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Single-step catalytic liquid-phase hydroconversion of DCPD into high energy density fuel *exo*-THDCPD[†]

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Hydroconversion of dicyclopentadiene (DCPD) into high energy density jet propellant JP-10 has been successfully achieved with a greener single-step route over supported gold catalyst. The physicochemical properties of the catalysts were studied with XRD, SEM, TEM, N₂-adsorption, NH₃-TPD. The influence of reaction conditions like temperature, pressure, time *etc.* were studied in detail. The studies reveal that pressure and temperature play crucial roles in the reaction. Moderate acid sites in the catalysts are chiefly involved in isomerization and gold catalyzes hydrogenation of the intermediates. Analysis of the product stream at different intervals indicates a dissociation–recombination mechanism for the reaction. Reusability of the catalyst was tested by conducting five runs with the same catalyst. Even after the fifth run, the catalyst retains relatively high conversion and selectivity to *exo*-tetrahydrodicyclopentadiene (*exo*-THDCPD).

1. Introduction

Cyclopentadiene and its derivative dicyclopentadiene (DCPD) with highly active norborane and cyclopentadiene units are the byproducts of pyrolysis of petroleum feedstocks.¹⁻³ It has two isomers, endo-dicyclopentadiene and exo-dicyclopentadiene. Most of the chemical and physical properties of these isomers are similar.⁴ Since space is limited in most aircraft, the amount of energy contained in a fuel is very important. Due to the strained cyclic structure the hydride of exo-DCPD, i.e. exo-tetrahydrodicyclopentadiene (exo-THDCPD), has a high energy density.^{5,6} Due to the high volumetric energy content (39.6 MJ L^{-1}), flash point (55 °C) and low freezing point (-79 °C), it is widely used as the main component of JP-10 fuel. JP-10 fuel contains 98.5% exo-THDCPD and the remainder is endo-THDCPD, and it provides much more propulsion energy than conventional distilled fuels.^{7–9} When high energy density fuels are used, it requires a smaller fuel tank, leaving more space for electronics and other components of the aircraft.¹⁰ Low freezing point, low viscosity, suitable flash point, high density and long term storage stability makes exo-THDCPD a suitable JP-10 fuel.^{11,12} exo-THDCPD is also additionally used in other fuel mixtures like JP-9, RF-1, RJ-5, etc.¹³ Moreover the chemical and physical properties of exo and endo isomers are similar, so the low percentage of endo-THDCPD does not affect the fuel properties adversely. But endo-THDCPD has a much higher freezing point (80 °C) than its exo isomer so it cannot be used directly in JP-10 fuel and needs to be isomerized.

Due to the easy availability and low cost of raw materials, jet propellant JP-10 has high importance in the next generation of advanced aircraft. Currently it is synthesized by the hydrogenation of dicyclopentadiene over palladium on alumina/carbon catalyst, or nickel on alumina catalyst, 14-17 and followed by the isomerization of hydrogenated product, endo-THDCPD, over strong acid catalysts.¹⁸⁻²¹ Hydrogenation is very important because the presence of unsaturated compounds leads to coke deposition on acidic sites and causes catalyst deactivation and it also affects the smoke point of the fuel. Generally hydrogenation proceeds at relatively milder conditions and presents both conversion and selectivity issues, and significant increase in temperature can be observed due to the exothermicity of the reaction. Complete hydrogenation of DCPD requires a high temperature which unfortunately leads to a decreased yield due to cracking of DCPD. Earlier studies revealed that strong acids like sulfuric acid or aluminium chloride can be very effectively used as catalysts for isomerization of endo-THDCPD to exo-THDCPD. But strong acidity of these catalysts causes many problems like low exo selectivity, formation of deposits, environmental problems like corrosion and, most importantly, a high amount of sodium hydroxide aqueous solution is used for the separation of products.²² Another disadvantage of using these catalysts is poor recyclability. Xing et al. reported a greener synthetic route for the production of exo-THDCPD from endo-THDCPD over acidic zeolites.²³ But due to the high deactivation rate of the catalysts, it is not an attractive route. Dzhemilev et al. reported Pd (acac)₂ as a good catalyst with 99.5% of exo-THDCPD, but its high cost limits its use at industrial scale.²⁴ Sun and Li recently reported a vapour phase isomerization of endo-THDCPD to exo isomer over zeolite catalysts.²⁵ But the use of a high amount of carrier gas with a low amount of endo-THDCPD and the high deactivation rate of catalysts were not suitable for industrial

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Scheme 1 Existing reaction pathway of synthesis of *exo*-THDCPD from *endo*-DCPD.

application. Therefore even today aluminium chloride is used as a catalyst for isomerization of *endo*-THDCPD. The existing route for the production of *exo*-THDCPD is shown in Scheme 1.

