Enhancement of Methane Conversion Using Electric Fields

**Quarterly Report
April - June 1995**

Richard G. Mallinson
Lance L. Lobban

July 1995

Work Performed Under Contract No.: DE-FG21-94MC31170

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
University of Oklahoma
Norman, Oklahoma

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from the Office of Scientific and Technical Information, 175 Oak Ridge Turnpike, Oak Ridge, TN 37831; prices available at (615) 576-8401.

Available to the public from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161; phone orders accepted at (703) 487-4650.

Enhancement of Methane Conversion Using Electric Fields

**Quarterly Report
April - June 1995**

Richard G. Mallinson
Lance L. Lobban

Work Performed Under Contract No.: DE-FG21-94MC31170

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
P.O. Box 880
Morgantown, West Virginia 26507-0880

By
University of Oklahoma
Office of Research Administration
1000 Asp Avenue, Suite 314
Norman, Oklahoma 73019-0430

July 1995

PROJECT ABSTRACT

The goal of this project is the development of novel, economical processes for the conversion of natural gas to more valuable products such as methanol, ethylene and other organic oxygenates or higher hydrocarbons. The methodologies of the project are to investigate and develop low temperature electric discharges and electric field-enhanced catalysis for carrying out these conversions. In the case of low temperature discharges, the conversion is carried out at ambient temperature which in effect trades high temperature thermal energy for electric energy as the driving force for conversion. The low operating temperatures relax the thermodynamic constraints on the product distribution found at high temperature and also remove the requirements of large thermal masses required for current technologies. With the electric field-enhanced conversion, the operating temperatures are expected to be below those currently required for such processes as oxidative coupling, thereby allowing for a higher degree of catalytic selectivity while maintaining high activity.

TABLE OF CONTENTS

ABSTRACT	ii
INTRODUCTION	1
TASK 2, ELECTRIC DISCHARGE, PROGRESS	1
TASK 3, ELECTRIC FIELD-ENHANCED CATALYSIS, PROGRESS	1
APPENDIX, paper draft	2

Introduction

This report summarizes the third quarter of the project. With funding from several research projects, The BET system (partially funded by this project) has arrived and is now operational, a new gas analysis GC with data station has arrived and is operational and is calibrated and being used for on-line gas analysis and a GC with a mass detector (partially funded by this project) is presently undergoing installation and training (this will be used for liquid product analysis). With these now available, our analytical capability is now sufficient to properly support the project.

Task 2: Electric Field Conversion

Material balance experiments have been accomplished which verify, within reasonable errors, the previous gaseous product and conversion data. The imminent arrival of and now installation of the GC-MS has delayed us from completing liquid sample analysis. These should now be completed essentially immediately. In the mean time we have conducted a number of other experiments at various frequencies and waveforms to look for qualitative variations in behavior.

We expect to now initiate high carbon dioxide feed experiments shortly.

Construction of the new reaction system is complete including the new power supply which has only just arrived. Leak checking has been completed and this system should be operational shortly.

Task 3. Electric Field Enhanced Conversion

The focus here has shifted towards a new system configuration in which we are initiating a DC discharge in proximity to a catalytic substance. In experiments so far, a number of interesting enhancements to thermal rates and selectivity patterns have been observed which go beyond the probable localized catalyst heating, as is discussed in a new draft paper (different than the one included in the last report) appended to this report. Also direct internal temperature measurement experiments are in progress to quantify the amount of plasma heating as well as reaction heat so that experiments with and without plasma may be compared properly. We have also initiated room temperature AC experiments, similar to those in Task 2, but with the use of a catalyst bed and no dielectric from which we have observed some interesting and encouraging results.

An Experimental Study on the Oxidative Coupling of Methane in a Corona Discharge Reactor

Changjun Liu¹, Abudlathim Marafee, Lance Lobban²

Department of Chemical Engineering, the University of Oklahoma, Norman, OK 73019

ABSTRACT

The oxidative coupling of methane (OCM) has been considered for converting methane directly into higher hydrocarbons. The present study on conversion of methane in a corona discharge packed bed reactor may significantly improve the process economics. Experimental investigations have been conducted in which all the reactive gases pass through the catalyst bed which is situated within the corona-induced plasma zone. Experiments were conducted over a wide range of temperatures (823 K to 1023 K) and input powers (0 to 6 w) with both positive and negative corona processes. Compared to the catalytic process in the absence of corona discharge, the corona discharge results in higher methane conversion and better selectivity for C₂ products. The conversion of methane increases with increasing reaction temperature, O₂ partial pressure and residence time during the corona-enhanced catalytic reactions while the selectivity and yield of C₂ products decrease with increasing O₂ partial pressure and residence time. Compared to results obtained in the absence of the corona, methane conversion in the presence of the corona was nearly five times larger and the selectivity for C₂ over eight times higher at 823 K. The conversion at higher temperature (more than 973 K) is limited by the availability of oxygen, which is consumed completely. A reaction mechanism is suggested to explain the observed reaction phenomena.

