

<p><b>KLM Technology Group</b></p> <p>Practical Engineering Guidelines for Processing Plant Solutions</p>	 <p><b>Engineering Solutions</b></p> <p><b>Consulting, Guidelines and Training</b></p> <p><a href="http://www.klmtechgroup.com">www.klmtechgroup.com</a></p>	Page : 1 of 102
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<p>KLM Technology Group P. O. Box 281 Bandar Johor Bahru, 80000 Johor Bahru, Johor, West Malaysia</p>	<p><b>Kolmetz Handbook of Process Equipment Design</b></p> <p><b>CATALYST SYSTEMS AND PREPARATION</b></p> <p><b>(ENGINEERING DESIGN GUIDELINES)</b></p>	Co Author Rev 01 Apriliana Dwijayanti
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## INTRODUCTION

### Scope

More than 80% of the present industrial processes established since 1980 in the chemical, petrochemical, and biochemical industries, as well as in the production of polymers and in environmental protection, use catalysts. More than 15 international companies have specialized in the production of numerous catalysts applied in several industrial branches. In the chemical industry and industrial research, catalysis plays an important role. Different catalysts are in constant development to fulfill economic, political and environmental demands.

Catalysts speed up a chemical reaction by lowering the amount of energy you need to get the reaction started. Catalysis are the backbone of many industrial processes, which use chemical reactions to turn raw materials into useful products.

The goal of a catalyst manufacturer is to produce and reproduce a commercial product which can be used as a stable, active, and selective catalyst. The best preparative solution is sought which results in sufficiently high surface area, good porosity, and suitable mechanical strength.

A new and improved catalyst can be a huge advantage for a competitive manufacturing cost. It's extremely expensive for a company to shut down the plant because of an error in the catalyst, so the correct selection of a catalyst or a new improvement can be key to industrial success.

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## General Design Consideration

Catalysis is a phenomenon by which chemical reactions are accelerated by small quantities of reagent substances, called catalysts. A suitable catalyst can enhance the rate of a thermodynamically feasible reaction but cannot change the position of the thermodynamic equilibrium. Most catalysts are solids or liquids, but they may also be gases. The catalytic reaction is a cyclic process. According to a simplified model, the reactant or reactants form a complex with the catalyst, thereby opening a pathway for their transformation into the product or products. Afterwards the catalyst is released and the next cycle can proceed. Catalysts do not have infinite life. Products of side reactions or changes in the catalyst structure lead to catalyst deactivation. In practice spent catalysts must be reactivated or replaced.

The goal of a catalyst manufacturer is to produce and reproduce a commercial product which can be used as a stable, active, and selective catalyst. The best preparative solution is sought which results in sufficiently high surface area, good porosity, and suitable mechanical strength. The first of these, surface area, is an essential requirement in that reactants should be accessible to a maximum number of active sites.

The properties of a good catalyst for industrial use may be divided into two categories:

1. properties which determine directly catalytic activity and selectivity, here such factors as bulk and surface chemical composition, local microstructure, and phase composition are important; and
2. properties which ensure their successful implementation in the catalytic process, here thermal and mechanical stability, porosity, shape, and dimension of catalyst particles enter.

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### Three Classes of Catalysts:

- Heterogeneous

The catalyst and the reactants are in different phases. Typical heterogeneous catalysts are inorganic solids such as metals, oxides, sulfides, and metal salts, but they may also be organic materials such as organic hydroperoxides, ion exchangers, and enzymes. Examples of heterogeneously catalyzed reactions are ammonia synthesis from the elements over promoted iron catalysts in the gas phase and hydrogenation of edible oils on Ni – kieselguhr catalysts in the liquid phase, which are examples of inorganic and organic catalysis, respectively.

- Homogeneous.

The catalyst and the reactants are in the same phase. Metal salts of organic acids, organometallic complexes, and carbonyls of Co, Fe, and Rh are typical homogeneous catalysts. Examples of homogeneously catalyzed reactions are oxidation of toluene to benzoic acid in the presence of Co and Mn benzoates and hydroformylation of olefins to give the corresponding aldehydes. This reaction is catalyzed by carbonyls of Co or Rh.

