

出國報告（出國類別：其他）

2016 第四屆化學迴圈國際研討會赴大陸南京出國報告

服務機關：核能研究所

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派赴國家：大陸

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報告日期：105年10月28日

摘要

本次公差行程為參加 2016 年第四屆化學迴圈國際研討會(4th International Conference on Chemical Looping)，與發表研究成果論文。本屆化學迴圈國際研討會於大陸南京舉行，期程：105 年 9 月 26 日至 9 月 28 日，研討會由大陸東南大學主辦，總報名人數超過兩百人，不乏來自各國化學迴圈相關研究團體或機構之專家學者。會議以化學迴圈技術為主軸，提供各專家學者分享最新研究與創新思想，衍生相關化學迴圈領域五大技術進行專題討論，包括先導工廠測試、氫氣產物與氣化反應、載氧體分析與改質、化學迴圈模型建構，以及鈣迴圈技術討論。此次參與第四屆化學迴圈國際研討會以口頭報告方式發表論文「Study on Combustion-supporting Behavior of Ilmenite in Chemical Looping Combustion Process」，該論文被安排於載氧體分析與改質會議中討論，藉此機會讓外界了解核研所(以下稱本所)對於化學迴圈研究的投入。會後彙整各分項議題之心得與建議簡述如下：化學迴圈為一頗具潛能之前瞻能源技術，本所若能充分掌握研究方向，將有助於國內提升能源技術之水平，除建立國內自主能源技術外，亦能與國際合作擴展能源技術之海外市場。

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一、目的

近年來，全球氣候議題持續升溫，各方研究顯示人為溫室氣體排放對於全球溫室效應有關鍵性的影響。目前對於二氧化碳的處理技術，包括：二氧化碳之捕獲技術、轉化及再利用技術、與儲存及固定技術等，皆已成為各國積極研究與發展的方向。為推動國家減碳政策，政府近年積極建構低碳能源發展藍圖。本所目前亦積極進行能源國家型科技計畫之「淨碳技術領域」相關研究發展計畫，期望從永續發展觀點推動自主潔淨能源技術之建立。本次出國公差為執行「碳基能源永續潔淨利用技術發展」分支計畫，赴大陸南京參加 2016 年第四屆化學迴圈國際研討會(4th International Conference on Chemical Looping)，此國際研討會今年由大陸東南大學主辦，議程為 9 月 26 日至 9 月 28 日，本屆會議實際參與人數超過兩百人，不乏來自各國化學迴圈相關研究團體或機構之專家學者。本所淨碳技術團隊在大會以口頭報告方式發表研究成果論文“Study on Combustion-supporting Behavior of Ilmenite in Chemical Looping Combustion Process”，藉此機會與國際學者專家討論、分享本所近年來在化學迴圈燃燒程序應用在淨碳技術的研究成果，並藉以掌握國際間化學迴圈燃燒程序發展之現況與趨勢，拓展與國際學者專家之關係及國際合作。

二、過 程

(一) 公差行程

本次公差前往大陸南京參加第四屆化學迴圈國際研討會(4th International Conference on Chemical Looping)，行程自民國 105 年 9 月 25 日至 9 月 29 日止，總計共 5 日，行程規劃大致如下表所示。

表 1. 公差行程表

日期	地點	工作內容概述
105/09/25 星期日	台北松山機場 → 上海虹橋機場 高鐵上海虹橋站 → 高鐵南京南站 高鐵南京南站 → 南京國際會議大酒店	去程、辦理會議註冊與報到
105/09/26 星期一	南京國際會議大酒店	出席第四屆化學迴圈國際研討會 4th International Conference on Chemical Looping，發表論文
105/09/27 星期二	南京國際會議大酒店、大陸東南大學	出席第四屆化學迴圈國際研討會 4th International Conference on Chemical Looping，參訪大陸東南大學實驗室
105/09/28 星期三	南京國際會議大酒店	出席第四屆化學迴圈國際研討會 4th International Conference on Chemical Looping
105/09/29 星期四	高鐵南京站 → 高鐵上海站 高鐵上海站 → 上海浦東機場	回程

(二) 第四屆化學迴圈國際研討會(4th International Conference on Chemical Looping)

本屆 ICCL 由大陸東南大學主辦，大會於民國 105 年 9 月 25 日至 9 月 28 日在大陸南京國際會議大酒店舉行(圖 1、圖 2)，為化學迴圈技術領域的年度國際盛會之一；會議主題以化學迴圈技術為主軸，提供各專家學者分享最新研究與創新思想，衍生相關化學迴圈領域五大技術進行專題討論，包括先導工廠測試、氫氣產物與氣化反應、載氧體分析與改質、化學迴圈模型建構，以及鈣迴圈技術討論。

ICCL 2016 之議程與詳細口頭報告安排時程如表 2 所示，會議自 9 月 25 日(星期日)開始註冊與報到，於 9 月 26 日星期一早上舉行開幕典禮，隨後進行 2 場 Keynote 演講；在短暫休息後，即開始平行場次口頭論文發表。壁報論文自 9 月 26 日星期一起開始展示至 9 月 28 日下午，壁報論文展示於會場中庭與提供咖啡茶敘之休息場地，由作者進行現場解說。9 月 27 日下午，大會安排參訪大陸南京東南大學沈來宏教授實驗室，由實驗室負責人講解說明氣化與化學迴圈實驗技術概況。大會共安排 4 場 Keynote 演講，3 場全體會議(Plenary Session)，其餘時段皆為平行場次口頭論文發表場次共計 94 場，五大技術議題列舉如下：

1. Pilot Plants
2. Hydrogen Production & Gasification
3. Oxygen Carrier
4. Modelling
5. Calcium Looping

此次參與第四屆化學迴圈國際研討會以口頭報告方式發表論文“Study on Combustion-supporting Behavior of Ilmenite in Chemical Looping Combustion Process”，該論文被安排於 9 月 26 日中午的平行場次「載氧體分析與改質會議(C-1 Oxygen Carrier)」中討論，藉此機會讓外界了解核研所對於化學迴圈研究的投入，同時在報告結束後也與多名研究人員進行流體化床及化學迴圈技術之討論，實為難得的經驗。

筆者在大陸的公差行程於 9 月 28 日告一段落，次日(9 月 29 日星期四)即自大陸上海浦東國際機場搭機，由於梅姬颱風影響，班機延誤兩個半小時，返回台灣桃園國際機場已為 9 月 30 日凌晨 12 點 38 分，結束本次公差行程。

