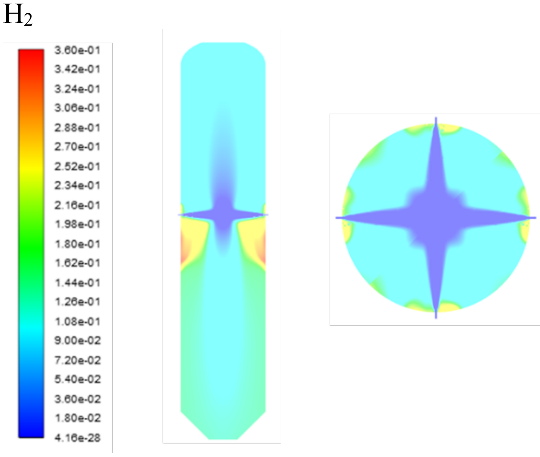
H_2



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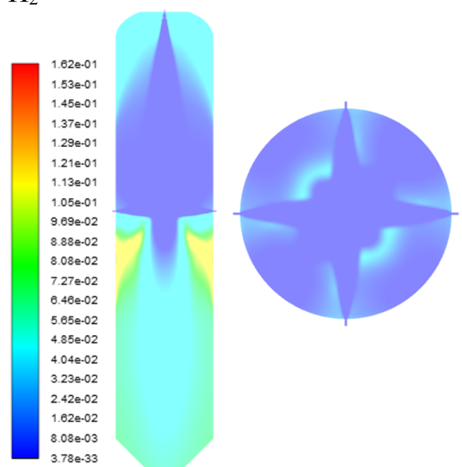
H_2



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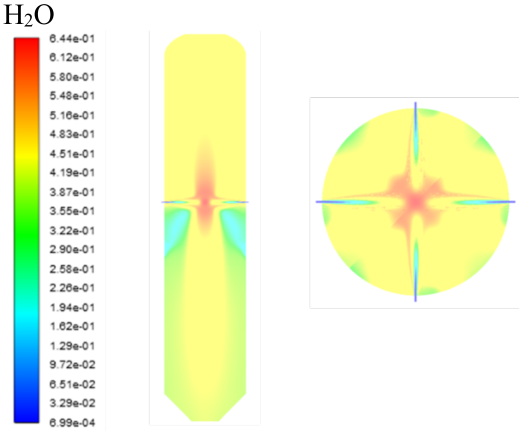
H_2O



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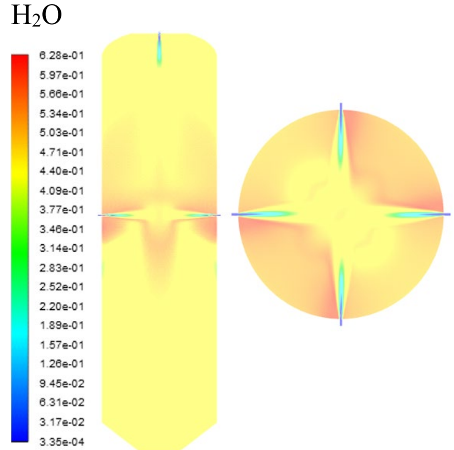
H_2O



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CO_2

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CO_2

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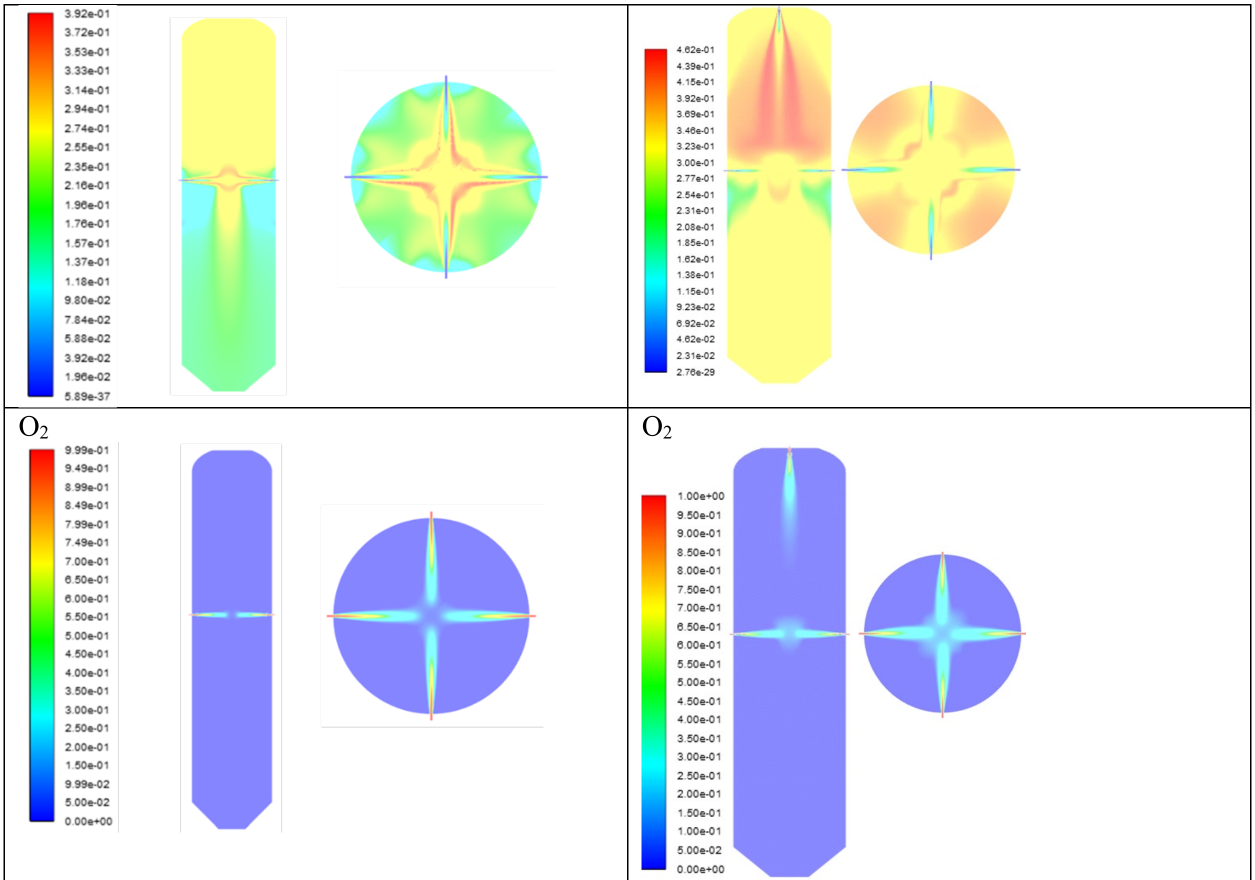


Exhibit 16. Distribution of Syngas Composition in the OMB four-burner gasifier (left column) and staged-OMB five burner gasifier (right column).

Task 8.0 – Technical and Economic Analysis

Based on data gathered in previous Tasks, UK CAER created an Aspen Plus process model to use for process optimization, performance evaluation and equipment sizing of the 1-5 MWe integrated gasification combined cycle (IGCC) or Coal-To-Liquids (CTL) unit. The analysis was consistent with the National Energy Technology Laboratory (NETL) “Quality Guidelines for Energy System Studies.” This cost and performance baseline study provides process descriptions, heat and material balances, and estimated costs for full-scale IGCC plants with and without CO_2 capture for GE, Shell and CB&I E-Gas gasification technologies. For the purposes of this comparison, the normalized costs for the UK CAER technology are considered and compared to the full-scale CB&I E-Gas IGCC plant without CO_2 capture.

Based on bare equipment costs with appropriate installation factors applied. The capital is reported as Q4 2020 dollars, with all source costs adjusted to a chemical engineering plant cost index (CEPCI) of 595.9. Trimeric estimated a total purchased equipment cost of $21.0 MM with a total plant cost of $35.1 MM. The total annual operating revenue, operating expenses, and indirect expenses are shown in **Exhibit 17**. The facility’s annual revenue and operating expenses consider the gasifier facility online 80% of the time during a calendar year which is consistent with the DOE reference report. Indirect expenses are not impacted by the fraction of time the facility is online. Overall, the gasification facility will lose money when operating – independent of capital expenditure.

Exhibit 17. Annual Revenue and Operating Costs for Gasification Facility.	
Revenue or Expense	**Dollars per Year**
Revenue	$ 2,473,000
Operating Expenses	$ (931,000)
Indirect Expenses	$ (2,339,000)
Total Profit (Loss)	$ (796,000)

The major variable operating cost for the facility is the cost of fuel. The cryogenic air separation unit (ASU) consumes nearly 19% of the gross power output of the reciprocating engines. Lowering the required feed oxygen concentration would allow switching from a cryogenic ASU to vacuum swing absorption (VSA) that has the potential to decrease capital cost and increase the amount of electricity that can be sold to the grid. The largest costs of the gasification facility are fixed operating costs comprising labor and overhead costs, property tax and insurance, and facility maintenance and upkeep. A larger production facility would improve the scaling of fixed operating costs against generated revenue.

As shown in **Exhibit 18**, the UK CAER staged OMB gasifier performance was compared with two small-scale (5.3 and 18 MWe gross) and two commercial-scale (763 and 738 MWe gross) gasification designs that generate power for electricity. The staged-OMB gasifier outperforms the other gasifiers on total syngas production fraction (H_2+CO), syngas heating value, and H_2/CO ratio. The commercial-scale gasifiers (DOE cases B4A and S4A) have a moderately higher H_2/CO ratio. Higher heating value allows for more power generation and smaller equipment size per unit mass of feed. Higher H_2/CO ratio is more economical for conversion of syngas to chemicals should a polygeneration facility to produce both electricity and chemicals be desired. The staged-OMB gasifier shows marginal differences for CO_2 content in the product syngas as well as oxygen demand.

<table>
<tr><td colspan="8">Exhibit 18. Syngas Production Performance Comparison of UK CAER Staged-OMB Gasification with Other Small and Commercial Scale Power Generating Gasification Facilities.</td></tr>
<tr><th>Description</th><th>Units</th><th>UK CAER Staged OMB Gasifier (Base Case)</th><th>UK CAER Staged OMB Gasifier (Sensitivity Case)</th><th>UK CAER Membrane Wall Gasifier [4]</th><th>UA Fairbanks HMI Gasifier [5]</th><th>DOE Case B4A (CB&I E-Gas™ Gasifier) [1]</th><th>DOE Case S4A (CoP E-Gas™ Gasifier) [2]</th></tr>
<tr><td>O_2/(H_2 + CO)</td><td>mol/mol</td><td>0.39</td><td rowspan="7">Performance of the 25 MW facility assumed the same as the base case.</td><td>0.51</td><td>0.24</td><td>0.36</td><td>0.48</td></tr>
<tr><td>Carbon Conversion</td><td>%</td><td>98.0</td><td>97.2</td><td>NA</td><td>99.2</td><td>99.1</td></tr>
<tr><td>Syngas Quality</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Higher Heating Value (HHV) at Outlet</td><td>Btu/SCF</td><td>268</td><td>262</td><td>167</td><td>240</td><td>242</td></tr>
<tr><td>H_2 + CO</td><td>Mole Fraction</td><td>0.81</td><td>0.70</td><td>0.46</td><td>0.71</td><td>0.69</td></tr>
<tr><td>H_2/CO</td><td></td><td>0.82</td><td>0.64</td><td>0.70</td><td>0.91</td><td>0.95</td></tr>
<tr><td>CO/CO_2</td><td></td><td>2.58</td><td>2.99</td><td>3.70</td><td>1.94</td><td>1.32</td></tr>
</table>

2) BACKGROUND AND TECHNOLOGY DESCRIPTION

2.1 Project Background and Objectives

Syngas is an important product/reagent used to produce a wide range of commercial products and consumables with some of the largest being synthetic petroleum products, ammonia, hydrogen, and methanol. These chemicals represent a massive multi-trillion-dollar market reaching across a wide variety of industries, such as (but not limited to) fuels, lubricants, and fertilizers. In addition, syngas is finding increased usage for the generation of electricity and transportation fuels. The major restraint to wide market commercialization is the high capital cost required for such an operation and the application of CO_2 capture. However, with the success of the UK CAER modular gasification process, the effects of this burden will be minimized, allowing for more rapid market penetration. The desire to produce electricity, fuels, and products while utilizing low carbon footprint technologies will serve as a market driver for the commercialization of the proposed technology.

The OMB gasifier has been commercialized, with the largest single train of 3,000 TPD coal feed, and over 60 gasifiers are in operation worldwide, mostly in China. It has a 15.3% market share worldwide in the entrained flow coal gasification sector. It shows good performance in fuel conversion, syngas quality, operational stability, and reliability. The successful completion of this project has the potential to provide many public benefits. Tantamount among these will be the continued utilization of abundant and low-cost U.S. coal to produce reliable electricity within a foreseen period while environmental concerns are affordably managed. Four major benefits from this project are: 1) development of a cost-effective approach to a modular gasifier configuration with multiple burners; 2) a novel entrained fluidization reactor design that reduces the potential for solid (e.g. coal) agglomeration and facilitates simple, yet effective, in-line ash separation; 3) an engineering design of configuration layout, fabrication, and construction and 4) reinforcement of confidence in the gasification deployment by completion of a detailed TEA and reactor performance simulation.

The main objective is to modify the UK CAER 1 TPD dry coal feed OMB gasifier to include a staged configuration simply by replacing the existing camera monitor with a burner at the top of the gasifier for staging-firing, and then demonstrate the potential gain, mainly the flexibility in fuel and load, operational stability and reliability, and refractory wall/burner protection, through parametric experiments. The project's staged-OMB gasifier is able to provide a load ranging from 20% to 150% of the design condition (e.g. gasifier with turn-down ratio of 7.5) compared to 40% to 120% of the same design condition (e.g. turn down ratio of 3) of the original OMB gasifier. The second objective is to standardize the burner design. Short burner service life is another issue for high temperature operation, resulting in a requirement of replacement. It becomes helpful to modularize burner design and installation so that all of the burners are identical and can be easily replaced when needed. The third objective is to investigate the effect of water quench on gas composition, i.e. on H_2 production by water gas shift (WGS) reaction. The addition of quench water would be able to promote the WGS to enrich the H_2 and H_2/CO ratio to a certain extent. The task is to improve the WGS by use of quenching water.

All Project Success Criteria were satisfied and are shown in **Exhibit 19**.

Exhibit 19. Project Success Criteria.

Completion Date	Success Criteria
FY18	Completion of the pilot scale staged-OMB modifications and reactor ready for operation

FY19	Gather data from the staged-OMB parametric testing showing improvements of the process modifications on flexibility and efficiency Gather data from in-situ WGS testing Improve carbon conversion of staged-OMB from baseline OMB conversion and cold gas efficiency by 2% with variation in feedstocks
FY20	Completion of the 3-D modeling of staged-OMB process based on data from UK CAER testing A finalized engineering process design and Aspen-Plus based simulation model; equipment list and sizing; technical-economic analysis including capital and O&M cost estimates; for the 1-5MW scale

Knowledge gained from the execution of this project includes analysis that supports the design, construction, and operation of the 1 TPD modular OMB gasifier to promote successful technology development and demonstrated the feasibility to be implemented in a real gasification environment. In addition to the specific goals and success criteria for this project, the UK CAER broader objective was to contribute to building a base of knowledge, techniques, people and infrastructure that will accelerate beneficial technology developments emerging from this project toward commercialization in a manner that benefits the economy and society by providing cost-efficient, sustainable environmental protection related to power generation from coal and other fossil fuels, which will remain essential in society for the foreseeable future.

2.2 Facility Description

As part of previous DOE funded research and development (R&D) projects (DE-NT0005988 and DE-FE0010482), an entrained-flow OMB gasifier has been fabricated, installed and operated at UK CAER with four burners, as shown in **Exhibit 20**. The entire facility consists of three systems. (a) The coal water slurry preparation and supply system: With a normal handling capacity of ~200 kg coal /h, the mill uses water and an additive to generate the coal water slurry as ~60 wt% coal and ~40 wt% water. The coal is ground using the rotation of stainless-steel balls. (b) The gasifier: The gasifier, which is 4 ft. in diameter and ~20 ft. in height, is constructed of a refractory and stainless-steel outer wall and is divided into two sections with the gasification chamber at the top and the quench chamber at the bottom. (c) The control and safety systems: A DeltaV Distributed Control System (DCS) from Emerson Company is used to control the unit startup, operation, and shutdown including emergency cut-off. Upon entering the gasification chamber, the coal/biomass water slurry and oxygen react to produce crude syngas and molten ash, which then passes to the quench chamber through a crossflow water spray and subsequent water bath. This acts as a first wash for the raw syngas and removes large ash particles while also quickly removing heat. Moreover, the syngas is completely saturated in this step due to the requirements of downstream purification processes. After the washed syngas leaves the quench chamber, it proceeds to a water scrubber which removes about 80% of the unconverted particles and remaining ash. The water scrubber is the last step in the gasification process before the syngas continues downstream for further processing.

This existing four-burner OMB gasifier was modified and operated along with the supporting systems during the course of this project.