- Biological - Enzymes

In biocatalysis, enzymes or microorganisms catalyze various biochemical reactions. The catalysts can be immobilized on various carriers such as porous glass, SiO<sub>2</sub>, and organic polymers. Prominent examples of biochemical reactions are isomerization of glucose to fructose, important in the production of soft drinks, by using enzymes such as glucoamylase immobilized on SiO<sub>2</sub>, and the conversion of acrylonitrile to acrylamide by cells of corynebacteria entrapped in a polyacrylamide gel.

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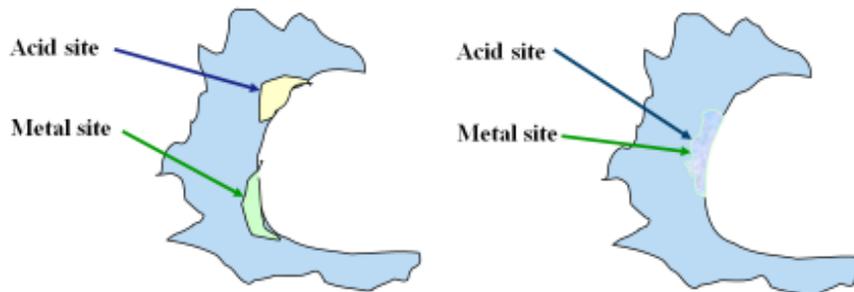
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The basic chemical principles of catalysis consist in the coordination of reactant molecules to central atoms, the ligands of which may be molecular species (homogeneous and biocatalysis) or neighboring atoms at the surface of the solid matrix (heterogeneous catalysis).

More than 80% of the present industrial processes established since 1980 in the chemical, petrochemical, and biochemical industries, as well as in the production of polymers and in environmental protection, use catalysts. More than 15 international companies have specialized in the production of numerous catalysts applied in several industrial branches. In 2008 the turnover in the catalysts world market was estimated to be about US-\$ 13 x 10<sup>9</sup>.

### ACTIVE SITE AND PROMOTERS

Catalyst must have proper balance of Metal and Acid function. Initial theory was the dual function was on two separate sites. Currently believed they exist a single complex site



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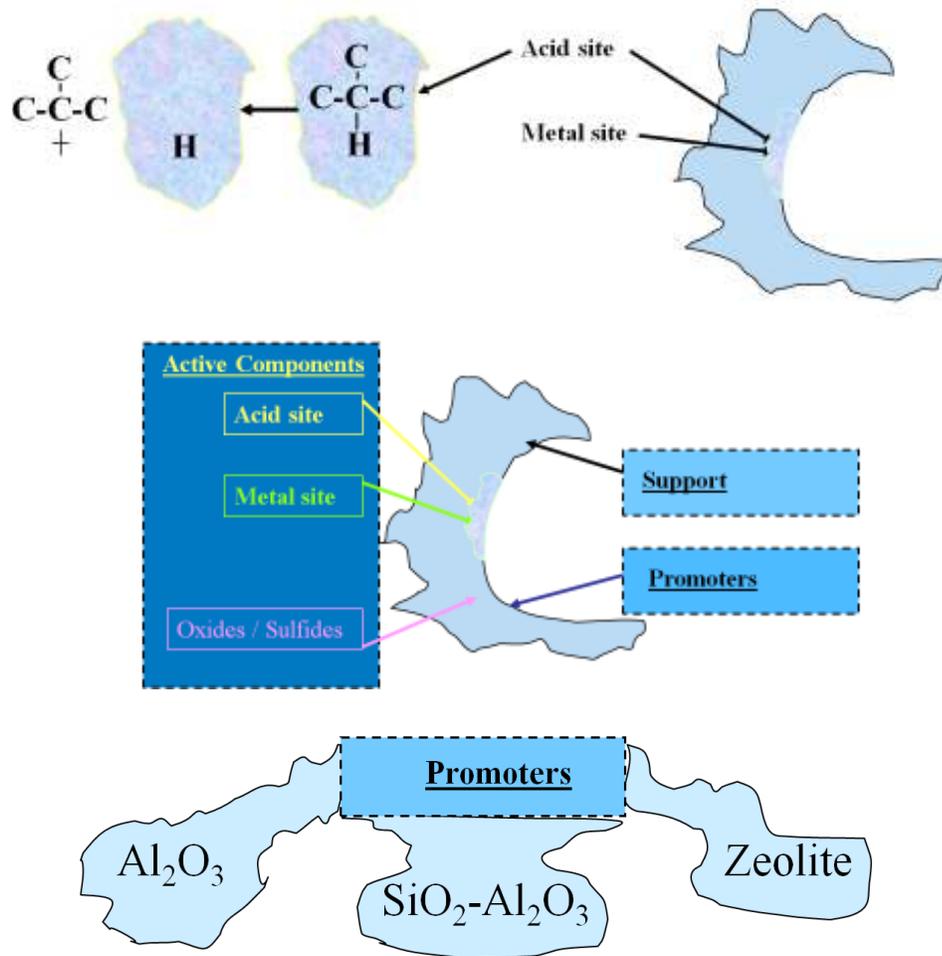


