

Miniplant-Scale Analysis of Oxidative Coupling of Methane Process

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ABSTRACT

For more than three decades, Oxidative Coupling of Methane (OCM) process has been comprehensively investigated as an attractive alternative for the commercially available ethylene production technologies such as ethane and naphtha cracking. Developing a suitable catalyst and proper reactor feeding policy, reviewing and deploying the efficient methods in the separation and purification of the undesired and desired products, possible energy saving and process intensification in different sections of the OCM process, each has been the subject of many researches in the past. In this paper, the interconnections of these aspects will be addressed by reviewing the performance of different alternative structures and unit operations in different sections of the OCM process. As a systematic approach in this analysis, a concurrent engineering approach supported by the experimental data which was extracted from an OCM miniplant scale facility was applied. Using an efficient porous packed bed membrane reactor and a proper set of operating conditions, up to 25% C₂-yield, 20% C₂H₄-yield, and 52% C₂H₄-selectivity and the highest observed fluidized bed reactor C₂-yield was achieved in this OCM miniplant. This experimental analysis was performed in the chair of process dynamics and operation at Berlin Institute of Technology under the main framework of Unifying Concepts in Catalysis (UniCat) project. The economic analysis of the industrial-scale operation showed promising potentials and also advantages of the final proposed OCM process-structure in this research.

1. Introduction

Ethylene is one of the largest production volume chemicals in the world which is also the main component for producing a variety of other chemicals especially in polymer industry. Being in line with the general trend of substituting oil with natural gas as the feedstock for the production of chemicals, methane can be utilized for ethylene production via Oxidative coupling of methane (OCM) process [1]. This process is again attracting attention after a gap of relatively inactive research period [2]. This process is especially attractive for countries like Iran due to the advantage of easy access to relatively cheap local natural gas resources. However, OCM process has not been so far implemented industrially as the previously reported catalysts have not been enough selective towards ethylene and more importantly they have not been enough stable [3]. There are other major structural and operating obstacles which have prevented the classic OCM process structure to be efficient and competitive [4, 5]. In order to analyze them, the structure of the classic OCM process is reviewed here. Three main duties in different sections of the OCM process are the selective methane conversion, selective carbon dioxide removal and selective ethylene separation and purification [6]. These are the tasks which can be handled by various unit operations as generally shown in Figure 1.

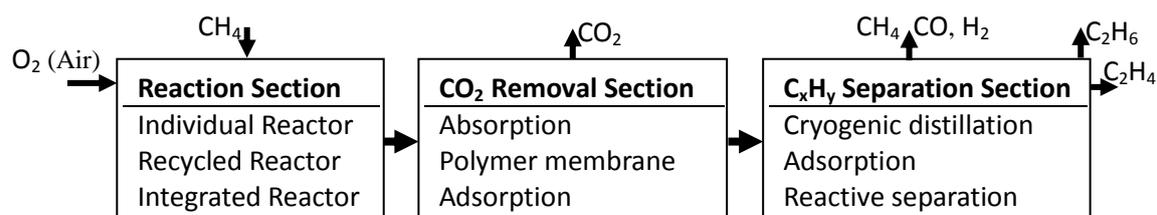


Figure 1. Conceptual block-flow representation of the OCM process structure and the alternative unit operations.

In the reaction section, methane reacts with oxygen in order to produce ethylene while it also produces significant amounts of carbon oxides. Securing high selectivity and conversion in the reaction section remains to be one of the main challenges in the OCM reactor. Controlling the operating temperature is another major challenge.

In the carbon dioxide separation section, it is targeted to remove the CO_2 and introduce the rest of the gas to a demethanizer where methane and other light gaseous species such as hydrogen and carbon monoxide are separated and ethylene and ethane will remain as the main desired products. Later, these last two components are separated from each other again using a cryogenic distillation and pure ethylene is obtained as the final product. Ethane can be introduced into the ethane cracking section and produce further ethylene. This is the classical structure for the OCM process which has been investigated in several researches [6,7] and even it has been recently announced to be implemented and tested by Siluria Company in a demonstration plant of the OCM process [8].

