UNDERSTANDING TRI-REFORMING OF METHANE USING HYDROTALCITE-DERIVED CATALYSTS FOR UTILIZATION OF CO_2 OF FLUE GASES FROM THERMAL POWER PLANTS

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by

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in fulfilment of the requirements for the award of the degree of Doctor of Philosophy

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DEDICATED

TO

MY FAMILY

CERTIFICATE

This is to certify that the thesis entitled, "**UNDERSTANDING TRI-REFORMING OF METHANE USING HYDROTALCITE-DERIVED CATALYSTS FOR UTILIZATION OF CO_2 OF FLUE GASES FROM THERMAL POWER PLANTS**" being submitted by **Mr. ROHIT KUMAR** to the Indian Institute of Technology, Delhi for the award of DOCTOR OF PHILOSOPHY is a record of bonafide research work carried out by him under guidance and supervision in conformity with the rules and regulations of Indian Institute of Technology, Delhi.

The research report and results presented in this thesis have not been submitted, in part or full, to any other university or institute for the award of ant degree or diploma.

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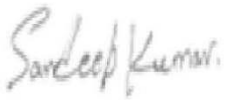

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ABSTRACT

The global warming and climate change are the biggest challenges of current century. These are often related to CO_2 emission. The conversion of CO_2 to fuels and chemicals could be an ideal strategy to curb CO_2 emission. In this context, tri-reforming of methane (TRM) is a promising technique. The flue gas from electric power plants are the largest contributor to CO_2 emission. TRM process does not requires pre-separation of CO_2 from flue gas. In this process, CO_2, H_2O and O_2 of flue gas react with CH_4 to generate synthesis gas. However, the deactivation of catalyst impedes large-scale implementation of TRM. The reforming catalysts tend to deactivate due to carbon deposition, active metal sintering and active metal oxidation. The high activity and stability of catalyst are the major challenges of TRM. The research work presented in this thesis aims to develop a highly active and stable catalyst for TRM reaction for utilization of industrial flue gas.

The support phase of a catalyst has significant influence on catalyst performance. Various metal oxides (Al_2O_3, SBA-15, ZrO_2, CeO_2-ZrO_2, TiO_2 and MgO) were used as a support of Ni catalyst. Their performances were compared under identical reaction condition. Based on CH_4 conversion, the initial activity of these catalysts followed the order: Ni/Al_2O_3 > Ni/SBA-15 > Ni/ZrO_2 > Ni/CeO_2-ZrO_2 > Ni/TiO_2 > Ni/MgO. Ni/Al_2O_3 derived from spinel precursor $NiAl_2O_4$ resulted in well-dispersed smaller Ni particles, stronger metal-support interaction, a higher degree of reducibility and higher basic sites concentration, which led to its superior activity over other catalysts. On the contrary, the stability of SBA-15 and ZrO_2 supported Ni catalysts was remarkably high in 10 h run. Hexagonal porous network of SBA-15 confined Ni particles that resulted in high resistance against metal sintering and carbon deposition whereas Ni/ZrO_2 offered resistance to Ni oxidation owing to its oxophilic property. Experimental investigations reveal that Ni/TiO_2 and Ni/MgO resulted in poor CH_4, CO_2 and H_2O conversions for TRM due to lower degree of reducibility. Furthermore, Ni/CeO_2-ZrO_2 catalyst exhibited lower conversion compared to Ni/Al_2O_3, Ni/SBA-15, and Ni/ZrO_2 due to larger Ni crystallite size.

