

FIELD SCALE TESTING OF THE THERMOCATALYTIC ETHYLENE
PRODUCTION PROCESS USING ETHANE AND ACTUAL COAL FIRED
FLUE GAS CO₂

FINAL SCIENTIFIC/TECHNICAL REPORT

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1. EXECUTIVE SUMMARY

CO₂ from coal fired power plants can be utilized directly or following capture as a chemical feedstock to produce valuable chemicals. Such approach provides economically attractive solutions to mitigate emission while offsetting the cost of carbon capture and storage from coal fired power plants which are responsible for large CO₂ emission (1,150-mmt CO₂ emission from US coal fired utility plants in 2018¹. However, due to its low energy state, chemical conversion of CO₂ is very energy intensive and/or necessitates reacting with highly reactive, often expensive and hazardous molecules (e.g., H₂). As a result, currently only a handful of chemical production processes use CO₂ as feedstock (e.g., Urea)².

This report provides a summary of the work performed and results obtained from a project supported by the US DOE (DE-FE0031713). In this study, Southern Research (SR) completed field-scale demonstration of a rationally designed novel nano-engineered catalyst driven thermochemical process to produce high yield of ethylene by using CO₂ derived from actual coal-fired flue gas and ethane. This process, referred to here as “CO₂-ODH” due to CO₂ use via oxidative dehydrogenation (ODH) mechanism, follows a modified pathway to classical steam cracking (SC) process of ethylene production thus paving the way for significantly reduced CO₂ footprint, marginally improved thermodynamics, higher product selectivity and lower reaction temperatures.

The project constituted six major tasks and lasted for 33 months (February, 2019 to November, 2021). During the first year of study, SR has completed the construction and retrofitting of the field scale skid. P&ID and HAZOP were completed by SR and reviewed by NCCC and the field scale module was eventually transported to NCCC for testing (Task 4). At the same time, ~320g of the novel nano-engineered catalyst was synthesized and its performance verified with a laboratory scale reactor using simulated flue gas CO₂ compositions (Task 2). Out of the examined flue gas impurities, only H₂O was found to be detrimental for both ethane and CO₂ conversion. The catalyst also showed partial sensitivity to the presence of O₂ and only a smaller O₂:CO₂ ratios (1:>20) was acceptable for best performance. On the other hand, the catalyst showed strong tolerance to the presence of SO₂ and NO. 500hr (76 cycles) run was completed with simulated flue gas which showed < 5% catalyst degradation and ethylene yield > 50%. 300-hr/100 cycles lab scale run was completed with simulated high concentration (99.5%) captured CO₂. The catalyst showed decent activity (28% average yield and 19 mmole/gcat.hr productivity). Ethylene yield varied by ±2% over the duration of the study which represents good catalyst stability.

Integration and commissioning of the field scale module took majority of the 2nd year. Due to the unavailability of coal fired flue gas as well as pandemic restriction severely impacted these activities. Nevertheless, the continuous runs started in July, 2021. 80g catalyst was loaded with a

¹ eia.gov

² Alper, E., & Orhan, O. Y. (2017). CO₂ utilization: Developments in conversion processes. *Petroleum*, 3(1), 109-126.

CO₂ to ethane ratio between 1.5-3.0 at GHSV of 9000 L/kgcat.hr. The runs were conducted at 650°C and near atmospheric pressure. Catalyst performance with captured (concentrated) CO₂ (CAP) was comparable with the results observed in laboratory scale. 35-40% single pass conversion of ethane with monetizable productivity of ethylene, CO and H₂ were achieved. Despite several system interruptions, the catalyst maintained strong activity and selectivity towards ethylene and CO. Use of such concentrated stream, also available from a wide variety of industrial sources, offers compelling economic and environmental sense potentially ensuring lower ethylene production cost (\$0.291/kg) along with substantial (>50%) reduction in Global Warming Potential (GWP). These economic and environmental aspects have been covered under Task 6.

On the other hand, presence of O₂ in the as-generated (dilute) flue gas stream (DFG) affected the usability of this stream as a CO₂ source. Although high ethane conversion was observed in this case, ethane combustion by O₂ was thermodynamically preferred which limited CO₂ conversion drastically. Both O₂ and H₂O levels need to be maintained as low levels (<1 vol% each) for this catalyst to selectively use CO₂ to generate ethylene. Later, excess ethane was used to pre-combust with O₂ in a preheater before the reactor. As a result, the catalyst could be operated for 500hrs with high conversion and much improved ethylene selectivity. However, both economic (ethylene production cost \$0.412/kg) and environmental benefits are largely diminished in this configuration.