1. On leave from the State Key Laboratory of C₁ Chemical Technology, Tianjin University, P.R.China

2. To whom correspondence should be addressed

INTRODUCTION

Natural gas, of which about 90% is methane, is an inexpensive and abundant resource. The oxidative coupling of methane (OCM) has been extensively studied for some time as a possible effective and economic way to convert methane to C_2 or higher hydrocarbons since the creative works of Keller and Bhasin.^[1] Catalysts for the OCM reaction may be classified as either reducible or irreducible metal oxides.^[2] Over reducible oxides, reactants (methane and oxygen) may be fed alternately. The redox mechanism of the reaction was suggested^[2] for the production of C_2 products, and the metal oxide acts as reducing and oxidizing agent rather than as a true catalyst. Irreducible metal oxides, such as catalysts with rare-earth oxides, Sr/La_2O_3 ,^[3] Sm_2O_3/Al_2O_3 ^[4], Ba/CeO_2 ^[5], Ba/La_2O_3 ^[6], Na_2O/Pr_2O_3 ^[7] and $LaAlO_3$ ^[8], act as catalysts which are favorable for the oxidative coupling of methane. However, over both reducible and irreducible catalysts oxides, the OCM reaction requires high reaction temperature, and the reaction probably proceeds both heterogeneously and homogeneously. Sufficiently high selectivity for C_2 hydrocarbons has not been met because of the nonselective heterogeneous and gas phase reactions to CO_x . The need for higher C_2^+ selectivity has led to research on electro-catalytic conversion of methane. Most such studies utilized membrane reactor systems as an advanced reaction method in which the membranes are also solid electrolytes. Eng and Stoukides^[9] have reviewed applications of these electrolyte materials in catalysis in detail. The three most common applications of solid electrolytes are for solid electrolyte potentiometry (SEP), solid oxide fuel cells (SOFC) and electrochemical oxygen pumping (EOP). Experiments have shown that higher C_2^+ selectivity is achieved using these electrocatalytic methods.^[9-15] The activity, however, is still low, because the performance of membrane catalysts is restricted by the oxygen ion transfer rate. C_2 selectivity is still not high enough because oxygen supplied through the membrane caused CO_x formation too.

The previous research has generally concluded that lattice oxygen (O^{2-}) is the active site for methane activation on the reducible catalysts, and O^- -type species is the active site on the

irreducible catalysts. We hypothesized that negatively charged gaseous oxygen species could also activate the methane molecule. If this is true, gas discharges, such as corona discharge, can provide us with a source of this negative oxygen ion, O^- or O_2^- , formed via electron attachment to oxygen molecules in the gas phase.^[17] A corona discharge process needs relatively low electric power and takes place at or near atmospheric pressure. The corona is usually generated by strong electric fields associated with small diameter rods, wires and needles on a plate electrode. Because the corona is relatively easy to establish, it has had wide applications in a variety of processes, including synthesis of chemicals.^[18] In fact, some plasma techniques have been applied for the ionization of methane. Two important applications of methane plasmas are the use of ionized methane as the ion source of a mass spectrometer and the production of diamond coatings. Progress in understanding methane plasmas and the chain reactions involving ionized methane can be found in the literature.^[19-21] Some researchers have investigated plasma techniques for the conversion of methane. As early as the 1920's, Alexander^[22] reported the complete oxidation of methane by gas discharge. Mach and Drost^[23] published results of methane conversion directly to C_2 hydrocarbons in a glow discharge reactor; in their work, methane radicals were excited by high energy electrons, and a steady state methane conversion of 98% was reported. Fujii and Syouji^[24,25] used mass spectrometry to analyze products from a methane/oxygen plasma in order to determine the effects of oxygen on a low pressure methane plasma. In fact, most of the previous researches were conducted at low pressure. Only conversion of CH_4 to C_2H_2 were reported to be conducted at atmospheric pressure^[26,27]. Because of the low pressure and the resulting low mass flow rate, as well as the poor understanding of plasma chemistry, applications of methane plasma for the industrial production of chemicals have not been developed.

