Rhodium Nanoparticle Size Effects on the CO₂ Reforming of Methane and Propane


Abstract: The CO₂ (dry) reforming of hydrocarbons offers an opportunity to convert greenhouse gases into synthesis gas, which can further transform to various valued products. Here we explore the influence of Rh particle size and support on the reforming of propane and methane. To that end, Rh nanoparticles with controlled sizes varying from 1.6-8.0 nm were synthesized following a polyl reduction method and then dispersed on three different solids: CeZrO₂, ZrO₂, and CeO₂. Catalytic turnover rates along with advanced characterization of fresh and spent catalysts reveal a linear correlation of turnover rates with Rh particle size for both methane and propane reforming. The nature and rate of coke deposition are highly dependent on the support used and its interaction with the metallic phase.

Introduction

The CO₂ (dry) reforming of alkanes, the reaction between CO₂ and paraffins to form synthesis gas (a mixture of CO and H₂), is known since 1928 for the pioneering work of Fischer and Tropsch.[1] Over the last few decades, the interest in this family of reactions has increased because it may allow the recycling of very large amounts of CO₂ through further processing the resulting syngas via Fischer-Tropsch synthesis.[2] CO₂ reforming reactions are highly endothermic and therefore require relatively high reaction temperatures to achieve high conversion of the reactants.[3] Under these conditions, the following series of reactions may occur:

\[
\begin{align*}
\text{CH}_4 \text{ decomposition} & \quad \text{CH}_4 \rightleftharpoons 2\text{H}_2 + \text{CO} \quad (\Delta H_{298K}^* = 75 \text{ kJ mol}^{-1}) \\
\text{Boudouard reaction} & \quad 2\text{CO} \rightleftharpoons \text{CO}_2 + \text{C} \quad (\Delta H_{298K}^* = -172 \text{ kJ mol}^{-1})
\end{align*}
\]

Methane dry reforming is especially attractive because, in the absence of coke formation, this reaction delivers an H₂/CO ratio of one, which is highly attractive for oxo process.

As it is the case for many metal nanoparticle catalyzed processes, reforming is claimed to be a structure sensitive reaction, meaning that catalytic activity (turnover rates) and selectivity (coking) strongly depend on metal nanoparticle size.[5] This is because nanoparticle morphology varies with its size: a fraction of step or edge sites is more prevalent with smaller nanoparticles, whereas a fraction of flat or terrace sites is more dominant in larger nanoparticles.[6] Associated with metal sintering, the size control of metal nanoparticles is the key to establish highly active and coke-resistant catalyst, which requires detailed fundamental investigation to exclusively address the size effects.

Here we explore the influence of Rh particle size and support on the reforming of propane and methane. Rh is known to be one of the most active and coke-tolerant catalysts for dry reforming.[7] Rh nanoparticles with narrow-size distribution were exclusively synthesized to produce in the 1.6-8.0 nm range following a polyl reduction method prior to immobilization on the support materials. These size-controlled nanoparticles were supported on three different solids: CeZrO₂, ZrO₂, and CeO₂. Supports are well known not only to disperse the metal particles and provide stability at high temperatures but also to offer oxygen storage capacity and reducibility (CeO₂, CeZrO₂), which contribute to mitigating (or enhancing) coke formation.[8] It was also proposed that support acts to activate CO₂ to assist CO₂ reforming via so-called bifunctional mechanism. In this study, temperature programmed reduction (TPR), CO-diffuse reflectance infrared Fourier transformed spectroscopy (DRIFTS), and transmission electron microscope (TEM) were used to characterize the reducibility of the supported Rh particles, surface...
metal/oxide interactions, and particle size distribution and dispersion. Raman spectroscopy, as well as temperature programmed oxidation (TPO) have been used to identify the structure of deposited coke. Our results demonstrate that nanoparticle size plays a major role in defining catalyst productivity, stability, and coke formation rates.

Results and Discussion

Catalyst synthesis and characterization
Rh nanoparticles were synthesized in ethylene glycol using PVP as an organic stabilizer. The average particle size changed between 1.6 to 8.0 nm upon changing the pH, as shown in Figure S1d and in line with the previous reports. Along with a change in particle size between 1.6 and 8.0 nm, a change in shape/morphology could also be observed (Figure S1c), from spherical for the smallest particles to cuboctahedron, octahedron, and finally, tetrahedron morphologies as particle size increased.