表 2. 4th International Conference on Chemical Looping 之議程

Summary															
Sept.25	Sept.26				Sept.27				Sept.28						
	Friendship Hall	Magnolia Hall	Violet Hall	Tulip Hall	Friendship Hall	Violet Hall	Tulip Hall	Friendship Hall	Magnolia Hall	Tulip Hall					
	9:00-9:10	Welcome				8:40-9:20	Keynote 3 Anders Lyngfelt				8:40-9:20	Keynote 4 Juan Adánez			
	9:10-9:50	Keynote 1 Liang-Shih Fan				9:20-9:30	Parallel Sessions				9:20-9:30	Parallel Sessions			
	9:50-10:30	Keynote 2 Laihong Shen				9:30-10:30	A-2 Pilot Plants	D-3 Modelling	C-4 Oxygen Carrier	9:30-10:30	A-3 Pilot Plants	B-4 Hydrogen Production Gasification	E-1 Calcium Looping		
	10:30-10:50	Parallel Sessions				10:30-10:50	BREAK				10:30-10:50	BREAK			
	10:50-12:30	A-1 Pilot Plants	B-1 Hydrogen Production Gasification		C-1 Oxygen Carrier	10:50-12:30	A-2 Pilot Plants	D-3 Modelling	C-4 Oxygen Carrier	10:50-12:30	A-3 Pilot Plants	B-4 Hydrogen Production Gasification	E-1 Calcium Looping		
14:00 - 22:00	12:30-14:00	Lunch				12:30-14:00	Lunch				12:30-14:00	Lunch			
Registration	14:00-16:00		B-2 Hydrogen Production Gasification	D-1 Modelling	C-2 Oxygen Carrier	Poster Session Lab Visit Tour				14:00-15:40	A-4 Pilot Plants				
	16:00-16:20	Break								15:40-16:00	Break				
	16:20-18:00		B-3 Hydrogen Production Gasification	D-2 Modelling	C-3 Oxygen Carrier					16:00-17:00	Panel Discussion				
	18:30	Banquet at Zijin Building Conference Hall								18:30	Conference Dinner at Mandarin Garden Nanjing				

Oral Presentations are presented in five sessions (A: Pilot Plants; B: Hydrogen Production & Gasification; C: Oxygen Carrier; D: Modelling; E: Calcium Looping) and held in four halls (Friendship Hall, Magnolia Hall, Violet Hall and Tulip Hall).

Sept.26	Friendship Hall 友谊厅
9:00-9:10	Welcome Chair: Laihong Shen, Young Ku
9:10-9:50	Keynote 1 Chemical Looping Partial Oxidation Liang-Shih Fan Ohio State University, USA
9:50-10:30	Keynote 2 Reactor for Chemical-Looping Combustion of Solid Fuels Laihong Shen Southeast University, China
10:30-10:50	Parallel Sessions
	Friendship Hall 友谊厅
	Magnolia Hall 白玉兰厅
	Tulip Hall 郁金香厅
	Session A - 1 Pilot Plants Chair: Juan Adánez, Ranjani Sriwardene
	Session B - 1 Hydrogen Production & Gasification Chair: Junichiro Otomo, Tobias Pröll
	Session C - 1 Oxygen Carrier Chair: Francisco García Labiano, Yao-Hsuan Tseng
10:50-11:10	Characterization of Oxygen Carriers during Combustion and CLC Conditions in a 12 MWth Circulating Fluidized Bed Biomass Boiler Main HANWING, Angelica CORCORAN, Dongmei ZHAO*, Fredrik LIND, Magnus RYDÉN Chalmers University of Technology, Sweden
10:50-11:10	Evolution of a Composite Redox-active Oxygen Carrier for Hydrogen Production Danny Mak, E.I. Papaioannou, B. Ray Newcastle University, UK
10:50-11:10	Reactivity of Oxygen Carriers after Recycling in Chemical Looping Combustion of Coal Tomonao SAITO*, Shi-Ying LIN Japan Coal Energy Center, Japan
11:10-11:30	Design and Operation of a 50 kWth Chemical Looping Combustion (CLC) Reactor Using Coal as Fuel Jinchen MA*, Haibo ZHAO, Pengjie NIU, Xin CHEN, Xin TIAN, Chuguang ZHENG Huazhong University of Science and Technology, China
11:10-11:30	Water Splitting for Hydrogen Production: From Chemical Looping Concept to Membrane Reactor Xing ZHU, Lingyue SUN, Kongshai LI Kunming University of Science and Technology, China
11:10-11:30	A Facile Synthesis of Ni-modified Fe ₂ O ₃ /Al ₂ O ₃ Oxygen Carrier for Improved Reduction Performance in Chemical Looping Combustion Process Wei-Chen Huang*, Jia-Siang Huang, Yu-Lin Kuo, Fan Hsu National Taiwan University of Science and Technology, Taiwan, China
11:30-11:50	On the Distribution of Residence Times of Solids in a Circulating Fluidised Bed Reactor for Chemical Looping Combustion Felix DONAT*, Wenting HU, Stuart A. SCOTT, John S. DENNIS University of Cambridge, UK
11:30-11:50	Development of a 2 kWth Chemical-Looping Reforming Reactor with Integrated Selective Metallic-Supported Pd Membranes for Highly Efficient In-Situ Pure H ₂ Production and CO ₂ Capture Jose Antonio MEDRANO*, Vincenzo SPALLINA, Alessandro BATTISTELLA Eindhoven University of Technology, Netherlands
11:30-11:50	Selective Oxidations via Chemical Looping: Selective Combustion of Hydrogen in Hydrocarbon Mixtures M.S.C. CHAN*, J.S. DENNIS University of Cambridge, UK
11:50-12:10	Development of Three-Tower (reactors) Technology for Chemical Looping Coal Combustion Shi-Ying LIN*, Tomonao SAITO Japan Coal Energy Center, Japan
11:50-12:10	Using Synthetic Cu-Fe Metal Oxides as Oxygen Carriers in Biomass Chemical-Looping Gasification Yuexin Ma, Haibo Zhao, Pengjie Niu* Huazhong University of Science and Technology, China
11:50-12:10	The Kinetics of Redox Reactions for Prospective Oxygen Carrier Material Made from Iron Ore Ewelina KSEPKO, Piotr BABINSKI, Lori NALBANDIAN Institute for Chemical Processing of Coal, Poland
12:10-12:30	Coal Based Pressurized Chemical Looping Combustion Combined Cycle Process Development and Analysis Zhen Fan, Liangyong Chen, Fang Liu, Jinhua Bao, Heather Nikolic, Kunlei Liu University of Kentucky, USA
12:10-12:30	Increasing the Carbon Capture Efficiency of the Ca/Cu Looping Process with Advanced Process Schemes Michela MARTINI*, Isabel MARTINEZ, Fausto GALLUCCI Eindhoven University of Technology, Netherlands
12:10-12:30	Study on Combustion-supporting Behavior of Ilmenite in Chemical Looping Combustion Process You-Pin Chyau*, Der-Ming Chang, Ching-Ying Huang, Hsuan-Hua Chang* Institute of Nuclear Energy Research, Taiwan, China
12:30-14:00	LUNCH