From the economical point of view, single-step processes are cost effective. Herein, we report the greener catalytic single-step liquid-phase synthesis of *exo*-THDCPD from DCPD over gold supported on silica–alumina. There is no published literature for the direct single-step synthesis of *exo*-THDCPD from DCPD by either homogeneous or heterogeneous routes. To the best of our knowledge, this is the first attempt for environmentally friendly cost-effective preparation of high energy density jet propellant JP-10.

2. Experimental

2.1. Materials

DCPD with a purity of 99% was purchased from Acros; analytical grade toluene, methanol and n-hexane were obtained from SD-Fine Chemicals, India. Reference *endo*-THDCPD was synthesized with the reported procedure^{14–17} from DCPD, then distilled and purified followed by confirmation of the physiochemical properties of the material with various analytical tools. The commercial *exo* isomer was used as a reference. Aurochloric acid was purchased from Merck. The support material mesoporous SiO₂-Al₂O₃ was obtained from Sasol with a silica/alumina ratio of 3 : 7 and used after calcination at 300 °C for five hours.

2.2. Synthesis of catalyst

Synthesis of the supported gold catalyst was carried out by the modified method of Sinha et al.²⁶ by deposition precipitation method (DP) and it was reduced with sodium borohydride. In a typical synthesis 1.5 wt% of gold precursor is stirred with 100 ml double-distilled water at 70 °C for one hour. Then the pH of the solution is maintained by adding NaOH solution. After reaching pH 7.5, 2 ml freshly prepared 0.1 molar sodium borohydride was added dropwise to reduce the gold. The colour of the solution is quickly changed from orange to wine red which indicates complete reduction to gold nanoparticles. The whole of the solution was stirred vigorously with the appropriate amount of support for two hours. After completion of reaction the precipitate was filtered and washed with distilled water until chloride-free and then dried over night at 100 °C. The catalyst was calcined at 300 °C for 8 hours at a rate of 1 °C per minute before use for catalytic evaluations.

2.3. Characterization of the catalyst

The physicochemical properties of the catalyst and support were characterized by X-ray diffraction (XRD), scanning electron

microscopy (SEM), and temperature programmed reduction (TPR) etc. X-Ray diffraction patterns were obtained using Cu Ka radiation (40 kV and 40 mA, Advanced Bruker D8 diffractometer). The SEM images were realized by field emission scanning electron microscope, FEI Quanta 200 F, using a tungsten filament doped with lanthanum hexaboride (LaB₆) as an X-ray source, fitted with an ETD detector with high vacuum mode using secondary electrons and an acceleration tension of 10 or 30 kV. Catalysts were analyzed by spreading them on a carbon tape. Energy-dispersive X-ray spectroscopy (EDX) was used in connection with SEM for elemental analysis. The elemental mapping was conducted with the same spectrometer. The TEM images and SAED patterns were taken on a Hitachi H7100 electron microscope operated at 75 kV. The porous properties of metal-loaded catalysts were examined by N2 adsorptiondesorption isotherms at 77 K (BelsorbMax, BEL, Japan) and the related data (surface area, S_{BET} ; pore volume, V_{T} ; pore diameter) were calculated. The amount and strength of the acid sites were measured by ammonia adsorption-desorption technique using a chemical adsorption instrument, Micrometrics 2900, with a thermal conductivity detector. About 0.20 g sample was saturated with NH₃ at 120 °C, then flushed with helium to remove the physically adsorbed NH₃, finally the desorption of NH₃ was carried out at a heating rate of 10 °C min⁻¹ in helium flow.

2.4. Hydrogenation and isomerization reaction

Gold and palladium deposited with different wt% loadings on mesoporous silica–alumina were used as the catalysts for the reaction. We studied the effects of temperature and pressure in the range from 50–140 °C and 10–40 bar respectively. Reusability of the catalysts were checked with repeated reactions on the same catalyst without any further activation against calcination, coke removal *etc.* Only multiple washing with solvent was used to clean the catalyst, followed by drying at 120 °C overnight.