The costly cryogenic distillation is a standard separation technique for separating the unreacted methane (demethanizer), ethylene and ethane. This technology has been commercialized and applied in various industrial plants [9]. Especially when an inert gas such as nitrogen is used in the reactor to control

the rapidly rising temperature due to exothermic OCM reaction, the cost of the separation and purification in downstream cryogenic distillation units will increase rapidly [10]. There are, however, several alternative approaches and technologies which can be utilized for this application as well as in the carbon dioxide separation section. Some of these technologies in miniplant-scale have been tested along with various reactor concepts in UniCat* miniplant constructed in Berlin Institute of Technology (TU Berlin). In a recommended alternative approach, ethylene is targeted to be separated from the OCM reactor outlet primarily via a selective adsorber while other components are separated later. The performance of such alternative structure has been also investigated in the UniCat miniplant experimental facility [10].

Typical experimental results of the performed analysis of different unit-operations in the UniCat miniplant will be reviewed in this paper as well as the potential interactions between the performance of the reaction section and downstream units. This is known as a concurrent engineering analysis approach which can lead to practical conclusions for improving the performance of the whole process. In this manner, the effects of unit-operations and their operating conditions are analyzed not only based on the performance indicators for each process-section, but also their effects are reevaluated in the context of the whole OCM process performance. Required energy and costs are the main criteria for screening the process structures and unit-operations in the first place. The possibilities for optimal heat and mass integration are also analyzed in this context. Therefore, the types of unit-operations, their preferred sequence and the operating conditions in each unit can be optimally designed.

The conventional alternative approach for process synthesis and analysis is called bottom-to-top process development approach. In this approach, first the lab-scale experimentations are performed and after a comprehensive optimization and analysis, pilot-plant scale investigations and tests will be performed under the optimized operation conditions in terms of temperature, pressure, etc. In the pilot-plant scale tests, the process will be tested also under industrially relevant operating conditions using the actual feed stream composition and for a long period (up to few weeks) of tests in order to ensure long-term operation of the reactor and downstream units. Then, the resulted information in this step will be scaled up usually to the demonstration-plant scale which is intended to operate continually and ensure the commercial competence in comparison to the available established technologies in the market. Another aspect in the bottom-to-top process development approach is that the reactor sections and its established performance is the first step, the heart and the center of developments of the downstream units.

The concurrent engineering approach employed in this research aims to shorten the process development time in which parallel to the lab-scale experimentations, a miniplant-scale facility is utilized to simultaneously test the bigger scale operation of the reactor and downstream units. This is an efficient approach for the OCM process since the OCM process does not have any established technological competitor. Therefore, after a successful pilot-plant operation, it can directly go to the industrial plant and commercial phase.

*UniCat: UniCat "Unifying Concepts in Catalysis" is a research group coordinated by the Berlin Institute of Technology (Technische Universität Berlin) and funded by the German Research Foundation (www.unicat.tu-berlin.de) Unifying Concepts in Catalysis.

2. Reaction Section

The main reactions and reaction rates representing the OCM reactions are summarized in Table 1 [11].

Table 1. Main OCM reactions and their reactions rates; The values of the kinetic parameters have been reported in [11].

Reactions	Equations	
$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	$r_j = \frac{k_{0,j} e^{-\frac{E_{a,j}}{RT}} P_C^{m_j} P_{O_2}^{n_j}}{(1 + K_{j,CO_2} e^{-\frac{\Delta H_{ad,CO_2,j}}{RT}} P_{CO_2})^2} \quad j=1, 3-6$	
$2CH_4 + 0.5O_2 \rightarrow C_2H_6 + H_2O$		
$CH_4 + O_2 \rightarrow CO + H_2O + H_2$		
$CO + 0.5O_2 \rightarrow CO_2$	$r_2 = \frac{k_0 e^{-\frac{E_a}{RT}} (K_{O_2} e^{-\frac{\Delta H_{ad,O_2}}{RT}} P_{O_2})^{n_2} P_{CH_4}^{m_2}}{[1 + (K_{O_2} e^{-\frac{\Delta H_{ad,O_2}}{RT}} P_{O_2})^{n_2} + K_{CO_2} e^{-\frac{\Delta H_{ad,CO_2}}{RT}} P_{CO_2}]^2}$	
$C_2H_6 + 0.5O_2 \rightarrow C_2H_4 + H_2O$		
$C_2H_4 + 2O_2 \rightarrow 2CO + 2H_2O$		
$C_2H_6 \rightarrow C_2H_4 + H_2$		
$C_2H_4 + 2H_2O \rightarrow 2CO + 4H_2$		
$CO + H_2O \rightarrow CO_2 + H_2$		
$CO_2 + H_2 \rightarrow CO + H_2O$		
		$r_7 = k_{0,7} e^{-\frac{E_{a,7}}{RT}} P_{C_2H_6}$
		$r_8 = k_{0,8} e^{-\frac{E_{a,8}}{RT}} P_{C_2H_4}^{m_8} P_{H_2O}^{n_8}$
		$r_9 = k_{0,9} e^{-\frac{E_{a,9}}{RT}} P_{CO}^{m_9} P_{H_2O}^{n_9}$
	$r_{10} = k_{0,10} e^{-\frac{E_{a,10}}{RT}} P_{CO_2}^{m_{10}} P_{H_2}^{n_{10}}$	