Detailed Scientific Program Oral Presentations

The keynote and plenary lecture invited speakers have 35 min + 5 min dedicated for discussion at their disposal. The presenters of the topical oral presentations have 15 min + 5 min discussion at their disposal. Presenters are kindly asked to upload their presentations in the designated session room before their presentation is scheduled. Also, please make sure your presentation is compatible with the AV system provided.

Sept.26	Magnolia Hall 白玉兰厅	Violet Hall 紫罗兰厅	Tulip Hall 郁金香厅
	Session B - 2 Hydrogen Production & Gasification Chair: Henrik Thunman, Dongmei Zhao	Session D - 1 Modelling Chair: Øyvind Langgren, Jing Liu	Session C - 2 Oxygen Carrier Chair: Arnold Lambert, Antonio Coppola
14:00-14:20	Plenary 1 Chemical Looping Coal Gasification with Calcium Ferrite and Barium Ferrite via Solid-Solid Reactions Hanjing Tian ¹ , Ranjani Siriwardane, Jarrett Riley USDOE-National Energy Technology Laboratory, USA	Integration of Solid Oxide Fuel Cells and Chemical Looping Combustion for Efficient Power Production with CO ₂ Capture Vincenzo Spallino ¹ , Pasquale Nocerino, Matteo C. Romano, Martin van Sint Annaland, Stefano Campanari, Fausto Gallucci Eindhoven University of Technology, Netherlands	Plenary 2 Heat Management Strategies in Chemical-Looping Combustion of Methane using a Thermal Storage Functional Oxygen Carrier Kongzhi Li, Hua Wang, Yonggang Wei, Xing Zhu, Ningning Li Kunming University of Science and Technology, China
14:20-14:40		Copper-Based Oxygen Carriers Supported with Alumina/Lime for Conversion of Gaseous Fuels Syed K HAIDER, Maria ERANS ¹ , Felix DONAT, Lunbo DUAN, Stuart A SCOTT, Vasilije MANOVIC, Edward J ANTHONY Cranfield University, UK	
14:40-15:00	Interaction Effect between Coal Ash and Oxygen Carrier for the Chemical Looping Gasification Qishun Wan, Yong zhuo Liu ¹ , Qingjie Guo Qingdao University of Science and Technology, China	The Effect of Different Particle Residence Time Distributions on the Chemical Looping Combustion Process Matthias A. SCHNELLMANN ¹ , Felix DONAT, Stuart A. SCOTT, Gareth WILLIAMS, John S. DENNIS University of Cambridge, UK	Thermochemical Energy Storage Based on the Reversible Reaction of Manganese Iron Oxide Michael WOKON, Dr. phil. Thomas BAUER, Dr.-Ing. Marc LINDER German Aerospace Center, Germany
15:00-15:20	Analysis of Char Gasification Enhancement during Chemical Looping Combustion Ewa MAREK, Yooqoo ZHENG, Ewelina KSEPKO University of Cambridge, UK	Molecular Dynamics Simulation of CuO Sintering Process in Cu-based Oxygen Carrier Particle Jinfa Gui, Haibo Zhao Huazhong University of Science and Technology, China	Ultra-Low NO _x emission of pulverized coal staged combustion coupling with chemical looping combustion Zhi Zhang ¹ , Denggao Chen, Zhenshan Li, Ningsheng Cai Tsinghua University, China
15:40-15:40	Numerical Study of the Scale-Up of Chemical Looping Reforming Xavier SCHEUER, Juray DE WILDE Université Catholique De Louvain, Belgium	Cu-Mn Mixed Oxide as Oxygen Carrier for CLOU Process Itzaki ADÁNEZ-RUBIO, Alberto ABAD, Pilar GAYÁN, Francisco GARCÍA-LABIANO, Luis F. de DIEGO, Juan ADÁNEZ ¹ Instituto De Carboquímica (ICB-CSIC), Spain	Reaction Kinetics and Morphological Variation of Fe-based Oxygen Carriers in Redox Cycles of Chemical Looping Systems Junichiro OTOMO, Yuya SATO, Kezuyuki MIYA, Noriaki KIKUCHI, Fumihiko KOSAKA The University of Tokyo, Japan
15:40-16:00	Characterization of Combined Fe-Cu Oxides as Oxygen Carrier in Biomass Gasification using Chemical Looping Huijun GE ¹ , Lalhong SHEN, Tao SONG Southeast University, China	Heat Management of Pre-Combustion Chemical Looping Technology using Packed Bed Reactors Vincenzo Spallino ¹ , Michel P.C. van Etten, Fausto Gallucci, Martin van Sint Annaland Eindhoven University of Technology, Netherlands	Manganese Containing Mixed-Oxides as Versatile Oxygen Carrying Agents for Chemical Looping Applications Seif Yusuf, Luke Neal, Nathan Gainsky, Fanxing Li North Carolina State University, USA
16:00-16:20	BREAK		
	Session B - 3 Hydrogen Production & Gasification Chair: Hanjing Tian, Fang He	Session D - 2 Modelling Chair: Mahdi Yazdanpanah, Fanxing Li	Session C - 3 Oxygen Carrier Chair: Stuart Ashley Scott, Kongzhi Li
16:20-16:40	Processing and Characterization of Fe-based Oxygen Carriers for Chemical Looping for Hydrogen Production Yoran DE VOS ¹ , Marijke JACOBS, Isabel VAN DRIESSCHE Flemish Institute for Technological Research (VITO), Belgium	Evaluation of a Promising Cu-based Oxygen Carrier for its Use at Industrial Scale in CLC of CH ₄ Arturo CABELLO, Pilar GAYÁN ¹ , Alberto ABAD, Luis F. de DIEGO, Francisco GARCÍA-LABIANO, María T. IZQUIERDO, Andrew SCULLARD, Gareth WILLIAMS, Juan ADÁNEZ Instituto De Carboquímica (ICB-CSIC), Spain	Evolution of Chemical Structure of Coal during its Chemical Looping Combustion with Fe ₂ O ₃ Oxygen Carrier Boowen Wang, Aijun Wang, Weishu Wang, Haibo Zhao, Chuanguo Zheng North China University of Water Resources and Electric Power, China