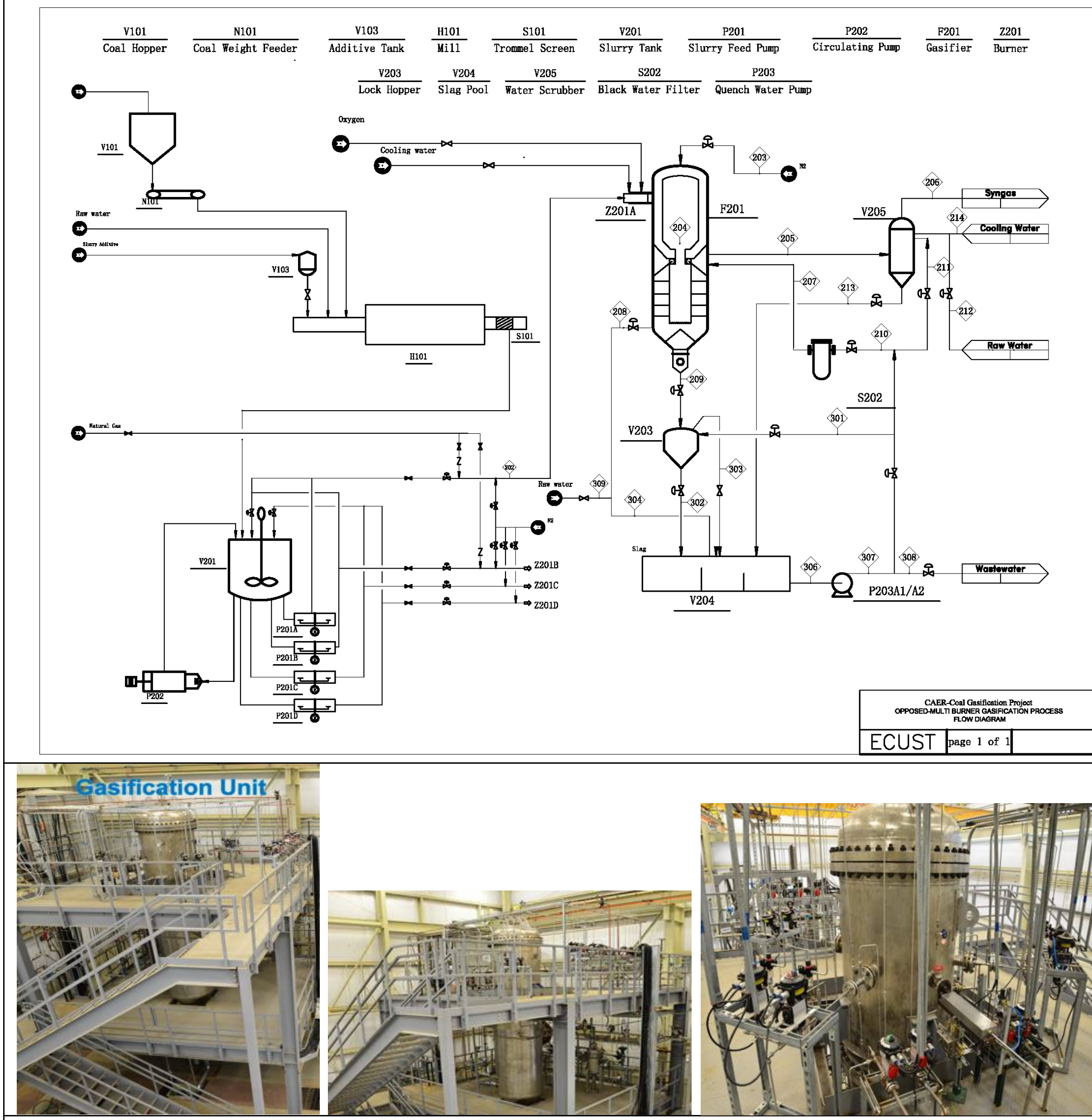


Exhibit 20. Process flow diagram and the OMB gasifier installed at UK CAER.

3) PROJECT TECHNICAL RESULTS

3.1 Construction of the Staged-OMB Gasifier

To be able to provide a modularized gasification technology at a scale of 1-5 MWe for distributed power generation and/or fuel production to achieve programmatic cost reduction and simultaneously add flexibility, a staged-OMB gasifier module with five burners has been demonstrated to tackle the concerns associated with gasifier fuel flexibility, turn-down ratio and service life of the refractory and burners. The addition of one vertical to the four horizontally opposed burners modifies the gas/solid flow pattern inside the gasifier, providing the capability to achieve a desired flow and residence time distribution. One vertical burner forms a jet spray-type down-flow with high momentum, resulting in a concentrated combustion/flame zone. In contrast, the OMB can provide essentially distributed flame zones due to the application of horizontal multi-burners to form an impinged high temperature zone. As a result, a better mixing and once-through fuel conversion may be obtained, over 98% from OMB in comparison with 94-95% from a vertical burner gasifier.

Burners 1-4 are the original four burners, installed in 4” flanges around the perimeter of the gasifier. The new fifth burner with a small flange is at the top of the OMB gasifier, as shown in **Exhibit 21**. Addition of the fifth burner involved significant mechanical and control modification. An endoscope was originally installed in the top flange which is 2”. In order for the new burner to fit this existing opening, the burner flange itself had to be machined down and a new 2” flange welded to it. The results of this work can be seen in **Exhibit 1**.

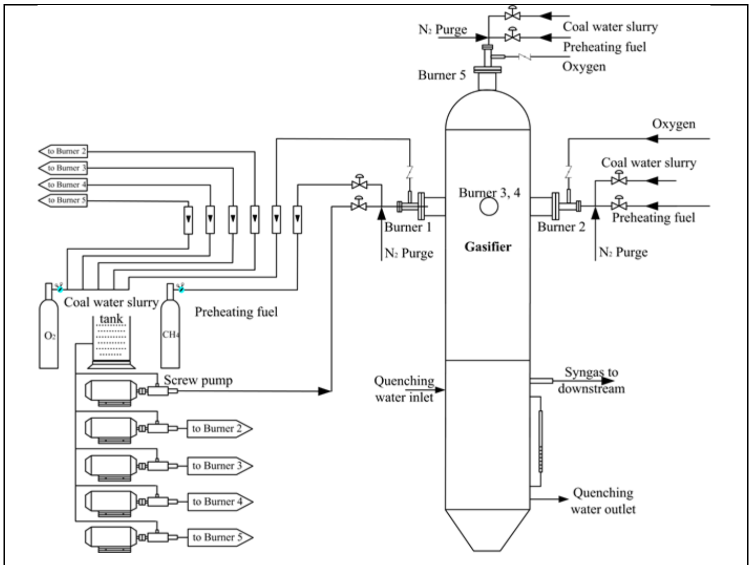


Exhibit 21. Schematic diagram of a staged-OMB gasifier with five burners.

In addition to the flange modification of the burner itself, the new burner required N_2, CH_4 and O_2 gas feeds as well as slurry inlet and recycle lines. Each of these gas lines also required a MFC and isolation control valve. Similarly, the slurry recycle and inlet lines each required a control valve. Mechanical supports for the instrumentation were designed and installed, as shown in **Exhibit 22 (top)**. All electrical and controls wiring required for new valves and MFCs was completed via termination of the components on the control system side. The cable was run from the control system to the final valve location using a cable tray, as shown in **Exhibit 22 (bottom)**. Next, all the tubing for the gas lines was completed, as shown in **Exhibit 23**. Slurry lines included tubing from pump discharge to the burners, and the recycle line back to the slurry tank.

Exhibit 23. Framing and support structures for fifth burner instrumentation (top) and cables and tubing from valve to control system (bottom).

Exhibit 24. Slurry lines from pump (top left), slurry tank (top right), recycle line (bottom left) and slurry inlet line (bottom right).

Work on the cyclone separator required welding for installation between the quench chamber and the water scrubber. This new cyclone separator is designed to remove approximately 50% of the total particulates exiting the gasifier in the syngas line. **Exhibit 24** shows the cyclone separator installation/construction progress. The addition of the cyclone separator allows for longer operational periods and helps prevent potential clogs downstream in the water scrubber that occurred twice during previous operation. Additionally, the cyclone separator has a sump coupled with a level control system.

Exhibit 24. Cyclone separator and bypass welding setup (left) and cyclone separator installed with sump level control (right).

The burner testing rig and setup jig are shown in **Exhibit 25**.This is a two-part assembly that allows each burner to be fine-tuned before final installation on the gasifier. The setup jig consists of a small set pin welded to a blind flange. This flange is then bolted to a cylinder that holds the burner cooling jacket and allows for proper setting of the burner. The burner testing stand provides a location to support the burner cooling jacket and a panel to feed slurry and gas to test the burner dynamics. It includes a video/image evaluation method to verify burner dynamics and performance before the burners are installed on the gasifier.

Exhibit 25. Burner testing rig and setup jig.

All the valves and MFCs were installed onto supports. They were connected to the control system with control wiring and integrated to the gasifier by mechanical plumbing. The installation was completed in such a way that the camera and fifth burner are interchangeable which provides future flexibility. **Exhibit 26** shows the valves and MFCs in the final locations, the completed plumbing and controls connections.

Exhibit 26. Valves for oxygen, nitrogen and natural gas to fifth burner (left) and the associated MFCs (right).

A new coal weight feeding system was installed. As shown in **Exhibit 27**, the new feeder is a general purpose, low-capacity weight belt feeder system designed to operate accurately and reliably in industrial environments with minimal maintenance. The integration of the feeder with the existing slurry preparation facility included electrical and controls wiring, integration with the control system, and testing system.

Exhibit 27. Thayer weight belt unit installed (left) and local control unit (right).

As shown in **Exhibit 28**, a coal elevator was installed to assist with loading of the coal into the feed preparation unit and the burner cooling water was reconfigured, to a once-through to closed loop, with the installation of a chiller.

Exhibit 28. Bucket elevator installed (left) and burner cooling water chiller installed (right).

3.2 Burner Atomization Optimization

Based on the oxygen velocity, experiments were carried out for adjusting the structure and distance between the burner tip and jacket. By using water as liquid phase and oxygen as gas phase, three parameters are used: the diameter of the shrinking of the liquid flow (D), the length of the shrinking flow (L) and the opening angle (A), as illustrated in **Exhibit 29**.

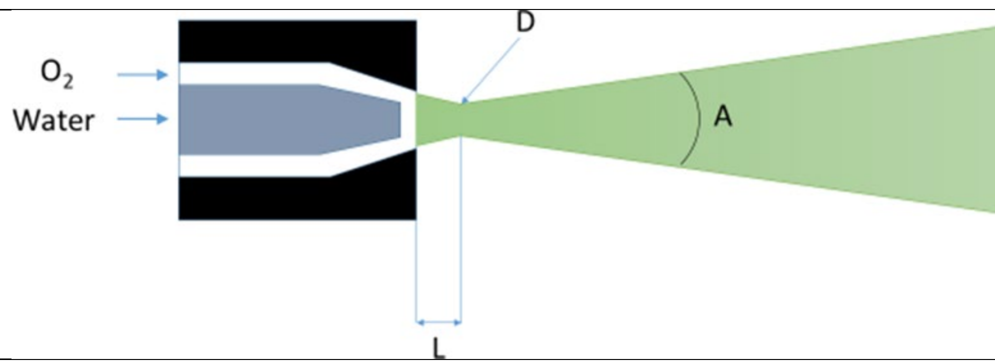


Exhibit 29. CWS burner atomization.

Exhibit 30 shows images captured during the burner atomization where the distances between the burner tip and jacket was varied from 1.00 to 0.00 mm. Three gas distances were chosen for testing the atomization. The opening angle was observed to decrease as the distance between the burner tip and jacket decreased, resulting in a change in atomization.

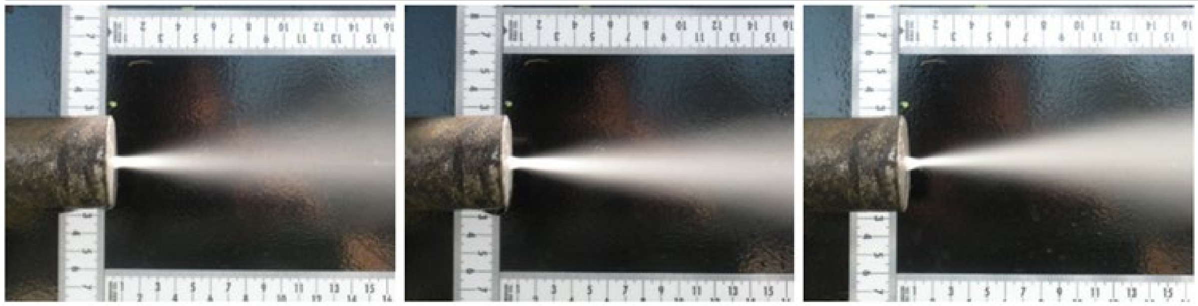


Exhibit 30. Atomization as a function of burner tip to jacket distance. (1.0 mm (left), 0.5 mm (center) and 0.0 mm (right)

From the images shown in **Exhibit 30**, D, A and L were measured as shown in **Exhibit 31**. A large opening angle of atomization is not good for the reaction of CWS with oxygen. Therefore, a the burner tip to jacket distance of 0.5 mm was chosen to ensure both an adequate velocity and a shearing force.

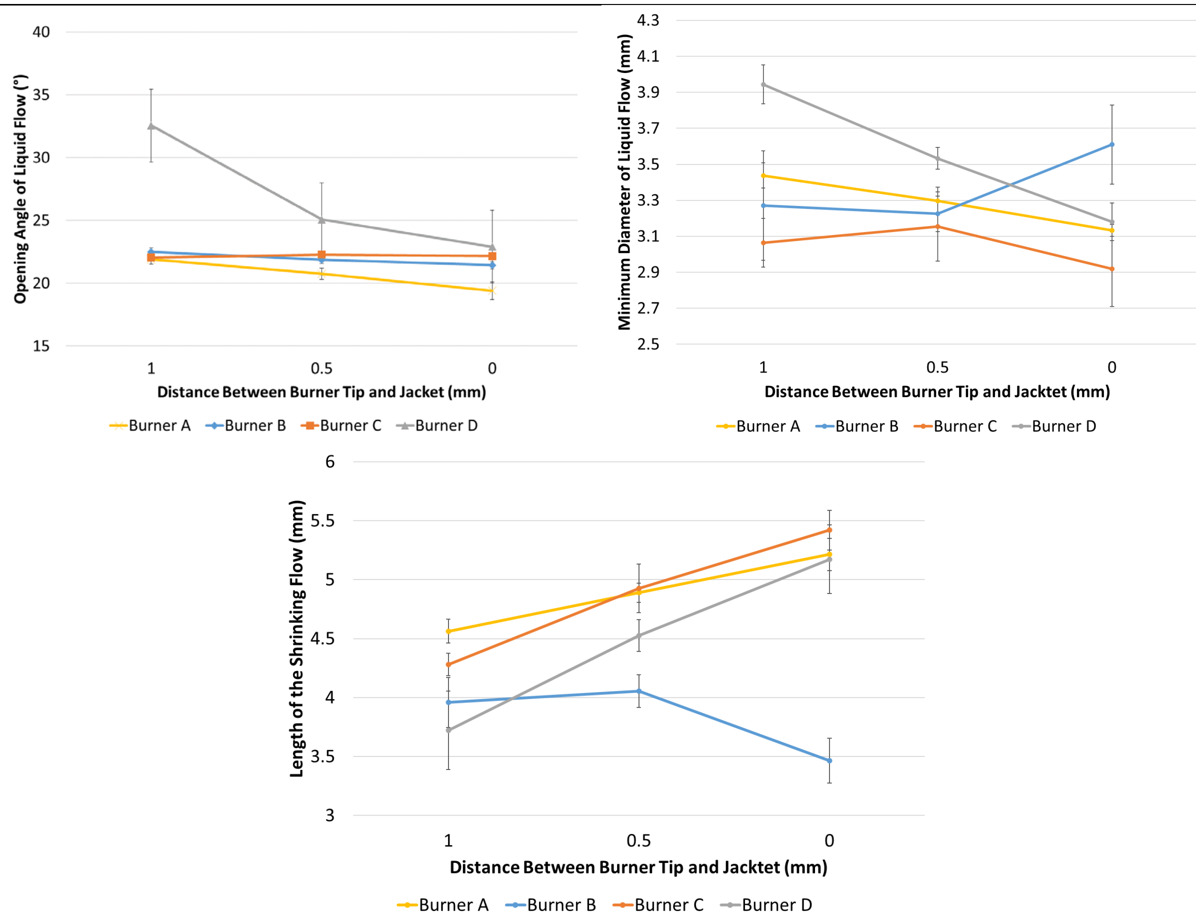


Exhibit 31. Measured diameter of the shrinking of the liquid flow (D), the length of the shrinking flow (L) and the opening angle (A).

Finally, after completion of the experiment for determining the effect of each variable, each burner velocity was tested at expected operating conditions. Then, nitrogen was added to each oxygen channel to attain a final velocity near 100 m/s. The final results are shown for each burner that was placed in service and utilized in the gasification system during the parametric and baseline operations, as shown in **Exhibit 32**.

Exhibit 32. Operating burner parameters.				
Burner	**Tip Diameter (mm)**	**Jacket Diameter (mm)**	**Velocity Before annular adjustment (m/s)**	**Velocity after annular adjustment (m/s)**
A	6.9	7.47	85	99
B	6.7	7.21	90	99
C	7.0	7.54	85	99
D	6.8	7.34	87	99

3.3 Operation Performance of Staged-OMB

UK CAER compared the performance with and without the staged-OMB configuration, simply by shutting off the top (the fifth) burner. Experimental test data was collected and analyzed to determine the impact of fluid dynamics on mixing and gasification, and on the gasifier performance, such as the controllability of the gasifier temperature profile for potential improvement of service life of the refractory wall and burners.