2. PROJECT ORGANIZATION AND STRUCTURE

SR has assembled a capable project team comprised of SR's Sustainable Chemistry and Catalysis group, Applied Research and Technology Commercialization (ARTC) and National Carbon Capture Center (NCCC). Catalyst scale-up, lab-scale evaluation and field scale module construction were conducted in SR's Energy and Environment laboratory facilities located in Birmingham, AL. Field testing was performed at NCCC site. SR was the prime contractor, responsible for conducting and overseeing all tasks, including catalyst development, testing and TEA/LCA studies. SR was also responsible for reporting to the DOE Program Manager. Among the partners, ARTC mainly provided guidance with respect to catalyst design, testing parameters and technology integration to ensure a solid foundation for commercialization of this technology.

SR maintains a strong working relationship with these partner organizations, and each organization has high interest in developing technology that can successfully address the issues surrounding coal-fired plant GHG mitigation and capture. Due to this common interest, complementary expertise and capabilities, the proposed partners have been fully committed to this project. The goal of bringing in all involved parties together was to work in close collaboration for a better outcome and learn from different perspectives as the technology is developed.

SR has set up periodic teleconference meetings with project partners for communicating project status, recommendation, progress and key issues. Milestone reviews and risk assessments were incorporated into the meetings. The DOE Program Manager was informed about the team meetings. Several contractual aspects were negotiated and agreed upon among the parties. These agreements clearly addressed how intellectual property (IP) rights would be managed and addressed aspects related to both pre-existing and new IP. During the duration of the project, any new findings were promptly documented with patent applications to protect IP, as necessary. A final "Invention Certification" report is submitted highlighting one issued and one filed US patent as a result of this work.

3. GOALS AND OBJECTIVES

The purpose of the proposed project is to scale up and field test a rationally designed catalyst driven ethylene production process using ethane and actual coal fired flue gas derived CO₂. The project will proceed at first by scaling up catalyst synthesis and validate performance levels using laboratory scale reactor. An integration of a field scale reactor skid with an existing coal fired power plant facility with direct access to actual flue gas and flue gas captured CO₂ will be executed. Following commissioning of the integrated skid, cyclic reaction runs will be conducted.

Budget period 1:

- Scale up synthesis of nano-engineered catalysts
- Validate performance of scaled up catalysts using laboratory scale reactor
- Integrate field scale skid with partner's post-combustion facility for direct actual flue gas derived CO₂ access.

- Process simulation with post reaction separation and capital cost estimation.

Budget period 2:

- Test the catalysts for stability under optimized process condition for extended periods of time (up to 500-hr).
- Techno-economic and life cycle assessment for potential commercialization of the process.

4. PROJECT TASKS AND ACCOMPLISHMENTS

The six major project tasks along with their timelines and key objectives have been presented in **Table 1**. This section highlights the accomplishments of the project team in completing the project tasks outlined in the Statement of Project Objectives (SOPO).

Table 1. Project tasks, timeline and key objectives

Task Name	Planned Start	Planned End	Adjusted Start-End	Key Objectives
Task 1: Project management and reporting	02/01/19	01/31/21	Completed on schedule	Complete PMP. Implement plan to execute project tasks according to the agreed cost and schedule
Task 2: Field scale preparation and testing	02/01/19	06/30/19	Completed on schedule	Synthesis of nano-engineered mixed oxide catalysts up to half a kg. Labscale verification of the scaled up catalyst
Task 2.1: Catalyst scale up	02/01/19	03/31/19	Completed on schedule	
Task 2.2: Catalyst testing in a labscale reactor	04/01/19	06/30/19	Completed on schedule	
Task 3: Technology maturation plan	07/01/19	07/31/19	Completed on schedule	Define TRL at start and end of project
Task 4: Procurement and integration of actual flue gas with skid	08/01/19	01/31/20		Field scale skid transported to NCCC facility for integration and retrofitting with coal fired flue gas generation. ASPEN simulation for the integrated process
Task 4.1 Field scale skid preparation and transportation to the host site	08/01/19	09/30/19	Completed on schedule	
Task 4.2 Integration with the host site and commissioning of the skid	10/01/19	01/31/20	12/11/20- 04/30/21	
Task 4.3 Development of a baseline ASPEN simulation model	09/30/19	01/31/20	Completed on schedule	
Task 5: Continuous operation with actual flue gas	02/01/20	11/30/20	05/03/21-11/30/21	500h x 2 continuous run using actual captured CO ₂ and direct flue gas stream
Task 6: Techno-economic and life cycle/ technology gap analysis	12/01/20	01/31/21	05/03/21-11/30/21	Provide TEA/LCA based on CO ₂ streams, recommendations on required flue gas compositions and gap analysis