Sept.26	Magnolia Hall 白玉兰厅	Violet Hall 紫罗兰厅	Tulip Hall 郁金香厅
16:40-17:00	Coal Chemical Looping Gasification for Synthetic Natural Gas Production Yangzhuo LIU, Tao LIU, Yongqing YUE Qingdao University of Science and Technology, China	Periodic Density Functional Study of the Interaction Mechanism of CO with Spinel-Type MnFe ₂ O ₄ Surface in Chemical-Looping Combustion Feng Liu ¹ , Jing Liu, Jinxin Dai, Yingju Yang, Zhen Zhang, Minjun Wang Huazhong University of Science and Technology, China	Autothermal Operation of a Pressurized Gas Switching Combustion Reactor with a Mn based Oxygen Carrier Abdelghafour ZAABOUB, Schaik CLOETE, Shahriar Amiri ¹ SINTEF Materials and Chemistry, Norway
17:00-17:20	Hydrogen Production by Integration of Steam Reformation with Chemical-Looping Combustion Viktor STENBERG ¹ , Magnus RYDÉN, Tobias MATTISSON Chalmers University of Technology, Sweden	Flowsheet Simulation of Chemical Looping Combustion Johannes HAUS ¹ , Ernst-Ulrich HARTGE, Stefan HEINRICH, Joachim WERTHER Hamburg University of Technology, Germany	Biomass Ash as Oxygen Carrier in Fluidized Bed Processes Daniel Schweitzer, Fabian Nagel, Max Schmid ¹ , Reinhold Spörl, Günter Scheffnecht University of Stuttgart, Germany
17:20-17:40	Various Support Iron-based Oxygen Carriers for Chemical Looping Hydrogen Generation in a Moving Bed Reactor Hsuan-Chih Wu ¹ , Young Ku, Yin-Zhe Wang ¹ National Taiwan University of Science and Technology, Taiwan, China	1D Model of Solid Fuel Conversion in the Bottom Bed of a Chemical Looping Combustion Unit Jesper ARONSSON, David FALLARÉS, Anders LYNGFELT Chalmers University of Technology, Sweden	Cement Bonded Fine Hematite and Copper Ore Particles as Oxygen Carrier in Chemical Looping Combustion Xin Tian ¹ , Haibo Zhao ¹ , Jinchun Ma Huazhong University of Science and Technology, China
17:40-18:00	Coal Direct Chemical Looping Hydrogen Production with K-Fe-Al Composite Oxygen Carrier Zhongliang Yu, Yanyan Yang, Chunyu Li Chinese Academy of Sciences, China	Characterization of Scaling Laws in Computational Fluid Dynamics Simulations of Chemical Looping Combustion AGARWAL, Ramesh K. and BANERJEE, Subhodeep Washington University in St. Louis, USA	Performance and Degradation Mechanisms of CLC Particles Produced by Industrial Methods Arnold Lambert ¹ , Airy Tiliand, William Pelletant, Stéphane Bertholin, Florent Moreau, Isabelle Clemenson, Mahdi Yazdanpanah IFP Energies nouvelles, France
18:30	Banquet at Zijin Building Conference Hall		

Sept.27	Friendship Hall 友谊厅	Violet Hall 紫罗兰厅	Tulip Hall 郁金香厅
8:40-9:20	Keynote 3 Chair: Joachim Werther Chemical-Looping Combustion of Solid Fuels – What is Needed To Reach Full-Scale? Anders Lyngfelt Chalmers University of Technology, Sweden		
9:20-9:30	Parallel Sessions		
	Friendship Hall 友谊厅	Violet Hall 紫罗兰厅	Tulip Hall 郁金香厅
	Session A - 2 Pilot Plants Chair: Ho-Jung Ryu, Francisco R García-García	Session D - 3 Modelling Chair: Stéphane Bertholin, Jørild Svealstuen	Session C - 4 Oxygen Carrier Chair: Ernst-Ulrich Hartge, Fabio MONTAGNARO
9:30-9:50	Experience of more than 1000h of Operation with Oxygen Carriers and Solid Biomass at Large Scale Teresa BERDUGO VILCHES ¹ , Fredrik LIND, Magnus RYDÉN, Henrik THUNMAN Chalmers University of Technology, Sweden	Comparison of Three Different Methods for the Determination of Solids Circulation Rates in Solid Looping Systems José A. MEDRANO, María NORDIO, Martín van SINT ANNALAND, Fausto GALLUCCI Eindhoven University of Technology, Netherlands	Manganese Ore Screening and Solid Fuel Testing Sebastian Sundqvist, Tobias Mattsson Chalmers University of Technology, Sweden