The commissioning of the fifth burner, burner E, began with heating up the gasifier using natural gas. The automated startup sequence was utilized to ignite the burner, and the temperature profiles were used to determine if the ignition was successful. After the gasifier temperature was stabilized at ~750 °C under the operation of burners A and B, burner E was ignited. After a couple hours there was a significant temperature rise at the of the gasifier, indicating that flow through burner E had stabilized. At this point, burners A and B were shut off and the natural gas and oxygen flow through burner E were set to the same value as the combination of burners A and B. This equivalent energy input from a different burner location gave us early insight into the temperature profile differences that could be expected from the addition of burner E. **Exhibit 33** shows the temperature profile changes throughout the commissioning of burner E.

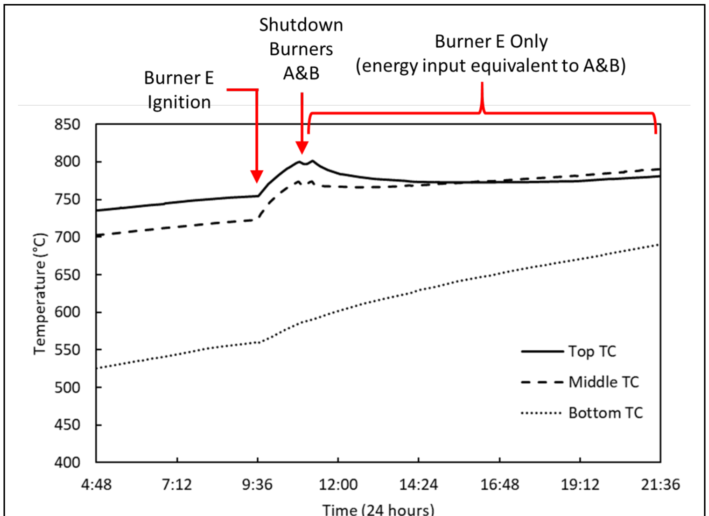


Exhibit 33. Gasifier temperatures measured with thermocouples (TCs) installed at the top, middle and bottom of the chamber during igniton and commissioning of burner E ignition.

After stabilization the temperatures at the top and middle of the gasification chamber resumed to the trajectory they were previously on and at after ~15 hours, the center temperature exceeded the top temperature. Additionally, the temperature at the bottom of the chamber continued to rise as if burners A and B were never shut off. This new temperature profile shows that, with the ignition of burner E, the high temperature zone moved and extended downward in the gasification chamber as was predicted because of the orientation of burner E being directly downward from the top of the gasifier.

Twelve parametric tests were completed allowing evaluation of five operation parameters. The tested parameters included: the number of burners loaded with CWS, the operating temperature, the CWS solids concentration, the oxygen to carbon O/C atomic ratio, and the operating pressure. During the completion of this parametric testing slag accumulated around the slag hole above the quench ring, and a new occurrence of a hot spot around the ignition rod flange was observed. A summary table compares the gasification performance under various condition, as shown in **Exhibit 34**.

Exhibit 34. Parametric Campaign Conditions.

Parametric Condition	**1**	**2**	**3**	**4**
Type of Coal	RV	RV	RV	RV
Gasification Temperature (ºC)	1400	1350	1400	1350
Gasification Pressure (MPaG)	0.1	0.1	0.1	0.1
CWS Solids Concentration (wt%)	57	57	57	57
Additive (coal-based, wt %)	0.3	0.3	0.3	0.3
Limestone (coal-based, wt %)	1	1	1	1
Feed O/C Atomic Ratio	1.00:1	1.03:1	1.04:1	1.02:1
Number of CWS Burners in Service	4	4	2	2
Number of Natural Gas Burners in Service	0	0	2	2
Heat Value Ratio (Natural Gas%:Coal%)	0:100	0:100	20:80	8:92

The carbon conversion, x, is calculated as:

$$x = \frac{C_{Coal-\ gas}}{C_{Total\ carbon\ in\ coal}}$$

The gas phase nitrogen balance is:

$$M_{N2} + M_{N-Coal} = M_{syngas} \times \varphi_{N2}$$

Where:
M_{N2}: nitrogen gas flow rate, Nm^3/hr
$M_{N\text{-}coal}$: nitrogen in coal, Nm^3/hr
M_{syngas}: nitrogen in syngas, Nm^3/hr
φ_{N2}: volume fraction measured by gas chromatography (GC)

The total carbon in the syngas is:

$$C_{syngas} = M_{syngas} \times (\varphi_{CO} + \varphi_{CO2} + \varphi_{COS}) \div 22.4 \times 12$$

Where:
$\Phi_{CO,CO2,COS}$: gas concentrations of CO, CO_2 and COS in the syngas.

The carbon from coal in syngas is:

$$C_{coal-gas} = C_{syngas} - (C_{CaCO3} + C_{Natural\ gas})$$

Where:
$C_{Coal\text{-}gas}$: carbon from coal in syngas
C_{CaCO3}: carbon decomposition from $CaCO_3$
$C_{Natural\ gas}$: carbon in natural gas
C_{syngas}: total carbon in syngas

<u>CWS Burners in Service</u>

The testing for the number of burners loaded with CWS focuses the effect of two and four burners at different operating temperatures. The main aim is to test the evolution of syngas composition and carbon conversion with changing the number of burners loaded with CWS. Two temperatures (1400 °C and 1350 °C) were evaluated. The pressure was set to 0.1 MPaG, and the RV coal from western Kentucky was used. Based on the calculations conducted with FactSage™, 1 wt% of limestone, on the mass basis of the raw coal before CWS preparation, was added to reduce the ash flow temperature. Additionally, in order to achieve a higher coal concentration in the CWS, the suspension additive Tamol SN was added to the coal water slurry. The O/C ratio of the reaction was set at 1.00:1 based on previous testing with Gibson coal. The gasification temperature could not be maintained with the loading of only two CWS burners due to heat loss; therefore, another two burners were operated with natural gas for temperature control. The molar ratio of natural gas to oxygen was set at 1:2 for complete combustion.

The syngas compositions are shown in **Exhibit 35**. When loading both two and four burners with CWS, the contents of both H_2 and CO are higher at 1400 °C than when operating at 1350 °C. Additionally, the content of CO_2 decreases with the lower operating temperature. Consequently, from the bottom bar chart in **Exhibit 34**, it can be seen that the effective syngas content (CO+H_2) and the carbon conversion operating at a temperature of 1400 °C are higher than when operating at 1350 °C for both two and four burner CWS operation.

When comparing two CWS burners to four, as shown in **Exhibit 36**, two burner operation had higher effective syngas content (CO+H_2) at both temperatures compared to the four burner operations at the same temperature. However, the carbon conversion was lower than that of four burner operation. This may be due to the supplement of natural gas to combat the heat loss. **Exhibit 34** shows that more natural gas was added for condition 3 than condition 4 because the temperature needed to be maintained at 1400 °C compared to 1350 °C. This shows that operation with four CWS burners can both maintain the gasification temperature and produce a higher content of effective syngas, with a higher carbon conversion, than operation with only two CWS burners.

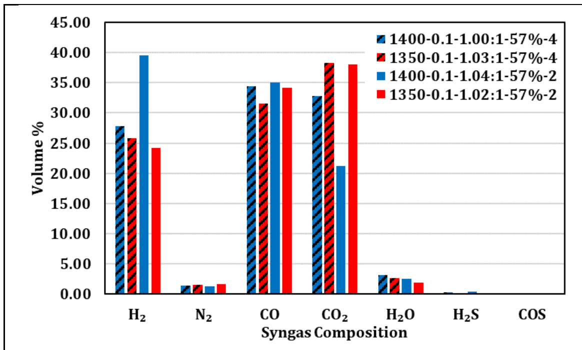


Exhibit 35. Syngas composition with number of CWS burners in service and gasification temperature.

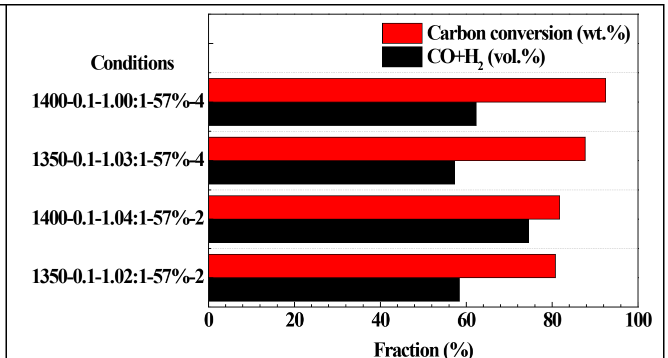


Exhibit 36. Carbon conversion with number of CWS burners in service and gasification temperature.

Operating Temperature

The results on the syngas composition, effective syngas content, and carbon conversion under various temperatures are shown in **Exhibits 37 and 38**. The H_2 content decreased with the increase in the operating temperature but are higher than the contents of CO and CO_2 for all three conditions. This indicates that part of natural gas is gasified to produce higher H_2 levels leaving some of the coal in the gasification chamber unreacted. At higher temperatures, the CO content decreases and the CO_2 content increases due to heat request. The effective syngas content is reduced while the carbon conversion increases with increasing operating temperature.

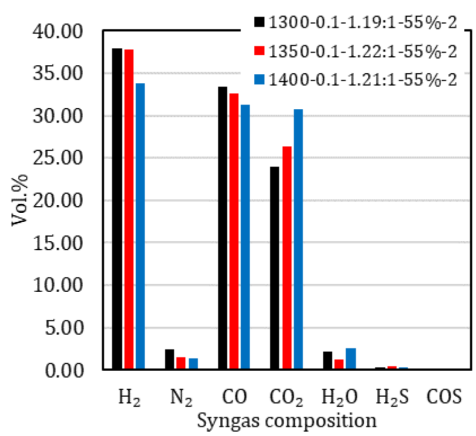


Exhibit 37. Syngas composition with different operating temperature.

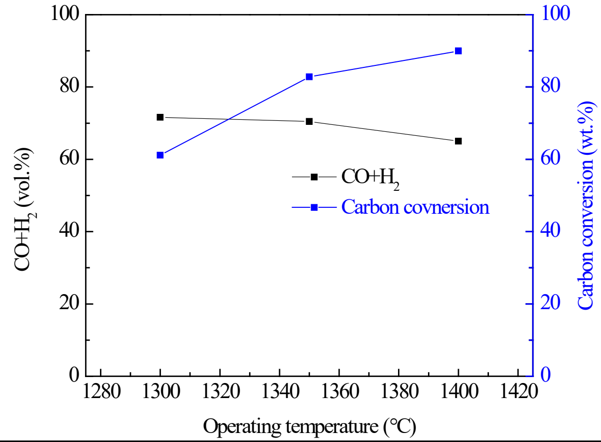


Exhibit 38. Carbon conversion of different operating temperature.

CWS Solids Concentration

Gasification performance is related to the coal concentration in CWS because water requires energy to evaporate. A higher coal concentration in the CWS will affect the viscosity and thus the pumpability of the slurry, and further will affect the atomization performance of the burner.

Exhibits 39 and 40 show the syngas composition, the effective syngas ratio, and the carbon conversion with the increasing CWS concentration when the operating temperature was held constant at 1350 °C. The CO_2 concentration decreases with increasing coal content due to less water evaporation, this points to an overall increase in gasification. This is also indicated by the increased amount of effective syngas produced at higher CWS concentrations. When looking at the H_2 and CO concentrations individually, for the second condition, at 57 wt% there was not an increase in H_2 but this condition had the highest CO concentration. This is likely because this condition had the lowest heating value input ratio of natural gas to coal, where coal gasification produces higher CO concentrations than H_2 and natural gas gasification is the opposite.

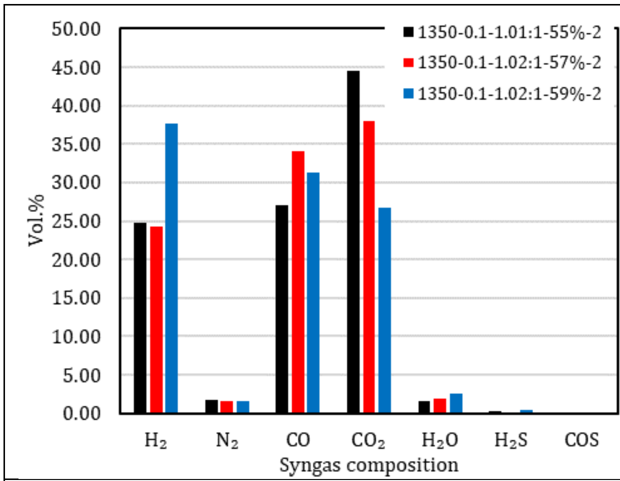


Exhibit 39. Syngas composition with different CWS solids concentration.

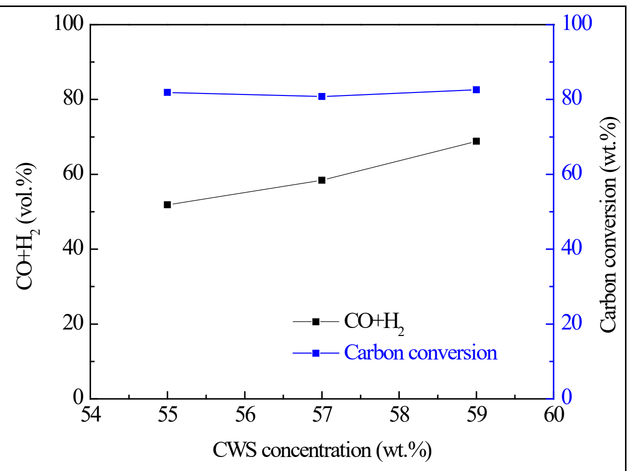


Exhibit 40. Carbon conversion with different CWS solids concentration.

O/C Atomic Ratio

The O/C atomic ratio is also a parameter used to evaluate for gasification performance in the coal-based chemical industry. Generally, this ratio in the OMB gasification process is lower than 1.00:1 because less oxygen in the gasifier leads the reaction to gasification and away from combustion. However, the minimum combustion must be met to provide energy for gasification and syngas sensible heat exiting the gasifier chamber. The effect of different O/C atomic ratios is shown in **Exhibits 41 and 42**.

Both H_2 and CO content are higher than the CO_2 content for all three conditions. However, the carbon conversion is low compared to the other testing conditions in the view of coal gasification. This means the effective syngas (H_2 and CO) mainly comes from the gasification of the natural gas; even though, the molar ratio of natural gas to oxygen is set at 1:2 for complete combustion.

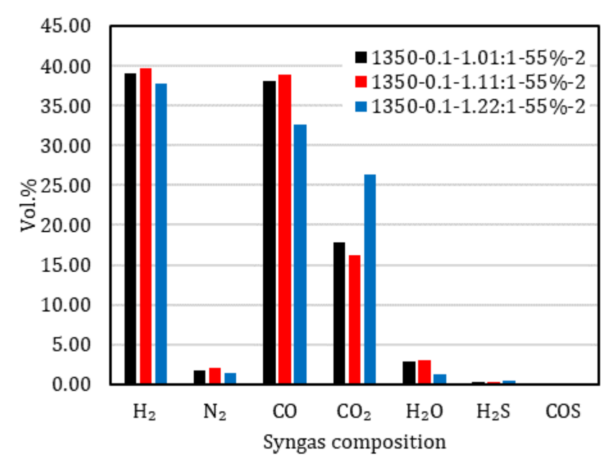


Exhibit 41. Syngas composition with different O/C atomic ratios.

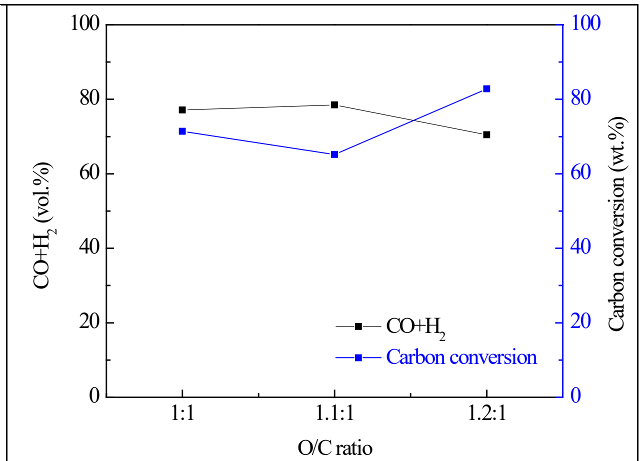


Exhibit 42. Carbon conversion with different O/C atomic ratios.

Operating pressure

Higher pressure benefits the gasification of coal in entrained flow gasifiers due to reduction of volume during the gasification process. Commercial entrained flow gasifiers generally operate at a pressure of 4-6 MPa. In this study, the staged-OMB gasifier is operated at much lower pressure conditions in the range of 0.1-0.15 MPaG.

