TABLE 1.1 Selected Heterogeneous Catalysts of Industrial Importance (*Continued*)

Reaction	Catalyst and reactor type (continuous operation unless otherwise noted)
Acid-catalyzed Reactions	
Catalytic cracking	Zeolite in SiO_2-Al_2O_3 matrix plus other ingredients (transport reactor)
Hydrocracking	Pd on zeolite in an amorphous matrix; NiMo on silica-alumina, various other dual-function catalysts (adiabatic fixed beds)
Paraffin isomerization	Pt on H-mordenite zeolite in alumina matrix
Catalytic reforming	Pt, Pt-Re or Pt-Sn on acidified Al_2O_3 or on zeolite in matrix (adiabatic, fixed beds, or moving bed, with interstage heating)
Polymerization	H_3PO_4 on clay (fixed bed)
Hydration, e.g., propylene to isopropyl alcohol	Mineral acid or acid-type ion-exchange resin (fixed bed)
CH_3OH + $isoC_4H_8$ → methyl tert. butyl ether (MTBE)	Acid-type ion-exchange resin
Reactions of Synthesis Gas	
$CO + 2H_2 \rightarrow CH_3OH$	Cu^I-ZnO promoted with Al_2O_3 (adiabatic, fixed beds with interstage cooling or multitube fixed bed)
$CO + 3H_2 \rightarrow CH_4 + H_2O$ (methanation)	Supported Ni (fixed bed)
$CO + H_2$ → paraffins, etc. (Fischer-Tropsch synthesis)	Fe or Co with promoters (multitube fixed bed or transport reactor)
Other	
Oxychlorination (e.g., $C_2H_4 + 2HCl + \frac{1}{2}O_2$ $C_2H_4Cl_2 + H_2O$)	$CuCl_2/Al_2O_3$ with KCl promoter
Hydrodesulfurization, hydrodenitrogenation, hydrotreating	$CoMo/Al_2O_3$ or $NiMo/Al_2O_3$, sulfided (adiabatic, fixed beds with interstage cooling)
$SO_2 + 2H_2S \rightarrow 3S + 2H_2O$ (Claus process)	Al_2O_3 (fixed beds)
$H_2O + CO \rightarrow CO_2 + H_2$ (water-gas shift)	Fe_3O_4 promoted with Cr_2O_3 (adiabatic fixed bed); for a second, lower temperature stage, Cu-ZnO on Al_2O_3; CoMo on support

From: "Heterogeneous Catalysis in Industrial Practice," Second Edition, C. N. Satterfield, McGraw-Hill (1991).

TABLE 1.1 Selected Heterogeneous Catalysts of Industrial Importance

Reaction	Catalyst and reactor type (continuous operation unless otherwise noted)
Dehydrogenation	
C_4H_{10} (butane) → butenes	$Cr_2O_3 \cdot Al_2O_3$ (fixed bed, cyclic)
Butenes → C_4H_6 (butadiene)	Fe_2O_3 promoted with Cr_2O_3 and K_2CO_3
$C_6H_5C_2H_5 \rightarrow C_6H_5CH{=}CH_2$ (ethyl benzene → styrene)	Fe_2O_3 promoted with Cr_2O_3 and K_2CO_3 (fixed bed, in presence of steam)
CH_4 or other hydrocarbons + $H_2O \rightarrow CO + H_2$ (steam reforming)	Supported Ni (fixed bed)
$(CH_3)_2CHOH \rightarrow CH_3COCH_3 + H_2$ (isopropanol → acetone + hydrogen)	ZnO
$CH_3CH(OH)C_2H_5 \rightarrow CH_3COC_2H_5 + H_2$	ZnO
Hydrogenation	
Of edible fats and oils	Ni on a support (slurry reactor, batch)
Various hydrogenations of fine organic chemicals	Pd or Pt on carbon (slurry reactor, usually batch)
$C_6H_6 + 3H_2 \rightarrow C_6H_{12}$	Ni or noble metal on support (fixed bed or slurry reactor)
$N_2 + 3H_2 \rightarrow 2NH_3$	Fe promoted with Al_2O_3, K_2O, CaO, and MgO (adiabatic fixed beds)
$C_2H_2 \rightarrow C_2H_6$ (selective hydrogenation of C_2H_2 impurity in C_2H_4 from thermal-cracking plant)	Pd on Al_2O_3 or sulfided Ni on support (adiabatic fixed bed)
Oxidation	
$SO_2 + \frac{1}{2}O_2$ (air) → SO_3	V_2O_5 plus K_2SO_4 on silica (adiabatic, fixed beds)
$2NH_3 + \frac{5}{2}O_2$ (air) → $2NO + 3H_2O$	90% Pt–10% Rh wire gauze, oxidizing conditions
$NH_3 + CH_4 +$ air → HCN (Andrussow process)	90% Pt–10% Rh wire gauze, under net reducing conditions
$C_{10}H_8$ or 1,2-$C_6H_4(CH_3)_2 + O_2 \rightarrow C_6H_4(CO)_2O$ (naphthalene or *o*-xylene + air → phthalic an hydride)	V_2O_5 on titania (multitube fixed bed)
n-$C_4H_{10} + O_2 \rightarrow C_4H_2O_3$ (butane + air → maleic anhydride)	Vanadia-phosphate (multitube fixed bed or fluidized bed)
$C_2H_4 + \frac{1}{2}O_2 \rightarrow (CH_2)_2O$ (ethylene oxide)	Ag on α-Al_2O_3, promoted with Cl and Cs (multitube fixed bed)
$CH_3OH + O_2 \rightarrow CH_2O + H_2$ and/or H_2O	Ag (adiabatic reactor) or $Fe_2(MoO_4)_3$ (multitube fixed bed)
$C_3H_6 + O_2 \rightarrow CH_2{=}CHCHO$ (acrolein) and/or $CH_2{=}CHCOOH$ (acrylic acid)	Bismuth molybdate plus other components
$C_3H_6 + NH_3 + \frac{3}{2}O_2 \rightarrow CH_2{=}CHCN + 3H_2O$	Complex metal molybdates (fluidized bed)
Complete oxidation of CO and hydrocarbons, for pollution control	Pt or Pd, or both, on monolith support
Simultaneous control of CO, hydrocarbons, and NO_x in auto exhaust	Same, plus Rh, with careful control of oxidizing/reducing conditions
Simultaneous control of NO_x and SO_x in flue gases	Vanadia on titania with addition of NH_3
$C_2H_4 + \frac{1}{2}O_2 + CH_3COOH \rightarrow CH_3COOCH{=}CH_2$ (vinyl acetate)	Pd on acid-resistant support (vapor phase, multitube fixed bed)
$C_4H_8 + \frac{1}{2}O_2 \rightarrow C_4H_6 + H_2O$	Promoted ferrite spinels