In addition to the size, the shape of the nanoparticle is also important. The BET surface areas of the calcined supports, CeZrO$_2$, ZrO$_2$, and CeO$_2$ were 31, 10, and 22 m$^2$ g$^{-1}$, respectively, in good agreement with the literature. XRF (Figure S1) was measured on all supports to confirm the absence of impurities that may affect catalytic performance.

The Rh nanoparticles were immobilized on the three different supports with loadings varying between 0.06 to 0.25 wt. % (Table 1). High-resolution TEM of the reduced catalysts reveals a good particle dispersion and the original nanoparticle size was preserved, but the unique morphology of pristine nanoparticle (Figure S1) was lost, resulting in hemispherical shape on the supports (Figure 1).

![Figure 1. HR-TEM images of reduced catalysts and corresponding histogram frequency. a. Rh/CeZrO$_2$ (~1.6 nm), and b. Rh/CeO$_2$ (~4.7 nm).](image)

![Figure 2. H$_2$-TPR profile of calcined (CeZrO$_2$, ZrO$_2$, and CeO$_2$) support and for the 4.7 nm Rh supported catalysts.](image)
amount of edge sites (band at 2094 cm⁻¹) increases upon increasing particle size.\[16\]

![Graph showing DRIFTS spectra of adsorbed CO at 35 °C over Rh/CeZrO₂, Rh/ZrO₂, and Rh/CeO₂ catalysts.](image)

Additional infrared bands were observed over the 2.5 and 8 nm Rh/ZrO₂ catalyst at 1840 and 1927 cm⁻¹, which are associated with bridge-bonded CO [CO(b)]. The infrared peaks related to bridge-bonded CO start to appear at lower coverages than those at 2027 and 2095 cm⁻¹ and shift to higher wavenumbers as coverage increases. The fact that bridge CO adsorption is only visible for ZrO₂ supported samples indicates the presence of much stronger metal-support interactions. In the same line, CO DRIFT profiles at varying temperatures (Figure 4S) show a different degree of interaction upon changing support, indicating a stronger interaction for the ZrO₂ based catalysts.

CeZrO₂, ZrO₂, and CeO₂ are commonly used supports for Rh. Rhodium can interact with ceria and zirconia results in the formation of Rh-O-Ce and Rh-O-Zr surface species, especially under oxidizing conditions.\[17\] These strong interactions do not only prevent sintering of the active metal but also affect its intrinsic catalytic activity.\[18\] Therefore, turnover frequencies calculated on the basis of available surface Rh atoms should be interpreted with care.

**Propane dry reforming**

Figure 4 compares turnover frequency (TOF) of a wide range of Rh nanoparticle sizes on different supports. Reactivity as a function of particle size can be classified into three different groups: (i) structure insensitive reactions, (ii) π-bond structure sensitivity when TOF increases with particle size, and (iii) σ-bond structure sensitivity when smaller particles are more active than larger ones.\[5a, 6\]

In general, reforming reactions are structure sensitive.\[19\] This is also the case for Rh: where the TOF increases upon increasing particle size from 1.8 to 8.0 nm. Catalyst TOFs are almost linearly related to the Rh nanoparticle size, independently of the support used. However, the surface atom reaction rate decreased with Rh dispersion. Although these results are not totally in agreement with some literature data,\[19\] according to Weckhuysen et al., an increase in TOFs with increasing particle size is considered to be a reasonable observation.\[8\] Reforming reactions involve the cleavage of both σ-bonds and π-bonds. These take place on edge and terrace sites; therefore, a combination of both is necessary, with CH₄ activation taking place at edge and CO₂ activation at terrace sites.\[5a, 6, 20\]

![Graph showing DRIFTS spectra of adsorbed CO at 35 °C over Rh/CeZrO₂, Rh/ZrO₂, and Rh/CeO₂ catalysts.](image)

The zirconia supported catalysts show relatively lower TOFs. These surface activities could be a result of low surface area compared to the other supports, along with a lower concentration of oxygen vacancies in bare zirconia\[21\] and to the stronger metal-support interactions discussed above. On the other hand, the ceria-supported catalyst could enhance the catalytic performance due to the ability of cerium to alternate between Ce³⁺ and Ce⁴⁺. A dual mechanism appears to arise on ceria-containing catalysts through coupling a surface redox process (surface oxygen exchange) and a reverse-splittor of bulk oxygen species.\[22\]