The role of metal-support interaction (MSI) in the performance of Ni/TiO_2, Ni/SBA-15, Ni/MgO, and Ni/Al_2O_3 catalysts was investigated. To impart weak metal-support interaction (WMSI), the catalysts were calcined at 400^oC. While calcination at 850^oC or above temperature generated strong metal-support interaction (SMSI) in each catalyst. Ni/SBA-15 and Ni/Al_2O_3

catalysts were calcined at 550°C and 700°C as well to impart medium-strength MSI. The experimental results revealed that Ni/TiO_2 and Ni/MgO catalysts having WMSI (Ni/TiO_2@400 and Ni/MgO@400) displayed high initial activity due to the higher extent of reduction and Ni dispersion. However, these catalysts deactivated during 10 h reaction run. On the other hand, the performances of Ni/TiO_2 and Ni/MgO catalysts having SMSI (Ni/TiO_2@850 and Ni/MgO@850) were unsatisfactory. For Ni/SBA-15 catalyst system, catalysts having weaker MSI (Ni/SBA-15@400, Ni/SBA-15@550 and Ni/SBA-15@700) were more active than the catalyst having stronger MSI (Ni/SBA-15@850). However, the stability of Ni/SBA-15 catalysts was governed by Ni confinement in the pores of SBA-15 rather than the strength of MSI. The activity of Ni/Al_2O_3 catalyst was found to increase with increase in the strength of MSI (Ni/Al_2O_3@400 < Ni/Al_2O_3@550 < Ni/Al_2O_3@700 < Ni/Al_2O_3@950). Ni/Al_2O_3 having SMSI had monodispersed Ni atoms in close association with Al_2O_3, which resulted in higher reforming activity compared to that of Ni/Al_2O_3 having WMSI. Moreover, the deactivation rate was found to decrease with increase in strength of MSI as stronger MSI enhanced Ni/Al_2O_3 catalyst's ability to combat deactivation due to the carbon deposition and Ni metal sintering. The chemical nature of carbon deposits over the Ni/Al_2O_3 catalyst was also observed to be affected by the strength of MSI as it tends to become more graphitic with a decrease in strength of MSI.

Materials derived from hydrotalcite were also explored as a catalyst in TRM reaction. For this study, five catalysts were prepared by co-precipitation method. These were Ni-Mg-Al, Ni-Mg-Al_me@500, Ni-Mg-Al_me@900, Ni-Cu-Mg-Al and Ni-Zn-Mg-Al. Ni-Mg-Al_me@500 and Ni-Mg-Al_me@900 were synthesized using memory effect (me) property of hydrotalcite. The non-promoted Ni catalyst, Ni-Mg-Al, displayed lower activity due to the low degree of reducibility. Although by adopting memory effect in preparation of hydrotalcite-derived Ni catalysts, the degree of reducibility was improved and higher initial activity was achieved for Ni-Mg-Al_me@500 and Ni-Mg-Al_me@900, but these catalysts were vulnerable to deactivation due to Ni oxidation, metal sintering and carbon formation. The addition of Cu resulted in formation of Ni-Cu alloy. It reduced the ensemble size of Ni, which resulted in higher activity and stability as compared to non-promoted Ni catalysts. However, post reaction characterization results revealed Ni oxidation of Ni-Cu-Mg-Al catalyst. The addition of Zn was found more effective in keeping the Ni in its metallic state thereby enhancing its stability. Moreover, the XPS results revealed that Zn addition electronically modified the Ni catalyst by charge transfer phenomenon and made Ni electron rich. As a result, Ni-Zn-Mg-Al catalyst exhibited remarkable tri-reforming activity.