In general, the following aspects are the main design concerns in reaction engineering of the OCM process.

- 1- Developing a stable and selective catalyst
- 2- The high exothermic reaction
- 3- Low ethylene yield achieved with low methane conversion and selectivity

These aspects should be addressed via a combination of catalyst and reactor design. In the catalyst level, UniCat group has screened out most of the catalysts suggested for the OCM process [e.g.3,12]. As a result, Mn/Na₂WO₄/SiO₂ was found to be one of the most stable and efficient OCM catalysts. Several different preparation methods for this catalyst have been investigated in UniCat [13,14]. Moreover, better understanding of the fundamental role of the material characteristics and catalytic reaction mechanisms on the performance of the OCM catalyst have been provided by theoretical and experimental investigations performed on the molecular level and separated surface reactions.

The resulted information was utilized to improve the performance of the catalyst. The accordingly prepared catalysts were continually screened out via lab-scale experimental setups and then the best catalysts were tested in the miniplant scale reactors. The results obtained from the big-scale catalyst performance analysis (up to 100 g), which is performed under industrial operation conditions, were shared with the catalyst developers and scientists working at the molecular level to finally achieve a truly stable and selective catalyst.

There are some pilot-plant scale catalyst preparation facilities in UniCat with the capability for implementing different methods and scales of OCM

catalyst preparations. The reported results in this manuscript are all based on Mn/Na₂WO₄/SiO₂ catalyst except otherwise mentioned.

Various types of reactors have been investigated for the OCM application. Figure 2 shows the wide spectrum of the reactor concepts which have been investigated for the OCM application.

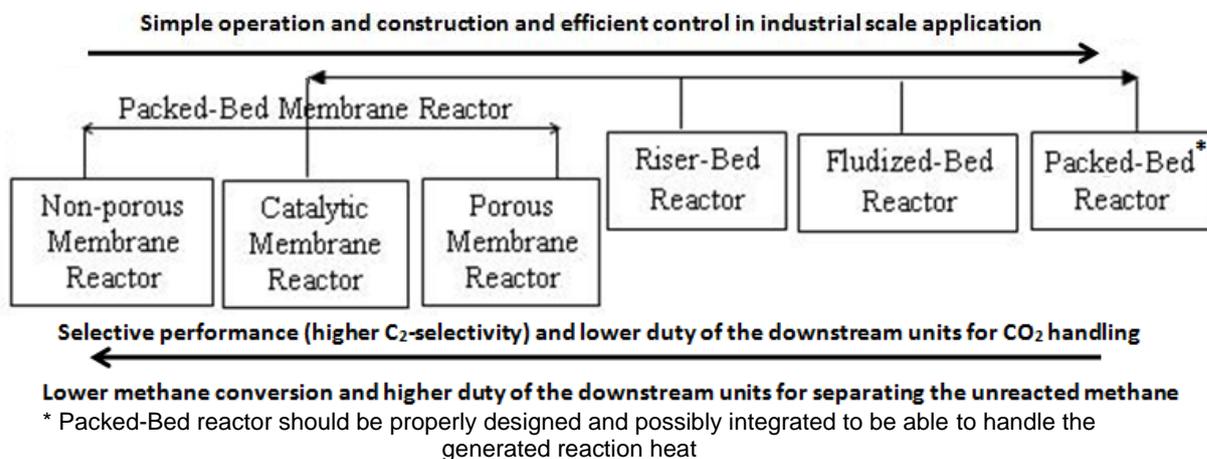


Figure 2. Selected spectrum of the alternative OCM reactor concepts.