We have previously studied the OCM reaction in a glow discharge reactor without using heterogeneous catalysts. We have found the gas ionization to be effective for obtaining high selectivity to C_2 products. Because of the restricted ionization rate, however, conversion of methane has been limited leading to low yields of C_2 products. Here we report the results of our investigation of the OCM reaction during a combination of the corona discharge and catalysis in a

packed bed reactor. The results suggest that the combination of corona discharge and heterogeneous catalysis may lead to a significant improvement in C_2 yields.

EXPERIMENTAL

The experimental process flow diagram is shown in Figure 1. The reactor was a quartz tube with an I.D. of 7 mm. The reactor was heated by a cylindrical furnace placed around the reactor. An Omega K-type thermocouple in a small alumina tube was attached to the outside wall of the reactor to monitor and control the reactor temperature. The flow rates of feed gases helium, methane and oxygen were regulated by three Porter Instrument Co. model 201 mass flow controllers. Helium was used as the dilution gas in the feed. The feed and effluent gases were analyzed by on-line gas chromatography (HP 5890 equipped with a molecular sieve packed column and a thermal conductivity detector). All experiments were carried out at atmospheric pressure.

The ionized gases were formed in a gap between two stainless steel electrodes. The upside wire electrode was concentric with the reactor tube, while the bottom electrode was circular and was positioned perpendicular to the reactor axis and 10 mm below the wire electrode. The bottom electrode was held at a potential of 0 volts (i.e., grounded). The catalyst bed (when present) was about 12 mm deep, thus the wire electrode extended about 2 mm into the catalyst bed. The discharge was created using a high voltage power supply (Model 210-50R, Bertan Associates Inc.). In the discharge volume, the interaction between accelerated charged particles (i.e., electrons and ions) and other chemical species (i.e. molecules and radicals) takes place. This interaction leads to the synthesis of new chemical species including ethane and ethylene (as well as CO and CO_2). In our experiments, a low input power(0~6w) was applied for all conditions.

The catalysts used in this experiment were Sr/La_2O_3 , prepared using the Pechini method^[20] as described in detail by Ajmera.^[16]

Methane and oxygen were mixed with helium and then introduced to the reactor at the desired flowrate of 100 cm³/min total. The reactor effluent flowed through a condenser, in which a mixture of dry ice and acetone was used to remove the residual water. The effluent gas from the condenser was analyzed by gas chromatography.

RESULTS and DISCUSSION

1. Corona Blank Test:

Studies of reaction in the absence of catalyst were conducted first. Discharge reactions during corona processes depend on the polarity of the discharge and the characteristics of the gas mixture, specifically on the electron attaching species. For the wire-plate electrode geometrical configurations, the term 'positive corona' is applied when the wire electrode potential is positive compared to the plate electrode potential. Both positive and negative corona processes (i.e., corona in the absence of catalyst) showed selectivity for C₂ products while no C₂ products formed in the blank reactor in the absence of corona discharge. As the voltage was increased, the current increased and with it the conversion in the reactor, until a saturation discharge current was found. Beyond this point, increases in voltage caused only small increases in either current or methane conversion. The saturation current was obtained at a supply voltage of about 1.6kV (-1.6 kV for negative corona discharge) at the reactor temperatures and gas compositions used in this study.

Table 1 shows the results of positive and negative corona processes at wire electrode potential of ± 5 kV. Results comparing the corona process with the corona packed bed process (i.e., corona in the presence of the catalyst bed) will be discussed in the following sections. From Table 1, there appears to be little difference in the results obtained with positive and negative corona discharges. The highest selectivity obtained was 59% and the highest C₂ yield was 2.4%. Methane conversion was kept low by using relatively high methane:oxygen ratios and small residence times.

Table 1 Comparison of positive and negative Corona processes without catalyst (100ml/min, 923.2K)

CH ₄ /O ₂	Wire electrode potential, kV	Selectivity for C ₂ products, %	Yield of C ₂ Products, %	Conversion of methane, %	Conversion of Oxygen, %	C ₂ H ₄ /C ₂ H ₆
20/2	+5	49	1.9	3.9	50	0.357
	-5	52	2.0	3.9	33	0.158
20/8	+5	41	2.4	6.0	24	0.500
	-5	42	1.2	2.7	16	0.000
20/10	+5	52	2.2	4.3	13	0.560
	-5	59	2.0	3.3	6.5	0.403

2. Catalyst Run

The saturation current was also observed for the corona discharge in the presence of the catalyst bed. The saturation current, for all catalysts and all reaction conditions tested, was 1.12 mA.