Results comparing data collected with an operating pressure of 0.10 and 0.15 MPaG are shown in **Exhibits 43 and 44**. The syngas H_2 content at 0.15 MPaG is lower than that at 0.1 MPaG, but the reverse tendency is present for the CO content. Although, the lower operating pressure at both temperatures produces more effective syngas content ($CO+H_2$), the carbon conversion for the higher pressure conditions is better than at lower pressure conditions. At lower pressure condition, more natural gas is added to maintain temperature, which could be causing more gasification of natural gas instead of coal. Additionally, when the pressure increases to 0.15 MPaG, coal gasification increases and the natural gas moves towards combustion for heat support, which is evidenced by the elevated carbon conversion paired with increased CO_2 levels seen at the higher pressure.

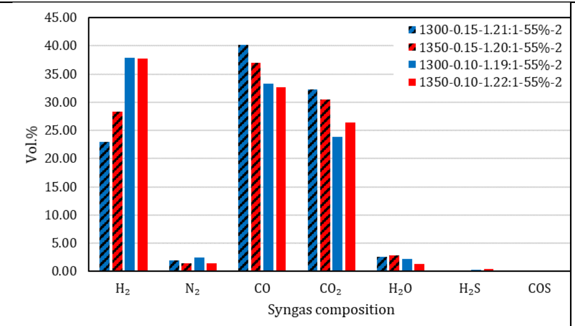


Exhibit 43. Syngas composition at different operating pressures.

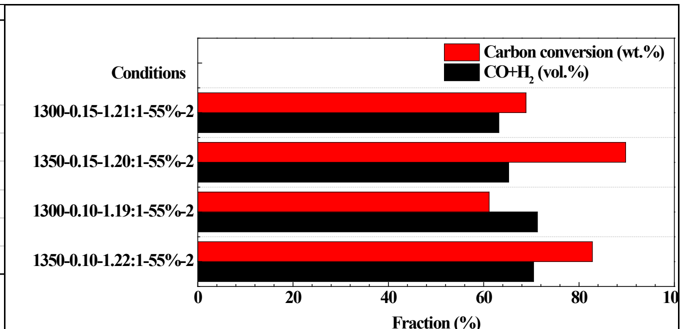


Exhibit 44. Carbon conversion and effective syngas composition at different operating pressures.

Effect of Oxidant and Fuel Stream Velocities

UK CAER designed and conducted experiments to vary the velocity of both the oxidant and fuel streams to evaluate the impact on gasification performance, caused by changes in atomization of fuel slurry, impinging of jet streams, flow pattern, gas-fuel mixing, fuel particles trajectory and residence time. By analyzing operation data with 2 burner operation at 1350 °C as the reference conditions, the effect of burner velocity on the syngas composition was assessed. **Exhibits 45 through 48** show the carbon conversion, effective syngas content (H_2+CO), CO/CO_2 ratio, and H_2/CO ratio due to changes in burner tip velocity expressed as a ratio of gas to CWS volumetric flows at the burner tip. No correlation was found between the burner tip velocity and any of the syngas parameters compared. This indicates that these velocities are above the critical velocity for atomization for this burner geometry.

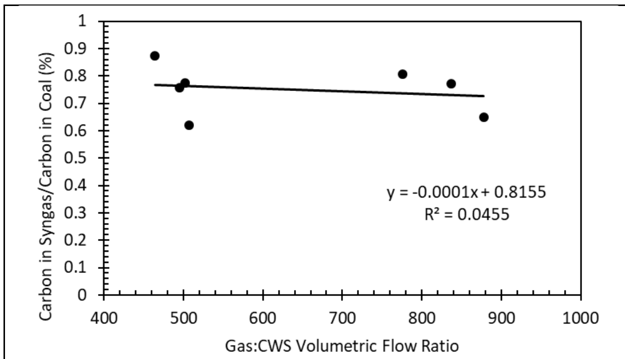


Exhibit 45. Burner velocity effect on carbon conversion.

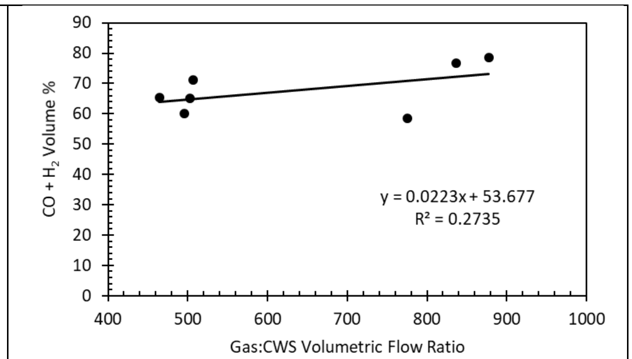


Exhibit 46. Burner velocity effect on effective syngas composition.

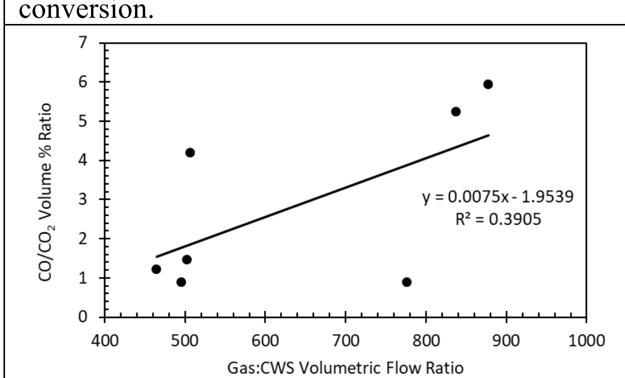


Exhibit 47. Burner velocity effect on syngas CO/CO_2 ratio.

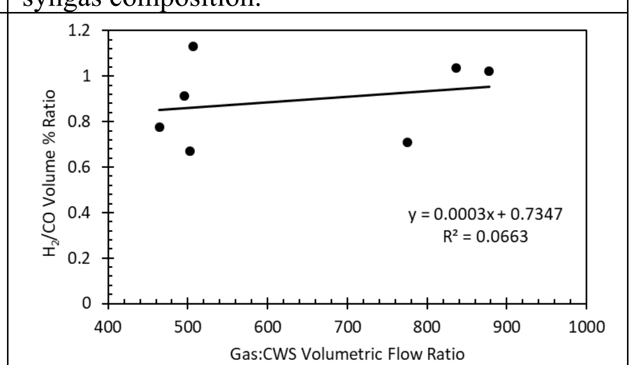


Exhibit 48. Burner velocity effect on syngas H_2/CO ratio.

The full set of operating conditions evaluated during the course of the project are summarized in **Exhibit 49**.

Exhibit 49. Gasifier performance and operating conditions evaluated.									
Operating Condition	**1**	**2**	**3**	**4, 9**	**5, 16**	**6, 13, 17**	**7**	**8, 11**	**10**
Type of Coal	RV	RV	RV	RV	RV	RV	RV	RV	RV
Gasification Temperature (ºC)	1400	1350	1400	1350	1300	1350	1400	1350	1350
Gasification Pressure (MPaG)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
CWS Solids Concentration (wt%)	57	57	57	57	55	55	55	55	59
Additive (coal-based, wt %)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Limestone (coal-based, wt %)	1	1	1	1	1	1	1	1	1
Feed O/C Atomic Ratio	1.00:1	1.03:1	1.04:1	1.02:1	1.19:1	1.22:1	1.21:1	1.01:1	1.02:1
Number of CWS Burners in Service	4	4	2	2	2	2	2	2	2
Number of Natural Gas Burners in Service	0	0	2	2	2	2	2	2	2
Heat Value Ratio (Natural Gas%:Coal%)	0:100	0:100	20:80	8:92	12:88	20:80	20:80	14:86	12:88
Syngas Content									
H_2 (vol%)	27.86	25.82	39.56	24.25	37.92	37.79	33.77	24.81	37.61
N_2 (vol%)	1.40	1.54	1.27	1.63.	2.40	1.44	1.3.6	1.79	1.55
CO (vol%)	34.43	31.52	35.00	34.13	33.34	32.66	31.24	27.07	31.24
CO_2 (vol%)	32.83	38.22	21.20	37.98	23.90	26.40	30.71	44.45	26.70
H_2O (vol%)	3.11	2.70	2.57	1.88	2.16	1.28	2.59	1.64	2.49
H_2S (vol%)	0.34	0.19	0.38	0.12	0.27	0.41	0.31	0.23	0.40
COS (vol%)	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.02
CO+H_2 (vol%)	62.29	57.34	74.56	58.38	71.26	70.45	65.01	51.87	68.85
CO/CO_2	1.09	0.86	8.60	0.90	4.25	1.28	1.04	0.85	1.56
H_2/CO	0.81	0.82	1.13	0.71	1.13	1.16	1.09	0.92	1.21

3.4 Slag Composition Study

Ash and slag samples were collected from the lock hopper, slag hole, slag pool, gasifier, and water scrubber for both the baseline (full load) and 2 burner (partial load) parametric testing. Samples were also taken from the cyclone separator, but not enough solids were present for analytical testing. The slag/ash samples directly correspond to the slag flow properties during operation. The slag from the lock hopper and slag pool had the highest ash fusion temperature above 1300 °C. The ash fusion temperature of other samples was below 1200 °C, which implies that the addition of limestone effectively reduces the ash fusion temperature of the coal. The ash fusion temperature of the raw coal is around 1500 °C.

X-ray diffraction (XRD) data collected from the slag samples is shown in **Exhibit 50**. Inside the gasifier, minerals in the slag are mainly anorthite, aluminum oxide/iron, and tricalcium cyclo-trisilicate. These mineral phases are formed as oxides of calcium, oxygen, aluminum, and silicate. Anorthite is the main mineral phase found in the gasifier wall, slag hole and lock hopper. With the addition of limestone, the ash fusion temperature has been decreased, but the limestone in the raw coal samples also transforms the chemical compositions. Comparing the main slag types from the gasifier section to other parts of the gasification system, the XRD spectra show that the state of calcium transforms from anorthite to calcium iron oxysulfide, coesite and gypsum. It should be noted that calcite is still found in the lock hopper. Further, as the syngas with ash proceeds through the stages of cleaning, quartz and gypsum become the main mineral phase in both the cyclone and water scrubber.

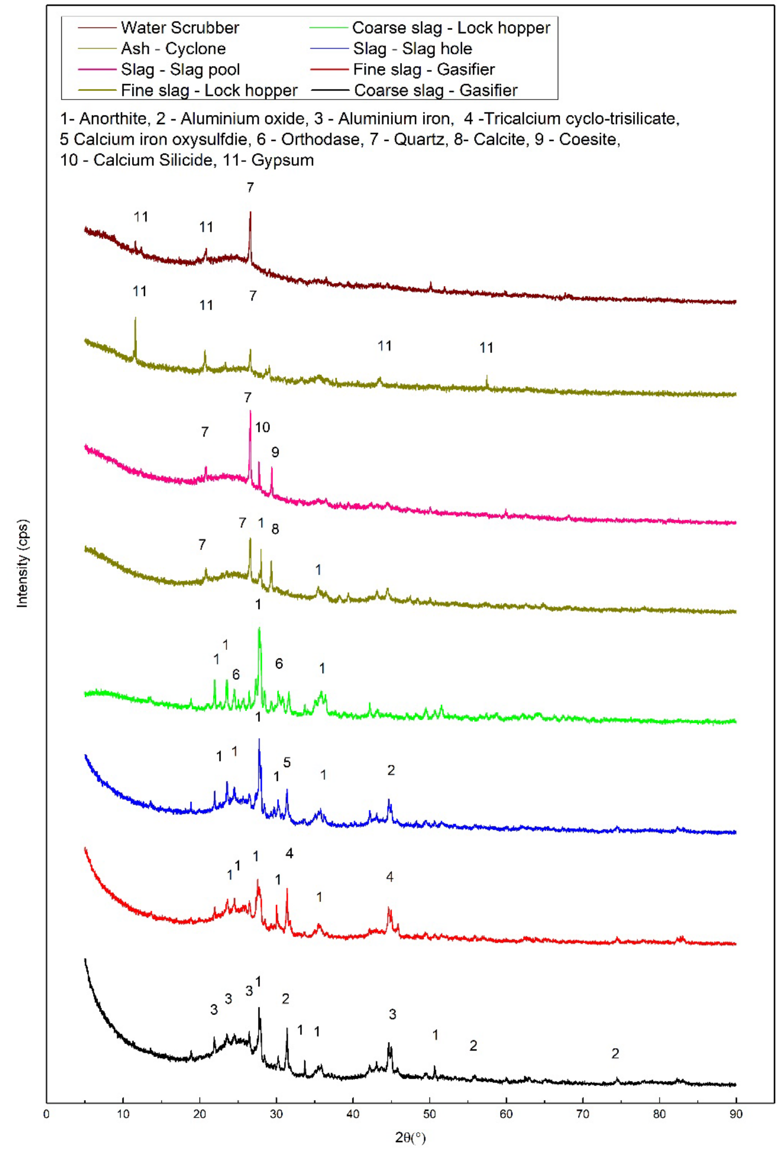


Exhibit 50. XRD Mineral Phase Transformation from the Gasification Chamber to the Slag Pool.

The slag samples were analyzed via x-ray fluorescence (XRF) for both baseline and parametric testing operations, and corresponding results are shown in **Exhibit 51.** The slag exit hole and gasification chamber (unreacted large ash, slag chunks, and clogged slag) contain higher contents of calcium. Samples from the lock hopper and water scrubber have a lower calcium content. For the slag chunk of the baseline operation, which was collected from the wall of the gasifier, it contained high content of alumina but less sulfur because the sulfur in the coal is converted to H_2S and emitted in the gas phase.

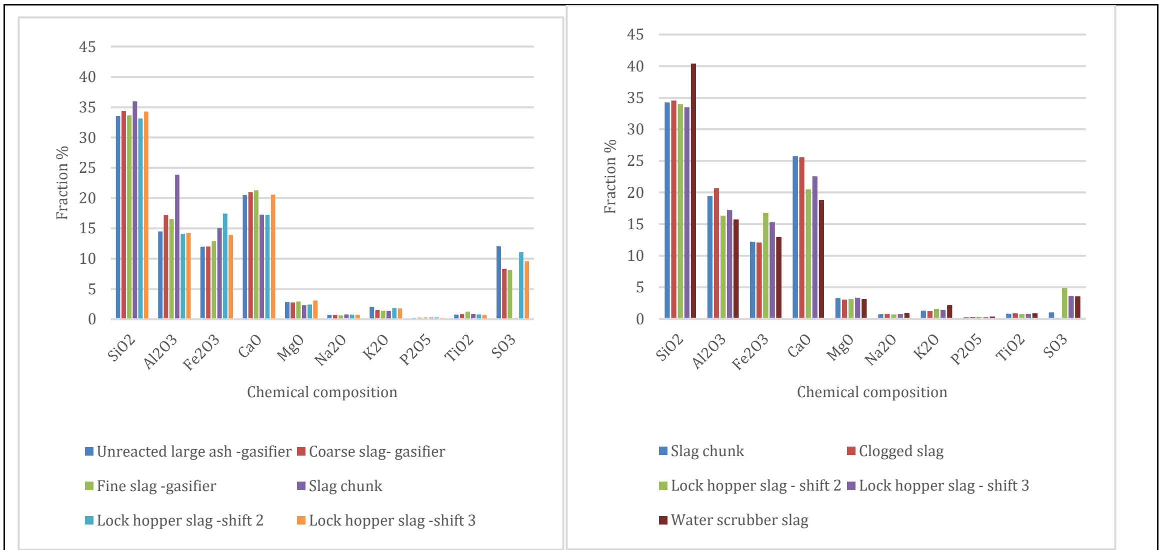


Exhibit 51. Chemical composition of coal ash and slag samples.

FactSage™ was applied to model the mineral phase of slag with the decreasing temperature, as shown in **Exhibits 52 and 53**. The main mineral phase in the slag as it is cooling down is anorthite, and its content is larger than other minerals. Anorthite is a high temperature melting mineral phase, melting at ~1553 ℃. Once this mineral phase forms in the liquid slag, the viscosity increases sharply. The predictions from FactSage modeling were verified by the XRD data shown in **Exhibit 51**. With decreasing temperature, the anorthite content in the slag increases significantly. Adding limestone in the raw coal sample reduces the ash fusion temperature but it will also increase the viscosity if the temperature is below the fusion temperature used for operation. Therefore, controlling the temperature near the slag hole is a key step to maintain stable operation of the staged-OMB gasifier.

