Conversion of Solar Energy to Fuels by Inorganic Heterogeneous Systems

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摘要 Over the last several years, the need to find clean and renewable energy sources has increased rapidly because current fossil fuels will not only eventually be depleted, but their continuous combustion leads to a dramatic increase in the carbon dioxide amount in atmosphere. Utilisation of the Sun’s radiation can provide a solution to both problems. Hydrogen fuel can be generated by using solar energy to split water, and liquid fuels can be produced via direct CO_2 photoreduction. This would create an essentially free carbon or at least carbon neutral energy cycle. In this tutorial review, the current progress in fuels’ generation directly driven by solar energy is summarised. Fundamental mechanisms are discussed with suggestions for future research.

关键词: solar energy photocatalysis carbon dioxide conversion water splitting

Abstract: Over the last several years, the need to find clean and renewable energy sources has increased rapidly because current fossil fuels will not only eventually be depleted, but their continuous combustion leads to a dramatic increase in the carbon dioxide amount in atmosphere. Utilisation of the Sun’s radiation can provide a solution to both problems. Hydrogen fuel can be generated by using solar energy to split water, and liquid fuels can be produced via direct CO_2 photoreduction. This would create an essentially free carbon or at least carbon neutral energy cycle. In this tutorial review, the current progress in fuels’ generation directly driven by solar energy is summarised. Fundamental mechanisms are discussed with suggestions for future research.

Keywords: solar energy, photocatalysis, carbon dioxide conversion, water splitting

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[1] offert M I, Caldeira K, Jain A K, Haites E F, Harvey L D D, Potter S D, Schlesinger M E, Schneider S H, Watts R G, Wig-ley T M L, Wuebbles D J. Nature, 1998, 395: 881

[2] ewis N S, Nocera D G. Proc Natl Acad Sci USA, 2006, 103: 15729

[3] nergy Information Administration. Annual Energy Review 2008. Washington DC: U.S. Department of Energy, 2009

[4] arber J. Chem Soc Rev, 2009, 38: 185

[5] ansen J E. Environmental Research Letters, 2007, 2: 024002

[6] ansen J E, Sato M, Kharecha P, Beerling D, Berner R, Mas-son-Delmotte V, Pagani M, Raymo M, Royer D L, Zachos J C. The Open Atmospheric Science Journal, 2008, 2: 217

[7] ttp://fossil.energy.gov/sequestration/geologic/index.html, U.S. Department of Energy, 2010

[8] albwachs M, Sabroux J C. Science, 2001, 292: 438

[9] histi Y. Biotechnol Adv, 2007, 25: 294

[10] Sharma Y C, Singh B, Upadhyay S N. Fuel, 2008, 87: 2355

[11] Tang J W, Cowan A. In: Griesbeck A, Oelgemoeller M, Ghetti F, eds. CRC Handbook of Organic Photochemistry & Photo-biology. 3rd Ed. London: CRC Press, 2012

[12] Kudo A, Miseki Y. Chem Soc Rev, 2009, 38: 253

[13] Roy S C, Varghese O K, Paulose M, Grimes C A. ACS Nano, 2010, 4: 1259

[14] Usubharatana P, McMartin D, Veawab A, Tontiwachwuthikul P. Ind Eng Chem Res, 2006, 45: 2558

[15] Centi G, Perathoner S. ChemSusChem, 2010, 3: 195

[16] Fujishima A, Honda K. Nature, 1972, 238: 37

[17] Yamaguti K, Sato S. J Chem Soc, Faraday Trans I, 1985, 81: 1237

[18] Selli E, Chiarello G L, Quartarone E, Mustarelli P, Rossetti I, Forni L. Chem Commun, 2007: 5022

[19] Duonghong D, Borgarello E, Gratzel M. J Am Chem Soc, 1981, 103: 4685

[20] Sato S, White J M. Chem Phys Lett, 1980, 72: 83

[21] Fu N, Wu Y, Jin Z, Lu G. Langmuir, 2010, 26: 447

[22] Li Y X, Me Y Z, Peng S Q, Lu G X, Li S B. Chemosphere, 2006, 63: 1312

[23] Domen K, Kudo A, Onishi T. J Catal, 1986, 102: 92

[24] Domen K, Kudo A, Onishi T, Kosugi N, Kuroda H. J Phys Chem, 1986, 90: 292

[25] Domen K, Kudo A, Shibata M, Tanaka A, Maruya K, Onishi T. Chem Commun, 1986: 1706