Task 1 – Project management and reporting

This task included management of technical, budgetary, and scheduling activities. In completing this task, SR provided required periodic reports to the DOE/NETL and managed informal correspondence and collaboration. SR also made technical briefings to DOE/NETL, and presented the project at several conferences sponsored by industry and the DOE. The partners provided valuable input to SR via regular correspondence. SR monitored the progress of the project against its original plan, reviewed and updated the project management plan, and reported on budget and

schedule variances to the DOE. Any issues arising from the review were documented and discussed with DOE/NETL and appropriate remedial actions were jointly addressed.

1. The formal project start date was agreed to be February 1, 2019.
2. The revised PMP was submitted and accepted by DOE-NETL in March 07,2019. No further modification on the PMP was made after this time.
3. All sub-contract drafts were prepared and negotiations initiated with partners. Each of the required sub-contracts was signed and concluded within the framework and terms agreed upon. The statement of work was agreed upon by all partners.
4. The progress of the project was presented in three (2019, 2020 and 2021) NETL carbon capture technology project review meetings.
5. Several other project progress presentations were made through out the project. A comprehensive list of presentations was provided in the Appendix at the end of this report.
6. In total of eleven quarterly technical reports were submitted. SR also provided monthly highlights of accomplishments and planning directly to the project manager.

Task 2 – Field scale preparation and testing

This task was divided into two subtasks which include a bench scale synthesis of catalyst (Task 2.1) and scaled-up catalyst performance verification using simulated flue gas stream in lab scale (Task 2.2). Specific accomplishments from the completion of Task 2 included:

1. 4 x 80g of the novel nanoengineered catalyst was synthesized in -20+35 mesh size.
2. Reproducibility of the various batches of catalysts were verified using surface area and pore size (BET), temperature programmed reaction (TPSR) and X-ray diffraction (XRD) for oxide phases and their dispersion.
3. Using the laboratory scale reaction skid, performance of the synthesized batches of catalysts were verified with respect to three major performance metrics e.g., conversion (ethane), selectivity (ethylene) and catalyst stability.
4. NCCC shared typical specifications of actual flue gas as well as captured CO₂ streams. Based on these specification, simulated compositions of each stream were decided and used in the lab scale evaluation.
5. During lab scale evaluation of simulated flue gas, the catalyst showed excellent stability over the course of 500hrs of run (70+ cycles of continuous operation and regeneration). The ethylene yield was as high as 57% with an ethylene selectivity of 95%. During the long term study the catalyst only deactivated by <5% most likely due to flow interruption events that occurred during the study
6. Using simulated captured CO₂ streams, a long duration (300-hr/100 cycles) laboratory scale ODH catalyst study was completed. The catalyst showed decent activity (28% average yield and 19 mmole/gcat.hr productivity). Ethylene yield varied by ±2% over the duration of the study which represents good catalyst stability.

Task 3. Technology maturation plan

Technology maturation plan was shared separately to DOE-NETL within the first six months of the project when it was due.

Task 4: Procurement and integration of actual flue gas with skid

1. SR constructed the field scale skid. P&ID and HAZOP were completed by SR and reviewed by NCCC on November 18, 2019.
2. The field scale skid was successfully transported to NCCC site on February 25, 2020.
3. Skid integration to NCCC site was completed during April 30, 2021 following significant delay due to pandemic.
4. ASPEN simulation for the proposed integrated process including purification has been completed both for direct flue gas (DFG) and captured CO₂ (CAP) utilization cases. For separation, schemes that are at or near commercial stage (TRL 6 or higher) have been considered. These include cryogenic separation, sorbent based PSA separations etc.