Hydrogenation and isomerization reactions were conducted in batch mode, in a 500 ml stainless steel autoclave (Autoclave engineers) at various temperature and pressure. The reactor was equipped with a magnetically driven stirrer, a dip tube, and an internal water cooling system. The temperature was controlled by programmable PID controller. Reactant, catalyst and solvent were placed inside the reactor and sealed, then the system was purged with hydrogen three times to remove air. The whole system was pressurized to 3 bar, and heating was started with 200 rpm stirring speed. When the system achieved the desired temperature it was pressurized to the required pressure. The hydrogen pressure, temperature and stirring were constant throughout the reaction. Aliquots were withdrawn at equal intervals through the special sampling port attached within the reactor. The tiny catalyst particles were separated by filtration and the product was analyzed by Varian CP 3800 gas chromatograph with VF-5ht-Ultimetal 30×0.25 (0.10) column. At the end of the reaction the reactor was allowed to cool down to room temperature and the catalysts were separated by filtration. The products were selectively distilled and were used for testing of various specific propellant properties. Density of the product is analyzed with DMA 4500 M Anton Parr density meter.

3. Results and discussion

3.1. Characterization of catalyst

Typical XRD patterns of the support material, catalyst and the used catalyst are shown in Fig. 1. The used and fresh catalysts show weak and broad [111] and [200] peaks due to Au particles. The porous properties of the catalysts were studied by N₂ adsorption–desorption isotherms at 77 K. The adsorption–desorption isotherms at 77 K. The adsorption–desorption isotherms and the pore size distribution curves are shown in Fig. 2 and 3 respectively. The other physicochemical properties of the catalysts are listed in Table 1. From these results it can be seen that the support material and catalysts shows type IV isotherm with H₁-type hysteresis loop at a p/p_0 of 0.6–0.9 and large mesopores with narrow pore size distribution. The pore size distributions were calculated from the adsorption isotherm, using



Fig. 1 Wide angle X-ray diffraction pattern of catalyst (a) Au/SiO_2 - Al_2O_3 , (b) used Au/SiO_2 - Al_2O_3 .

BJH method, and are shown in Fig. 3. From these results it is clear that impregnation of gold and repeated reaction of the catalyst has no change in the nature of the isotherm, *i.e.* support pore structure is sustained with impregnation and high temperature reactions. But Table 1 indicates a change in physical properties like surface area, total pore volume, mean pore diameter. The differences in surface area and total pore volume of the support and catalysts indicate the presence of gold deposited inside the pores. The differences between the used catalysts with fresh catalyst indicate the presence of coke inside the catalyst. Since gold is deposited inside and outside the pores, the pore structure and size are very important. The presence of large pores in the support material is suitable for the diffusion of reactant and



Fig. 2 N₂-adsorption desorption curve of support and catalyst (a) $SiO_2-Al_2O_3$, (b) Au/SiO_2-Al_2O_3, (c) used Au/SiO_2-Al_2O_3.



Fig. 3 Pore size distribution of catalyst and support (a) SiO₂-Al₂O₃, (b) Au/SiO₂-Al₂O₃, (c) used Au/SiO₂-Al₂O₃.

product because the size of the *exo* and *endo* THDCPD is high, *i.e.*, with a critical dimension of 0.67 nm \times 0.60 nm and a kinetic diameters σ 0.60 \times 0.53 nm.¹⁷

The morphologies of the synthesized catalysts were examined by scanning electron microscope. A representative SEM image of the catalyst is shown in Fig. 4. Au dispersion on the support was confirmed with the EDX analysis. The elemental mapping of the catalyst reveals a homogeneous distribution of Au on the silica–alumina support surface (Fig. 5). The dispersion and size of gold on the support material were analyzed by TEM and are shown in Fig. 6 (the corresponding SAED is shown in the ESI†). From the figure it is clear that the <10 nm size particles with average particle size of 3-6 nm are dispersed throughout the support. The SAED patterns from the fine nanoparticles exhibit diffuse rings.

Table 1 Physic	cochemical pro	perties of	catalyst
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S. No	Catalysts	Surface area $(m^2 g^{-1})$	Total pore volume $(cm^3 g^{-1})$	Mean pore diameter (nm)	Surface acidity NH ₃ (mmol g ⁻¹)
1	SiO ₂ -Al ₂ O ₃	232	0.827	14.19	0.65
2	Au/SiO ₂ -Al ₂ O ₃	203	0.723	14.19	0.79
3	Au/SiO ₂ -Al ₂ O ₃ ^a	197.3	0.470	9.5	0.57

^a Catalysts after 5th reaction run.