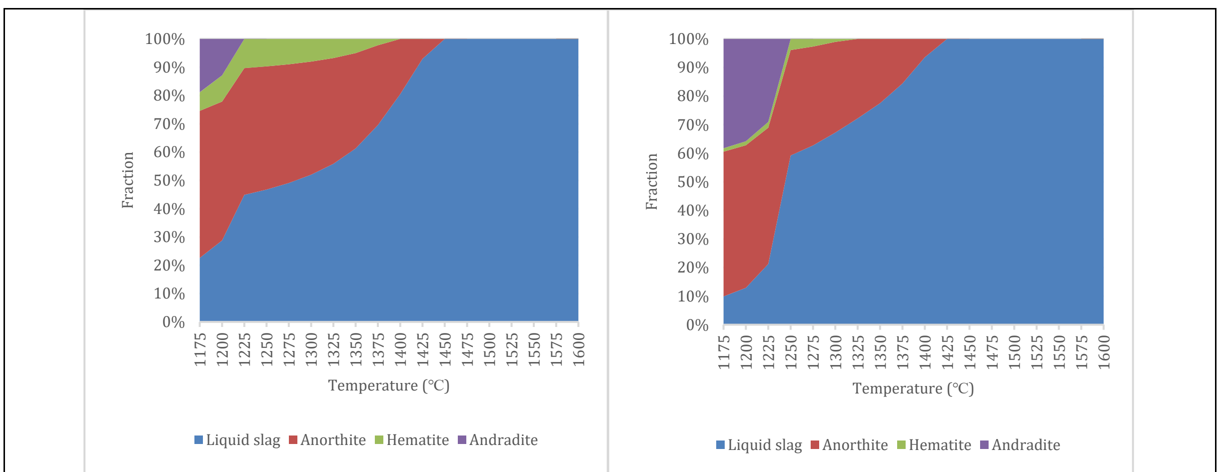
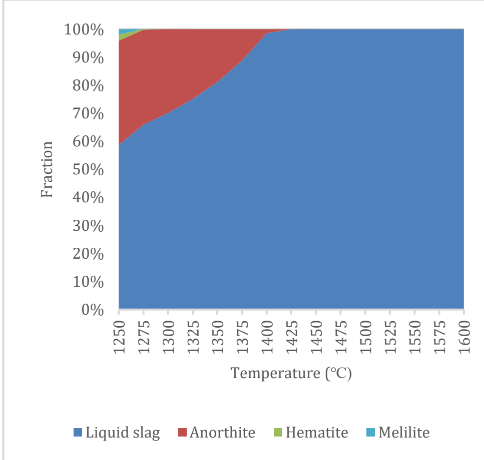


Exhibit 52. Phase Diagram of Slag Samples for Baseline (Left: slag chunk and Right: coarse/fine slag)



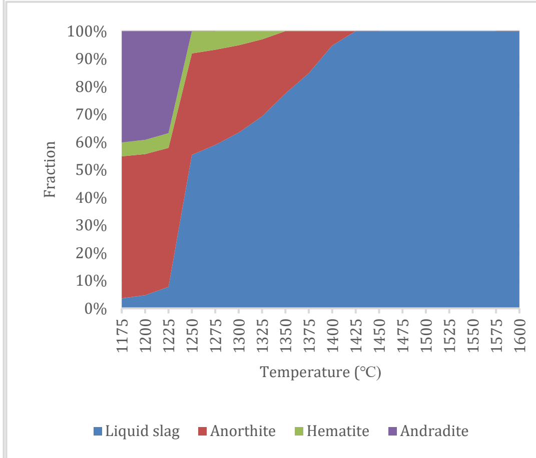
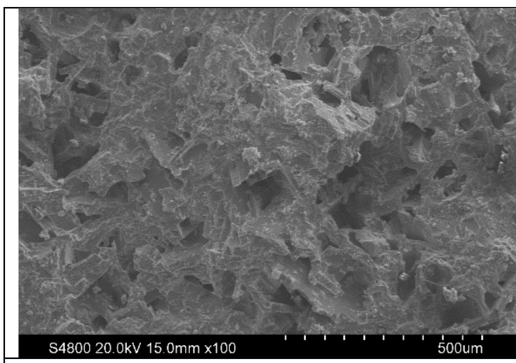


Exhibit 53. Phase Diagram of Slag Samples for Parametric Testing (Left: slag chunk and Right: coarse/fine slag)

Scanning electron microscopy (SEM) was used to observe the micro-structure and morphology of the slag samples, and the corresponding results are shown in **Exhibit 54**. The cross-section displays porous structures for both slag samples of baseline and parametric testing. However, the pore size on the cross-section of baseline slag samples is smaller than that of the parametric testing, which may be due to cooling bubbles and less carbon conversion in the molten slag layer.



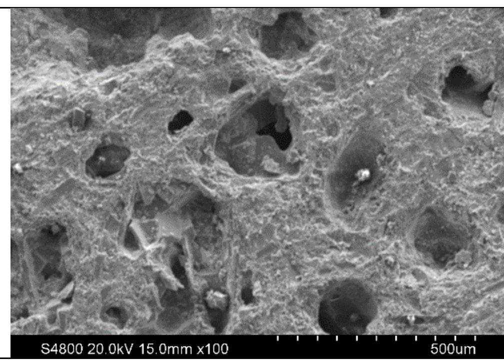


Exhibit 54. Cross-section surface of morphology of slag.

The SEM-EDS analysis results from one slag sample are shown in **Exhibit 55**. C, O, Al, Si, Ca, and Fe are the main elements present. Thus, residual carbon is in the slag and affects the ash fusion temperature and porous structure of slag.

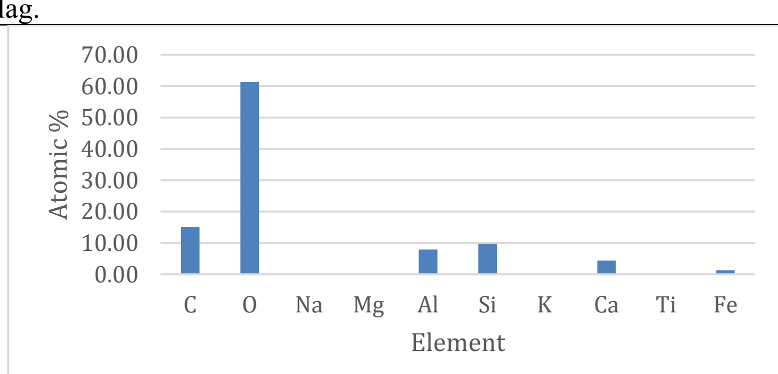


Exhibit 55. SEM-EDS elemental content of the cross-sectional surface of slag.

3.5. Fuel Flexibility with Fuel Blend

Exhibit 56 summarizes the coal information for fuel flexibility. Gibson coal contains a higher ash fusion temperature and T-25 than the other coals. The ash fusion temperature of River View coal is lower than Gibson coal in the reducing atmosphere. However, the T-25 of River View coal is higher than the desired operating temperature, so a small amount of limestone is likely to be required for operation. For the PRB coal, both the ash fusion temperature in the reducing and oxidizing atmospheres and T-25 are lower than Gibson coal and River View coal.

Exhibit 56. Coal information summary.

Parameter	Gibson coal	River View coal	PRB coal ACM	PRB coal SCM	PRB coal CRM
Moisture (%)	14.47	12.14	26.11	24.94	29.64
Volatiles (%)	31.15	35.62	31.68	31.53	31.17
Ash (%)	6.63	8.19	5.42	4.14	5.17
Fixed C (%)	47.75	44.05	37.44	39.54	34.50
S (%)	1.20	2.92	0.25	0.33	0.29
C (%)	64.26	63.05	51.92	54.05	49.27
H (%)	4.52	4.64	3.57	3.78	3.48
O (%)	7.47	6.35	12.6	11.51	11.9
N (%)	1.45	1.45	0.77	0.65	0.72
BTU/lb	11535	11514	8800	9350	8425
FT-reducing (°C)	1337	1198	1215	1198	1217
FT-oxidizing (°C)	1404	1346	1249	1336	1249
T-250 (°C)	1440	1298	1197	1159	1215

The CWS stability is summarized in **Exhibit 57.** The unit (mL) means the settling distance from the surface to the solid level. The CWS with Tamol SN has a better stability than the Daracem 55 as evidenced by the smaller amount of settling distance and longer time to settling. This can be found for both RV coal and Gibson coal. Comparing two coal water slurries with Tamol SN, the RV coal has a much stronger stability than the Gibson coal.

Exhibit 57. CWS Stability with Daracem 55 and Tamol.

	RV Coal Settling Distance (mL)		**Gibson Coal Settling Distance (mL)**	
Time (min)	**Daracem 55**	**Tamol SN**	**Daracem 55**	**Tamol SN**
10	0	0	0	0
20	0	0	0	0
30	0	0	0	0
60	4	0	7	0
120	6	0	7	0
180	6	0	10	10

240	6	0	10	10
300	6	0	10	
360	6	0		
420	6	0	10	11
1200	7	7	10	15

Using the FactSage™ melt database for viscosity modeling, results show that the Gibson coal T-25 is higher than that for RV coal in both reducing and oxidizing atmospheres. Adding 1 wt% limestone to the RV coal reduces the T-25 to 1250 °C in the oxidizing environment and 1160 °C in the reducing environment. Adding 2 wt% limestone to the RV coal reduces the T-25 to 1090 °C and 1040 °C for oxidizing and reducing atmospheres, respectively. The data is shown in **Exhibit 58**. The viscosity curves of all RV and Gibson coals with and without added limestone are shown in **Exhibit 59**. Therefore, with 1-2% limestone in RV coal, the T-25 can be reduced to the desired range, below 1200 °C. After all analyses, it was determined that RV coal is acceptable for utilization in the UK CAER staged-OMB gasifier.

Exhibit 58. T-25s for RV and Gibson coals.

Samples	T-25 (°C)
Gibson coal - oxidization	1575
Gibson coal - reduction	1625
Gibson coal + 3.52%limestone -oxidization	1225
Gibson coal + 3.52%limestone - reduction	1190
River View -Oxidization	1400
River view -Reduction	1350
River view coal +1wt% limestone-oxidization	1250
River view coal +1wt% limestone-reduction	1160
River view coal +2wt% limestone-oxidization	1090
River view coal +2wt% limestone-reduction	1040

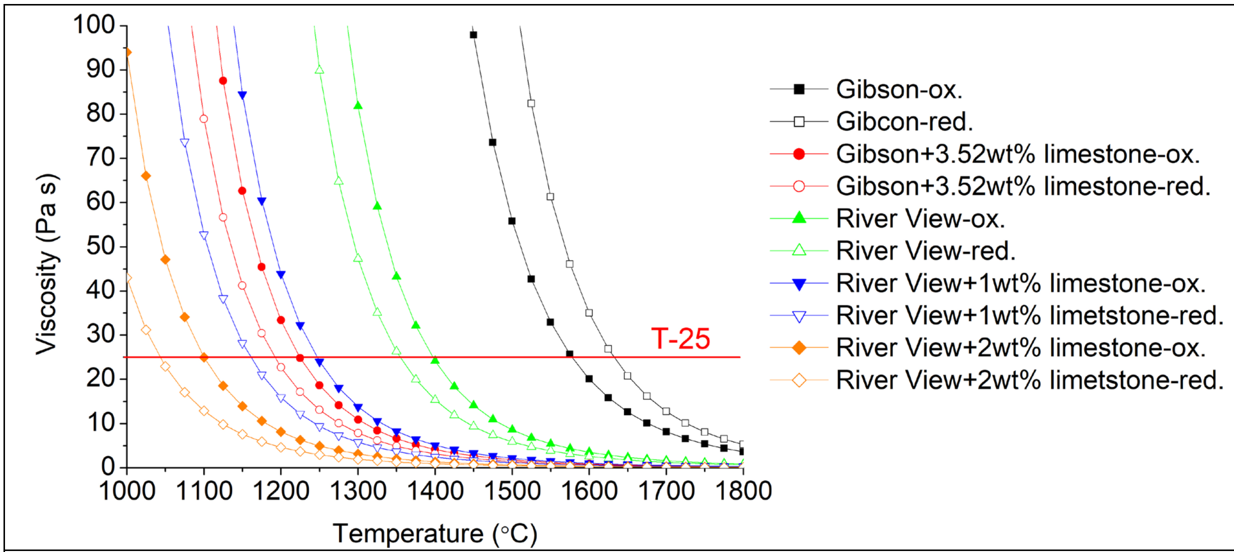


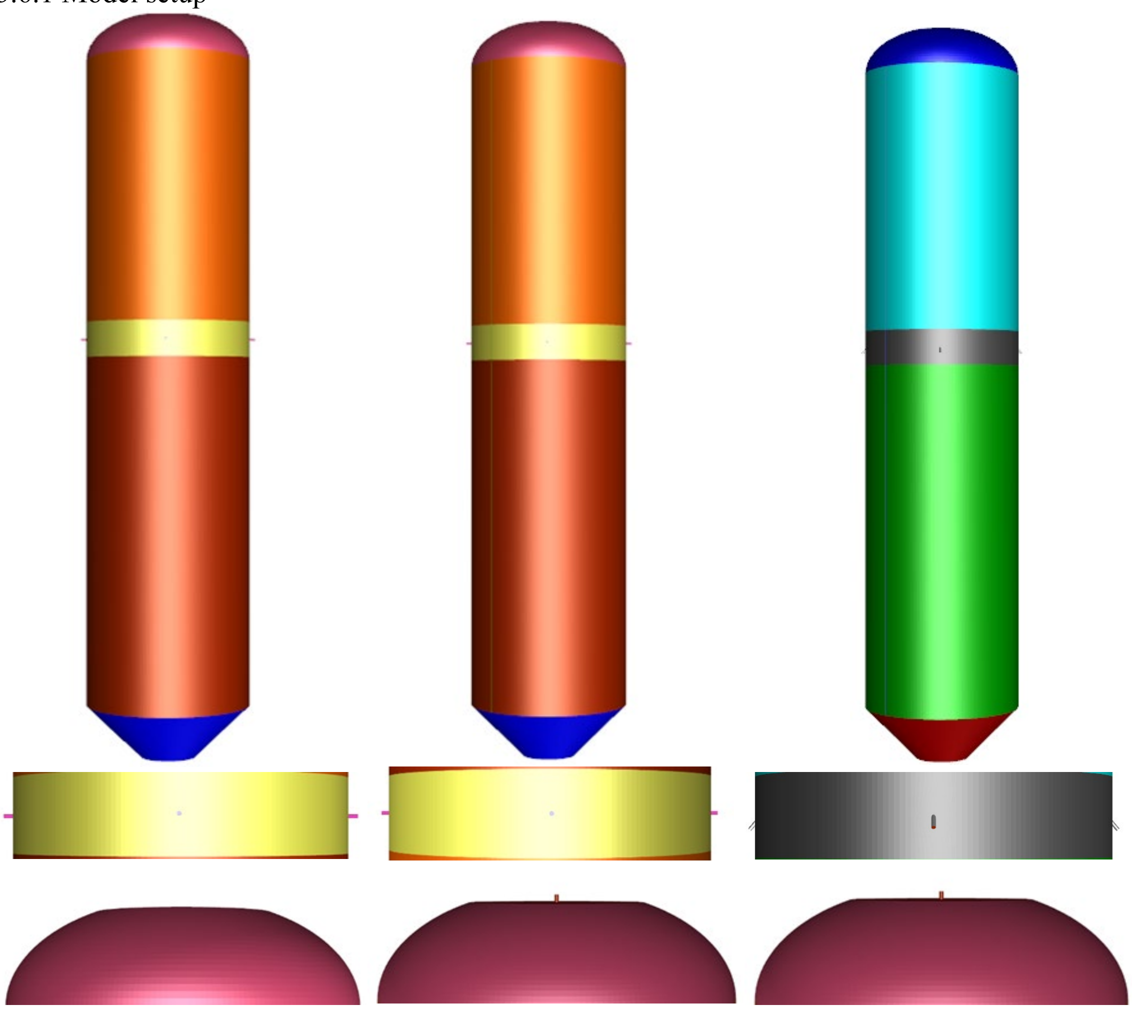
Exhibit 59. FactSage™ modeling viscosities.

3.6 3-D Simulation of Staged-OMB Gasifier and Burner Effect

UK CAER developed an experimentally-verified, 3-D gasifier model and used it as an analysis tool to simulate the staged-OMB gasifier with different operating conditions and designs. By using this model, UK CAER has performed a systematic and parametric study to understand the impact of fluid dynamics and fuel properties, as well as the arrangement of burners, on the gasifier flow field, impinging, mixing, and resulting temperature profile and performance, including the jet momentum on the impinging of jet streams, on the residence time distribution of fuel particles, and the flame zone temperature and distribution.

UK CAER evaluated the burner arrangement through simulation, such as the load effect of the top burner on the impingement of jets of the lower row, as well as the impinging between two burner rows and the resulting temperature distribution and controllability. A heat and mass balance model (H&MB) was developed for process simulation using Aspen Plus® to predetermine the conditions for 3-D simulation and for testing, such as feed ratios and operation temperature for a given fuel type.