Then, the reducible CeO₂ support could be accountable for promoting the O⁺-assisted activation (OA) pathway (CH₄⁺ + O⁺ → CH₃⁺ + OH⁺) for alkane activation over the Rh/CeO₂.\[23\]
Methane dry reforming

In the case of methane dry reforming, the obtained results show a substantial difference in activities over different supports and particle sizes. As illustrated in Figure 5, the Rh/CeZrO$_2$ and Rh/CeO$_2$ catalysts display a nearly linear correlation between TOF and nanoparticle size. In contrast, in the case of Rh/ZrO$_2$, no clear trend can be extracted.

In case of methane reforming, we found that the support plays a bigger role. ZrO$_2$-supported catalysts seem to be structure insensitive. CO DRIFTS (vide supra) showed the occurrence of CO bridge adsorption on the surface of ZrO$_2$ supported catalysts with Rh particle sizes over 2.4 nm. This strong CO affinity may be responsible for the decreased surface activity of these catalysts. In addition, ZrO$_2$ promotes the formation of oxygen vacancies on the catalyst surface that lead to the presence of a larger number of uncoordinated metal atoms. CeO$_2$, on the other hand, is known for its high oxygen storage capacity, which may facilitate the gasification/oxidation of coke. The synergy between ZrO$_2$ and CeO$_2$ in the mixed oxide results in an enhancement in catalytic activity, as shown in Figure 5. We attribute this to a better dispersion of Rh on the binary oxide derived from a higher surface area along with the higher oxygen storage capacity of Ce containing supports.

On the nature of coke species

Carbon formation/deposition during reforming reactions constitutes a significant challenge. Side processes such as (i) methane/propane decomposition, and (ii) Boudouard reaction mainly contribute to the formation of carbon deposits. Noble metals, i.e., Rh, are known for low carbon deposition rates under reforming reactions, and the carbon formed differs in nature from that found with, i.e., Ni based catalysts.

The dry reforming of propane is highly endothermic ($\Delta H^{298 K} = 621.3$ kJ/mol) and more complex: on one hand, the cleavage of a C-H bond in C$_3$H$_8$ is easier than in CH$_4$. Herein, we found that CO$_2$ reforming of propane over Rh catalysts is highly structure sensitive and considerably depended on the Rh nanoparticle size, in good agreement with the literature. However, the structure sensitivity in methane dry reforming is less pronounced than for propane. This may be the consequence of C-C bond dissociation being the rate-limiting step in the case of propane reforming in contrast to C-H dissociation for methane.

In fact, the activation of CO$_2$ under dry reforming conditions is known to not being the rate-limiting step. Indeed, in all cases reported here, CO$_2$ conversion is higher than that of CH$_4$. Furthermore, it has been reported that the turnover rate of CH$_4$ is proportional to CH$_4$ pressure but not to CO$_2$, CO or H$_2$ concentration.

Last but not least, even though metallic Rh$_0$ has been identified as the most active site in reforming reactions, the presence of surface oxygen vacancies in the selected supports further enhances catalytic activity by facilitating CO$_2$ dissociation.

Temperature-programmed oxidation profiles are shown in Figure 6, for the spent catalysts after 420 minutes of propane/methane dry reforming at 575°C (Figure S7). The TPO profiles reveal that carbon deposition was strongly dependent on the nature of the supports. In general, TPO profiles show three peaks, one at around 100°C ascribed to reactive superficial carbide species, a significant peak at 300°C, and a smaller peak at 500°C, which can be attributed to coke precursors or strongly adsorbed hydrocarbons and disordered carbon species, i.e., amorphous carbon, respectively. There is no peak in the high-temperature region, i.e., 600°C, which is attributed to carbon whiskers.

The carbon deposits during dry reforming of propane/methane over ZrO$_2$-supported catalysts leading to a low-intensity peak at low temperatures region, i.e., 100°C, compared to the CeO$_2$-supported catalysts, which contain mainly reactive superficial carbide species. This behavior could be a result of the enhancement of oxygen vacancy and mobility, leading to removal of carbon species on the ZrO$_2$ surface through lattice oxygen.
Furthermore, selected spent catalysts (2.8 nm Rh-supported catalysts) after 420 min of propane dry reforming at 575 °C were analyzed by Raman spectroscopy. The Raman spectra reveal that carbon deposition has characteristic D and/or G bands of carbon (at 1250–1350 cm⁻¹ and 1500–1700 cm⁻¹, respectively), as shown in Figure S5. In agreement with the TPO profiles, D band appears in all the supported catalysts associated with disordered carbon species, i.e., amorphous carbon; with only the ZrO₂-supported catalyst showing the presence of graphitic carbon [39].