Figure 1. Active site and promotor illustration

### Active component

- Metals - platinum, rennin, rhenium, nickel and cobalt
- Oxides -  $\text{Cr}_2\text{O}_3$ ,  $\text{MoO}_3$
- Acid -  $\text{MoO}_3$ ,  $\text{NiO}$

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### Promoters

- Support
  - Cl (also adds acidity to Al<sub>2</sub>O<sub>3</sub>)
- Active component
  - S (inhibits hydrogenolysis in Pt and Ni)
  - Re, Ir, Sn (as above and retards sintering)

The principle of active sites is not limited to metals. Active sites include metal cations, anions, Lewis and Brønsted acids, acid – base pairs (acid and base acting simultaneously in chemisorption), organometallic compounds, and immobilized enzymes. Active sites may include more than one species (or atom) to form multiplets or ensembles. A mandatory requirement for these sites to be active is that they are accessible for chemisorption from the fluid phase. Hence, they must provide free coordination sites. Thus, active sites are to be considered as atoms or groups of atoms which are embedded in the surface of a matrix in which the neighboring atoms (or groups) act as ligands.

The surface complexes formed by atoms or molecules are now known to usually resemble a local structure similar to molecular coordination complexes. The performance of real industrial catalysts is often adjusted by modifiers (additives). A modifier is called a promoter when it increases the catalyst activity in terms of reaction rate per site. Modifiers may also affect a catalyst's performance in an undesired manner. In this case the modifier acts as a catalyst poison. The simple distinction between promoters and poisons is less straightforward for reactions yielding more than one product in parallel or consecutive steps, of which only one is the desired product.

Modifiers can change the binding energy of an active site or its structure, or disrupt an ensemble of atoms, e.g., by alloying an active with an inactive metal. As an example, the iron-based ammonia synthesis catalyst is promoted by Al<sub>2</sub>O<sub>3</sub> and K<sub>2</sub>O. Alumina acts as a textural promoter, as it prevents the rapid sintering of pure iron metal. It may also stabilize more active sites on the iron surface (structural promoter). Potassium oxide appears to affect the adsorption kinetics and dissociation of dinitrogen and the binding energy of nitrogen on adjacent iron sites (electronic promoter).

The most fundamental principle in catalysis is that of the catalytic cycle. A catalyst is a substance that transforms reactants into products, through an uninterrupted and repeated cycle of elementary steps in which the catalyst is changed through a sequence of reactive intermediates, until the last step in the cycle regenerates the catalyst in its original form. The catalytic substance or active sites may not be present

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originally, but may be formed by activation during the start-up phase of the catalytic reaction.

The cycle must be uninterrupted and repeated since otherwise the reaction is stoichiometric rather than catalytic. The number of turnovers, a measure of catalyst life, must be greater than unity, since the catalyst would otherwise be a reagent. The total amount of catalyst (active sites) is typically small relative to the amounts of reactants and products involved (catalytic amounts). The activity of the catalyst is defined by the number of cycles per unit time or turnovers or turnover frequency (TOF; unit:  $s^{-1}$ ). The life of the catalyst is defined by the number of cycles before it dies.

## SOLID CATALYST

Solid catalysts are extremely important in large scale processes for the conversion of chemicals, fuels, and pollutants. Many solid materials (elements and compounds) including metals, metal oxides, and metal sulfides, are catalysts. Only a few catalytic materials used in industry are simple in composition, e.g., pure metals (e.g., Ni) or binary oxides (such as  $\gamma$ -Al<sub>2</sub>O<sub>3</sub>, TiO<sub>2</sub>).