(1) Effect of corona discharge on methane conversion

Figure 2 shows the effect of the positive corona on methane conversion at varying temperatures and at a methane:oxygen feed ratio of 4:1. Particularly at low temperature there appears to be a synergistic effect in which the conversion in the corona packed bed process is greater than the sum of the conversions in the corona and packed bed processes separately. Compared with packed bed results, the methane conversion in the corona packed bed is almost five times higher while the selectivity for C₂ is over eight times larger. The yield of C₂ products is increased by a factor of over 40. Figure 3 shows similar results at a methane:oxygen feed ratio of 2:1. Figures 2 and 3 suggest that the corona discharge enhancement is greater at lower CH₄/O₂ ratio. At higher temperature (i.e., above 973 K) the enhanced catalytic performance is limited by the availability of oxygen which, even in the absence of the corona, is completely consumed. Part of the enhancement is due to heating by the plasma of the catalyst bed. Preliminary measurements of the packed bed temperature during corona discharge indicate, however, that increased catalyst temperature does not account for all the observed enhancement.

Figures 4 and 5 show the C₂ selectivity and yield, respectively, for the packed bed and corona packed bed processes. Over the entire range of conditions studied, the presence of the corona increases the both the selectivity and yield achieved over the packed bed alone.

(2) Effect of oxygen partial pressure in the feed

Figure 6 shows the conversion, selectivity, and yield obtained as a function of oxygen partial pressure at 923 K. For the corona discharge process, the oxygen partial pressure has only slight influence, with methane conversion and C₂ yield increasing slightly with oxygen partial pressure and C₂ yield decreasing slightly. For either the packed bed or corona packed bed processes, the trends are the same but more pronounced. The results of Figure 6 were obtained with the positive corona discharge.

(3) Polarity effect

Table 1 demonstrates the effects of polarity. In all cases the plate electrode is grounded; for positive corona the wire electrode is held at +5 kV while for negative corona the wire electrode is held at -5 kV. The highest C₂ yields were obtained with positive corona packed bed processes.

Table 2: Comparison of positive and negative corona processes with catalyst (100ml/min, 923.2K)

CH ₄ /O ₂	Wire electrode potential, kV	Selectivity for C ₂ products, %	Yield of C ₂ Products, %	Conversion of methane, %	Conversion of Oxygen, %	C ₂ H ₄ /C ₂ H ₆
20/2	0	42	4.2	9.8	93	0.194
	+5	55	6.7	12.2	100	0.284
	-5	54	5.9	11.0	100	0.262
20/8	0	25	5.8	23.7	99	0.503
	+5	34	9.4	28.0	100	0.691
	-5	33	8.9	27.2	100	0.678
20/10	0	23	6.7	29.6	88	0.612
	+5	27	9.6	36.0	100	0.775
	-5	31	8.3	26.5	90	0.538

(4) Effects of residence time

Methane conversion increases slightly with residence time over the range of flow rates used in our experiments. C_2 selectivity decreases and C_2 yield remains roughly constant for the corona packed bed process. The results are shown in Figure 7. The small effect of residence time is due to the high oxygen conversion at 923 K.

3. Discussion

It is generally accepted that the rate limiting step of heterogeneously catalyzed OCM is the activation of methane to methyl radicals. The same is assumed to be true in the corona and corona packed bed processes. A gas discharge will be created by electron impact or electron attachment reactions with gaseous species. These reactions will change the chemical state of reactants which may react further in the gas phase. In the corona packed bed process electrons may collide with gas phase molecules and the catalyst surface. In addition, gas discharge may be initiated by microbreakdown or by interaction with charged solid particles. The plasma species may interact with and/or modify the catalyst surface, and the microelectric field between catalyst particles may change catalyst properties.