9:50-10:10	Chemical Looping Combustion of Four Different Solid Fuels Using a Manganese-Silicon-Titanium Oxygen Carrier Matthias SCHMITZ, Carl Johan LINDERHOLM [*] , Anders LYNGBELT Chalmers University of Technology, Sweden	Two-fluid CFD-based Model for 1 MW _{th} Chemical Looping Pilot Plant: Modelling and Validation of Air and Fuel Reactors Jan MAY, Peter OHLEMÜLLER, Falah Alobaid, Jochen STRÖHLE [*] , Bernd EPPLE TU Darmstadt, Germany	Assessment of Natural Ilmenite and Synthetic Oxygen Carrier for Chemical Looping Combustion of Victorian Brown Coal David STOKIE, Srikanth CHAKRAVARTULA SRIVATSAA, Sankar BHATTACHARYA, Franz SIKERNIS, Corinne BEAL, Seng LIM Monash University, Australia
10:10-10:30	Biomass with CO ₂ Capture Using CLC: Results in a 500 Wth unit Teresa MENDIARA, María Teresa IZQUIERDO, Antón PÉREZ-ASTRAY, Alberto ABAD, Luis F. de DIEGO, F. GARCÍA-LABIANO [*] , Pilar GAYÁN, Juan ADÁNEZ Instituto de Carboquímica (ICB-CSIC), Spain	Application of Chemical Looping Air Separation in Oxy-Fuel Combustion for Power Production with CO ₂ Sequestration Shiyi CHEN [*] , Wenguo XIANG, Min ZHU, Shiwei MA, Zhao SUN Southeast University, China	Development of Iron-based Particles Enriched with Copper Oxide as Low Cost Oxygen Carriers for Solid Fuels Combustion with CO ₂ Capture by Chemical Looping Technology Anita SKULIMOWSKA, Asunción ARANDA, Luca DI FELICE [*] , Agnieszka CELIŃSKA Institutt for energiteknikk(IFE), Norway
10:30-10:50	BREAK		
10:50-11:10	Development and Scale-Up of Copper-Based Chemical Looping with Oxygen Uncoupling Kevin J. WHITTY [*] , JoAnn S. LIGHTY, Andrew FRY University of Utah, USA	CFD Simulation of a 10 kW Chemical Looping with Oxygen Uncoupling System: Effects of Process and Fuel Parameters Matthew A. Hamilton [*] , Kevin J. Whitty, JoAnn S. Lighty University of Utah, USA	Chemical Looping with Air Separation (CLAS) in a moving bed reactor with CuO/ZrO ₂ Oxygen Carriers Young Ku, Hsuan-Chih Wu [*] , Chia-Wei Chang, Shr-Han Shiu, Yao-Hsuan Tseng, Hao-Yeh Lee, Yu-Lin Kuo Taiwan University of Science & Technology, Taiwan, China
11:10-11:30	Use of Manganese Ores as Oxygen Carriers in Chemical-Looping Combustors for Solid Fuels Carl LINDERHOLM [*] , Anders LYNGBELT Chalmers University of Technology, Sweden	Numerical Simulation of In-Situ Gasification Chemical Looping Combustion- Effect of Operating Conditions Xiaojia Wang, Baosheng Jin, Yali Shao and Yong Zhang Southeast University, China	Reactivity and Stability of Various Supported Fe-Cu Composite Oxygen Carriers for CLHG Young Ku, Yu-Cheng Liu, Jing-An Chen, Yu-Lin Shen [*] , Hsuan-Chih Wu, YaoHsuan Tseng, Hao-Yeh Lee, Yu-Lin Kuo National Taiwan University of Science and Technology, Taiwan, China
11:30-11:50	Annular Carbon Stripper for Chemical-Looping Combustion of Coal Mao Cheng, Hongming Sun, Ye Lia, Zhenzhan Liu, Ningsheng Cai Tsinghua University, China	Development and Validation of 1D Process Model with Autothermal Operation of a 1 MW _{th} Chemical Looping Pilot Plant Peter OHLEMÜLLER [*] , Falah ALOBAD, Alberto ABAD, Juan ADANEZ, Jochen STRÖHLE, Bernd EPPLE TU Darmstadt, Germany	Theoretical Calculation and Experimental Evaluation of Interactions Between Ash and Oxygen Carriers in Chemical-Looping Combustion - K, Ca, Si and Fe ₂ O ₃ , Mn ₃ O ₄ and Synthesized ilmenite Dongmei Zhao, Robin Deniz [*] , Henrik Leion Chalmers University of Technology, Sweden
11:50-12:10	4000 Hours of Operation with Oxygen-Carriers in Industrial Relevant Scale (75 MWth) Bengt-Åke ANDERSSON, Fredrik LIND, Angelica CORCORAN, Henrik THUNMAN [*] Chalmers University of Technology, Sweden	System-Level Analysis of CO ₂ Mitigation Efficiency in Chemical-Looping Combustion Combined Cycle Power Plants Chen CHEN, Lu HAN, George M. BOLLAS [*] University of Connecticut, USA	Development of Mechanically Strong Manganese-based Oxygen Carriers by Spray Drying Method Marijke JACOBS [*] , Pieter WELTENS, Yoran DE VOS, Dazheng JING, Tobias MATTISSON, Frans SNUKERS Flemish Institute for Technological Research (VITO), Belgium
12:10-12:30	Implementation of Design Improvements into a 50 kWth CLC Pilot Plant with Coal Alberto ABAD [*] , José A. BUENO, Raúl PÉREZ-VEGA, Francisco GARCÍA-LABIANO, Pilar GAYÁN, Luis F. de DIEGO, Juan ADÁNEZ Instituto De Carboquímica (ICB-CSIC), Spain	Evolution and Reaction Mechanism of Iron-Based Oxide Microparticles in Chemical Looping Lang Qin, Zhuo Cheng, Mengqing Guo, Jonathan Fan, Liang-Shih Fan The Ohio State University, USA	Chemical Cycling Testing of Fe ₂ O ₃ -Al ₂ O ₃ Oxygen Carrier for Chemical Looping Combustion Juha Lagerboom, Toni Pikkariainen [*] VTT Technical Research Centre of Finland Ltd, Finland
12:30-14:00	LUNCH		
14:00-18:00	Poster Session	Lab Visit	Tour
18:30	Conference Dinner at Mandarin Garden Nanjing		

Sept.28 Friendship Hall 友谊厅

8:40-9:20
Keynote 4
Chair: Carl Johan LINDERHOLM
Overview of Operational Experience for Solid Fuels CLC
Juan Adánez
Instituto de Carboquímica (CSIC), Zaragoza, Spain

9:20-9:30 Parallel Sessions

Friendship Hall 友谊厅 Magnolia Hall 白玉兰厅 Tulip Hall 郁金香厅

Session A - 3 Pilot Plants
Chair: Anders Lyngfelt, Pilar Gayan Sanz

Session B - 4 Hydrogen Production & Gasification
Chair: Alberto Abad, Baowen Wang

Session E - 1 Calcium Looping
Chair: Haibo Zhao, Tomonao Saito

9:30-9:50
Chemical Looping Combustion Development in Korea
Jeom-in BAEK^{*}, Usik KIM, Hyoungun JO, Tae Hyoung EDM,
Joong Beom LEE, Ho-Jung RYU
Korea Electric Power Corporation Research Institute, Korea

Experimental Investigation on Chemical Looping Gasification of Biomass Char using Fe-Ni Bimetallic Oxygen Carrier
Zhen Huang, Fang He, Dezhen Chen
Chinese Academy of Sciences, China

Characterization of the Calcium Looping Performance of a Limestone in a Novel Twin-Bed Test Reactor
Antonio COPPOLA^{*}, Liberato GARGIULO, Fabrizio SCALA, Piero SALATINO
Consiglio Nazionale delle Ricerche, Italy