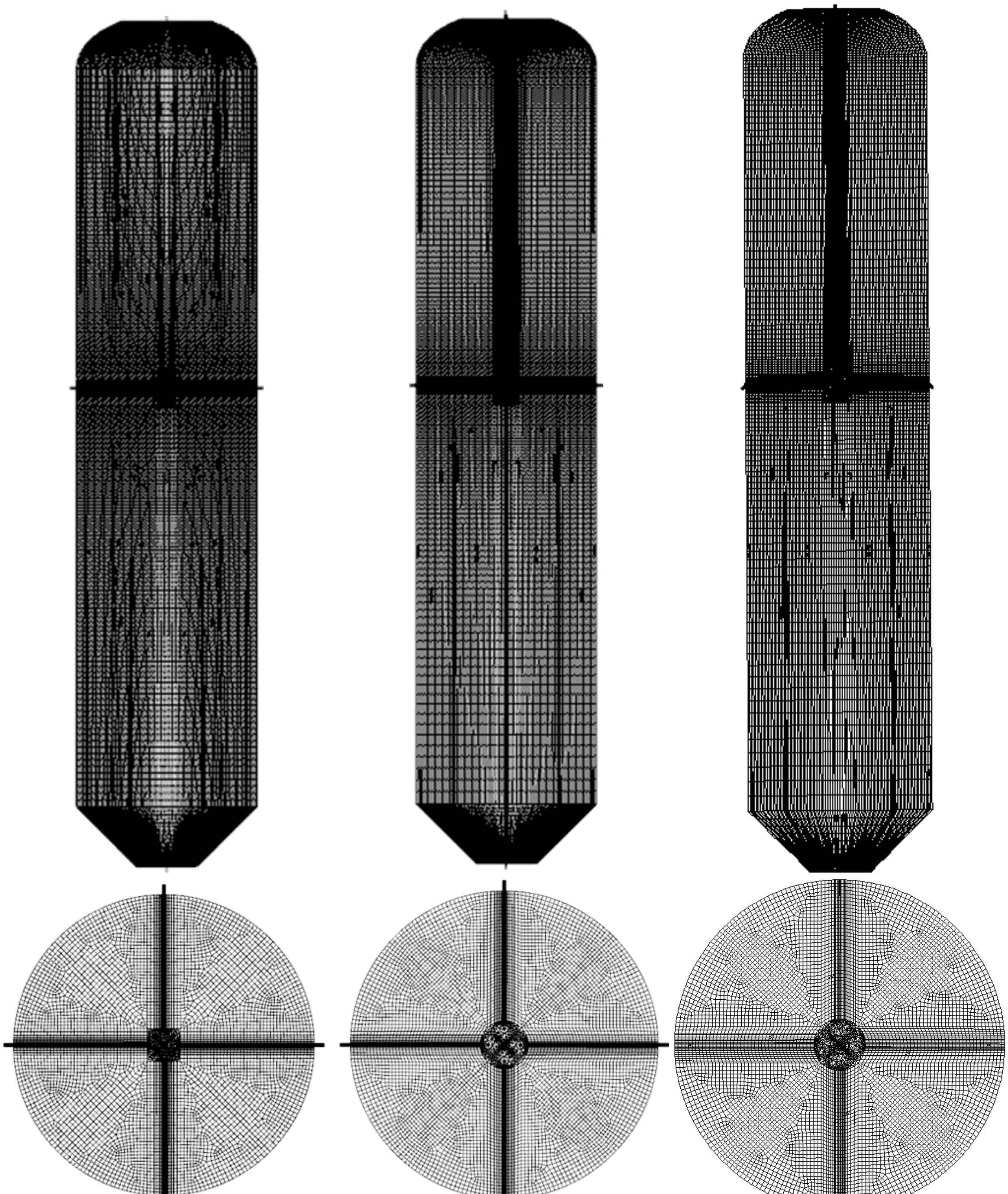
3.6.1 Model setup



OMB gasifier (four burners) **Staged-OMB gasifiers (five burners, I and II)**

Exhibit 60. Simulation models of OMB and Staged-OMB gasifiers.

The computational model and grid of the gasifier are shown in **Exhibits 60 and 61**. Since the velocity, temperature and concentration gradients near the discharge outlet and burner plane are large, and the size of the burner is relatively small compared with the size of the gasification chamber, the density of the grid in those zones is enlarged respectively. Three configurations were evaluated, shown in the **Exhibit 60**, OMB, Staged-OMB I with one burner installed on the top of the gasifier, and Staged-OMB II with the four opposed burners being tilted 50° above the horizontal plane. The burner sizes on the OMB gasifier, Staged-OMB I and II gasifiers are set at the same scale.



OMB gasifier (four burners) **Staged-OMB gasifiers (five burners, I and II)**

Exhibit 61. Grids of OMB and Staged-OMB gasifiers.

3.6.2 Simulation conditions

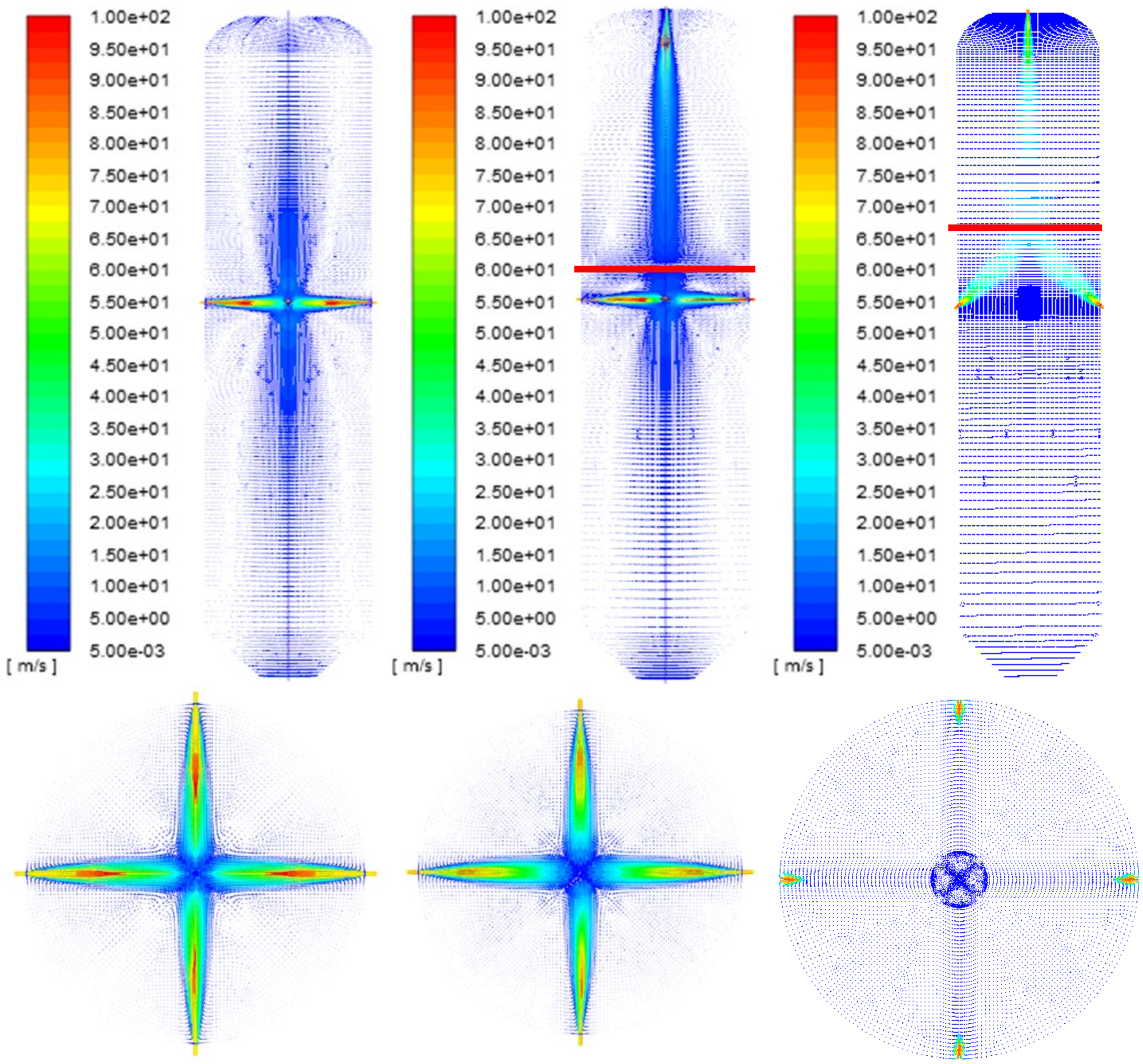
Complex physical and chemical processes occur in the entrained flow gasifier, including fluid turbulence, convection and radiation heat transfer, particle dispersion movement, coal slurry atomization, droplet evaporation, coal particle volatilization, particle surface chemical reaction, gas phase chemical reaction and other processes. In this simulation, Realizable $k-\varepsilon$ turbulence model was used for the flow. P1 model was used for the radiation process in the gasifier chamber. Discrete phase model was used for particle dispersion motion. The atomization process of coal slurry is ignored, and it is assumed that the atomization is fully atomized at the burner outlet. The atomization particle size distribution meets the R-R distribution, with an average particle size of 80 μm and a range of 50-120 μm. A two-step competitive model was used for the devolatilization process. The unreacted core shrinkage model was selected as the chemical reaction model on the particle surface. EDC model was used for gasification chemical reaction.

3.6.3 Simulation results

<u>Velocity distribution in gasifier</u>

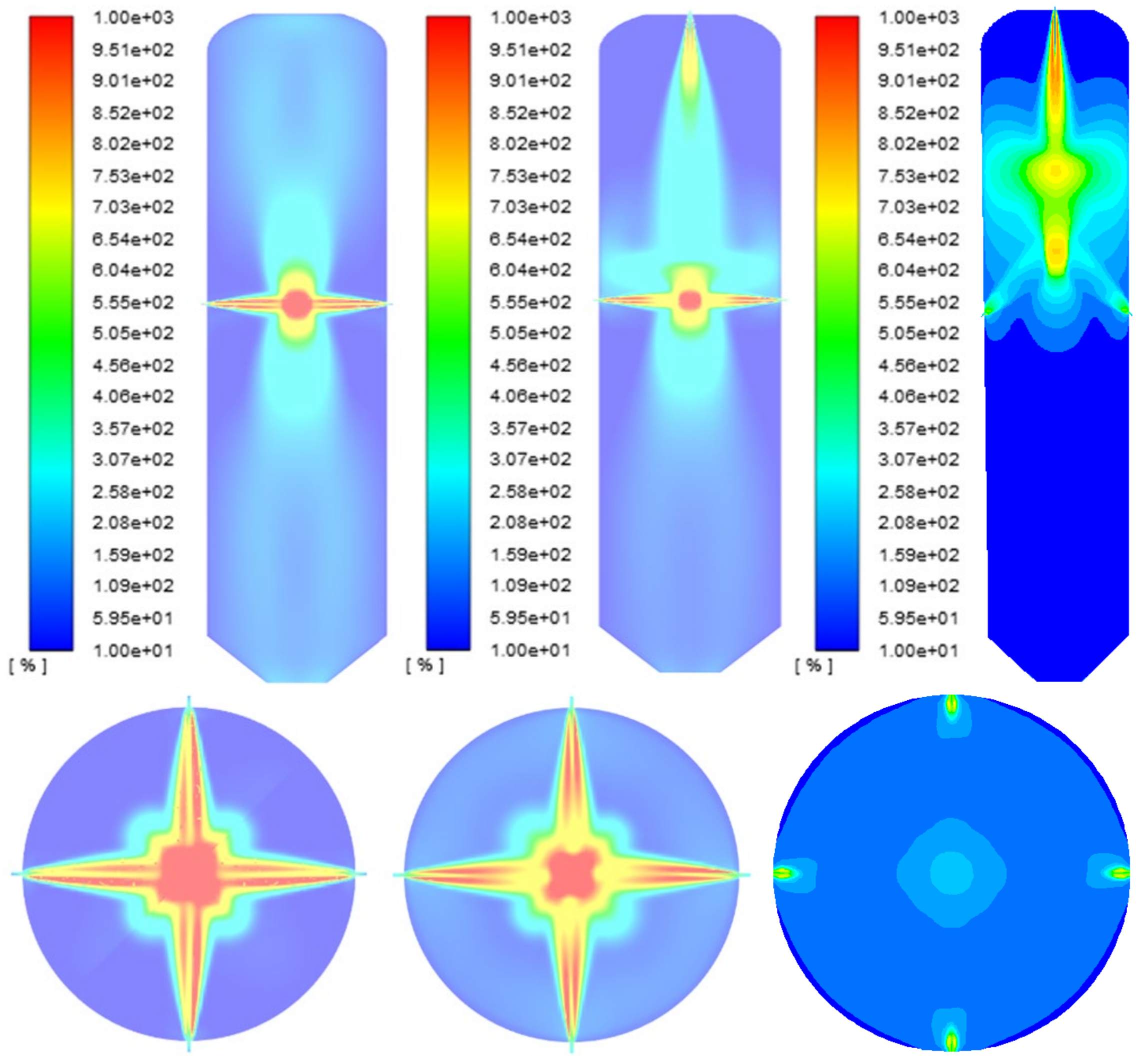
Exhibits 62 and 63 show the velocity vector diagram and turbulence intensity profile of the OMB and staged-OMB gasifiers with different burner tilt angles, respectively. Results show that, for the OMB gasifier, there is an impinging zone on the center of the gasifier formed by opposed injected jet streams from burners. In the impinging area, due to the blocking effect of the fluid impact, the turbulence intensity in the impact area is large, and the mixing degree between the fluids is improved. For the Staged-OMB I gasifier the upward flow in the center collides with the jet stream form the burner at the top of the gasifier. Because the five-burner gasifier adds an impact area in the upper part of the chamber, the turbulence intensity on the upper part is higher, and the mixing between the fluids is further obtained. Two recirculation zones form between the impinging zone and the fluid flow of the fifth burner, as shown in **Exhibit 64**. Compared with the Staged-OMB I with secondary at 0.8D above the nozzle plane, the Staged-OMB II upward jet would impinge at1.5D above the nozzle plane. The secondary impact position of Staged-OMB II is higher than that of Staged-OMB I but with less turbulence intensity. This means that Staged-OMB I has greater advantages in enhancing mixing and is more beneficial to gasification reaction.

Exhibit 65 shows the fluid velocity distribution of the local area on the dome zone of the two gasifiers. A backflow of the fluid is clearly found in the OMB gasifier. The burner is located in the middle of the gasifier, and the distance from the dome is bigger than the staged-OMB gasifier. The velocities of refractive flow and recirculation flow is close to each other, showing symmetry. For the staged-OMB gasifier, the addition of the fifth burner on the dome increased the fluid mixing degree in the upper part of the gasifier chamber.



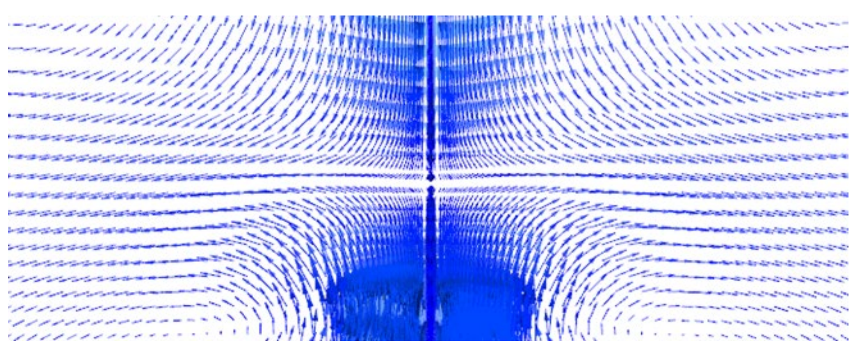
OMB gasifier (four burners) **Staged-OMB gasifiers (five burners, I and II)**

Exhibit 61. Velocity vector diagrams of OMB and Staged-OMB gasifiers**.**

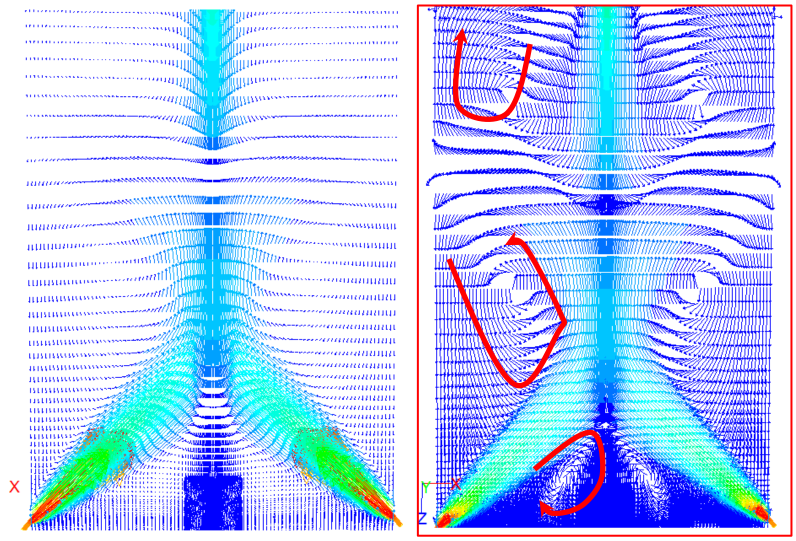


OMB gasifier (four burners) **Staged-OMB gasifiers (five burners, I and II)**

Exhibit 63. Turbulence intensity distribution of the OMB and Staged-OMB gasifiers.



Staged-OMB II gasifier



Staged-OMB I gasifier

Exhibit 64. Velocity vector diagram of impinging zone in upper chamber of Staged-OMB gasifiers.