The use of Solid catalyst comprised of small particles containing catalytically active materials on the surface there of are desirable for a wide variety of chemical reactions. As one example, it would often be desirable in certain catalyzed chemical reactions which are historically catalyzed by liquid catalyst to replace the liquid catalysts with solid catalyst to simplify the process, and to reduce environmental concerns associated with such liquid catalyst.

As one example, the production of highly branched hydrocarbons Such as trimethyl pentane for use as gasoline blending components for octane enhancement traditionally involves alkylation using conventional Strong liquid catalysts Such as hydrofluoric or sulfuric acid. The use of these liquid acid catalysts creates certain environmental concerns. With hydrofluoric acid, the concern is the possibility of the release of toxic vapors. With Sulfuric acid, there is no acute toxic release problem, but there is the need to truck away and treat the waste acid which involves thermal decomposition and preparation of fresh acid. The transportation of the waste and fresh acid is closely regulated to prevent spills.

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In view of the potential problems with the liquid acid catalysts Such as used for alkylation, it is desirable to use less hazardous and toxic and more environmentally acceptable catalysts. Specifically, it is desirable to use Solid catalysts rather than liquid catalysts. However, the use of solid catalysts at least for certain reactions such as alkylation has not been very successful. The main problem is the very short catalyst life which is sometimes measured in terms of hours or possibly a few days.

One type of catalyst which holds promise for such reactions comprises a catalytically inert core which is covered with a shell comprised of, or containing, the catalytically active material. Such thin film or shell catalysts are not in themselves novel. These supported catalysts of the prior art are characterized by a number of factors which influence their usefulness. One is the penetration of the catalytic coating into the core when a porous core material such as alpha-alumina is used.

It is well known to those skilled in the art that porous supports can be impregnated with a solution containing a catalyst precursor which fills the pores within the oxide support. This method is often referred to as the dry impregnation method or the incipient wetness method. Impregnation using slurries containing colloidal particles, i.e., a sol, using this prior art technique shows that there is substantial penetration of the sol into the substrate.

This, as well as the coating techniques themselves, result to varying degrees in a non-uniform coating thickness. In addition, prior art preparation methods result in a range of pore diameters and in films of various thicknesses. The pore diameters within the film and the film thicknesses strongly influence the rate of diffusion of the reactants to the active Sites in the pores and of the reaction products out of the film.

As the pore diameters decrease and as the film thicknesses increase, the diffusion of reactants and products will lead to deleterious reaction products which foul the catalyst Surface. This concept of catalyst deactivation has been recognized in the published literature. A high flux of reactants and products is necessary to obtain a high number of molecules reacted per unit of time for each active catalyst site and, more importantly, to suppress undesired reaction products which foul the Surface. This is partially due to the long residence time within the intricate network of pores resulting in unwanted Side reactions in conventional catalyst or in thin film catalysts of uncontrolled film thickness.

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In the following a variety of families of existing catalysts

1. unsupported (bulk) catalysts;
2. supported catalysts;
3. confined catalysts (ship-in-a-bottle catalysts);
4. hybrid catalysts;
5. polymerization catalysts

### Unsupported (Bulk) Catalysts

#### 1. Metal Oxides

Oxides are compounds of oxygen in which the O atom is the more strongly electronegative component. Oxides of metals are usually solids. Their bulk properties largely depend on the bonding character between metal and oxygen. Metal oxides make up a large and important class of catalytically active materials, their surface properties and chemistry being determined by their composition and structure, the bonding character, and the coordination of surface atoms and hydroxyl groups in exposed terminating crystallographic faces.

Aluminas are amphoteric oxides, which form a variety of different phases depending on the nature of the hydroxide or oxide hydroxide precursor and the conditions of their thermal decomposition. Bayerite, nordstrandite, boehmite, and gibbsite can be used as starting materials. Acidic and basic sites and acid-base pair sites have been identified on the surfaces of aluminas. Alumina surfaces develop a rich surface chemistry and specific catalytic properties.

Besides their intrinsic catalytic properties and their use as catalysts in their own right (e.g., for elimination reactions, alkene isomerization, and the Claus process, aluminas are frequently used as catalyst supports for oxides and metals. The surface area and particle size of aluminas can be controlled by the preparation conditions, and their redox and thermal stability give the supported active phases high stability and ensure a long catalyst lifetime.