As seen in Figure 2, the operational and safety concerns for the industrial application of the reactor concepts such as membrane reactor which usually provide higher selectivity towards the desired products (ethylene and ethane: C₂) are higher than the fixed-bed and fluidized-bed reactors. For instance, in a membrane reactor, oxygen-rich and methane-rich atmosphere can come into contact when membrane breaks. Controlling the operating temperatures in the membrane and fixed-bed reactor is also a major operating concern. Moreover, there is always a tradeoff between the observed C₂-selectivity and methane conversion in an OCM reactor.

Among these reactor concepts, fixed-bed, membrane reactor, fluidized-bed reactor and integrated reactors were investigated in the UniCat miniplant. There are other types of reactors which have been investigated for the OCM application, but their practical application due to their low performance or the operating difficulties is apparently limited.

2. 1. Fluidized-bed reactor

Handling the exothermic nature of the OCM reaction is an operating challenge. Providing an isothermal operation is the main characteristic of the fluidized-bed reactor in OCM application [15,16].

In the UniCat miniplant, a fluidized-bed reactor made of quartz glass with an inner diameter of 40 mm was used under the reaction temperature range of 750 °C-840 °C. An electrical tube furnace and a multipoint thermocouple in 10 points respectively control and measure the temperature profile along the reactor. Outlet gas composition of all sections in the OCM miniplant was analyzed by online infrared gas analyzer and time to time with a gas chromatograph. The whole system was automatically controlled using process Siemens-7 system as shown in Figure 3 and the value of all parameters and indicators was recorded on-line.

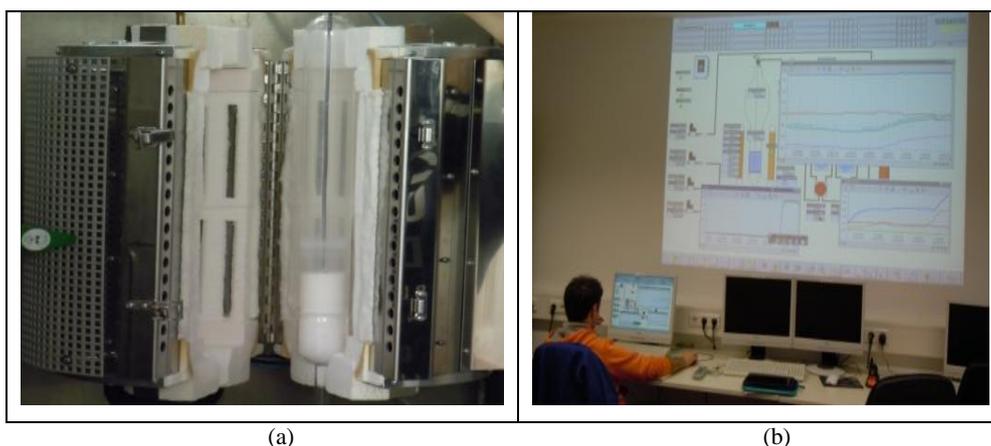


Figure 3. The picture of a) reactor set-up b) the control room and recording the values of the parameters.

The isothermal performance of the OCM fluidized-bed reactor was observed even under the low diluted reaction atmosphere by tracking the temperature profile which always indicates less than 20 °C temperature variation along the bed. Using significant portion of the gas dilution in other OCM reactor types is unavoidable in order to control the reaction temperature profile and safe operation.

Typical performance of the fluidized-bed shows that the selectivity towards C_2 production is comparable with the selectivity towards carbon oxide production. So, in that aspect, the performance of the fluidized-bed reactor is not among the best achievable selective OCM performances. Moreover, depending on the catalyst type, the ethylene-to-ethane production ratio is varied and usually significant portion of less value ethane is produced. The performance of this reactor and in fact other OCM reactors show that maximum selectivity and yield can be expected by tuning the operating reaction temperature. The best performance for instance was achieved in the range of 800 °C-820 °C.

Securing proper levels of selectivity, yield and methane conversion are also extremely important for the performance of the downstream separation units. Figure 4 enables one to simultaneously consider the effect of operating temperature on different performance indicators.

Considering the performance of available catalysts, the best expected performance of an OCM fluidized-bed reactor is in the range of 20-23% C_2 -yield and C_2 -selectivity of 50-60%. This means that more than 50% of the methane remains unreacted and around 50% of the reacted methane will appear in the form of carbon oxides. Separating these components in downstream units requires lots of energy and efforts. Therefore, parallel to cost-benefit analysis performed based on the amount of the reactant-consumption-Ethylene-production in the reactor section, the consequences of achieving these levels of performance indicators on the whole process performance should be also analyzed.