The carbon deposition by Rh surface (μmolc/molRh surface) during propane/methane dry reforming displays a clear nanoparticle size-dependency. As illustrated in Figure 7, it shows a linear correlation between the carbon deposition by Rh surface and nanoparticle size. During propane dry reforming reaction, this particle size dependence is more substantial than methane dry reforming, whereas a slight maximum particle size dependence was observed over CeZrO₂-supported catalysts. This behavior confirms, in spite of the very small amounts of coke formed in almost every case, the structure sensitivity of carbon deposition with Rh nanoparticles size [6, 32].

Figure 7. Carbon formation under propane (left) and methane (right) dry reforming normalized by surface Rh.

Figure S6 shows the carbon deposition by Rh loading (μmolc/molRh total) during propane/methane dry reforming as a function of Rh particle sizes. The normalized carbon deposition displays a flat linear correlation with the Rh nanoparticle size, but during propane dry reforming ZrO₂-supported catalysts, carbon depositions slightly decrease as the particles increases. In the case of methane dry reforming, CeZrO₂-supported catalysts carbon depositions slightly increase as the particles increases.

Conclusion

The present study demonstrates the structure sensitivity of reforming reactions carried out over Rh nanoparticles and the non-negligible influence of support redox properties on catalytic performance. A clear linear correlation between surface activity and nanoparticle size could be observed for both propane and methane dry reforming over Rh supported catalysts (except for those supported on ZrO₂ during dry reforming). Reforming reactions involve cleavage of σ-bonds (from the paraffin and CO₂) and π-bonds (from CO₂). Even though σ-bond activation takes place on edge sites and this would suggest a higher activity for smaller nanoparticles, the activation of CO₂ requires the presence of step edges and terraces, only present in bigger nanoparticles. In the same line, supports with a high density of mobile lattice oxygen species such as CeO₂ further promote CO₂ activation, contributing to a higher overall activity. Last but not least, the nature of the support (specially its redox properties) further contributes to defining the nature of coke species and may affect the activity of the metal active phase.

Experimental Section

Materials

All chemicals were purchased from Sigma-Aldrich and used as received unless otherwise stated.

Synthesis of Rhodium Nanoparticles

Rh nanoparticles (NPs) were synthesized by the polyol reduction method and prepared by refluxing an ethylene glycol (EG) solution of Na₃RhCl₆ and Polyvinylpyrrolidone polymer (PVP) under a nitrogen atmosphere [39]. To achieve different particle size distributions, the pH of the synthesis mixture was adjusted in the range of 0.5 to 12.5. The pH of the solution with Rh precursor mixed with a PVP-EG solution was 1.5. NaOH was added to achieve higher pH. For more details, 0.33 g of Na₃RhCl₆ (0.85 mmol) was added to a 250 mL three-necked flask containing a PVP solution dissolved in EG (2.5 g in 150 mL). A required amount (1 M) of sodium hydroxide (NaOH) aq. was added into the flask to increase the pH of the solution when desired to control the Rh particle size. After stirring for several minutes, the solution was refluxed at 160 °C for three hours under an N₂ atmosphere. The change of the solution color from dark red into black indicates the completion of the reduction. The solution was washed in acetone, then redispersed in ethanol (250 mL). The ethanol solution of the Rh NPs was used for the deposition process (vide infra).

Deposition of Rh NPs on supports

Supports are well known not only to disperse the metal particles and provide stability at high temperatures but also to offer oxygen storage capacity (CeO₂, CeZrO₂) and reducibility (CeO₂ and ZrO₂), which contribute to mitigating (or enhancing) coke formation [8]. Prior to immobilization of metal particles, three different supports, CeZrO₂, ZrO₂, and CeO₂ were calcined at 850 °C for 20 h (temperature ramp 5 °C min⁻¹). A (0.2 wt. %) ethanol solution containing the desired amount of Rh NPs was impregnated in 2.0 g of the calcined support suspended in 100 mL of H₂O. The solution was stirred overnight for 16 h, then centrifuged and washed with excess water. The obtained samples (see Table 1) were calcined in a muffle furnace under static air at 600 °C for 5 h using a ramp rate of 10 °C min⁻¹.