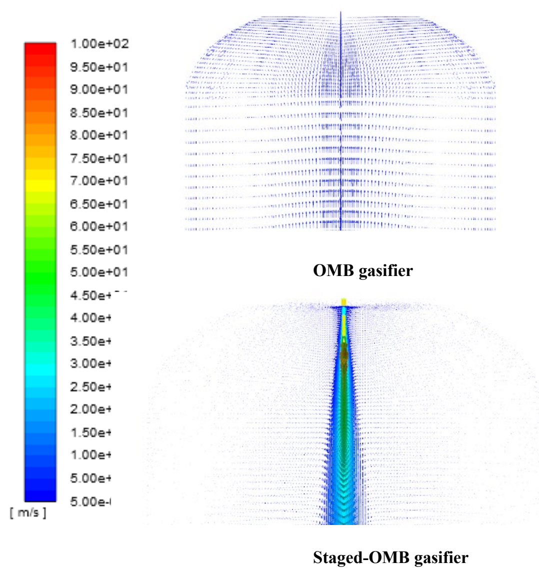


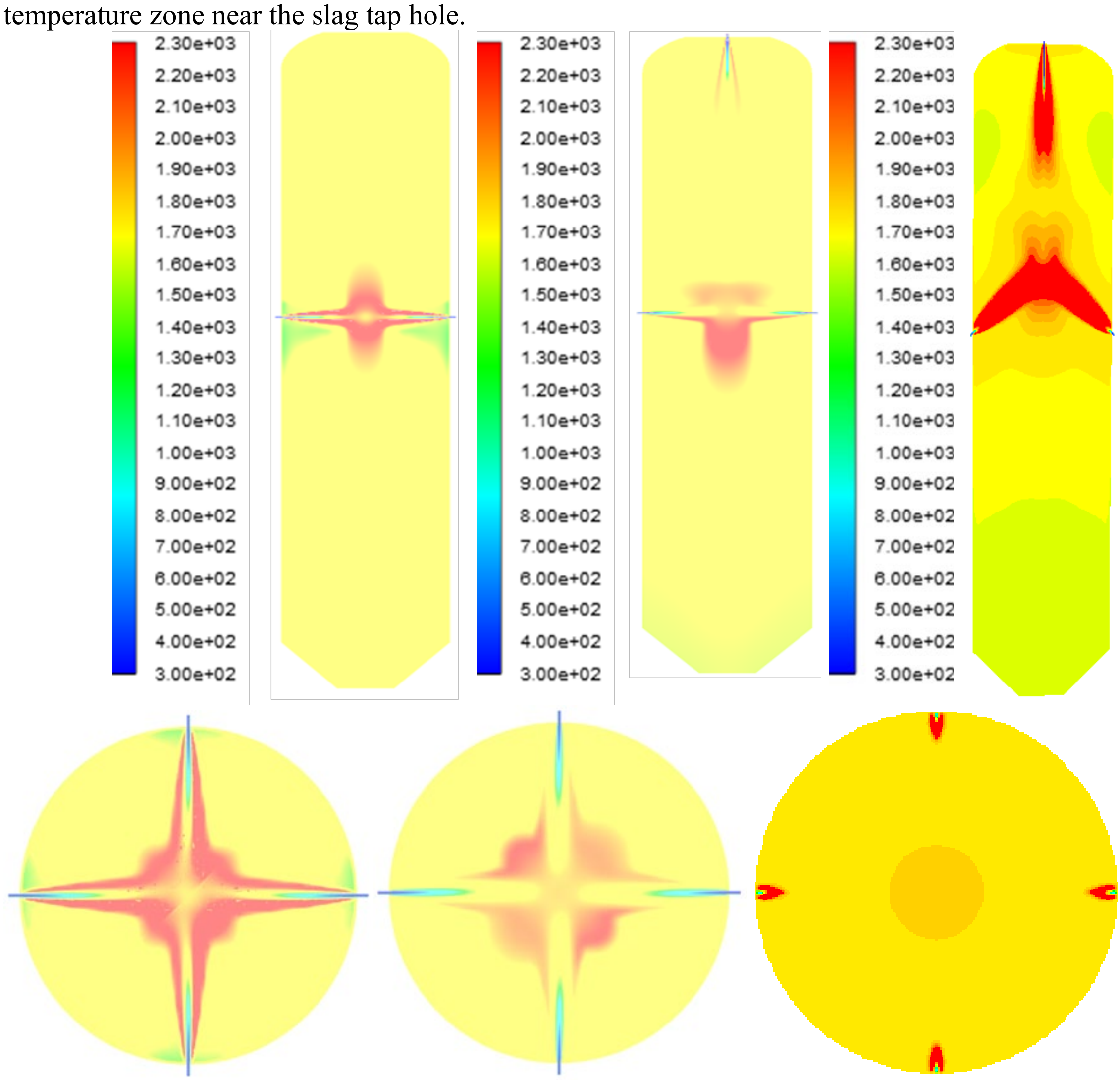
Exhibit 65. The fluid velocity distribution of the local area on the dome zone.

Temperature distribution in gasifier

Exhibit 66 shows the temperature distribution of the OMB and staged-OMB gasifiers. On the burner plane, the temperature in the impinging zone is similar for the OMB and staged-OMB gasifiers. It can be seen the jet center and mixing zone of the coaxial jet flow are the low-temperature zone due to heat transfer resistance and gasification, and high-temperature zone due to combustion of CO/H_2-rich fluids, respectively.

For the rest of the chamber, the high temperature is mainly concentrated near the jet boundary and around the impact area of the flow stream. The temperature near the wall of the gasifier is relatively low and uniform, indicating that the temperature distribution in the multi-burner gasifier is reasonable. In addition, the temperature near the plane center of the burner is not the highest, only about 1700K, because the oxygen is burned off by the syngas sucked by the jet stream. In the 4-burner plane impinging area, the coal slurry water evaporates and part of the coal particles react with carbon dioxide and water vapor via the secondary gasification reaction, which lowers the temperature. For the case of Staged-OMB I, a fluid secondary impingement occurred in the upper chamber. The high temperature zone seen on the 4-burner plane is moved down to below the burner plane. In the refractive flow region, the coal particles entrained by the gas flow continue gasifying, and the entrainment of the syngas with a relatively low temperature leads to the temperature of the refraction flow zone gradually decreasing. However, for the case of Staged-OMB II, with the tilt angle of 50°, the high temperature zone moves above the burner plane. However, this results in a low-temperature zone above the slag tap hole that could potentially impact slag discharge.

Exhibit 66 also compares the temperature distribution on the burner plane. It is clear that the higher temperature zone is found in the OMB gasifier, while the temperatures in the cases of Staged-OMB I and Staged-OMB II are lower. **Exhibit 67** shows the temperature distribution of slag hole zone. The temperature in OMB gasifier is about 1200 °C, lower than the temperature value of the Staged-OMB I gasifier, nearly 1400 °C. The temperature of Staged-OMB II is much lower than the former two configurations, about 1000 °C. This proves that the addition of the fifth burner can push the high-temperature zone down and closer to the slag hole zone which benefits the slag discharge. But tilting the opposed burners up would cause a lower temperature zone near the slag tap hole.



OMB gasifier (four burners) **Staged-OMB gasifiers (five burners, I and II)**

Exhibit 66. Temperature distribution of the OMB and Staged-OMB gasifiers

OMB gasifier (four burners) **Staged-OMB gasifiers (five burners, I and II)**

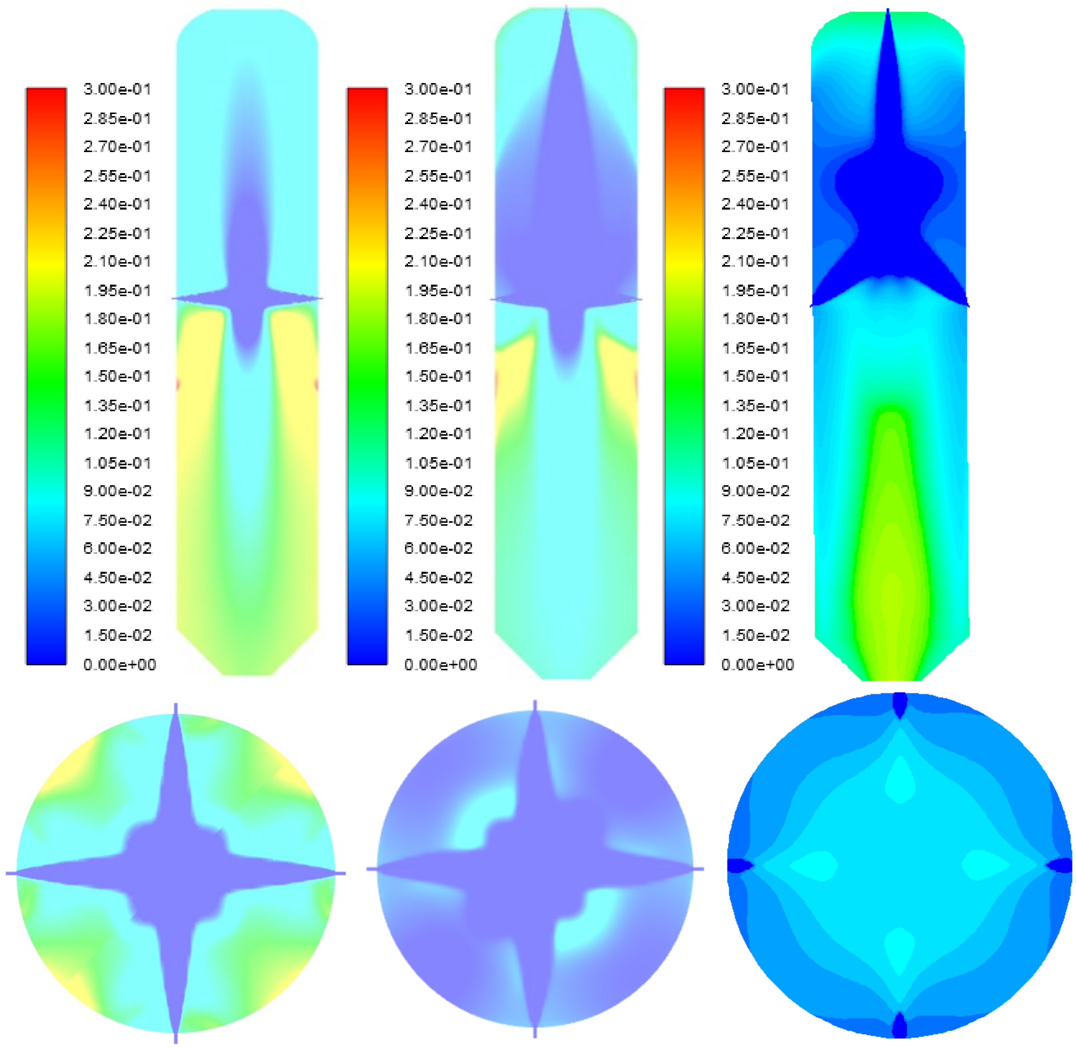
Exhibit 67. Temperature distribution of slag hole zone**.**

Syngas concentration distribution in gasifier

Exhibits 68 to 71 present syngas concentration profiles, including CO, H_2, H_2O, CO_2, and O_2, from three simulated cases. In general the concentrations of CO and H_2 is high for the operation of staged-OMB gasifiers, due to the high mixing efficiency from five burners. Comparing Staged-OMB I and Staged-OMB II, results show that the concentration of CO in both cases is low in the top zone of the gasifier due to the strengthened impinging zone. However, the CO concentration increases below the four-burner plane. For the case of Staged-OMB I, the H_2 concentration is low on the top zone while two high H_2 concentration zones are found near the fifth burner for the case of Staged-OMB II. Below the four-burner plane, the distribution of H_2 concentration displays similar results.

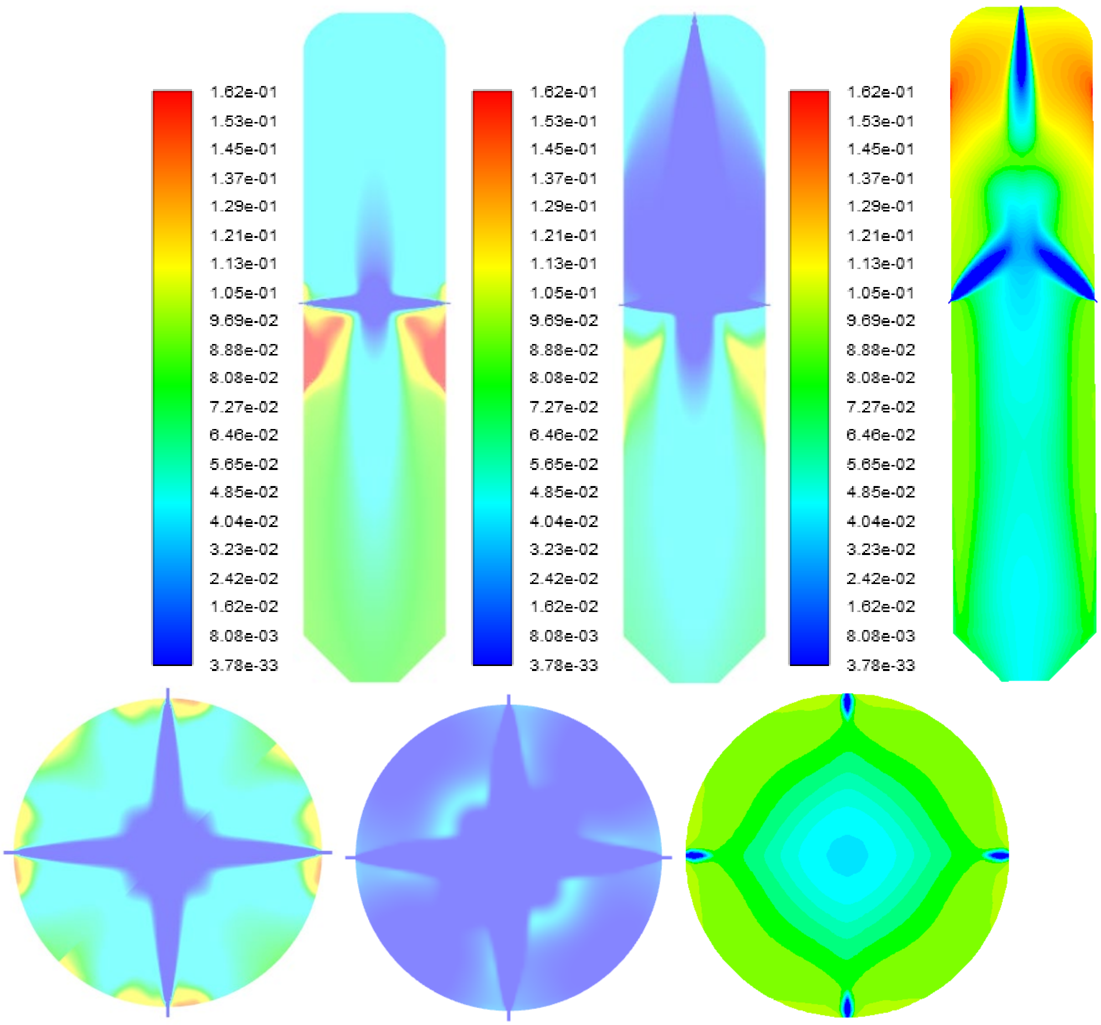
There is a large amount of H_2O in the outer boundary area of the jet stream which mainly comes from two aspects: one is generated by entrapment of H_2 combustion; the other is generated by evaporation of water from coal slurry. For the staged-OMB gasifiers, due to the addition of an impinging zone in the upper flow field, the backflow stream in the upper furnace will carry H_2O to disperse in the upper furnace. Therefore, with the development of refraction flow, the secondary reaction is enhanced, and the concentration of H_2O decreases in the lower hearth area of the two configurations, reaching equilibrium in the pipe flow area.

CO_2 in the OMB is concentrated in the jet boundary area, mainly generated by swirling and synthetic combustion. The carbon dioxide concentration in the staged-OMB gasifier concentrates on the border near the burner for the case of Staged-OMB I. For the case of Staged-OMB II, higher concentration of CO_2 is found in the jet flow zone of all five burners.



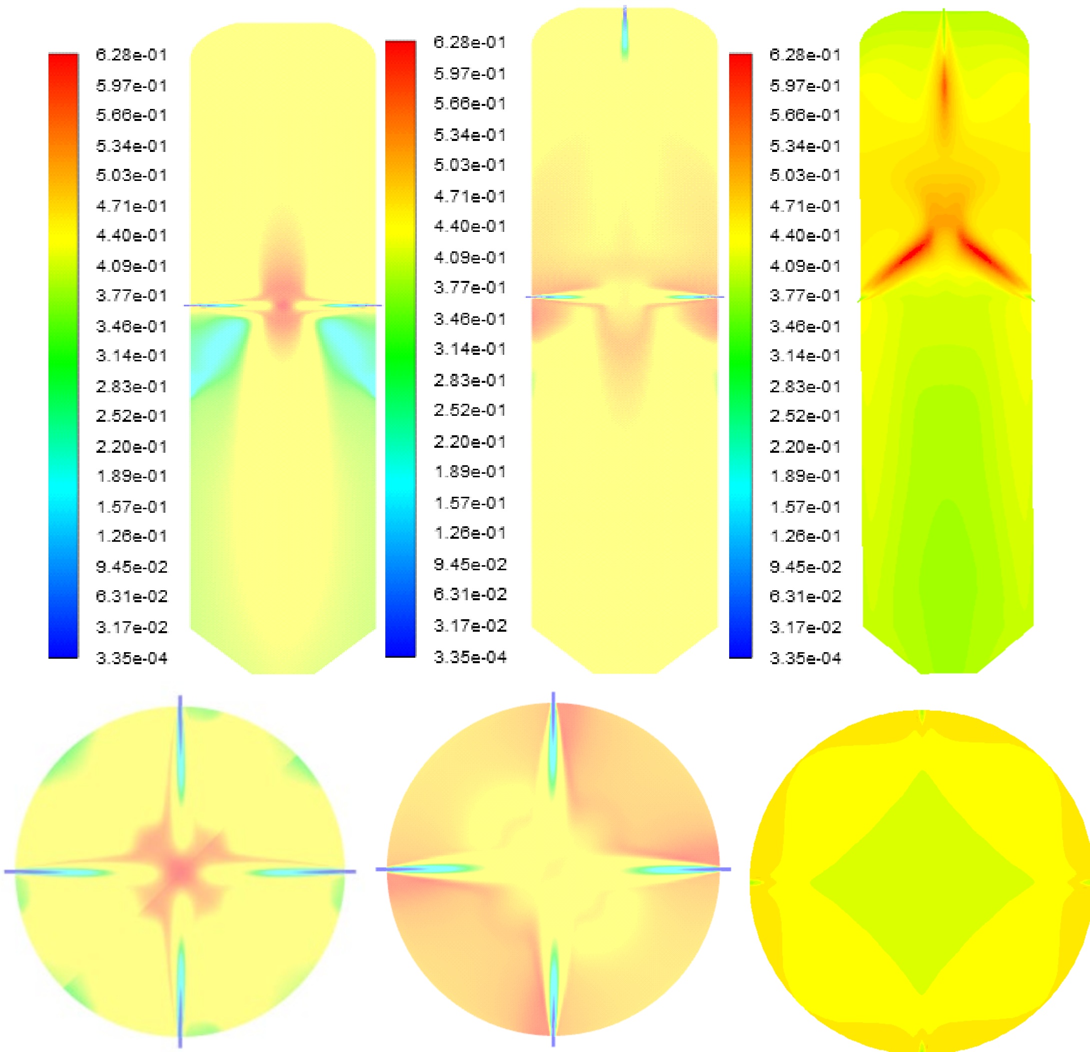
OMB gasifier (four burners) **Staged-OMB gasifier (five burners, I and II)**

Exhibit 68. CO concentration distribution.