Ni-Zn-Mg-Al catalyst was further studied for TRM by varying its M^{II}/M^{III} ratio and Ni loading. The increase in M^{II}/M^{III} ratio of Ni-Zn-Mg-Al catalyst having 10 wt.% Ni loading enhanced basic properties of catalysts in terms of both basic site concentration and basic site strength; but only at the cost of Ni dispersion. The Ni-Zn-Mg-Al catalyst of M^{II}/M^{III} ratio = 3.0 (3.0-Cat.) gave the best catalytic performance among the catalysts of varying M^{II}/M^{III} ratio due to the trade-off between basic properties and Ni dispersion. This study further investigates the effect of Ni loading for Ni-Zn-Mg-Al catalysts having M^{II}/M^{III} ratio = 3.0. The CH_4, CO_2 and H_2O conversions increased significantly on increasing Ni loading from 1.25 wt.% to 5 wt.%. However, these values increased only slightly with further increase in Ni loading to 15 wt.%. Moreover, at 15 wt.% Ni loading, the catalyst underwent coking, resulting in its deactivation. On the other hand, the Ni particles of catalysts having low Ni content (1.25 and 2.5 wt.%) deactivated due to sintering. The catalyst of 5 wt.% Ni loading (5%-Cat) exhibited remarkable stability. In 80 h experimental run at 800^oC temperature, 1 atm pressure, feed-stream composition CH_4:CO_2:H_2O:O_2:N_2 = 1:0.28:0.56:0.08:0.33 and space velocity of 44743 mL/g.h, the CH_4, CO_2 and H_2O conversions over 5%-Cat were 78.2%, 80.6% and 70.4% respectively. The negligible drop in CH_4 and CO_2 conversion rates firmly establishes the striking stability of 5%-Cat over 80 h time on stream. Moreover, the average H_2/CO molar ratio of synthesis gas produced in 80 h run was 1.96, quite appropriate for methanol and Fischer-Tropsch synthesis processes.

The kinetic behaviour of 5%-Cat for tri-reforming of methane reaction was investigated in the temperature range of 700^oC-800^oC with the partial pressure of CH_4, CO_2, H_2O and O_2 ranging between 0.47-0.57 atm, 0.03-0.10 atm, 0.08-0.21 atm and 0.007-0.045 atm respectively. Three different elementary reaction steps were assumed to be the rate determining and thus three different Langmuir-Hinshelwood kinetic models were developed. Dual-site mechanism was considered in model development in which CH_4 activates on metallic Ni sites and other co-reactants activate on non-Ni sites of 5%-Cat. The models were optimized using Generalized Reduced Gradient algorithm. The model considering methane dissociation and reaction between adsorbed carbon and adsorbed oxidants as rate determining fitted well with experimental data. The correlation coefficient of parity plot was 0.95. The activation energies of methane cracking and carbon oxidation are calculated to be 111.4 and 206.1 kJ/mol respectively.

सार

ग्लोबल वार्मिंग और जलवायु परिवर्तन वर्तमान सदी की सबसे बड़ी चुनौतियां हैं। ये CO_2 उत्सर्जन से संबंधित होते हैं। CO_2 से ईंधन और रसायनों का रूपांतरण CO_2 उत्सर्जन को रोकने के लिए एक आदर्श रणनीति हो सकती है। इस संदर्भ में, मीथेन का त्रि-सुधार (टी.आर.एम.) एक आशाजनक तकनीक है। CO_2 उत्सर्जन में सबसे बड़ा योगदान इलेक्ट्रिक पावर प्लांटों की गरम धुयें गैस का है। टी.आर.एम. प्रक्रिया को गरम धुयें गैस से CO_2 के पूर्व-पृथक्करण की आवश्यकता नहीं होती है। इस प्रक्रिया में, गरम धुयें गैस के CO_2, H_2O और O_2 संश्लेषण गैस उत्पन्न करने के लिए मीथेन के साथ प्रतिक्रिया करते हैं। हालांकि, उत्प्रेरक का निष्क्रियकरण टी.आर.एम. के बड़े पैमाने पर कार्यान्वयन में बाधा डालता है। उत्प्रेरक कार्बन जमाव, सक्रिय धातु सिंटरिंग और सक्रिय धातु ऑक्सीकरण के कारण निष्क्रिय हो जाते हैं। उत्प्रेरक की उच्च सक्रियता और स्थिरता बनाये रखना टी.आर.एम. की प्रमुख चुनौतियां हैं। इस थीसिस में प्रस्तुत शोध कार्य का उद्देश्य टी.आर.एम. प्रक्रिया में औद्योगिक गरम धुयें गैस के उपयोग के लिए एक अत्यधिक सक्रिय और स्थिर उत्प्रेरक विकसित करना है।