Table 1. Composition of the synthesized Rh-based catalysts over CeZrO₂, ZrO₂, and CeO₂ supports.

<table>
<thead>
<tr>
<th>Size (nm)</th>
<th>Rh wt.%</th>
<th>Size (nm)</th>
<th>Rh wt.%</th>
<th>Size (nm)</th>
<th>Rh wt.%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6</td>
<td>0.23</td>
<td>1.6</td>
<td>0.12</td>
<td>1.6</td>
<td>0.06</td>
</tr>
<tr>
<td>1.8</td>
<td>0.25</td>
<td>1.8</td>
<td>0.22</td>
<td>1.8</td>
<td>0.25</td>
</tr>
<tr>
<td>2.8</td>
<td>0.24</td>
<td>2.8</td>
<td>0.22</td>
<td>2.8</td>
<td>0.25</td>
</tr>
<tr>
<td>4.7</td>
<td>0.14</td>
<td>4.7</td>
<td>0.15</td>
<td>4.7</td>
<td>0.22</td>
</tr>
</tbody>
</table>
Characterization methods
Powder X-ray diffraction (PXRD) patterns were acquired on a Bruker D8 Advance operated at 40 kV and 40 mA using Cu Ka (λ = 1.5418 Å) radiation typically applying a scan speed of 0.5 s per step, and a step size of 0.1° acquisition from 5 to 90° 2θ range.

Nitrogen (N2) adsorption experiments were carried out at 77 K using Micromeritics ASAP 2420 instruments. Before the measurement, the composite sample was degassed at 350 °C for 8 h under reduced pressure. From the obtained isotherms, the specific surface area was calculated using the BET equation (SBET), and the external surface (Sext) and micropore volume (Vmirc) were calculated by the t-plot method.

Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) was performed to measure the exact metal content using a 5100 ICP-OES instruments (Agilent) under Ar atmosphere and an SPS 4 Autosampler (Agilent). Digestion was done at 240 °C and 35 bar on an UltraWAVE apparatus (Milestone) using a mixture of acids prepared in the following volume ratio 6:2:1 of hydrochloric (HCl), nitric (HNO3), and hydrofluoric acid (HF) for all samples. A new calibration curve (four plots) was used for each set, and all samples were duplicated except the buffer sample. Moreover, Laboratory Reagent Blank (LRB), Laboratory Fortified Blank (LFB), Quality Control Sample (QCS), and Continuing Calibration Verification (CCV) samples were recorded to validate the results as recommended in several standards methods.

Transmission electron microscopy (TEM) and scanning transmission electron microscopy (STEM) was performed on a TITAN ST (for STEM) and a TITAN CT (FEI Company); operated at 300 kV and 120 kV, respectively, were used for imaging. The TEM and STEM were used to study the structure and morphology of the nanoparticles and obtain the Rh particle size distribution.

X-ray fluorescence (XRF) measurements were obtained in a HORIBA XGT-700. For every measurement, different spots were analyzed for each support calcined used in the synthesis of the catalysts.

CO / CO2 DRIFTS measurements were acquired using a Thermo Scientific Nicolet 6700 FT-IR spectrometer with a mercury cadmium telluride (MCT) detector and a Harrick Praying Mantis diffuse reflectance accessory. The optical velocity was set to 0.63, and the aperture was set to 64. The samples were placed in a Harrick High-Temperature Reaction Chamber with ZnSe windows. The cell was first flushed with argon and then heated at 250 °C for one hour to remove moisture, followed by 5% H2 treatment at a flow rate of 5 mL min⁻¹ before introducing 10% CO or CO2 gas at a flow rate of 5 mL min⁻¹.

Temperature programmed reduction (TPR) was performed on a modified GC (Shimadzu GC-8A). 20 mg of sample was placed in the U-shaped quartz reactor between two layers of quartz wool. Following, 50 mL min⁻¹ of He flow was introduced for 15 min. Then, the flow was changed to 50 mL min⁻¹ of 10% H2 in Ar. The sample was afterward heated with 5 °C per minute temperature rate until 800 °C. An analysis of exhaust gases was performed on a TCD.