9:50-10:10
Performance of a 150 kW Chemical Looping Combustion Reactor System for Gaseous Fuels Using a Copper-based Oxygen Carrier
Øyvind LANGDØRGEN^{*}, Inge SAANUM, Nils Eriand L. HAUGEN
SINTEF Energy Research, Norway

Chemical Looping Dry Reforming of Methane using Mixed Oxides of Iron and Cerium
F.R. Garcia-Garcia, J.S. Dennis, I.S. Metcalfe
University of Cambridge, UK

Comparison of Energy Penalty in Post-Combustion and Pre-Combustion Calcium Looping Systems using Aspen Plus
DAI, Wei, BANERJEE, Subhdeep, AGARWAL, Ramesh K.
Washington University in St. Louis, USA

10:10-10:30
Piloting of Bio-CLC for BECCS
Toni Pikkariainen^{*}, Ilkka Hiltunen, Sebastian Teir
VTT Technical Research Centre of Finland Ltd, Finland

Effects of Support on the Performance of Chemical Looping Hydrogen Generation using Iron Oxides
Ma Shiwei^{*}, Xiang Wenguo, Chen Shiyi
Southeast University, China

CO₂ Capture Behaviour of Carbide Slag under High Concentration of Steam as Calcination Atmosphere during Calcium Looping Cycles
Wan Zhang^{*}, Yingjie Li, Zirui He, Chunmei Lu
Shandong University, China

10:30-10:50 BREAK

10:50-11:10
Plenary 3
Zero Emissions Pressurized Chemical Looping Combustion for Heavy Oil Extraction
Dennis Lu
Canmet ENERGY, Canada

Mixed Oxide Based Redox Catalysts for Hydrogen and Liquid Fuel Co-Production via a Hybrid Solar-Redox Scheme
Vasudev Haribal, Feng He, Fanxing Li^{*}
North Carolina State University, USA

Experiments on the Processes of biomass Chemical Looping Gasification based on CaO Sorbent
Yi Feng, Qinhui Wang, Hongtao Fan, Zhongyang Luo
Zhejiang University, China

11:10-11:30
Low Dioxin Emission from Chemical Looping Combustion of Digested Sludge
Xiuming HUA^{*}, Lidan YIN, Yidi WANG
Tsinghua University, China

Calcium Looping Process integrated with a Concentrated Solar Power System: Assessment of Limestone Performance
Claudio TREGAMBI, Fabio MONTAGNARO^{*}, Piero SALATINO, Roberto SOLIMENE
Università degli Studi di Napoli Federico II, Italy

11:30-11:50
Fluid Dynamic Evaluation of a Next Scale Reactor Design for Chemical Looping Combustion of Gaseous Fuels
Michael STOLLHOF^{*}, Stefan PENTHOR, Karl MAYER, Hermann HOFBAUER
Vienna University of Technology, Austria

Chemical Looping Combustion and Gasification Technologies: Pilot Plant Process Development and Operation
Dikai XU, Tien-Lin HSIEH, Andrew TONG^{*}
Ohio State University, USA

Experiments on in-situ Gasification Chemical Looping Combustion (IG-CLC) of Plastic Waste with CaO-Decorated Iron Ore for Inhibiting Chlorobenzene
Jinxing Wang, Haibo Zhao, Jinchen Ma
Huazhong University of Science and Technology, China

11:50-12:10	Effect of Solid Residence Time on CO ₂ Selectivity in a Semi-Continuous Chemical Looping Combustor <i>Ho-Jung RYU[#], Dong-Ho LEE, Dowon SHUN, Jong-Ho MOON, Jeom-In BAEK</i> Korea Institute of Energy Research, Korea	Carbon Deposition and Sintering Characteristics on Iron-Based Oxygen Carriers in Catalytic Cracking Process of Coal Tar <i>Xu JIANG, Yangpeng LI, Fei HUANG, Yongzhuo LIU, Cuiqing WANG[#]</i> Qingdao University, China	HCl Capture Performance of Cycled Mg-stabilized Carbide Slag from Calcium Looping Cycles for CO ₂ Capture <i>Changyun Chi[#], Yingjie Li, Lei Shi, Xiaotang Ma</i> Shandong University, China
12:10-12:30	The Roles of Iron-Based Oxygen Carriers in Pressurized Chemical Looping Combustion of Solid Fuel <i>Liangyong Chen, Zhen Fan, Fang Liu, Jinhua Bao, Heather Nikolic, Kunlei Liu</i> University of Kentucky, USA		Effect of dilute CH ₄ and CO ₂ concentration on the stability of limestone in Calcium Looping Processes <i>Sovankumar Patel, Priscilla Tremalin, Behdad Moghtaderi, James Sandford, Kalpit Shah[#]</i> The University of Newcastle, Australia
12:30-14:00	LUNCH		
Sept.28	Friendship Hall 友谊厅		
	Session A - 4 Pilot Plants Chair: Shi-ying Lin, Andrew Tong		
14:00-14:20	Commercial Scale Preparations of CuO-Fe ₂ O ₃ -Alumina Oxygen Carrier with various techniques: Bench Scale Fluidized Bed Tests with Coal/Air and Methane/Air and Pilot Scale (51 Kwth) Chemical Looping Combustion Tests With Methane/Air <i>Ranjani Siriwardane[#], Hanjing Tian, Jarrett Riley, William Benincosa, Douglas Straub, Justin Weber, George Richards</i> National Energy Technology Center (NETL), USA		
14:20-14:40	Fate of Sulfur in Chemical Looping Combustion of Gaseous Fuels Using a Copper Based Oxygen Carrier <i>Robert F. PACHLER[#], Mario KOLLERITS, Karl MAYER, Stefan PENTHOR, Hermann HOFBAUER</i> Vienna University of Technology, Austria		
14:40-15:00	Chemical Looping Combustion of High Sodium Lignite in the Fluidized Bed: Combustion Performance and Sodium Transfer <i>Tao Song, Ernst-Ulrich Hartge, Stefan Heinrich, Laihong Shen, Joachim Werther</i> Hamburg University of Technology, Germany		
15:00-15:20	Practical Potential and Technological Limitations of Power Generation via Chemical Looping Combustion of Gaseous Fuels <i>Florian ZEROBIN, Tobias PRÖLL</i> University of Natural Resources and Life Sciences, Austria		
15:20-15:40	Reactivity of Ilmenite in Pressurized Chemical-looping Combustion with CO <i>Xuao Lu[#], Dennis Y. Lu, Firas N. Ridha, Robin W. Hughes</i> North China Electric Power University, China		
15:40-16:00	BREAK		
16:00-17:00	Panel Discussion Chair: Kevin Whitty		