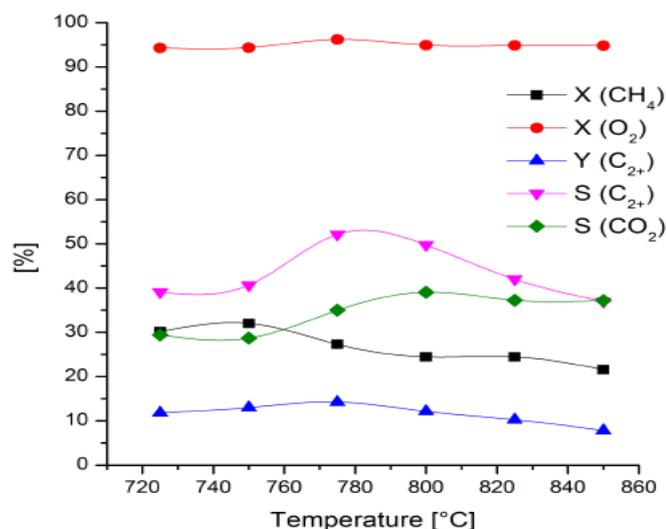


Figure 4. Simultaneous analysis of the effect of operating temperature on the performance of the OCM fluidized-bed reactor in terms of conversion (X), yield (Y) and selectivity (S) for La₂O₃/CaO catalyst.

2. 2. Fixed-bed and membrane reactor

Fixed-bed reactor is a standard reactor which has been often used for OCM application in small-scale for fast catalyst screening and kinetic development up to the large-scale for testing the industrial operating conditions especially with regard to handling the significantly generated reaction heat. However, in all scales hot-spot formation is an issue and integrating the exothermic OCM and other endothermic reactions such as reforming seems to be an option in this case. Using significant amount of diluent gas is also necessary in this case. The combination of these measures allows establishing the desired temperature profile along the catalytic bed which has been proven to be a decisive factor for improving the performance of the OCM reactor [17]. Such a temperature profile might be established easier when the oxygen is distributed along the catalytic bed in a controlled way as it is the case in membrane reactor [18-20].

In a porous packed-bed membrane reactor, oxygen is distributed via an inorganic membrane and therefore significant methane conversion and high C₂-selectivity can be secured. The quantity and profile of the gas permeation along the ceramic membrane can be tuned [19-21]. This is achieved by implementing a proper modification approach on the original stable ceramic membrane (for instance α -alumina membrane) characterized by its micro pores with the diameter of 10 micron and its significant void fraction. Such membrane modifications are needed to reduce the pore size up to the nano-pores and significantly reduce the pore volume as well as the reactivity of the original membranes for instance using the silica-containing materials [19,20]. In this manner, typical performance of the OCM membrane reactor showed 10-15 percent higher selectivity in comparison to the fluidized-bed and fixed-bed reactor for similar operating conditions. The observed selectivity and yield also depend on the amount of methane-to-oxygen ratio and the dilution as can be seen in Figure 5.