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Silicas are weakly Brønsted acidic oxides which occur in a variety of structures such as quartz, tridymite and cristobalite. The most commonly used silica in catalysis is amorphous silica. The surface hydroxyl groups are only weakly Brønsted acidic and therefore hardly develop any catalytic activity. Silicas are not used as active catalysts, but they play an important role as oxide supports and for the synthesis of functionalized oxide supports.

Magnesium oxide is a basic solid. It has the simple rock salt structure, with octahedral coordination of magnesium and oxygen. An initial molecular orbital calculation indicated that the electronic structure is highly ionic, with the  $Mg^{2+}O^{2-}$  formalism being an accurate representation of both bulk and surface structures.

Transition metal oxides can be structurally described as more or less dense packings of oxide anions, the interstices of which are occupied by cations. The bonding, however, is never purely ionic, but rather mixed ionic-covalent, sometimes also developing metallic character (e.g., bronzes). The surface of these oxides is often partially occupied by hydroxyl groups, so they possess some acidic character. Titania  $TiO_2$  exists in two major crystallographic forms: anatase and rutile.

Anatase is the more frequently used modification since it develops a larger surface area, although it is a metastable phase and may undergo slow transformation into the thermodynamically stable rutile phase above ca. 900 K.  $VO_x/TiO_2$ , which plays a significant role in selective oxidation and  $NO_x$  reduction catalysis. Titania is a semiconductor with a wide band gap and as such is an important material for photocatalysis.

Zirconia has attracted significant interest in the recent past as a catalyst support and as a base material for the preparation of strong solid acids by surface modification with sulfate or tungstate groups. The most important crystallographic phases of  $ZrO_2$  for catalytic applications are tetragonal and monoclinic. The latter is the thermodynamically stable phase.  $ZrO_2$  is the base material for the solid-state electrolyte sensor for the measurement of oxygen partial pressure in, e.g., car exhaust gases.

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Iron oxide  $\text{Fe}_2\text{O}_3$  and chromium oxide  $\text{Cr}_2\text{O}_3$  catalyze the oxidative dehydrogenation of butenes to butadiene.  $\text{Fe}_2\text{O}_3$ -based catalysts are used in the high-temperature water gas shift reaction and in the dehydrogenation of ethylbenzene. Vanadium pentoxide  $\text{V}_2\text{O}_5$  is active for the selective oxidation of alkenes to saturated aldehydes. Acidic transition metal oxides such as vanadium pentoxide and molybdenum trioxide  $\text{MoO}_3$  can be used for the synthesis of formaldehyde by oxidative dehydrogenation of methanol, while the more basic iron oxide  $\text{Fe}_2\text{O}_3$  leads to total oxidation. Zinc oxide  $\text{ZnO}$  is used as a catalyst for the oxidation of cyclohexanol to cyclohexanone.

Aluminum silicates are among the most important ternary oxides. Four-valent Si atoms are isomorphously substituted by trivalent Al atoms in these materials. This substitution creates a negatively charged framework of interconnected tetrahedra. Exchangeable cations are required for charge compensation when protons are incorporated as charge-compensating cations, OH groups bridging Si and Al atoms are created which act as Brønsted acidic sites.

Amorphous silica – alumina can be prepared by precipitation from solution. This mixed oxide is a constituent of hydrocarbon cracking catalysts.

Zeolites Hydrothermal synthesis can be used for preparation of a large family of crystalline aluminosilicates, known as zeolites, which are microporous solids with pore sizes ranging from ca. 3 to 7 Å. Characteristic properties of these structurally well-defined solids are selective sorption of small molecules (molecular sieves), ion exchange, and large surface areas. The H forms of zeolites develop strong Brønsted acidity and play a major role in large-scale industrial processes such as catalytic cracking, the Mobil MTG (methanol-to-gasoline) process and several others.

Clays are aluminosilicate minerals (montmorillonite, phyllosilicates (smectites), bentonites, and others). Montmorillonite is an aluminohydroxysilicate and is the main constituent of most clay minerals. It is a 2 : 1 clay, i.e., one octahedral  $\text{AlO}_6$  layer is sandwiched between two tetrahedral  $\text{SiO}_4$  layers. They can be used as catalyst supports. The structural layers can be linked together by introducing inorganic pillars which prevent the layers from collapsing at higher temperatures when the swelling agent is evaporated (pillared clays). A bimodal micro-/mesoporous pore size distribution can thus be obtained. Pillaring can be achieved with a wide variety of reagents including hydroxyl aluminum polymers, zirconia hydroxyl polymers, silica, and

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silicate pillars. Catalytically active components may be built in by the pillaring material, e.g., transition metal oxide pillars.