एक उत्प्रेरक के सपॉर्ट हिस्सा का उत्प्रेरक प्रदर्शन पर महत्वपूर्ण प्रभाव पड़ता है। Ni उत्प्रेरक के सपॉर्ट हिस्सा के रूप में विभिन्न धातु आक्साइड (Al_2O_3, SBA-15, ZrO_2, CeO_2-ZrO_2, TiO_2 और MgO) का उपयोग किया गया था। उनके प्रदर्शन की तुलना समान प्रतिक्रिया में की गई। CH_4 रूपांतरण के आधार पर, इन उत्प्रेरकों की प्रारंभिक सक्रियता इस तरह था: Ni/Al_2O_3>Ni/SBA-15>Ni/ZrO_2>Ni/CeO_2-ZrO_2>Ni/TiO_2>Ni/MgO। $NiAl_2O_4$ से प्राप्त Ni/Al_2O_3 में Ni कण अच्छी तरह से छितरे हुए, मजबूत धातु- सपॉर्ट इंटरैक्शन, उच्च स्तर की रेड्यूसबिलिटी और उच्च क्षार उत्पन्न हुई, जिससे अन्य उत्प्रेरकों की तुलना में बेहतर प्रदर्शन किया । तथापि, SBA-15 और ZrO_2 समर्थित Ni उत्प्रेरकों की स्थिरता 10 घंटे रन में उल्लेखनीय रूप से अधिक थी। SBA-15 के हेक्सागोनल झरझरा नेटवर्क ने Ni कणों को समायोजित रखा, जिसके परिणामस्वरूप धातु के सिंटरिंग और कार्बन के जमाव के खिलाफ उच्च प्रतिरोध पैदा हुआ, जबकि Ni/ZrO_2 ने Ni ऑक्सीकरण के लिए अपनी ऑक्सीफिलिक संपत्ति के कारण प्रतिरोध दिखाया। प्रायोगिक जांच से पता चलता है कि Ni/TiO_2 और Ni/MgO ने टी.आर.एम. प्रक्रिया में

कम स्तर की रेड्यूसबिलिटी के कारण कम CH_4, CO_2 और H_2O रूपांतरणों को दिखाया। इसके अलावा, Ni/CeO_2-ZrO_2 उत्प्रेरक ने Ni/Al_2O_3, Ni/SBA-15 और Ni/ZrO_2 की तुलना में बड़े Ni क्रिस्टलीय आकार के कारण निम्न रूपांतरण का प्रदर्शन किया।