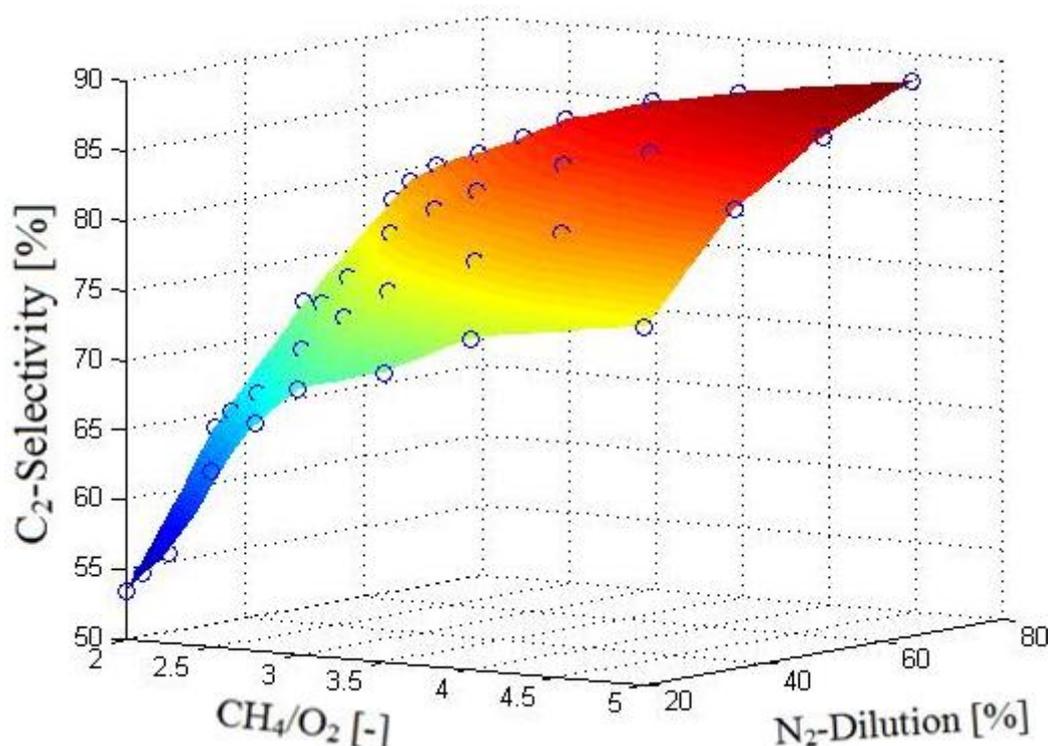


Figure 5. The observed C_2 -selectivity in an OCM porous packed-bed membrane reactor for different levels of methane-to-oxygen ratios and gas dilutions.

Since the OCM reaction is really fast, if the reaction temperature can be controlled, enough methane conversion in the packed-bed membrane reactor is usually secured under various levels of dilution. Therefore, the yield follows the same trend as selectivity and dilution usually increases the yield and selectivity of the desired products. As shown in Figure 5, this is clearly seen using 20-40% dilution. Separating the diluting agent, however, will impose a significant cost in the downstream units. Therefore, 20-40% of proper diluent such as carbon dioxide can be utilized which increases the reactor performance while it can be separated relatively easy in the downstream units.

On the other hand, different levels of methane conversion are expected by varying the methane-to-oxygen ratio. Up to ratio 5, methane conversion is significant. For higher ratios, methane conversion might not be industrially relevant. Figure 5 shows that the methane-to-oxygen ratio in the range of 2-3 has a significant impact on the observed C_2 -selectivity.

Utilizing the porous packed-bed membrane reactor enables to develop a network and integrated reactor concepts such as the ones reported and discussed recently by the authors [22,23].

In the view of the OCM miniplant as shown in Figure 6, the position of the membrane and fixed-bed reactors have been shown beside the downstream units.



Equipment	Dimensions	Operating conditions
(1) Absorption column	40 mm ID, 5 m Length	20-40 °C, 10-32 bar
(2) Desorption column	100 mm ID, 4 m Length	110-130 °C, 1-3 bar
(3) Membrane Reactor	7 mm ID, 20 cm Length*	700-880 °C, 1-6 bar
(4) Adsorption	60 mm ID, 1 m Length	Ads. 40 °C, Des. 200 °C

Figure 6. A view of the UNICAT OCM miniplant including the absorption, desorption, adsorption and membrane reactor (top); Dimensions and operating conditions of these units (bottom table)

*: dimensions of the permeable zone

3. Downstream Units in OCM Process

In the downstream units of the UniCat OCM miniplant, carbon dioxide and ethylene separation were mainly investigated. The main motivation was to establish a separation unit which is more efficient than the costly operations such as cryogenic distillations. In this way, utilizing the available high pressure potentials in different sections of the OCM process should be also given a special attention.

3. 1. Carbon dioxide removal

Amines are the first choices to be used as the absorber for many of the industrial gas streams containing carbon dioxide. Also, in the UniCat OCM miniplant, monoethanolamine (MEA) and methyl-diethanolamine (MDEA) were used which showed to have the best performance in terms of energy investment around 10 bar operating pressure [23,24]. However, even in that range of operation, the cost of carbon dioxide separation is significant and it is better to utilize the absorption for lower duty of carbon dioxide separation. The deployed absorption and regeneration column have been also shown in Figure 6.