In our experiments, the dc electric field induces electrons with electron energy of about 5eV^[29,30]. These relatively low energy electrons have insufficient energy to ionize methane, which has an ionization potential greater than 12eV^[31], but their energy is sufficient to initiate dissociative attachment reactions of oxygen leading to negatively charged oxygen ions.^[17,30] Due to its electronegative nature, oxygen easily forms negative ions either by direct attachment or by dissociative attachment. The increasing probability of a collision in the catalyst layer should also lead to the electron energy decrease and electron attachment. Similar to O^- species on solid catalysts, the oxygen ions in the plasma extract a hydrogen from methane molecules to activate the methane. Additionally, if the microelectric field between the charged particles is sufficiently strong, surface adsorption performance could be modified which could also enhance the

conversion of methane by increasing the amount of chemisorbed oxygen or methane on the charged catalyst surface. Further research is being conducted to understand the mechanism of electric field enhancement. In general, the mechanism for the OCM reaction is described as follows:

(1) Discharge reactions:

Other possible reactions include charge transfer, metastable species formation, detachment, and electron-ion, ion-ion and atom recombinations. The dissociative attachment reaction needs less energy so it is more favorable.^[17,30]

(2) Homogeneous reactions

From the gas O^- formed by dissociative attachment, the following homogeneous reactions will occur:

Methane radical formation:

Ethane formation:

Ethylene formation:

Oxidative dehydrogenation of ethane:

CO_X formation

(3) Heterogeneous reactions

Adsorption of oxygen:

Attachment:

Methane radical formation:

The reactions between methane radicals and oxygen will occur readily in the gas phase. This reaction mechanism may explain the electric field enhancement phenomena. The means by which the corona enhances methane conversion will include the gas discharge reaction as well as the reactions occurring between plasma species and the catalyst surface and the possible adsorption enhancement caused by the electric field.

CONCLUSIONS

The present results demonstrate that:

1. The combination of catalyst and corona discharge shows a selectivity and activity enhancement beyond that achieved by either process alone for the oxidative coupling of methane . The lower the temperature the greater the enhancement.
2. Both positive and negative corona processes exhibit a saturation discharge current.
3. Increasing oxygen partial pressure in the feed gases will increase conversion of methane and yield of C_2 products.
4. The positive corona shows slightly better enhancement than does the negative corona.

REFERENCES

1. G.E.Keller and M.M.Bhasin, *J. Catal.*, 73, 1982, p.9.
2. J.S.Lee and S.T.Oyama, *Catal.Rev.- Sci.Eng.*, 30, 1988, p.249.
3. J.M.DeBoy and R.F.Hicks, *J. Catal.*, 113, 1988, p.517.
4. M.J.Capitan, P.Malet, M.A.Centeno, A.Munoz-Paez, I.Carrizosa and J.A.Odriozola, *J.Phys.Chem.*, 97, 1993, p.9233.
5. K.Otsuka, Y.Shimizu and T.Komatsu, *Chem.Lett.*, 1987, p.1835.
6. N.Yamagata, K.Igarashi, H.Saitoh and S.Okazaki, *Bull.Chem.Soc.Jpn.*, 66, 1993, p.1799.
7. A.M.Gaffney, C.A.Jones, J.J.Leonard and J.A.Sofranko, *J.Catal.*, 114, 1988, p.422.
8. H.Imai and T.Tagawa, *J.Chem.Soc., Chem.Comm.*, 1986, p.52.
9. D.Eng and M.Stoukides, *Catal.Rev.- Sci.Eng.*, 33, 1991, p.375.
10. D.Eng and M.Stoukides, *J.Catal.*, 130, 1991, p.306.
11. H.Nagamoto, K.Hayashi and H.Inoue, *J.Catal.*, 126, 1990, p.671.
12. K.Omata, S.Hashimoto, H.Tominaga and K.Fujimoto, *Appl. Catal.*, 52, 1989, L1.
13. K.Otsuka, S.Yokoyama and A.Morikawa, *Chem.Lett.*, 1985b, p.319.
14. K.Fujimoto, K.Asami, K.Omata and H.Hashimoto, *Stud.Surf.Sci., Catal.*, 61, 1991, p.525.
15. S.Seimanides, *J.Electrochem.Soc.*, 1986, p.1353.
16. A.B.Dhirendra, Masters degree thesis, the University of Oklahoma, 1995.
17. A.Grill, *Cold Plasma in Materials Fabrication*, From fundamentals to applications, IEEE press, New York, 1994.
18. G.Flamant, *Pure & Appl. Chem.*, 66(6), 1994, p.1231.
19. K.Tachibana, M.Nishida, H.Harima and Y.Urano, *J. Phys.D:Appl.Phys.*, 17, 1984, p.1727.
20. M.E.Fraser, D.A.Fee and R.S.Sheinson, *Plasma Chem. and Plasma Processing*, 5(2), 1985, p.163.