Ni/TiO_2, Ni/SBA-15, Ni/MgO, और Ni/Al_2O_3 उत्प्रेरक के प्रदर्शन में धातु-सपॉर्ट इंटरैक्शन की भूमिका की जांच की गई। कमजोर धातु-सपॉर्ट इंटरैक्शन को लागू करने के लिए, उत्प्रेरक को 400°C पर कैल्सीनेशन किया गया था। जबकि 850°C या उससे अधिक तापमान पर कैल्सीनेशन प्रत्येक उत्प्रेरक में मजबूत धातु-सपॉर्ट इंटरैक्शन उत्पन्न किया। Ni/SBA-15 और Ni/Al_2O_3 उत्प्रेरक के लिये मध्यम-शक्ति का धातु-सपॉर्ट इंटरैक्शन प्रदान करने के लिए 550°C और 700°C पर कैल्सीनेशन किए गए थे। प्रयोगात्मक परिणामों से पता चला कि Ni/TiO_2 और Ni/MgO उत्प्रेरक जिनके पास कमजोर धातु-सपॉर्ट इंटरैक्शन (Ni/TiO_2@400 और Ni/MgO @ 400) था, ने उच्च स्तर की रेड्यूसबिलिटी और Ni फैलाव के कारण उच्च प्रारंभिक सक्रियता प्रदर्शित की। हालाँकि, ये उत्प्रेरक 10 घंटे प्रतिक्रिया रन के दौरान निष्क्रिय हो गए। दूसरी ओर, मजबूत धातु-सपॉर्ट इंटरैक्शन से संबंधित Ni/TiO_2 और Ni/MgO उत्प्रेरक का प्रदर्शन (Ni/TiO_2@850 और Ni/MgO@850) असंतोषजनक था। Ni/SBA-15 उत्प्रेरक के लिए, कमजोर धातु-सपॉर्ट इंटरैक्शन (Ni/SBA-15@ 400, Ni /SBA-15@550 और Ni/SBA-15@700) वाले उत्प्रेरक अधिक मजबूत धातु-सपॉर्ट इंटरैक्शन (Ni/SBA-15@850) वाले उत्प्रेरक से अधिक सक्रिय थे। हालांकि, Ni/SBA-15 उत्प्रेरकों की स्थिरता धातु-सपॉर्ट इंटरैक्शन की ताकत के बजाय SBA-15 के छिद्रों में उपस्थित Ni द्वारा नियंत्रित की गई थी। Ni/Al_2O_3 उत्प्रेरक की सक्रियता में धातु-सपॉर्ट इंटरैक्शन की ताकत बढ़ने के साथ (Ni/Al_2O_3@400 <Ni/Al_2O_3@550 <Ni/Al_2O_3@700 <Ni/Al_2O_3@950) वृद्धि पाया गया। मजबूत धातु-सपॉर्ट इंटरैक्शन वाले Ni/Al_2O_3 में मोनोडिस्फ़र Ni परमाणु Al_2O_3 के साथ निकट था, जिसके परिणामस्वरूप कमजोर धातु-सपॉर्ट इंटरैक्शन वाले Ni/Al_2O_3 की तुलना में उच्च सक्रियता थी। इसके अलावा, निष्क्रियता दर को धातु-सपॉर्ट इंटरैक्शन की ताकत में वृद्धि के साथ कम पाया गया क्योंकि मजबूत धातु-सपॉर्ट इंटरैक्शन ने कार्बन जमाव और Ni धातु सिंटरिंग के कारण निष्क्रियकरण को कम किया। Ni/Al_2O_3 उत्प्रेरक पर कार्बन जमाव की रासायनिक प्रकृति भी धातु-सपॉर्ट इंटरैक्शन की ताकत से प्रभावित हो गई क्योंकि यह धातु-सपॉर्ट इंटरैक्शन की ताकत में कमी के साथ अधिक ग्रेफाइटिक बन गया।

टी.आर.एम. प्रक्रिया में उत्प्रेरक के रूप में हाइड्रोटेलेसाइट से प्राप्त सामग्री को भी प्रयोग गया। इस अध्ययन के लिए, पांच उत्प्रेरक तैयार किए गए थे। ये Ni-Mg-Al, Ni-Mg-Al_me@500, Ni-Mg-Al_me@900, Ni-Cu-Mg-Al और Ni-Zn-Mg-Al थे। Ni-Mg-Al_me@500 और Ni-Mg-Al_me@900 को हाइड्रोटेलेकाइट की स्मृति प्रभाव संपत्ति का उपयोग करके संश्लेषित किया गया। Ni-Mg-Al, को कम स्तर की रेड्यूसबिलिटी के कारण कम सक्रिय पाया गया। यद्यपि हाइड्रोटेलेसाइट-व्युत्पन्न Ni उत्प्रेरकों की निर्माण में स्मृति प्रभाव को अपनाने से, रेड्यूसबिलिटी में सुधार हुआ था और Ni-Mg-Al_me@500 और Ni-Mg-Al_me@900 के लिए उच्च प्रारंभिक सक्रियता प्राप्त हुई थी, लेकिन ये उत्प्रेरक Ni ऑक्सीकरण, धातु सिंटरिंग और कार्बन गठन के कारण निष्क्रिय हो गए। Cu के Ni-Mg-Al में जोड़ से Ni-Cu मिश्र धातु का निर्माण हुआ। इसने Ni के कण के आकार को कम कर दिया, जिसके परिणामस्वरूप गैर-प्रवर्तित Ni उत्प्रेरक (Ni-Mg-Al) की तुलना में उच्च सक्रियता और स्थिरता प्राप्त हुई। हालांकि, पोस्ट रिएक्शन परिणामों में Ni-Cu-Mg-Al उत्प्रेरक के Ni ऑक्सीकरण का पता चला। Zn को जोड़ने से इसके धात्विक अवस्था में Ni को बनाए रखने में अधिक प्रभावी पाया गया जिससे इसकी स्थिरता बढ़ गई। इसके अलावा, XPS परिणामों से पता चला है कि Zn ने इलेक्ट्रॉनिक रूप से Ni उत्प्रेरक को चार्ज ट्रांसफर घटना द्वारा संशोधित किया और Ni को इलेक्ट्रॉन समृद्ध बनाया। परिणामस्वरूप, Ni-Zn-Mg-Al उत्प्रेरक ने उल्लेखनीय सक्रियता प्रदर्शित की।