Temperature programmed oxidation (TPO) was performed using a modified GC (Shimadzu GC-8A). For the coke combustion step, the temperature was increased up to 800 °C using a heating ramp of 5 °C min⁻¹ under 1% O2/He flow of 50 mL min⁻¹ and kept at 800 °C for 30 minutes to ensure the total coke combustion. TPO analyses were carried out by circulating the gases from the reactor outlet to a methanation reactor, where CO and CO2 were converted into CH4. Then, CH4 was continuously measured by an FID detector. Typically, 10 mg of coked catalysts were loaded into the analysis cell. The equipment was calibrated by pulsing CO diluted in Ar.

Raman spectroscopy was recorded using a LabRAM Aramis microscope (HORIBA). Three lasers (473 nm (Cobolt), 633 nm (Melles-Griot), and 785 nm (Sacher Laserotechnik)) at an incident power of 2 mW (as measured by a Coherent Laserscheck power meter) were used. The spot size of the system was 1 μm².

Catalytic tests
Methane dry reforming (MDR) was carried out using a Microactivity Reference unit (PID Eng&Tech) at 575 °C and atmospheric pressure. The catalyst was placed in a tubular quartz reactor with an inner diameter of 6 mm using 20 mg of catalysts between two layers of quartz wool in fixed-bed mode at atmospheric pressure. Gas detection for H2, CO, CO2, Ar, and light hydrocarbons was conducted using an Agilent technologies 3000A Micro GC. The catalysts were pretreated by flowing 10 % H2 in Ar with 100 mL min⁻¹ flow at 625 °C for 90 min with a ramping rate of 10 °C min⁻¹. The catalyst was then treated in 10 % CH4, 10 % CO2, 80 % Ar with a 100 mL min⁻¹ flow. This flow was maintained for 7 hours to evaluate the catalytic performance and stability.

Propane dry reforming (PDR) was carried out over different catalyst samples using a Microactivity Reference unit (PID Eng&Tech) at 575 °C and ambient pressure. The catalyst was placed in a tubular quartz reactor with an inner diameter of 6 mm, using 30 mg of catalysts between two layers of quartz wool in fixed-bed mode at atmospheric pressure. Gas detection for H2, CO, CO2, Ar, and light hydrocarbons was conducted using an Agilent technologies 3000A Micro GC. The catalysts were pretreated by flowing 10 % H2 in Ar with 100 mL min⁻¹ flow at 625 °C for 90 min with a ramping rate of 10 °C min⁻¹. The catalyst was then treated in 10 % C3H8, 30 % CO2, 60 % Ar with a 100 mL min⁻¹ flow. This flow was maintained for 7 h to evaluate the catalytic performance and stability.

The turnover frequency (TOF) is defined as the methane/propane consumption rate per the number of exposed surface Rh atoms on each catalyst per unit time. In this study, the active site is based on each Rh atom on the outer surface of the Rh particles. TOF was calculated by normalizing conversion with the loading amount of active metals for each catalyst. TOF calculation of Rh-supported catalysts is summarized as follow:

- The Rh metal particles diameter (d) were determined using imaging software using TEM images.
- The Rh particles are assumed to be hemispherical.
- Rh TEM-Dispersions (D) = moles/molecule/mass surface (7)
- TOF (s⁻¹) = Xmethane/propane / Fmethane/propane / D Rh (8)

This article is protected by copyright. All rights reserved.
Acknowledgements

The authors acknowledge Saudi Aramco for financial support.

The authors acknowledge Prof. Takanabe, University of Tokyo, for fruitful discussions.

Keywords: Rhodium • Nanoparticles • dry reforming • methane • propane

Conflict of Interest

The authors declare no conflict of interest.

[References]

The influence of Rh particle size supported on three different solids: CeZrO$_2$, ZrO$_2$, and CeO$_2$ were explored on the reforming of propane and methane. Catalytic turnover rates along with advanced characterization of fresh and spent catalysts reveal a linear correlation of turnover rates with Rh particle size for both methane and propane reforming. The nature and speed of coke deposition are highly dependent on the support used and its interaction with the metallic phase.

Institute and/or researcher Twitter usernames:

Prof. J. Gascon (@jorgascon)

M. Alabdullah (@Mo7ammad1990)

KAUST Catalysis Center (KCC) (@KCCkaust)

King Abdullah University of Science and Technology (@KAUST_News)