21. A.Ohl, *Pure & Appl.Chem.*,66(6),1994,p.1397.
22. P.P.Alexander, *J.Am.Weld Soc.*,8,1929,p.48.
23. R.Mach and H.Drost, *6th International Sym. on Plasma Chem.*, Montreal, Quebec, Canada,1983.
24. T.Fujii and K.Syouji, *Phys.Rev.E*,49(1),1994,p.657.
25. T.Fujii and K.Syouji, *J.Phys.Chem.*,97,1993,p.11380.
26. Amouroux J. and Talbot J., *Ann. Chim. (Masson, Paris)*, t.3,No.3,1968,p.219.
27. Nester, S., Potapkin,B.,A. Fridman.e.d., "Kinetical and statistical modelling of chemical reactions in gas discharge"(in Russian), ATOMINFORM, Moscow,1988,p.224.
28. J.Chang, P.A.Lawless and T.Yamamoto, *IEEE Trans. on Plasma Sci.*, 19(6),1991,p.1152.
29. Y.L.M.Creyghton, E.M.van Veldhuizen and W.R.Rutgers,*Proc.10th.Int.Symp.on Plasma Sci.*,Bochum,paper 3.2~5,1991.
30. B.Eliasson and U.Kogelschatz, *IEEE Trans.on Plasma Sci.*,19,1991,p.1063.
31. S.L.Sorensen, A.Karawajczyk,C.Stromholm and M.Kirm,*Chem.Phys.Letter*, 232,1995, p.554.(including its references).
32. A. von Engel, *Ionized Gases*, 2nd ed.,Oxford at the Clarendon Press,1965,p.88.

FIGURE 1 THE CORONA PACKED BED REACTOR SYSTEM

FIGURE 2 EFFECT OF ELECTRIC FIELD ON REACTION RATE OF METHANE AND CONVERSION OF OXYGEN

FLOWRATE: 100 ml/min CH₄/O₂: 20/5 INPUT POWER: 5.6w
 WITH CATALYST, NO ELECTRIC FIELD ●
 WITH CATALYST AND ELECTRIC FIELD ▲
 NO CATALYST, WITH ELECTRIC FIELD ■

FIGURE 3 EFFECT OF ELECTRIC FIELD ON REACTION RATE OF METHANE AND CONVERSION OF OXYGEN

FLOWRATE: 100 ml/min CH₄/O₂: 20/10 INPUT POWER: 5.6w
 WITH CATALYST, NO ELECTRIC FIELD ●
 WITH CATALYST AND ELECTRIC FIELD ▲
 NO CATALYST, WITH ELECTRIC FIELD ■

FIGURE 4 EFFECT OF ELECTRIC FIELD ON SELECTIVITY FOR C2 PRODUCTS

FLOWRATE: 100 ml/min

INPUT POWER: 5.6w

WITH CATALYST, NO ELECTRIC FIELD ●

WITH CATALYST AND ELECTRIC FIELD ▲

FIGURE 5 EFFECT OF ELECTRIC FIELD ON YIELD OF C2 PRODUCTS

FLOWRATE: 100 ml/min

INPUT POWER: 5.6w

WITH CATALYST, NO ELECTRIC FIELD ● WITH CATALYST AND ELECTRIC FIELD ▲

FIGURE 6 RESULTS WITH DIFFERENT INITIAL OXYGEN PARTIAL PRESSURE

FLOWRATE: 100 ml/min INPUT POWER: 5.6w
 TEMPERATURE: 923.2K INITIAL METHANE PARTIAL PRESSURE: 0.2 atm
 ● WITH CATALYST, NO ELECTRIC FIELD
 ▲ WITH CATALYST AND ELECTRIC FIELD
 ■ POSITIVE CORONA PROCESS WITHOUT CATALYST

FIGURE 7 EFFECT OF RESIDENCE TIME ON REACTION

INPUT POWER: 5.6w TEMPERATURE: 923.2K
 INITIAL METHANE PARTIAL PRESSURE: 0.2 atm
 INITIAL OXYGEN PARTIAL PRESSURE: 0.1 atm
 WITH CATALYST, NO ELECTRIC FIELD ●
 WITH CATALYST AND ELECTRIC FIELD ▲
 POSITIVE CORONA PROCESS WITHOUT CATALYST ■