Ni-Zn-Mg-Al उत्प्रेरक का टी.आर.एम. के लिए इसके M_{II}/M_{III} अनुपात और Ni लोडिंग में भिन्नता का अध्ययन किया गया। Ni-Zn-Mg-Al उत्प्रेरक के M_{II}/M_{III} अनुपात में वृद्धि 10 wt% Ni लोडिंग ने क्षार संख्या और क्षार शक्ति दोनों को बढ़ाया; लेकिन Ni फैलाव खराब हो गया। M_{II}/M_{III} अनुपात = 3.0 (3.0-Cat) के Ni-Zn-Mg-Al उत्प्रेरक ने बेहतर क्षार गुणों और बेहतर Ni फैलाव के कारण भिन्न M_{II}/M_{III} अनुपात के उत्प्रेरक की तुलना में सबसे अच्छा प्रदर्शन दिया। यह अध्ययन आगे Ni-Zn-Mg-Al उत्प्रेरक के लिए Ni लोडिंग के प्रभाव की जांच करता है जिसमें M_{II}/M_{III} अनुपात = 3.0 है। CH_4, CO_2 और H_2O रूपांतरण 1.25 wt% से 5 wt% तक Ni लोडिंग बढ़ाने पर काफी बढ़ गए। हालांकि, ये Ni लोडिंग में 15 wt% तक की वृद्धि के साथ केवल थोड़ा बढ़ गए। इसके अलावा, 15 wt% Ni लोडिंग पर, उत्प्रेरक पर अधिक कार्बन जमाव था, जिसके परिणामस्वरूप इसकी निष्क्रिय हो गया। दूसरी ओर, कम Ni लोडिंग (1.25 और 2.5 wt%) वाले उत्प्रेरक के Ni कणों को सिंटरिंग के कारण निष्क्रिय हो गया। 5 wt% Ni लोडिंग

(5%-कैट) का उत्प्रेरक उल्लेखनीय स्थिरता प्रदर्शित करता है। 80 घंटे रन में 800°C तापमान, 1 atm प्रेशर, फीड-स्ट्रीम कम्पोज़िशन CH_4:CO_2:H_2O:O_2:N_2 =1:0.28:0.56:0.08:0.33 और स्पेस वेलोसिटी 44743 mL/gh पर, यह उत्प्रेरक CH_4, CO_2 और H_2O रूपांतरण क्रमशः 78.2%, 80.6% और 70.4% दिखाया। 80 घंटे की रन में CH_4 और CO_2 रूपांतरण दरों में नगण्य गिरावट दृढ़ता से 5%-कैट की स्थिरता को स्थापित करती है। इसके अलावा, 80 घंटे रन में निर्मित संश्लेषण गैस का औसत H_2/CO मोलर अनुपात (1.96) मेथनॉल और फिशर-ट्रोप्स संश्लेषण प्रक्रियाओं के लिए काफी उपयुक्त है।