[26] Domen K, Naito S, Onishi T, Tamaru K, Samo M. Chem Phys Lett, 1982, 92: 433

[27] Domen K, Naito S, Onishi T, Tamaru K, Samo M. J Phys Chem, 1982, 86: 3657

[28] Domen K, Naito S, Soma M, Onishi T, Tamaru K. Chem Commun, 1980: 543

[29] Kim J, Hwang D W, Kim H G, Bae S W, Lee J S, Li W, Oh S H. Top Catal, 2005, 35: 295

[30] Chang S M, Doong R A. J Phys Chem B, 2004, 108: 18098

[31] Sayama K, Arakawa H. J Phys Chem, 1993, 97: 531

[32] Jiang L, Wang Q Z, Li C L, Yuan J A, Shangguan W F. Int J Hydrogen Energy, 2010, 35: 7043

[33] Sayama K, Arakawa H, Domen K. Catal Today, 1996, 28: 175

[34] Kato H, Kudo A. Chem Phys Lett, 1998, 295: 487

[35] Kato H, Kudo A. J Phys Chem B, 2001, 105: 4285

[36] Kato H, Asakura K, Kudo A. J Am Chem Soc, 2003, 125: 3082

[37] Mitsui C, Nishiguchi H, Fukamachi K, Ishihara T, Takita Y. Chem Lett, 1999, 1327

[38] Ikeda S, Fubuki M, Takahara Y K, Matsumura M. Appl Catal A, 2006, 300: 186

[39] Kudo A, Kato H, Nakagawa S. J Phys Chem B, 2000, 104: 571

[40] Kato H, Kudo A. Chem Lett, 1999, 1207

[41] Yoshino M, Kakihana M, Cho W S, Kato H, Kudo A. Chem Mater, 2002, 14: 3369

[42] Sato J, Kobayashi H, Inoue Y. J Phys Chem B, 2003, 107: 7970

[43] Sato J, Kobayashi H, Saito N, Nishiyama H, Inoue Y. J Photochem Photobiol A, 2003, 158: 139

[44] Zhang W F, Tang J W, Ye J H. Chem Phys Lett, 2006, 418: 174

[45] Zhang W F, Tang J W, Ye J H. J Mater Res, 2007, 22: 1859

[46] Chen D, Ye J H. Chem Mater, 2007, 19: 4585

[47] Sato J, Saito N, Nishiyama H, Inoue Y. J Photochem Photo-biol A, 2002, 148: 85

[48] Yanagida S, Azuma T, Sakurai H. Chem Lett, 1982: 1069

[49] Reber J F, Meier K. J Phys Chem, 1984, 88: 5903

[50] Wu M, Gu W Z, Li W Z, Zhu X W, Wang F D, Zhao S T. Sci Technol Catal, 1995, 92: 257

[51] Kobayakawa K, Teranishi A, Tsurumaki T, Sato Y, Fujishima A. Electrochim Acta, 1992, 37: 465

[52] Tang J W, Ye J H. J Mater Chem, 2005, 15: 4246

[53] Tang J W, Zou Z G, Ye J H. J Phys Chem B, 2003, 107: 14265

[54] Kudo A, Omori K, Kato H. J Am Chem Soc, 1999, 121: 11459

[55] Kudo A, Ueda K, Kato H, Mikami I. Catal Lett, 1998, 53: 229

[56] Yu J Q, Kudo A. Adv Funct Mater, 2006, 16: 2163

[57] Zou Z G, Ye J H, Sayama K, Arakawa H. Nature, 2001, 414: 625

[58] Mills A, Porter G. J Chem Soc, Faraday Trans I, 1982, 78: 3659

[59] Darwent J R. J Chem Soc, Faraday Trans II, 1981, 77: 1703

[60] Darwent J R, Porter G. Chem Commun, 1981: 145

[61] Yan H J, Yang J H, Ma G J, Wu G P, Zong X, Lei Z B, Shi J Y, Li C. J Catal, 2009, 266: 165