Bismuth molybdates are among the most important catalysts for selective oxidation and ammoxidation of hydrocarbons. An industrially used Bi molybdate catalyst was optimized in several steps. This material is supported on 50% SiO<sub>2</sub> and was subsequently optimized further to give a catalyst.

## 2. Metals and Metal Alloys

Metals and metal alloys are used as bulk, unsupported catalysts in only a few cases. Metal gauzes or grids are used as bulk catalysts in strongly exothermic reactions which require catalyst beds of small height. Typical examples are platinum – rhodium grids used for ammonia oxidation in the nitric acid process and silver grids for the dehydrogenation of methane to formaldehyde.

Skeletal (Raney-type) catalysts, particularly skeletal nickel catalysts, are technologically important materials which are specifically applied in hydrogenation reactions. However, their application is limited to liquid-phase reactions. They are used in particular for the production of fine chemicals and pharmaceuticals. Skeletal catalysts are prepared by the selective removal of aluminum from Ni – Al alloy particles by leaching with aqueous sodium hydroxide. Besides skeletal Ni, cobalt, copper, platinum, ruthenium, and palladium catalysts have been prepared, with surface areas between 30 and 100 m<sup>2</sup> g<sup>-1</sup>.

One of the advantages of skeletal metal catalysts is that they can be stored in the form of the active metal and therefore require no pre-reduction prior to use, unlike conventional catalysts, the precursors of which are oxides of the active metal supported on a carrier. Fused catalysts are particularly used as alloy catalysts. The synthesis from a homogeneous melt by rapid cooling may yield metastable materials with compositions that can otherwise not be achieved

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### 3. Carbides and Nitrides

Monometallic carbides and nitrides of early transition metals often adopt simple crystal structures in which the metal atoms are arranged in cubic close-packed (ccp), hexagonal closepacked (hcp), or simple hexagonal (hex) arrays. Bulk carbides and nitrides, e.g., of tungsten and molybdenum, can be prepared with surface areas between 100 and 400 m<sup>2</sup> g<sup>-1</sup> by advanced synthetic procedures, so that they can be applied as bulk catalysts. Carbides and nitrides are exceptionally good hydrogenation catalysts, and they are active in hydrazine decomposition.

Carbides of tungsten and molybdenum are also highly active for methane reforming, Fischer – Tropsch synthesis of hydrocarbons and alcohols, and hydrodesulfurization, and the nitrides are active for ammonia synthesis and hydrodenitrogenation. The catalytic properties of carbides can be finetuned by treatment with oxygen, which leads to the formation of oxycarbides.

#### Supported Catalysts

Supported catalysts play a significant role in many industrial processes. The support provides high surface area and stabilizes the dispersion of the active component (e.g., metals supported on oxides). Active phase – support interactions, which are dictated by the surface chemistry of the support for a given active phase, are responsible for the dispersion and the chemical state of the latter. Although supports are often considered to be inert, this is not generally the case. Supports may actively interfere with the catalytic process.

Typical examples for the active inter play between support and active phase are bifunctional catalysts such as highly dispersed noble metals supported on the surface of an acidic carrier. To achieve the high surface areas and stabilize the highly disperse active phase, supports are typically porous materials having high thermostability. For application in industrial processes they must also be stable towards the feed and they must have a sufficient mechanical strength.

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Many of the bulk materials unsupported (bulk) catalysts may also function as supports. The most frequently used supports are binary oxides including transitional aluminas,  $\alpha$ - $\text{Al}_2\text{O}_3$ ,  $\text{SiO}_2$ , MCM-41,  $\text{TiO}_2$  (anatase),  $\text{ZrO}_2$  (tetragonal),  $\text{MgO}$  etc., and ternary oxides including amorphous  $\text{SiO}_2 - \text{Al}_2\text{O}_3$  and zeolites. Additional potential catalyst supports are aluminophosphates, mullite, kieselguhr, bauxite, and calcium aluminate. Carbons in various forms (charcoal, activated carbon) can be applied as supports unless oxygen is required in the feed at high temperatures.