Task 5: Continuous operation with actual flue gas

1. Using amine based actual captured CO₂ stream, the catalyst performance was evaluated at field scale at 650°C. The run started on August 24, 2021 and lasted for 73 days and over 500hr run data was collected. 80g catalyst was used. Feed ethane composition was as high as 33% and CO₂ concentration 60%. Catalyst showed great stability of performance in cycle operation (reaction-regeneration) despite various interruptions. Monetizable amounts of ethylene (~300 g/kg.hr), CO (400 g/kg.hr) and H₂ (3-4 g/kg.hr) were obtained.
2. In case of direct flue gas, both natural gas and coal fired flue gases were used. Catalyst performance was evaluated at 650°C and with 80g catalyst. The run started on November 11, 2020 and lasted for 19 days. Feed ethane composition was 3-4%. High levels of O₂ (O₂:CO₂ ~0.5) greatly affected reaction performance as O₂ combustion was thermodynamically favored. The resulting ethylene and CO (30-40 g/kg hr) formation were significantly lower than in captured case. Although the catalyst appeared highly stable under these conditions, presence of such high levels of O₂ would largely diminish most of the economic and environmental benefits.

Task 6: Techno-economic and life cycle/ technology gap analysis

1. Both direct flue gas as well as captured CO₂ utilization cases have been considered in TEA. Major observations from the TEA are as follows:
 - 1.1. Captured CO₂ utilization (CAP) offers better economics than direct flue gas utilization (DFG) case. Production cost is approximately 30% lower in CAP case.
 - 1.2. Cost of production (\$0.291/kg ethylene) in CAP case is on par with the lower range of production cost obtained from the commercial process (\$0.29/kg ethylene).
 - 1.3. CAP case has higher raw material cost, but reduced utility and capital cost compared to DFG.
2. SR used open LCA software for the LCA evaluation of the process as per NETL guidance. Proposed product system has been compared with comparison (state-of-the-art, SOT) system using SCPC coal fired power plant as the electricity and CO₂ generator. Both captured CO₂ as well as direct flue gas utilization cases have been considered. Multiproduct functional units have been assigned for accurate comparison. 50% and higher reduction in global warming potential (GWP) would result from the proposed system.

5. TECHNICAL APPROACH

This project follows on from a prior catalyst development and laboratory scale evaluation study (DE-FE0029570). A novel nanoengineered catalyst was designed that efficiently converts ethane

and CO₂ to ethylene and CO. This study was designed to conduct catalyst scale up and validate catalyst performance at field scale using actual flue gas or CO₂ sources. This will elevate TRL level from 2/3 to 5/6.

6. GENERAL PROCESS DESCRIPTION

The proposed route for ethylene production deviates from the traditional ethylene production process (SC) in utilizing a catalyst and CO₂ as a “soft” oxidant. In the conventional SC process steam is used to dehydrogenate ethane at very high temperatures (~900°C). On the other hand, the mechanism of the proposed reaction, commonly referred to as oxidative dehydrogenation (ODH), utilizes an oxidant in presence of a catalyst to abstract a hydrogen molecule from an alkane. The oxidant transforms hydrogen into H₂O and thus makes this reaction thermodynamically more favorable. Oxidizing ability of various gases for carbon gasification is in the order of O₂ (105) > H₂O (3) > CO₂ (1) > H₂ (0.003). Use of molecular oxygen as oxidant can effectively reduce the reaction temperature and inhibit coking, however, issues such as low selectivity due to the production of CO_x species from hydrocarbons and the heightened industrial process safety concerns for using oxygen as feed are some of the major stumbling blocks³. Alternatively, CO₂ can provide solutions on multiple fronts by:

- (i) Acting as a “softer” oxidant preventing deep oxidation
- (ii) Eliminating steam consumption from ethylene production process
- (iii) Providing a suitable medium for heat supply for the endothermic dehydrogenation reaction (no loss of latent heat)
- (iv) Being an inexpensive and abundant feedstock and contributing to GHG reduction via CO₂ conversion
- (v) Being an active coke removal agent (CO₂+ C = CO) from the catalyst
- (vi) Acting simultaneously as a diluent and reactant

The reaction networks are included in **Table 2**.

Table 2. Reaction network of conventional SC and proposed ODH process for ethylene production.