Adsorption of NH_3 was used to determine the acidity of the catalysts. It provides the total acidity (Table 1) and strength of the acid sites. Fig. 7 shows the NH_3 -TPD curves of the catalysts calcined at 300 °C. Both strong and weak acid sites were present in the support and fresh catalyst. But there is a decrease in both strong and weak acid sites in the used catalyst, which may be one of the reasons for the decrease in the catalyst activity, as discussed later.



Fig. 4 SEM image of the catalyst Au/SiO₂-Al₂O₃.



Fig. 5 Elemental mapping of the catalyst (a) silica (b) alumina (c) gold.



Fig. 6 TEM images of the fresh (left) and used (right) catalysts.



Fig. 7 NH₃–TPD curves of (a) $SiO_2-Al_2O_3$, (b) Au–SiO₂–Al₂O₃, (c) used Au/SiO₂–Al₂O₃.

3.2. Hydrogenation and isomerization of DCPD to *exo*-THDCPD (JP-10) over Au/SiO₂-Al₂O₃ catalysts

Hydrogenation and isomerization of DCPD is a multiphase catalytic reaction over gold catalysts. Literature reports that the synthesis of JP-10 involves two steps: (1) hydrogenation of DCPD in to endo-THDCPD on a hydrogenation catalyst and (2) isomerization of endo product into exo-THDCPD over acidic catalyst.¹⁸⁻²¹ This process is economically less favorable and environmentally not friendly. Bifunctional catalysts with strong acid sites and hydrogenating metal are promising systems to overcome the drawbacks. In view of this, gold on silica-alumina catalyst could be a suitable solution. The relative strength of surface acidity and reducing ability of gold determine a new reaction pathway with high selectivity to exo-THDCPD. Based on our studies of changing various parameters with time, we concluded that the suitable reaction time is 6 hours with a temperature of 130 °C and a pressure of 30 bar (Fig. 8). It is clear from Fig. 8 that DCPD has very quickly cracked into two cyclopentadiene molecules within one hour and then slowly it converts selectively into exo-THDCPD on gold catalyst. After the reaction time the catalyst gives an exo selectivity of 93.54 with 5% endo-THDCPD. From the figure we can see that a steep decrease of CPD and corresponding increase of exo-THDCPD with a very slow increase of endo-THDCPD. Moreover, the yield of exo-THDCPD continuously increased with the reaction time and a yield of 94% is attained after six hours. These results prove that the supported gold catalyst is highly efficient and selective for the single step hydrogenation and isomerization of DCPD. Distillation of the reaction mixture produces 99% pure exo-THDCPD. The fuel properties like density and freezing point of the purified product were analyzed and it matched with those for pure exo-THDCPD.

3.3. Influence of reaction parameters

Conversion of DCPD (and its equilibrium monomer CPD) follows competing pathways leading to different products and the reaction conditions influence the selectivity. *endo*-THDCPD



Fig. 8 Percentage of composition of intermediate and products: (\blacksquare) DCPD, (\bullet) *endo*-THDCPD, (\blacktriangle) *exo*-THDCPD, (\blacktriangledown) CPD, (\blacklozenge) conversion, (\blacktriangleleft) selectivity, (\triangleright) yield (130 °C and 30 bar).



Fig. 9 Effect of pressure on reaction stream at 130 °C: (■) selectivity, (●) conversion.

forms faster (the kinetically controlled product) than exo-THDCPD (the thermodynamic product). The conditions of the reaction, such as temperature, time and pressure, control the favored reaction pathway, either the kinetically controlled or the thermodynamically controlled one. The influence of reaction parameters like temperature, pressure and time were systematically investigated to arrive at optimized conditions. The reaction pressure has a very high impact on conversion and selectivity. From Fig. 9 it can be seen that exo-THDCPD selectivity of the reaction shows a sudden increase from 20 bar pressure to 30 bar pressure. But conversion has not been much affected. Analysis of the reaction products at different intervals reveals that reaction pathway was directed by pressure. From Fig. 10 it is clear that at lower pressures initially (1 hour) the formation of endo-THDCPD was very high and presence of CPD is less. After 2 hours endo-THDCPD concentration decreased while CPD concentration increased. But a slight increase in endo-THDCPD is



Fig. 10 Percentage of composition of intermediate and products: (\blacksquare) DCPD, (\bullet) *endo*-THDCPD, (\blacktriangle) *exo*-THDCPD, (\blacktriangledown) CPD, (\blacklozenge) conversion, (\blacktriangleleft) selectivity, (\blacktriangleright) yield (130 °C and 15 bar).