Silicon carbide,  $\text{SiC}$ , can also be used as a catalyst support with high thermal stability and mechanical strength.  $\text{SiC}$  can be prepared with porous structure and high surface area by biotemplating. This procedure yields ceramic composite materials with biomorphic microstructures. Biological carbon preforms are derived from different wood structures by high temperature pyrolysis (1100 – 2100 K) and used as templates for infiltration with gaseous or liquid Si to form  $\text{SiC}$  and  $\text{SiSiC}$  ceramics.

Supported metal oxide catalysts consist of at least one active metal oxide component dispersed on the surface of an oxide support. The active oxides are often transition metal oxides, while the support oxides typically include transitional aluminas (preferentially  $\gamma$ - $\text{Al}_2\text{O}_3$ ),  $\text{SiO}_2$ ,  $\text{TiO}_2$  (anatase),  $\text{ZrO}_2$  (tetragonal), and carbons. Supported vanadia catalysts are extremely versatile oxidation catalysts.  $\text{V}_2\text{O}_5/\text{TiO}_2$  is used for the selective oxidation of o-xylene to phthalic anhydride.  $\text{MoO}_3 - \text{Al}_2\text{O}_3$  and  $\text{WO}_3 - \text{Al}_2\text{O}_3$  (promoted by oxides of cobalt or nickel) are the oxide precursors for sulfide catalysts for hydrotreating of petroleum (hydrodesulfurization, hydrodenitrogenation, hydrocracking).

Metals typically have high surface free energies and therefore a pronounced tendency to reduce their surface areas by particle growth. Therefore, for applications as catalysts they are generally dispersed on high surface area supports, preferentially oxides such as transitional aluminas, with the aim of stabilizing small, nanosized particles under reaction conditions. This can be achieved by some kind of interaction between a metal nanoparticle and the support surface (metal – support interaction).

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Model supported metal catalysts having uniform particle size and structure can be prepared by anchoring molecular carbonyl clusters on support surfaces, followed by decarbonylation. In industrial application, supported metal catalysts are generally used as macroscopic spheres or cylindrical extrudates. Applications of supported metal catalysts, such as noble (Pt, Pd, Rh) or non-noble (Ru, Ni, Fe, Co) metals supported on Al<sub>2</sub>O<sub>3</sub>, SiO<sub>2</sub>, or active carbon include hydrogenation and dehydrogenation reactions.

Ag on Al<sub>2</sub>O<sub>3</sub> is used for ethene epoxidation. Supported Au catalysts are active for low-temperature CO oxidation. Multimetal catalysts Pt – Rh – Pd on Al<sub>2</sub>O<sub>3</sub> modified by CeO<sub>2</sub> as oxygen storage component are used on a large scale in three-way car exhaust catalysts. Pt supported on chlorinated Al<sub>2</sub>O<sub>3</sub> is the bifunctional catalyst used for catalytic reforming, isomerization of petroleum fractions, etc.

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## DEFINITIONS

**Active site** - The effective site at which a given heterogeneous catalytic reaction can take place. Also known as active center.

**Aromatics** – Six carbon atoms form a ring, all bonds are unsaturated.

**Boiling point** - of a substance is the temperature at which the vapor pressure of a liquid equals the pressure surrounding the liquid[1][2] and the liquid changes into a vapor.

**Catalyst** - A material which will increase or decrease the speed of a chemical reaction without changing its own chemical identity

**Catalyst Poisons** - substances that induce the “poisoning” of catalysts (usually heterogeneous catalysts), that is, reduce their catalytic activity or completely stop the catalytic effect. The poisoning of heterogeneous catalysts occurs as a result of the adsorption of the poison or the product of its chemical transformation on the surface of the catalyst. The poisoning may be temporary or permanent.

**Catalyst selectivity** - The relative activity of a catalyst in reference to a particular compound in a mixture. The relative rate of a single reactant in competing reactions.

**Catalyst stripping** - Introduction of steam to remove hydrocarbons retained on the catalyst; the steam is introduced where the spent catalyst leaves the reactor.

**Catalytic activity** - The ratio of the space velocity of a catalyst being tested, to the space velocity required for a standard catalyst to give the same conversion as the catalyst under test.