Steam cracking (SC) - SOA
<p>Reaction network: <i>Main reaction:</i> $C_2H_6 = C_2H_4 + H_2 \quad \Delta H^\circ = 137 \text{ kJ/mol}$</p> <p><i>Side Reactions:</i> $C_2H_6 + H_2 = 2CH_4$; $2C_2H_6 = C_3H_8 + CH_4$; $C_3H_6 = C_2H_2 + CH_4$; $C_2H_2 + C_2H_4 = C_4H_6$; $C_2H_4 + C_2H_6 = C_3H_6 + CH_4$</p>
ODH
<p>Reaction network: <i>Overall reaction:</i> (a) $C_2H_6 + CO_2 = C_2H_4 + CO + H_2O \quad \Delta H^\circ = 134 \text{ kJ/mol}$</p> <p><i>Desired reactions:</i> (b) $C_2H_6 = C_2H_4 + H_2$; (c) $CO_2 + H_2 = CO + H_2O$; (d) $C + CO_2 = 2CO$</p> <p><i>Undesired reactions:</i> (e) $C_2H_6 + H_2 = 2CH_4$; (f) $C_2H_6 + 2CO_2 = 4CO + 3H_2$</p>

³ Baroi, C., Gaffney, A. M., & Fushimi, R. (2017). Process economics and safety considerations for the oxidative dehydrogenation of ethane using the M1 catalyst. *Catalysis Today*, 298, 138-144.



Figure 1. Laboratory scale reaction skid used for this project. Process flow schematics on the left and photographic image on the right.

7. FIELD SCALE UNIT CONSTRUCTION

The field scale unit designed and fabricated at SR was equipped with accurate metering and processing schemes of various relevant gases including, N₂, air, flue gas, captured CO₂, ethane. Both flue gas and captured CO₂ go through small processing before entering the reactor mainly to separate H₂O. A membrane separator was added in the flue gas line to strip off residual moisture as H₂O was found to be an activity inhibitor for this reaction. A preheater was also added upstream to the reactor to preheat feed and to consume flue gas O₂ by flowing excess ethane. Although ethane is consumed in this scheme, it can provide exothermic heat that can potentially alleviate the utility requirement from this reaction. Separate lines for flue gas, captured CO₂, ethane, air, nitrogen and SO₂ were connected. Following reaction, most of the effluent gases were combusted in the oxidizer and a slip stream was extracted for GC analysis. The unit was enclosed in a class I Div II enclosure. Construction of skid had been finalized after conducting a HAZOP study on November 18th with representatives from NCCC. A photographic image of the skid is presented in Figure 1.

8. FIELD SCALE REACTION ANALYSIS

For each reaction study, 80g of catalyst was loaded at the center of a stainless steel reactor tube. A multi-point thermocouple was inserted in the reactor tube and was in contact with the catalyst to record accurate catalyst temperatures at different locations. The catalyst particles were sized between 600 and 800- μm to prevent pressure rise across the reactor. The loaded reactor was

vertically assembled inside a furnace to mimic fixed bed catalytic reactor system. The product effluent gas was chilled in a condenser (5°C) to remove moisture before traveling to an online Micro GC for gas analysis. The Micro GC is calibrated for all major reaction constituents including ethane (C₂H₆), ethylene (C₂H₄), CO, CO₂, CH₄, O₂, N₂, H₂. N₂ was used as an internal standard for accurate mass balance. Following equations were used to determine various performance metrics.

$$\text{Conversion of ethane} = \frac{2 \times n_{C_2H_4} + n_{CH_4}}{2 \times n_{C_2H_4} + n_{CH_4} + 2 \times n_{C_2H_6}} \times 100$$

$$\text{Conversion of CO}_2 = \frac{n_{CO}}{n_{CO_2} + n_{CO}} \times 100$$

$$\text{Selectivity to ethylene} = \frac{2 \times n_{C_2H_4}}{2 \times n_{C_2H_4} + n_{CH_4}} \times 100$$

Ethylene yield = Ethane conversion × ethylene selectivity

Ethylene productivity in mmoles per gm cat per hr

$$= \frac{\text{molar flow rate of ethane} \left[\frac{\text{mmoles}}{\text{hr}} \right] \times \text{Conversion} \times \text{Selectivity}}{\text{gm catalyst}}$$

Here, n values represent GC composition in the product.

9. OPERATING CONDITIONS

Operating condition ranges carried out during laboratory scale ODH testing are summarized in **Table 4**.

Table 3. Range of ODH operating condition using laboratory scale skid.