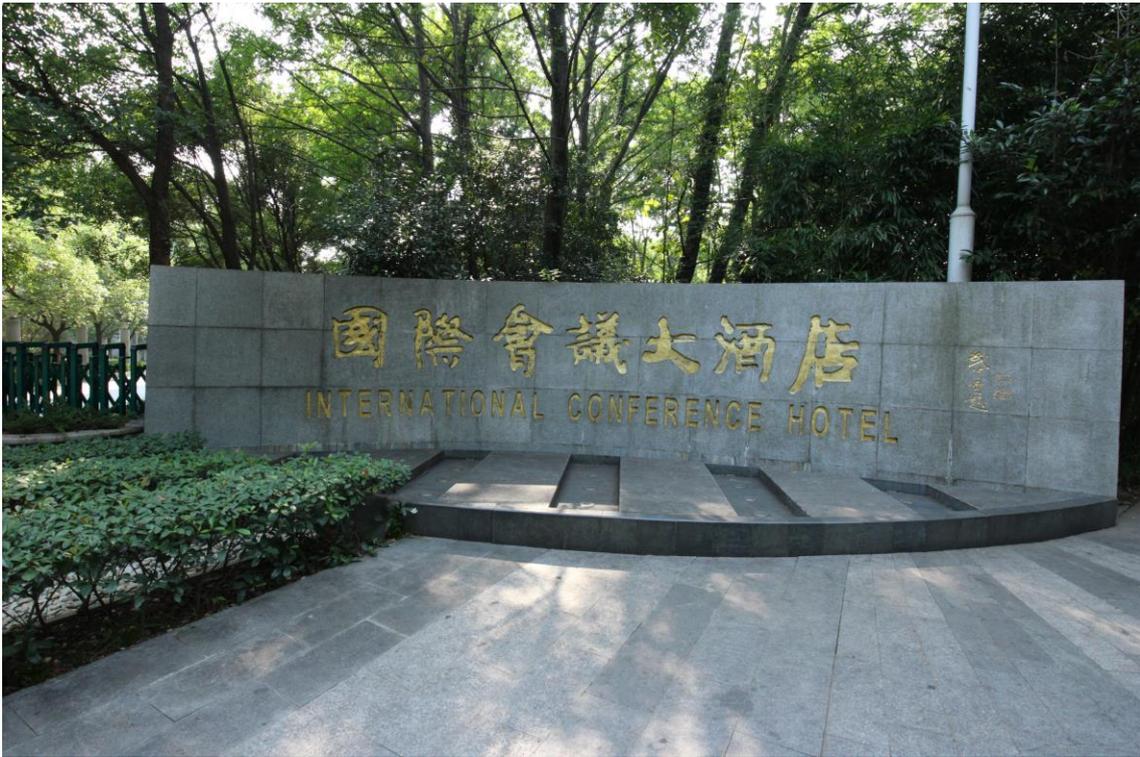


圖 1. 4th International Conference on Chemical Looping 舉辦地點酒店



圖 2. 4th International Conference on Chemical Looping 會場

三、心得

目前本所積極進行能源國家型科技計畫之「淨碳技術領域」相關研究發展計畫，並配合能源局能專計畫項下之「潔淨低碳多元應用暨氣體處理技術發展」計畫，期望從永續發展觀點推動自主潔淨能源技術之建立。本次出國公差為執行「碳基能源永續潔淨利用技術發展」分支計畫，筆者代表本所化學組淨碳分組出席 2016 年第四屆化學迴圈國際研討會(4th International Conference on Chemical Looping)，並以口頭報告方式發表研究成果論文“Study on Combustion-supporting Behavior of Ilmenite in Chemical Looping Combustion Process”，期望藉由本次會議，了解與掌握國際間化學迴圈燃燒程序發展之現況與趨勢，拓展與國際學者專家之關係及國際合作。本報告將依序分別選擇重點摘要於下文中。

(一) 4th International Conference on Chemical Looping 大會議程

第四屆化學迴圈國際研討會於 105 年 9 月 25 日至 9 月 28 日在大陸南京國際會議大酒店舉行，由大陸東南大學主辦，此會議提供國際間化學迴圈技術相關研究機構之工程師、研究人員、教授等專家學者一個開放平台，分享與展示他們的最新研究成果與創新思想。大會議題以化學迴圈技術為主軸，包含該技術目前的發展趨勢和未來規劃與需求，衍生相關五大技術議題進行專題討論，包括先導工廠測試、氫氣產物與氣化反應、載氧體分析與改質、化學迴圈模型建構，以及鈣迴圈技術討論。

ICCL 2016 會議於 9 月 25 日(星期日)開始註冊與報到(圖 3~圖 4)；大會的開幕典禮於 9 月 26 日(星期一)早上舉行(圖 5~圖 6)，本屆大會由大陸東南大學的沈來宏教授擔任主席，典禮流程包括貴賓致詞、開幕等，在大會主席沈教授致詞歡迎各國與會嘉賓後，即開始大會的會議議程，分為主題演講(Keynote Speech)、全體會議(Plenary Session)、論文口頭發表、及壁報論文展示四部分，將分章節依序描述於本報告中。



圖 3. ICCL 2016 會場內之報到櫃檯



圖 4. 筆者攝於 ICCL 2016 大會場館



圖 5. 開幕典禮會場內景象



圖 6. 開幕典禮大會主席致詞

1. Keynote Speech

大會於星期一早上安排兩場 Keynote Speech，星期二與星期三早上各安排一場 Keynote Speech；相關各應邀講員之資料與講題列舉如下：

Keynote 1- Chemical Looping Partial Oxidation

Prof. Liang-Shih Fan

Ohio State University, USA

Keynote 2- Reactor for Chemical-Looping Combustion of Solid Fuels

Prof. Lai-Hong Shen

Southeast University, China

Keynote 3- Chemical-Looping Combustion of Solid Fuels – What Is Needed To Reach Full-scale