Polymeric membrane (for instance MATRIMID® polyimide flat-sheet membrane) was also used to separate the carbon dioxide for the OCM process application [24-26]. Since the available membranes for this application cannot secure a selective separation, significant portion of the hydrocarbons will be lost for separating the whole carbon dioxide content of the gas stream leaving the OCM reactor. Instead, such polymer-based separation technology can be

utilized to primarily separate big portion of the carbon dioxide content (up to 40%) in a selective and energy-efficient way. The rest of the carbon dioxide can be separated using the amine absorber as a hybrid separation system.

3. 2. Adsorption

Adsorption is not a trivial choice for an industrial scale OCM process. However, if a proper adsorber can facilitate the energy intensive operations for separating the carbon dioxide, unreacted methane and ethylene, adsorption becomes an attractive alternative for OCM process. This was experimentally investigated and confirmed in the UniCat OCM miniplant. This becomes even more attractive if the OCM process can be put into the context of an integrated OCM and methane reforming process for instance.

For the adsorption unit, usually fixed-cost can be an issue and finding a cheap adsorber is strongly preferred. Fortunately, the experimental data showed that cheap activated carbon can be a promising adsorber to be utilized in OCM process primarily to target separating ethylene and ethane right after the OCM reactor. However, along with more than 99% of ethylene, 70% of ethane and around half of the carbon dioxide content will be also adsorbed. Such performance is achieved using a combination of Pressure Swing Adsorption (PSA) and Temperature Swing Adsorption (TSA).

Later, the adsorbed carbon dioxide will be separated from the desorbed gas using an amine absorber where carbon dioxide separation will be secured in a relatively selective and energy-efficient manner. Next, the stripped carbon dioxide will be used as a carrier-desorbing gas agent as shown in Figure 7. The rest of the unabsorbed carbon dioxide along with the un-reacted methane and other light gases can be processed in a reformer section.

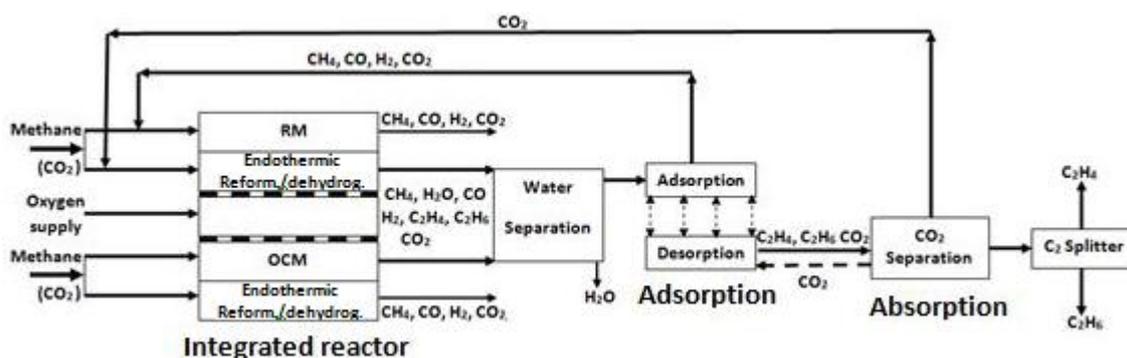


Figure 7. Block-flow diagram of the integrated OCM-methane reforming process using the adsorption unit and the integrated OCM-reforming-/dehydrogenation reactor.

Ethane can be recycled back to an integrated reactor where OCM and ethane dehydrogenation for instance take place simultaneously. It is also suggested to use carbon dioxide as diluent gas in the OCM reactor especially in the integrated reactor structure such as dual membrane reactor. Therefore, one of the main messages of the miniplant analysis of the OCM process which is to avoid using an inert gas like nitrogen in the feed stream will be implemented.

4. Techno-Economic Analysis

Having considered the specifications of the above mentioned unit operations in the OCM process and the estimated utility costs [27] required in each section, the following can be concluded with regard to the economical aspects of the OCM process:

4. 1. Raw materials

Methane price is very different in different parts of the world. For instance, the methane price is around 140 €/t in the gas pipeline import targeted countries like Europe, while it can be available for up to 20-30 €/t (it counts only for processing fee) in the main exporter countries like Iran, Russia and even USA.

It is preferred to use pure oxygen in the OCM reactor and not air since nitrogen imposes intolerable operating cost on the whole OCM process. The oxygen price can be also comparable with the price of methane in countries like Iran. In fact, not only with regard to the oxygen supply, but also for other design factors such as the types of utilities and downstream units, the specifications of the available local infrastructures (if any) will determine the preferred source of each utility and reactants. For instance, considering construction of an Air Separation Unit beside the OCM plant might be preferred in some cases.