Parameters	Variation
CO ₂ composition	FG: Actual flue gas (both coal and gas fired) CAP: Actual captured CO ₂
CO ₂ : C ₂ H ₆ ratio	1.5-3.0 : 1
Ethane concentration (Max vol%) in feed	5.0 (FG case) and 33 (CAP case)
Temperature	650°C
Pressure	Atmospheric
Space velocity	9000 scc/gcat.hr

10. FIELD SCALE TEST RESULTS AND DISCUSSIONS

10.1. Captured CO₂ (CAP)

For captured CO₂ (CAP) the source was the product of an amine capture unit collocated at NCCC with a CO₂ concentration of > 99.5%. This CO₂ source is commonly known as the Slipstream Solvent Test Unit (SSTU). A total flow rate of 9.6 L/min was used to flow through a packed bed of 80g catalyst at 650°C. CO₂ to ethane ratio was 3 at the beginning and was eventually adjusted

to 1.5 on the 200hr mark. Ethane concentration in the feed was 33.33vol% with remainder being CO₂ (50%), N₂ (15%), O₂ (1%) and SO₂ (80 ppm). The 500-hr run was completed in approximately 72 days. Several interruptions occurred during that timeframe. These interruptions are captured in the following table.

Table 4. Interruption log for the captured CO₂ run

Day	Cause/Comment
August 24, 2021	Run started
August 30, 2021	Air supply drained
August 31, 2021	Interlock system tripped. Needed resetting
September 3, 2021	SO ₂ leak detected. Blower for vent down. Ethane and SO ₂ supply shut down. Run paused for 5 days
September 9, 2021	Ethane flow rate increased to lower CO ₂ :ethane ratio to 1.5
September 10, 2021	Breaker tripped. Reaction at room temperature
September 12, 2021	PC4 down until Sep 21. Reaction on standby till then.
September 27	Breaker tripped again. Reaction at room temp. Catalyst reactivated
September 29	Ethane depleted. Reaction running only on CO ₂ and N ₂
October 19	Construction/welding in the area. Reaction paused
October 20	Planned power outage. Reaction paused

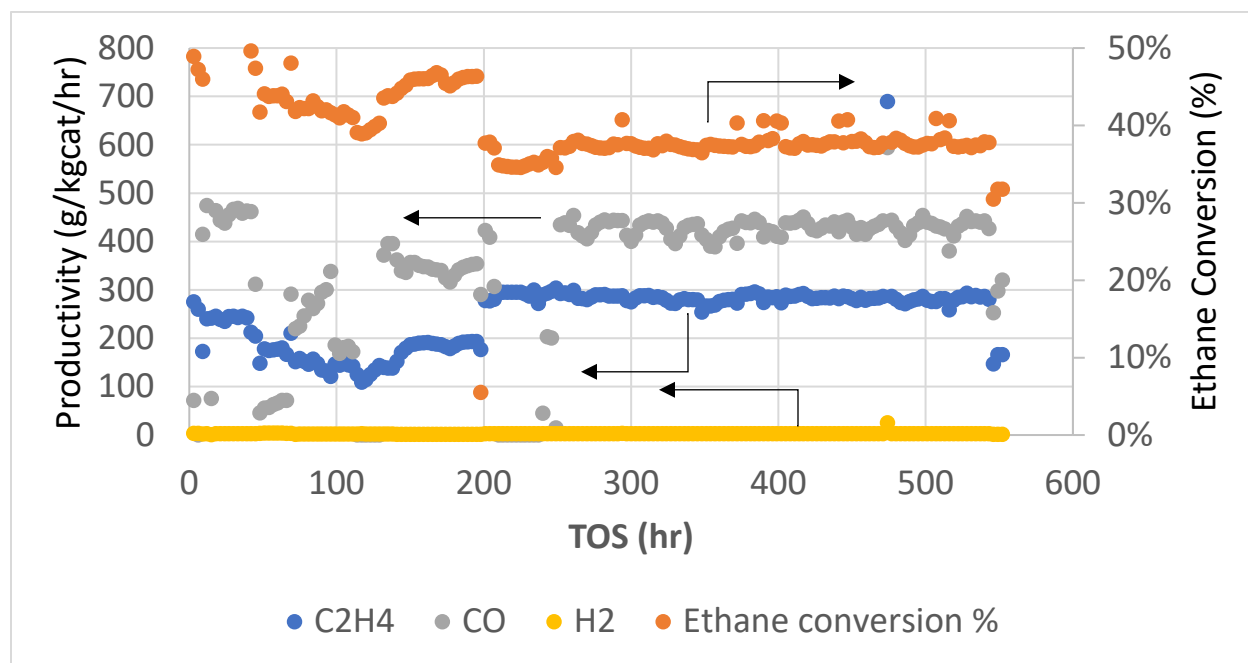


Figure 2. CO₂-ODH field scale run data using actual captured CO₂ stream with 80g catalyst. CO₂ to ethane conversion ratio ~1.5.