[62] Kalyanasundaram K, Borgarello E, Duonghong D, Gratzel M. Angew Chem, Int Ed, 1981, 20: 987

[63] Hara M, Hitoki G, Takata T, Kondo J N, Kobayashi H, Domen K. Catal Today, 2003, 78: 555

[64] Hara M, Nunoshige J, Takata T, Kondo J N, Domen K. Chem Commun, 2003: 3000

[65] Takata T, Hitoki G, Kondo J N, Hara M, Kobayashi H, Domen K. Res Chem Intermed, 2007, 33: 13

[66] Yamasita D, Takata T, Hara M, Kondo J N, Domen K. Solid State Ionics, 2004, 172: 591

[67] Liu M Y, You W S, Lei Z B, Zhou G H, Yang J J, Wu G P, Ma G J, Luan G Y, Takata T, Hara M, Domen K, Li C. Chem Commun, 2004: 2192

[68] Hitoki G, Takata T, Kondo J N, Hara M, Kobayashi H, Domen K. Electrochemistry, 2002, 70: 463

[69] Maeda K, Takata T, Hara M, Saito N, Inoue Y, Kobayashi H, Domen K. J Am Chem Soc, 2005, 127: 8286

[70] Maeda K, Teramura K, Domen K. J Catal, 2008, 254: 198

[71] Maeda K, Teramura K, Lu D L, Takata T, Saito N, Inoue Y, Domen K. Nature, 2006, 440: 295

[72] Osterloh F E. Chem Mater, 2008, 20: 35

[73] Halmann M. Nature, 1978, 275: 115

[74] Canfield D, Frese K W. J Electrochem Soc, 1983, 130: 1772

[75] Yamashita H, Nishiguchi H, Kamada N, Anpo M, Teraoka Y, Hatano H, Ehara S, Kikui K, Palmisano L, Sclafani A, Schia-vello M, Fox M A. Res Chem Intermed, 1994, 20: 815

[76] Inoue T, Fujishima A, Konishi S, Honda K. Nature, 1979, 277: 429

[77] Yahaya A H, Gondal M A, Hameed A. Chem Phys Lett, 2004, 400: 206

[78] Anpo M, Chiba K. J Mol Catal, 1992, 74: 207

[79] Ichikawa S, Doi R. Catal Today, 1996, 27: 271

[80] Sasirekha N, Basha S J S, Shanthi K. Appl Catal B, 2006, 62: 169

[81] Matthews R W. J Catal, 1988, 113: 549

[82] Xia X H, Jia Z H, Yu Y, Liang Y, Wang Z, Ma L L. Carbon, 2007, 45: 717

[83] Varghese O K, Paulose M, LaTempa T J, Grimes C A. Nano Lett, 2009, 9: 731

[84] Wu J C S. Catal Surveys Asia, 2009, 13: 30

[85] Wang Z Y, Chou H C, Wu J C S, Tsai D P, Mul G. Appl Catal A, 2010, 380: 172

[86] Lo C C, Hung C H, Yuan C S, Wu J F. Sol Energy Mater Sol Cells, 2007, 91: 1765

[87] Matsumoto Y, Obata M, Hombo J. J Phys Chem, 1994, 98: 2950

[88] Yan S C, Ouyang S X, Gao J, Yang M, Feng J Y, Fan X X, Wan L J, Li Z S, Ye J H, Zhou Y, Zou Z G. Angew Chem, Int Ed, 2010, 49: 6400

[89] Liu Q, Zhou Y, Kou J H, Chen X Y, Tian Z P, Gao J, Yan S C, Zou Z G. J Am Chem Soc, 2010, 132: 14385

[90] Anpo M, Yamashita H, Ichihashi Y, Fujii Y, Honda M. J Phys Chem B, 1997, 101: 2632