4. 2. Operating cost

With regard to the operating pressure, some level of over pressure is needed for industrial application of the OCM process as the pressure drop and optimal usage of the compression potential in the sequential units should be addressed. However, most of the results reported so far for OCM reactor have been extracted under atmospheric pressure. We have tested the OCM reactor under pressure and found that usually the C₂-yield in higher pressure is reduced. This should be also taken into consideration by design of the OCM reactor and process. For the carbon dioxide separation as well as the adsorption and cryogenic distillation, wide range of operating pressure can be applied. For choosing the right operating pressure in each case, the following aspects should be taken into consideration:

Water is usually separated via compression

Ethylene loss in the absorption column becomes very high for the operating pressure more than 20 bar.

Higher operating pressure means higher compression duty and cost

It is preferred to have the higher compression task for the heaviest desired hydrocarbons and not for the gas contacting carbon dioxide and water

10 bar operating pressure in the carbon dioxide amine absorber was experimentally tested and found to be preferred. PSA-TSA system was also working in this range of pressure efficiently.

The best of our experimental results showed 20% ethylene-yield and 64% ethylene-selectivity. According to our analysis, such performance can be considered as an industrially relevant viable performance with the safe-margin of 2% ethylene-yield in the countries like Iran. The operating cost for the production of each tone of ethylene via the proposed OCM structure would be around 650 Euro in which around 10% is the compression cost, and around

60% is the cost of raw materials. Such economic performance is comparable with the available ethane cracking technologies.

5. Conclusion

An individual performance of several reactors as well as ethylene and carbon dioxide separation units were experimentally investigated in a miniplant-scale experimental facility for OCM process. Some of the best reported results of the OCM reactors for membrane and fluidized bed reactors were achieved in this study. For instance, in the UniCat miniplant membrane reactor, more than 25% C₂-yield, 20% C₂H₄-yield, and simultaneously 52% C₂H₄-selectivity were achieved. The integrated performances of these units were also analyzed under a concurrent engineering approach in which the effects of operating and design parameters on the performance of the whole OCM or integrated OCM-reforming process were simultaneously investigated. Reactors in which either OCM and ethane dehydrogenation reactions or OCM and methane reforming reactions are integrated are among the preferred reactor concepts to be utilized in industrial scale operation.

Adsorption unit was found to be an efficient downstream unit not only for the OCM process, but also for the integrated OCM-methane reforming process. As using a diluting gas is necessary to control the OCM reaction temperature, 20-40% carbon dioxide was found to be the preferred choice for being utilized since it not only has less costly impact on the whole process performance, but also it can improve the integration of the OCM and methane reforming process, specially dry methane reforming. This can be also used as the carrier gas in the adsorption unit.

Techno-economic analysis of the proposed OCM process structure showed that it has the potential to compete with the available established technologies for ethylene production especially in countries like Iran.

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آنالیز فرآیند جفت شدن اکسایشی متان در واحدهای با ابعاد کوچک

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چکیده

با استفاده از واحدهای با ابعادی بزرگتر از واحدهای آزمایشگاهی و کوچکتر از واحد نیمه صنعتی، عملکرد انواع راکتورها شامل راکتورهای بستر سیال و غشایی، انواع فرآیندهای جداسازی دی اکسید کربن شامل فرآیندهای جذب آمینی و غشاهای پلیمری و نیز فرآیند جذب سطحی برای جداسازی مستقیم اتیلن، مورد بررسی آزمایشی قرار گرفتند. این بررسی ها در قالب مهندسی همزمان فرآیند انجام گرفته و بهبود عملکرد کاتالیست از لحاظ انتخابگری و پایداری نیز مورد توجه قرار گرفت. در راکتور غشایی مورد استفاده در این واحد و تحت شرایط عملیاتی مناسب، یکی از بهترین عملکردهای راکتوری به میزان بیش از ۲۵ درصد بازدهی تولید اتان و اتیلن (بیش از ۲۰ درصد بازدهی تولید اتیلن) و بیش از ۵۲ درصد انتخابگری تولید اتیلن مشاهده گردید. ارزیابی اقتصادی واحد صنعتی این فرآیند نمایانگر قابلیت و مزایای فرآیند نهایی پیشنهاد شده در این تحقیق می باشد.

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