Despite the interruptions, the catalyst showed excellent stability over the course of 500hrs (Figure 6). The run was conducted in reaction-regeneration cycles with each data point on figure represent one cycle data. Within each cycle the reaction was operated for 2hrs which was followed by a 15-30 min regeneration in air. Due to interruptions early on, the ethylene productivity fluctuated. However, with less interruptions beyond 200-hr mark, ethane conversion and ethylene productivity became stable.

Ethane conversion was 40-50% at higher CO₂:ethane molar ratio (up to TOS=200hr). This was due to reasonably lower ethane concentration in the feed stream (19%). As the CO₂:ethane ratio was lowered by increasing ethane flow rate (ethane concentration 33.3% in feed) at 200-hr, the conversion dropped to 30-40%. However, the catalyst still showed great stability. CO:ethylene in product was ~1.5. Marginally higher CO levels indicate presence of dry reforming. Overall, amount of monetizable products formed from this reaction were ethylene (~300 g/kgcat.hr), CO (400 – 450 g/kgcat.hr) and H₂ (2-3 g/kgcat.hr). Marginal methane was formed as unselective product.

10.2. Direct flue gas (DFG)

Both gas (10% CO₂) and coal (12% CO₂) fired flue gases were used for this run. Source of flue gas was decided based on availability. Both streams contained substantial presence of O₂ (7.1%). Such high presence of O₂ greatly perturbed the selectivity of the desired reaction. 80g of catalyst was loaded with a flue gas flow rate of 11.5L/min and ethane flow rate of 0.5 L/min and 650C. Concentration of ethane in the feed stream was around 4.2%. Resulting CO₂:ethane ratio was 3 and O₂:CO₂ ratio 0.6:1. O₂ being a more powerful oxidant than CO₂, it was completely consumed by ethane via combustion resulting in more CO₂ and H₂O concentration (activity inhibitor) in the feed. Approximately 50% ethane was combusted by the O₂ present. This combustion resulted in a substantial increase in reaction temperature. Nevertheless, the remaining ethane was converted to ethylene at a much lower efficiency. Hence, resulting ethylene and CO throughputs were substantially lower than the captured CO₂ streams (See Figure 7). However, the catalyst showed great stability under these conditions. Hence, although reasonable throughput was obtained from lab-scale evaluation, using actual flue gas streams with much higher O₂ content resulted in a performance degradation.

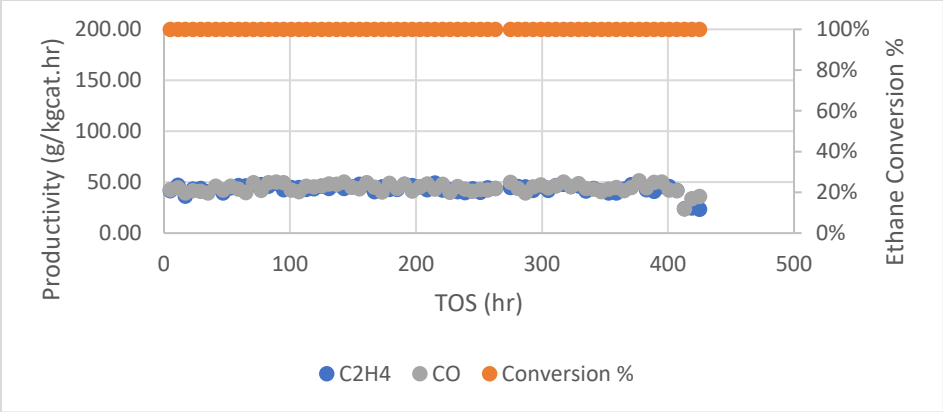


Figure 3. CO₂-ODH field scale run data using actual flue gas stream with 80g catalyst.