[91] Ikeue K, Nozaki S, Ogawa M, Anpo M. Catal Lett, 2002, 80: 111

[92] Ulagappan N, Frei H. J Phys Chem A, 2000, 104: 7834

[93] Lin W Y, Han H X, Frei H. J Phys Chem B, 2004, 108: 18269

[94] Lin W Y, Frei H. J Am Chem Soc, 2005, 127: 1610

[95] Takeda H, Koike K, Inoue H, Ishitani O. J Am Chem Soc, 2008, 130: 2023

[96] Lehn J M, Ziessel R. Proc Natl Acad Sci USA, 1982, 79: 701

[97] Craig C A, Spreer L O, Otvos J W, Calvin M. J Phys Chem, 1990, 94: 7957

[98] Fujita E. Coord Chem Rev, 1999, 185-186: 373

[99] Li G Q, Kako T, Wang D F, Zou Z G, Ye J H. J Phys Chem Solids, 2008, 69: 2487

[100] Brus L E. J Chem Phys, 1984, 80: 4403

[101] Lippens P E, Lannoo M. Phys Rev B, 1989, 39: 10935

[102] Wang Y, Suna A, Mahler W, Kasowski R. J Chem Phys, 1987, 87: 7315

[103] Henglein A. Chem Rev, 1989, 89: 1861

[104] Yoneyama H. Catal Today, 1997, 39: 169

[105] Ma B J, Wen F Y, Jiang H F, Yang J H, Ying P L, Li C. Catal Lett, 2010, 134: 78

[106] Maeda K, Xiong A K, Yoshinaga T, Ikeda T, Sakamoto N, Hisatomi T, Takashima M, Lu D L, Kanehara M, Setoyama T, Teranishi T, Domen K. Angew Chem, Int Ed, 2010, 49: 4096

[107] Adachi K, Ohta K, Mizuno T. Solar Energy, 1994, 53: 187

[108] Cook R L, Macduff R C, Sammells A F. J Electrochem Soc, 1988, 135: 3069

[109] Zhang J, Xu Q, Feng Z, Li M, Li C. Angew Chem, Int Ed, 2008, 47: 1766

[110] Kudo A, Kato H. Chem Phys Lett, 2000, 331: 373

[111] Inoue H, Nakamura R, Yoneyama H. Chem Lett, 1994: 1227

[112] Bard A J, Fox M A. Acc Chem Res, 1995, 28: 141

[113] Tamaki Y, Furube A, Murai M, Hara K, Katoh R, Tachiya M. Phys Chem Chem Phys, 2007, 9: 1453

[114] Yoshihara T, Katoh R, Furube A, Tamaki Y, Murai M, Hara K, Murata S, Arakawa H, Tachiya M. J Phys Chem B, 2004, 108: 3817

[115] Bahnemann D, Henglein A, Lilie J, Spanhel L. J Phys Chem, 1984, 88: 709

[116] Tang J W, Durrant J R, Klug D R. J Am Chem Soc, 2008, 130: 13885

[117] Serpone N, Lawless D, Khairutdinov R. J Phys Chem, 1995, 99: 16646

[118] Murai M, Tamaki Y, Furube A, Hara K, Katoh R. Catal To-day, 2007, 120: 214

[119] Yamakata A, Ishibashi T, Onishi H. J Phys Chem B, 2001, 105: 7258

[120] Ikeda T, Nomoto T, Eda K, Mizutani Y, Kato H, Kudo A, On-ishi H. J Phys Chem C, 2008, 112: 1167

[121] Tachikawa T, Fujitsuka M, Majima T. J Phys Chem C, 2007, 111: 5259

[122] Yamakata A, Ishibashi T, Kato H, Kudo A, Onishi H. J Phys Chem B, 2003, 107: 14383

[123] Tang J W, Cowan A, Durrant J R, Klug D R. J Phys Chem C, 2011, 115: 3143

[1] M. ESMAILI, A. HABIBI-YANGJEH.Microwave-Assisted Preparation of CdS Nanoparticles in a Halide-Free Ionic Liquid and Their Photocatalytic Activities[J]. 催化学报, 2011,32(6): 933-938

[2] K. KOCI1,*, K. ZATLOUKALOVA1, L. OBALOVA1, S. KREJCIKOVA2, Z. LACNY1, et al.Wavelength Effect on Photocatalytic Reduction of CO_2 by Ag/TiO_2 Catalyst[J]. 催化学报, 2011,32(5): 812-815

[3] Juergen CARO.微结构的纳米设计膜反应器中的催化[J]. 催化学报, 2008,29(11): 1169-1177