Fig. 11 Percentage of composition of intermediate and products: (\blacksquare) DCPD, (\bullet) *endo*-THDCPD, (\blacktriangle) *exo*-THDCPD, (\blacktriangledown) CPD, (\blacklozenge) conversion, (\blacktriangleleft) selectivity, (\blacktriangleright) yield (130 °C and 20 bar).

again noted after three hours of the reaction indicating reversible conversion between CPD and *endo*-THDCPD. Here the highly reactive norborane bond is first hydrogenated followed by the hydrogenation of the second cyclopentyl ring, while the isomerization into *exo*-THDCPD is a much slower reaction and hence less favored at these conditions. Increasing the reaction pressure to 20 bar (Fig. 11), the formation of *endo*-THDCPD is suppressed. But at 40 bar pressure (Fig. 12) the presence of CPD was very high – this may be because at very high pressure CPD is more stabilized and has lower adsorption on the catalyst and hence is less reactive. Normally, at high pressure the rate of hydrogenation is very high and dissociation of molecules is much less. But due to the very slow heating rate of the reaction (1 °C min⁻¹, with 2–3 bar H₂) before the initiation of the



Fig. 12 Percentage of composition of intermediate and products: (\blacksquare) DCPD, (\bullet) *endo*-THDCPD, (\blacktriangle) *exo*-THDCPD, (\blacktriangledown) CPD, (\blacklozenge) conversion, (\blacktriangleleft) selectivity, (\blacktriangleright) yield (130 °C and 40 bar).

hydrogenation reaction most of the dicyclopentadiene molecules would dissociate and would be hydrogenated at high pressure by recombination and then isomerized to form *exo*-THDCPD. From these results it can be concluded that pressure plays a crucial role for the selective synthesis of *exo*-THDCPD from *endo*-DCPD on the bifunctional Au/silica–alumina catalyst.

The effect of temperature on the reaction stream is shown in Fig. 13. Conversion and selectivity of the reaction varies with temperature. At lower temperature the formation of *exo*-THDCPD was comparatively lower. But on increasing the temperature the formation of *exo*-THDCPD increases with an increase of cyclopentadiene concentration. This is an indication that at higher temperature the dissociation of DCPD is high but at lower temperature it is less.

Reaction time is another important parameter used in this study. All the studies give the information that the minimum time required for completion of the reaction was six hours. But within an hour, conversion of DCPD reaches maximum but the selectivity for *exo*-THDCPD is low. We carried out a number of reactions at temperatures greater than 150 °C and noted a loss of selectivity. It might be due to the formation of oligomers, *i.e.* the oligomerization of DCPD with CPD. From all these results it can be concluded that pressure plays a crucial role along with temperature and time.

3.4. Proposed reaction pathway and mechanism

The existing reaction pathway for the formation of *exo*-THDCPD is shown in Scheme 1. The norborane ring with lower bond strength and bond order is hydrogenated first and then the cyclopentadiene bond will be hydrogenated on the metal catalyst, followed by isomerization of the product with acid catalysts wherein the *endo*-norbornyl fragments of THDCPD are isomerized into *exo* configurations but the *endo* cyclopropyl fragments remain unchanged.²⁷ Here we discuss a reaction pathway which is similar to the synthesis of dicyclopentadiene from

cyclopentadiene.²⁸ The most plausible reaction pathway is shown in Scheme 2. The reaction is a dissociation-recombination, *i.e.* the dicyclopentadiene first dissociates into two cyclopentadiene molecules on the acid sites and redimerizes into exo-DCPD followed by rapid hydrogenation into thermodynamically stable exo-THDCPD on the gold surface. The work of Xang et al. on the isomerization of endo-DCPD to exo-DCPD also shows that this type of rearrangement is possible.²⁹ This assumption is proved by withdrawing samples at regular intervals, which reveals that within one hour nearly 97% of the DCPD is converted into 88% of cyclopentadiene and 5% exo-THDCPD (Fig. 7). After 6 hours reaction time nearly 99.5% of the CPD is converted to exo-THDCPD. It is also noted that the presence of endo-THDCPD is much less and slowly increases as the reaction progresses. This is a clear indication that the reaction selectively goes through our proposed pathway and not via the hydrogenated intermediate pathway. GC analysis also showed the absence of 3,4-DHDCPD and 8,9-DHDCPD in the reaction stream, but these intermediates are found in the reaction with palladium on silica-alumina catalyst. Zou et al. selectively produced endo-THDCPD through these intermediates and they have not reported the presence of exo-THDCPD.^{17,30} To clarify the reaction pathway we studied the reaction in the absence of hydrogen and confirmed the formation of exo-DCPD. It may be also