मीथेन की त्रिकोणीय सुधार (टी.आर.एम.) प्रक्रिया के लिए 5%-कैट के गतिज व्यवहार की जांच 700°C-800°C के तापमान सीमा में की गई थी, जिसमें CH_4, CO_2, H_2O और O_2 के आंशिक प्रेशर क्रमशः 0.47-0.57 atm, 0.03-0.10 atm, 0.08-0.21 atm और 0.007-0.045 atm थी। तीन अलग-अलग प्राथमिक प्रतिक्रिया चरणों को दर निर्धारण करने वाला माना गया और इस तरह तीन अलग-अलग लैंगमुइर-हिंसेलवुड कैनेटिक मॉडल विकसित किए गए। मॉडल-विकास में दोहरे साइट तंत्र पर विचार किया गया था जिसमें CH_4 धातु Ni साइटों पर सक्रिय होता है और अन्य सह-प्रतिक्रियाकर्ता गैर-Ni साइटों पर सक्रिय होते हैं। मॉडल को सामान्यीकृत-कम-ग्रेडिएंट एल्गोरिथ्म का उपयोग करके अनुकूलित किया गया था। मीथेन पृथक्करण और कार्बन ऑक्सीकरण को दर निर्धारण करने वाला मॉडल प्रायोगिक डेटा की सही भविष्यवाणी करने में कामयाब रहा। समता भूखंड का सहसंबंध गुणांक 0.95 था। मीथेन पृथक्करण और कार्बन ऑक्सीकरण की सक्रियण ऊर्जा की गणना क्रमशः 111.4 और 206.1 kJ/mol की जाती है।

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NOMENCLATURE

d	d-spacing	nm
D	Internal diameter of reactor	mm
D_p	Average catalyst particle size	nm
D_{pore}	Mesopore size	nm
E_{app}	Apparent activation energy	
F	Volumetric flow rate of feed	L/s
K_1	Adsorption constant of CH_4	atm^{-1}
k_2	Rate constant of methane decomposition reaction	$mol.g^{-1}s^{-1}$
K_3	Adsorption constant of CO_2	atm^{-1}
K_4	Adsorption constant of H_2O	atm^{-1}
K_5	Adsorption constant of O_2	atm^{-1}
k_6	Rate constant of reaction between adsorbed carbon and adsorbed oxidants	
L	Height of catalyst bed	cm
S_{BET}	Total surface area	m^2/g
S_{meso}	Mesopore surface area	m^2/g
S_{micro}	Micropore surface area	m^2/g
V_{micro}	Micropore volume	cm^3/g
W	Weight of catalyst	G
ΔH	Change in enthalpy	J/mol.K
ΔS	Change in entropy	J/mol

Greek letters

λ	X-ray wavelength	Å
β	Full width at half maximum	Å
θ	Peak position	^{o}

Subscripts

i	Reactant or product species

Acronyms

atm	Atmosphere
BET	Brunauer–Emmett–Teller
BJH	Barrett-Joyner-Halenda
CCS	Carbon capture and sequestration
CCU	Carbon capture and utilization
CNT	Carbon nanotube
DRM	Dry reforming of methane
EDX	Energy dispersive X-ray
ev	Electron volt
FWHM	Full width at half maximum
GHSV	Gas hourly space velocity
h	Hour
HTlc	Hydrotalcite-like compound
JCPDS	Joint Committee on Powder Diffraction Standards
me	Memory effect
M^{II}/M^{III} ratio	Divalent to trivalent metal molar ratio
MMSI	Medium metal-support interactions
MP-AES	Microwave plasma atomic emission spectroscopy
MSI	Metal-support interactions
nm	Nanometer
POM	Partial oxidation of methane
PSD	Particle size distribution
RDS	Rate determining step
RMSE	Root mean square error
RWGS	Reverse water-gas shift
SAXS	Small angle X-ray scattering
SEM	Scanning electron spectroscopy
SMSI	Strong metal-support interactions
SRM	Steam reforming of methane
STP	Standard temperature and pressure
TCD	Thermal conductivity detector
TEM	Transmission electron spectroscopy
TEOS	Tetraethyl orthosilicate
TGA	Thermo-gravimetric analysis
TOS	Time on stream
TPD	Temperature programmed desorption
TPO	Temperature programmed oxidation
TPR	Temperature programmed reduction
TRM	Tri-reforming of methane
WMSI	Weak metal-support interactions
XPS	X-ray photoelectron spectroscopy
XRD	X-ray diffraction