**Catalytic cracker** - a unit in an oil refinery in which mineral oils with high boiling points are converted to fuels with lower boiling points by a catalytic process

**Catalytic hydrogenation** - Hydrogenating by means of catalysts such as nickel or palladium.

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**Catalytic ignition** - A type of reheat ignition system. The catalytic igniter consists of a platinum or rhodium element in a case fitted into housing secured to the burner hub. Fuel flows to the mouth of a venturi tube that is open to a gas stream from the turbines, and the fuel-air mixture is sprayed onto the elements of the igniter. The chemical reaction lowers the flash point of the mixture sufficiently for spontaneous ignition of the mixture.

**Catalytic polymerization** - Polymerization of monomers to form high-molecular-weight molecules in the presence of catalysts.

**Catalytic Reforming** – is a chemical process used to convert petroleum refinery naphtha distilled from crude oil (typically having low octane ratings) into high octane liquid products called reformates, which are premium blending stocks for high octane gasoline.

**Catalytic reforming** - Rearranging of hydrocarbon molecules in a gasoline boiling-range feedstock to form hydrocarbons having a higher antiknock quality.

**Claus Process:** The process in which one third of the H<sub>2</sub>S is burned to SO<sub>2</sub> which is then reacted with the remaining H<sub>2</sub>S to produce elemental sulfur.

**Coke** - A carbonaceous solid material made by the destructive heating of high-molecular-weight petroleum-refining residues.

**Denitrogenation** - Removal of nitrogen dissolved in the bloodstream and body tissues by breathing 100% oxygen for an extended period.

**Density** - is a measure of mass per unit of volume. Density is a measure of mass per volume. The average density of an object equals its total mass divided by its total volume.

**Desulfurization** - The process of removing sulfur from a substance, such as flue gas or crude.

**Fluidized-Bed** – A last technology of catalytic cracking which most efficient and effective to be implied.

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**Hydrotreating** - Oil refinery catalytic process in which hydrogen is contacted with petroleum intermediate or product streams to remove impurities, such as oxygen, sulfur, nitrogen, or unsaturated hydrocarbons.

**Naphthenes** – Carbon atoms form rings (Cyclo-paraffins) and all bonds saturated with hydrogen atoms.

**Olefins** – Do not occur naturally in crude oil. Formed during processing by dehydrogenation of paraffins and naphthenes. Similar in structure to paraffins except at least two carbon atoms connected with double bond.

**Oxidation** - This occurs when plastics are heated in contact with oxygen. They will oxidize or combine with the oxygen. The first sign of this is a change in color and then a change in properties.

**Paraffins** - Carbon atoms connected by a single bond and other bonds saturated with hydrogen atoms.

**Reactor** – A vessel where main catalytic cracking reaction achieved

**Pyrolysis** - is the thermal decomposition of materials at elevated temperatures in an inert atmosphere. It involves a change of chemical composition and is irreversible. The word is coined from the Greek-derived elements pyro fire and lysis separating.

**Semi-crystalline** - polymers are determined not only by the degree of crystallinity, but also by the size and orientation of the molecular chains.

**Synthetic polymers** - are derived from petroleum oil, and made by scientists and engineers. Examples of synthetic polymers include nylon, polyethylene, polyester, Teflon, and epoxy.

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## REFERENCES

1. Olaf, Helmut, Karl, and Thomas . 2009. Heterogeneous Catalysis and Solid Catalysts. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim
2. Robert J. Farrauto . 2012. Handbook of Industrial Chemistry and Biotechnology. Industrial Catalysis: A Practical Guide. Springer Science. New York
3. K Kolmetz et al, Kolmetz Handbook of Process Equipment Design, KLM Technology Group, Ammonia Unit Selection, Sizing, and Troubleshooting, Engineering Design Guideline, 2019
4. K Kolmetz et al, Kolmetz Handbook of Process Equipment Design, KLM Technology Group, Hydrotreating Unit Selection, Sizing, and Troubleshooting, Engineering Design Guideline. 2013
5. K Kolmetz et al, Kolmetz Handbook of Process Equipment Design, KLM Technology Group, Reactor Systems Selection, Sizing, and Troubleshooting, Engineering Design Guideline. June 2013
6. K Kolmetz et al, Kolmetz Handbook of Process Equipment Design, KLM Technology Group, Refinery Fluidized Catalytic Cracking Unit Selection, Sizing, and Troubleshooting, Engineering Design Guideline. June 2017

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