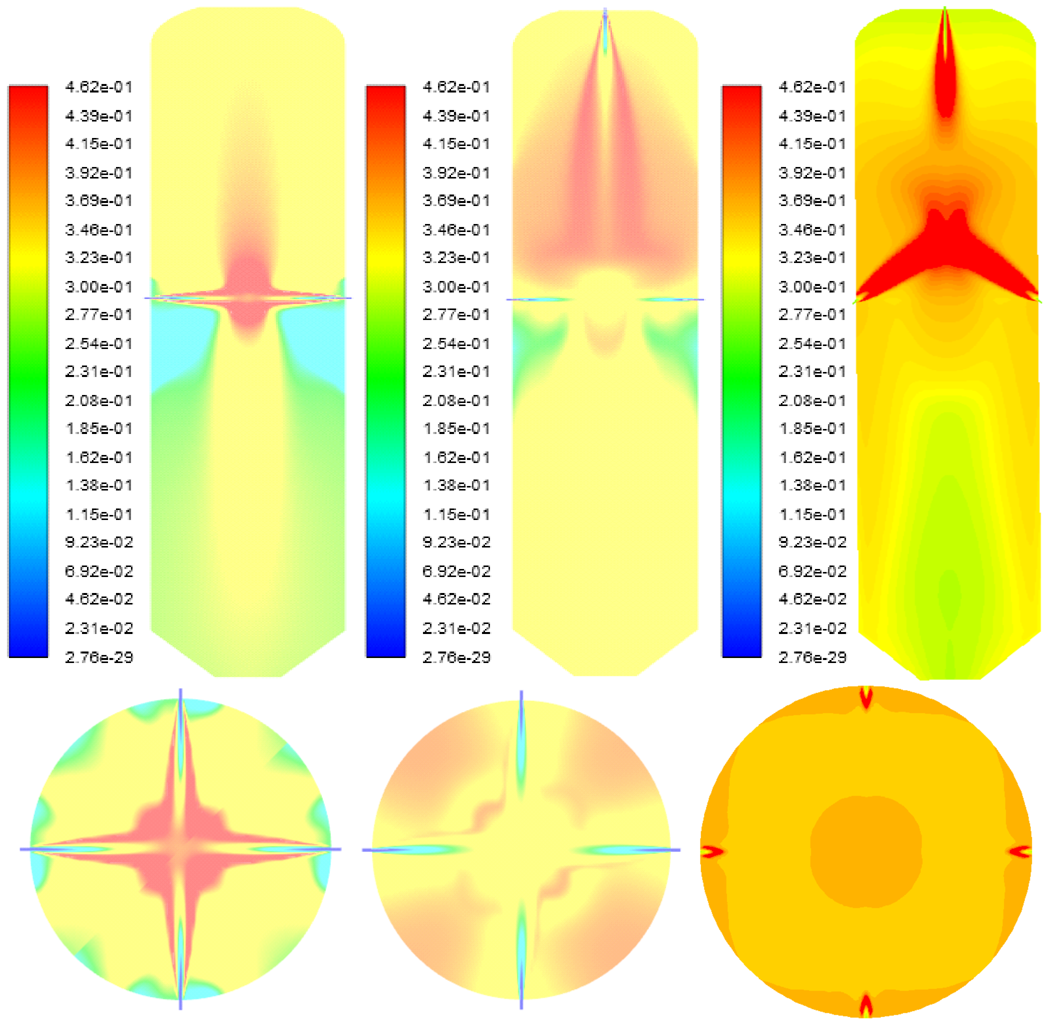
OMB gasifier (four burners) **Staged-OMB gasifier (five burners, I and II)**

Exhibit 69. H_2 concentration distribution.



OMB gasifier (four burners) **Staged-OMB gasifier (five burners, I and II)**

Exhibit 70. H_2O concentration distribution.



OMB gasifier (four burners) **Staged-OMB gasifier (five burners, I and II)**

Exhibit 71. CO_2 concentration distribution.

3.6.4. Summary

(1) Based on the principle of impinging flow, the mixing degree between the fluids in the staged-OMB gasifier is enhanced.

(2) The fifth burner adds an extra recirculation zone above the impinging zone and this pushes down the high temperature zone closer to the slag hole.

(3) The high temperature area of the gasifier is mainly concentrated near the boundary of the jet and the center of the gasifier, and the temperature distribution near the wall of the gasifier is relatively low and uniform.

(4) With adding the fifth burner, more CO and H_2 are found and distributed in the gasifier.

(5) With burners designed 50 degrees above the plane, the high temperature zone moves up to the zone between the fifth burner and four-burners plane. This structure change also causes the movement of higher H_2O and CO_2 concentration zones from the burner plane to the zone above the burner plane.

3.7 Technical and Economic Analysis

Based on data gathered above, UK CAER created AspenPlus® simulation to use for process optimization, performance evaluation and equipment sizing of the 1-5 MWe IGCC or CTL unit. The analysis was consistent with the NETL's "Quality Guidelines for Energy System Studies." UK CAER provided a detailed equipment list and sizing and performed comparison evaluations on capital and O&M cost and investment cost using the NETL System reports as basis.

Sub-recipient Trimeric worked closely with UK CAER in the performance of a techno-economic analysis to demonstrate the process's economic viability at the commercial scale. The objectives of the analysis were to determine economic advantages of the UK CAER's staged-OMB gasifier in comparison to a conventional gasifier. UK CAER provided Trimeric with the H&MB stream tables and performance estimates, and Trimeric used the data to perform a comparative financial analysis. The data from the NETL IGCC or CTL Baseline study was referenced to assure an "apples–to-apples" comparison.

This cost and performance baseline study provides process descriptions, heat and material balances, and estimated costs for full-scale IGCC plants with and without CO_2 capture for GE, Shell and CB&I E-Gas gasification technologies. UK CAER and Trimeric have submitted separate evaluation reports to US DOE NETL. Key results are summarized here.

UK CAER Staged-OMB Gasifier Economics

A fixed capital cost estimate, reported in Q4 2020 dollars, was developed for the CWS, staged-OMB gasifier unit to produce hydrogen-rich syngas to generate power. The capital costs are based on bare equipment costs with appropriate installation factors applied. A total purchased equipment cost of $21.0 MM with a total plant cost of $35.1 MM were estimated. The capital cost estimate does not include capital costs for coal preparation. **Exhibit 72** summarizes the purchased equipment costs and total plant costs by area.

Exhibit 72. Purchased Equipment Costs and Total Plant Costs by Process Area.

Process Area	Purchased Equipment Costs ($MM)	Total Plant Costs ($MM)	% of TPC
Air Separation Unit	2.24	3.36	9.6
Gasification	2.43	8.21	23.4
Acid Gas Removal	8.18	10.42	29.7
Engines / Power Recovery	7.66	12.1	34.5
Balance of Plant	0.51	1.02	2.9
Total	**21.02**	**35.12**	

The total annual operating revenue, operating expenses, and indirect expenses are shown in **Exhibit 73**. The gasifier facility produces power from coal feedstock as its only revenue stream. Electricity is produced via reciprocating internal combustion engines; thermal energy is not recovered from the gasification or power production process areas.

Exhibit 73. Annual Revenue and Operating Costs for UK CAER Staged-OMB Gasifier Facility.

Revenue or Expense	Dollars per Year
Facility Revenue	$ 2,473,000
Facility Operating Expenses	$ 931,000

Facility Indirect Expenses	$ 2,339,000
Total Profit (Loss)	$ (796,000)

Note: 80% onstream factor used. [1].

The primary variable operating expenses include: coal (fuel), water makeup, wastewater disposal, solids slag disposal, COS catalyst disposal, and LO-CAT® H2S removal chemicals and solids disposal. Indirect, or fixed, operating expenses include staffing, maintenance, taxes, and insurance. As shown in **Exhibit 60**, the gasifier facility, as configured, will lose money when operating – independent of any upfront capital cost requirements. The most significant variable operating cost for the facility is the cost of fuel (54% of the total variable operating expenses). The ASU consumes nearly 19% of the gross power output of the reciprocating engines. The indirect expenses are substantial and are impacted by the low power production of the facility.

UK CAER Staged OMB-Gasifier Comparison to Other Gasifier Designs

The UK CAER staged OMB-gasifier was compared with four other gasification units generating power: two small-scale (5.3 and 18 MWe gross) and two commercial-scale (763 and 738 MWe gross). A sensitivity was performed on the process scale of the staged-OMB gasifier, increasing the total gross electrical output from 5.1 MWe to 25 MWe. Equipment was scaled using the ratio of total gross power raised to the exponent of 0.6. Variable costs were scaled linearly with gross power produced. The reciprocating engines were replaced by a combustion turbine assuming the technology is available at this scale for energy production from syngas. A summary of the facilities is provided in **Exhibit 74**.

The syngas production performance was compared for the five facility designs as shown in **Exhibits 75 and 76.** The staged-OMB gasifier outperforms the other gasifiers on total syngas production fraction (H_2+CO), syngas heating value, and H_2/CO ratio. Both commercial-scale gasifiers (DOE case B4A and S4A) have a moderately higher H_2/CO ratio. Higher heating value allows for more power generation and smaller equipment size per unit mass of feed. Higher H_2/CO ratio is more economical for conversion of syngas to chemicals should a polygeneration facility be desired. The staged-OMB gasifier shows marginal differences for CO_2 content in the product syngas as well as oxygen demand.

A comparison of the facility costs using cost of electricity (COE) is summarized in **Exhibit 7**7. The contributions to the COE include the following: capital cost (assumed to be the total plant cost), fuel, variable operating costs, and fixed operating costs.

As shown in **Exhibit 77**, the staged-OMB gasifier has a higher COE than most of the cases except the membrane-wall gasifier. Fuel and variable O&M are low in comparison with the other reference cases. The major contributors to the total COE ($281/MWh) are the capital cost (59%) and the fixed O&M (31%). While the staged-OMB gasifier decreased the gasification process area capital cost, the overall plant cost is largely defined by the other process areas. In the capital investment, gasification accounts for only 23% of the total plant cost with power production (34%) and acid gas removal (30%) being the most expensive process areas.

COE decreases from $281/MWh to $137/MWh when the facility scale is increased from 5.1 to 25 MWe gross electrical output. Capital costs are significantly lower normalized to throughput because economies of scale favor larger facilities. Fixed O&M costs decrease because labor costs were assumed constant, but the facility output is higher.

Exhibit 75. Facility Comparison for Technoeconomic Analysis.						
Description	**UK CAER Staged-OMB Gasifier (Base Case)**	**UK CAER Staged-OMB Gasifier (Sensitivity Case)**	**UK CAER Membrane-Wall Gasifier** [4]	**UA Fairbanks HMI Gasifier** [5]	**DOE Case B4A (CB&I E-Gas^{TM} Gasifier)** [1]	**DOE Case S4A (CoP E-Gas^{TM} Gasifier)** [2]
Gross Power (MW_e)	5.1	25	5.3	18	763	738
Other Products	--	--	Steam Hydrocarbon Liquids and Waxes	Steam	--	--
Fuel Supply	Coal water slurry (North Dakota Lignite)	Coal water slurry (North Dakota Lignite)	Coal Fines (Impoundment Fines)	Coal + Biomass (Usibelli Sub-Bituminous/Woo d Chips)	Coal water slurry (Illinois No.6 – Bituminous)	Coal water slurry (Powder River Basin – Subbituminous)
Oxidant Supply	Cryogenic ASU (99.6 vol% O_2)	Cryogenic ASU (99.6 vol% O_2)	Cryogenic ASU (>95 vol% O_2)	Air (21 vol% O_2)	Cryogenic ASU (>95 vol% O_2)	Cryogenic ASU (>95 vol% O_2)
Power Block	Reciprocating internal combustion engines	Combustion Turbine	Reciprocating internal combustion engines + turboexpander	Reciprocating internal combustion engines + diesel engine generator	Combustion turbine + steam turbine	Combustion turbine + steam turbine
Acid Gas Removal	COS Hydrolysis LO-CAT®	COS Hydrolysis LO-CAT®	MDEA Unit SulfaTreat	Short contact time caustic scrubber	COS Hydrolysis MDEA Unit Claus Unit	COS Hydrolysis MDEA Unit Claus Unit
Sulfur Load (LTPD)	1.55	7.60	0.58	0.10	55.23	51.18

Exhibit 76. Syngas Production Performance Comparison.							
Description	**Units**	**UK CAER Staged-OMB Gasifier (Base Case)**	**UK CAER Staged-OMB Gasifier (Sensitivity Case)**	**UK CAER Membrane-Wall Gasifier** [1]	**UA Fairbanks HMI Gasifier** [2]	**DOE Case B4A (CB&I E-Gas™ Gasifier)** [3]	**DOE Case S4A (CoP E-Gas™ Gasifier)** [4]
$O_2/(H_2+CO)$	Mol/Mol	0.39	Performance of the 25 MW facility assumed the same as the base case.	0.51	0.24	0.36	0.48
Carbon Conversion	%	98.0		97.2	N/A	99.2	99.1
Syngas Quality							
HHV @ Outlet	Btu/SCF	268		262	167	240	242
H_2+CO	Mole Frac	0.81		0.70	0.46	0.71	0.69
H_2/CO	--	0.82		0.64	0.70	0.91	0.95
CO/CO_2	--	2.58		2.99	3.70	1.94	1.32

Exhibit 77. Cost of Electricity Comparison.							
Description	**Units**	**UK CAER Staged-OMB Gasifier (Base Case)**	**UK CAER Staged-OMB Gasifier (Sensitivity Case)**	**UK CAER Membrane-Wall Gasifier**	**UA Fairbanks HMI Gasifier**	**DOE Case B4A (CB&I E-Gas™ Gasifier)**	**DOE Case S4A (CoP E-Gas™ Gasifier)**
Gross Power	MW_e	5.3	25	5.3	18	763	738
COE	$/MWh	281	137	355	156	99	74
Capital	$/MWh	164	78	175	93	58	45
Fuel	$/MWh	15	15	0	63	14	7
Variable O&M	$/MWh	13	13	90		10	7
Fixed O&M	$/MWh	88	32	91		17	15

Technical measures that can be considered to improve the economics for the proposed 5 MW staged-OMB gasifier facility are listed below:

Alternate Coal Type: Lower sulfur coal could reduce the capital and operating expense for acid gas removal. If the sulfur load was the same as with the membrane-wall gasifier case (0.58 LTPD), the COE could be reduced by 15% to $239/MWh. However, input from UK CAER indicated that coal processing with sulfur removal prior to gasification would be more economically favorable for this scale.

Larger Production Scales: The largest operating costs for the gasification facility are the indirect expenses comprising labor and overhead costs, property tax and insurance, and facility maintenance and upkeep. A larger production facility would improve the scaling of fixed operating costs against generated revenue.

Replace Engines with Turbines: The reciprocating engines have high capital cost because of the engine efficiency and sizeable derate (50%) due to the low heating value of the syngas and limited application experience. Significant cost escalators are incurred for this special design. Combustion turbines are not available for small-scale processes. Advancements in turbine design at small scale, or increasing the facility throughput, would be required to switch from reciprocating engines to combustion turbines. Increasing the production scale from 5 to 25 MW, and shifting from reciprocating engines to a combustion turbine, yielded a 51% reduction in the COE from $281/MWh to $137/MWh.

References

1. H. Nikolic and K. Liu, "Gasification Combined Heat and Power from Coal Fines," U.S. DOE NETL, 2019.

2. H. Goldstein, "Making Coal Relevant for Small Scale Applications: Modulur Gasification for Syngas/Engine CHP Applications in Challenging Environments," U.S. DOE NETL, 2019

3. Department of Energy, "Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity," DOE/NETL, 2019.

4. Department of Energy, "Cost and Performance Baseline for Fossil Energy Plants Volume 3a: Low Rank Coal to Electricity: IGCC Cases," U.S. DOE NETL, 2011.