pointed out that it is reported in the literature too that *exo*-DCPD is formed when *endo*-DCPD is heated at elevated temperature and pressure in the absence of hydrogen for a prolonged period. A dissociation–recombination mechanism has been suggested to explain this phenomenon.²⁹

We also carried out a control experiment with cyclopentene under the same reaction conditions and we could not observe any partially hydrogenated intermediate, thus excluding the interaction of cyclopentene in the reaction mechanism.

3.5. Reusability of the catalyst

The successful recovery and reuse of the catalysts is an essential aspect of green chemistry. So, heterogeneous catalysts play a crucial role to produce an environmentally friendly chemical environment. In addition, multiple use and regeneration of the catalysts gives economical advantages. Hence we studied the life of the catalyst with multiple reaction runs. Reusability of the catalyst was tested with the same catalyst without any regeneration. Catalyst was repeatedly washed with toluene and dried overnight at 120 °C and used as such. The results obtained after reuse are given in Fig. 14. It clearly indicates that the selectivity to *exo*-THDCPD continuously decreases (with increase in CPD yield)





Fig. 13 Effect of temperature on reaction stream at 30 bar: (\blacksquare) *endo*-THDCPD, (\blacklozenge) CPD, (\bigstar) *exo*-THDCPD.

Fig. 14 Reusability of the catalyst upon selectivity and conversion: (\blacksquare) conversion, (\bullet) selectivity, (\blacktriangle) yield.



Scheme 2 Proposed single step reaction pathway of synthesis of *exo*-THDCPD from *endo*-DCPD.

but the conversion of DCPD decreases only slightly with repeated reactions. A detailed study of the used catalyst reveals that the main reason for the loss in activity is coke formation. From Table 1 we can see that there is a huge decrease in the pore diameter and pore volume of the used catalyst which is due to the deposition of coke in the pores of the support which not only restricts the transportation of the reactant and products but also blocks the active acid sites. NH₃-TPD analysis shows a decrease in the total acidity from fresh to used catalyst. ICP-AES analysis confirmed negligible loss of gold from the catalyst. Most zeolite catalysts lose their activity within hours⁴ due to coke deposition but deactivation is much less in our catalyst and it shows comparatively higher activity and selectivity. The deactivation of the catalyst with respect to the presence of coke was studied by TGA analysis and the results obtained are shown in the ESI.† A gradual increase in coke is observed after each cycle. TEM analysis of the fresh and used catalyst did not show any observable increase in the Au particle size (Fig. 6). More detailed studies on the activity of regenerated catalysts after coke removal is being done.

4. Conclusions

Gold supported on mesoporous silica-alumina was used to catalyze the hydrogenation and isomerization of dicyclopentadiene to high density jet propellent JP-10 (exo-THDCPD). The experimental results show that the catalyst is highly active and selective for the synthesis of JP-10. The presence of gold selectively produces exo-THDCPD on the moderately acidic support with nearly complete conversion. The operational parameters like temperature, pressure and time have considerable effect on the performance of the reaction. Detailed study of the reaction by varying various parameters confirmed that the suitable reaction condition is a temperature of 130 °C and at 30 bar pressure with a reaction time of six hours giving 99% conversion with highest selectivity. Based on the proposed mechanism, the formation of exo-THDCPD is a dissociation-recombination and this is confirmed from the analysis of the reaction products. The multiple reuse of the catalyst gives the information that the catalyst is reusable and comparatively tolerant to coke deposition.

It can be concluded that this catalyst could completely replace the existing liquid acid and AlCl₃ in the second step of synthesis of JP-10 to make the process environmentally friendly. In addition it may become more economical since the fuel is produced by a single step and the ease of separation makes it more promising for commercial production.

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