Prof. Anders Lyngfelt

Chalmers University of Technology, Sweden

Keynote 4- Overview of Operational Experience for Solid Fuels CLC

Dr. Juan Adanez

Instituto de Carboquimica (CSIC), Zaragoza, Spain

由於篇幅考量，本報告選擇與本單位研究較相關之演講分別摘要重點於下文中。

(1) Chemical Looping Partial Oxidation

本篇 Keynote Speech 排定於 9 月 26 日早上，演講者為 Prof. Liang-Shih Fan 來自 Ohio State University, USA。該演講之重要資料如圖 7~圖 21 所示。該演講討論混和金屬氧化物作為化學迴圈載氧體時，其離子擴散、奈米結構、粒子表面的變化，以及其氧化還原機制。講者於演講中也提到研究團隊對於重製技術(reforming process)例如甲烷的氧耦合作用(oxygen coupling of methane)以及直接氣化技術如何達成高純度合成氣目標的相關研究，同時講者也將該研究的模擬方法與技術經濟分析與商業化潛力一起進行闡述。



圖 7. Keynote Speech 1-1

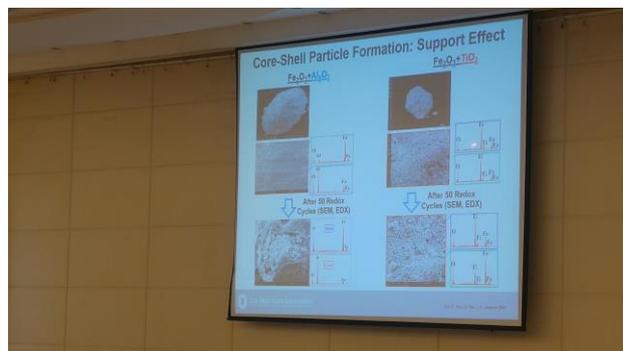


圖 8. Keynote Speech 1-2

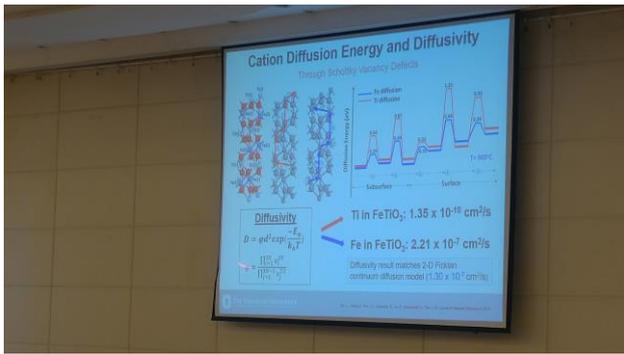


圖 9. Keynote Speech 1-3

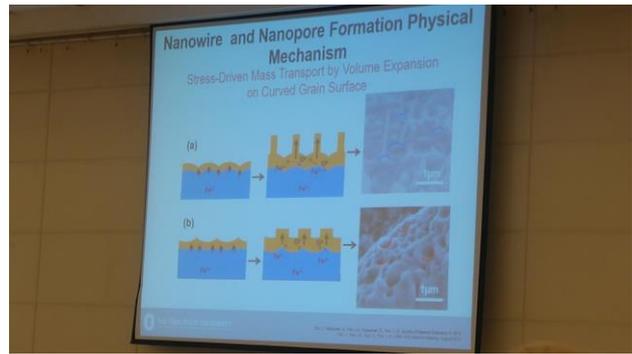


圖 10. Keynote Speech 1-4

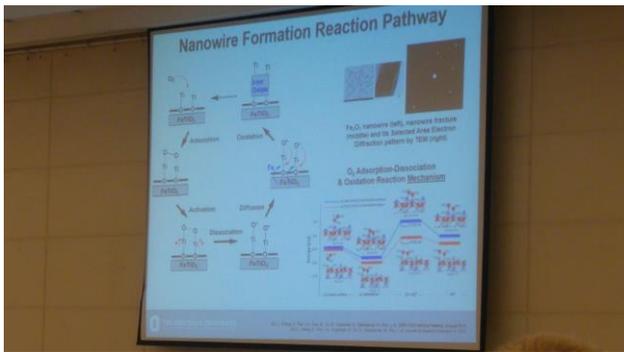


圖 11. Keynote Speech 1-5

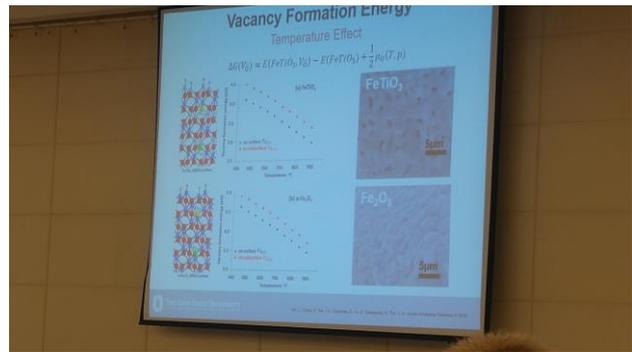


圖 12. Keynote Speech 1-6

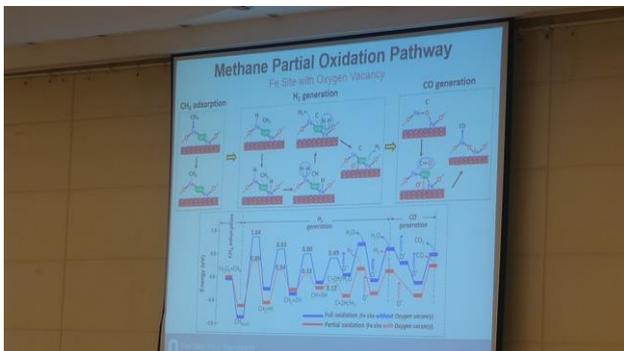


圖 13. Keynote Speech 1-7

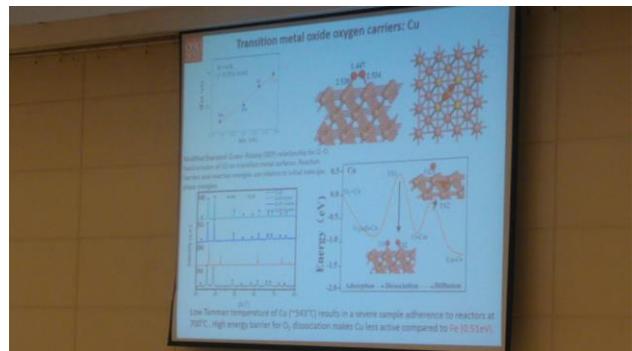


圖 14. Keynote Speech 1-8

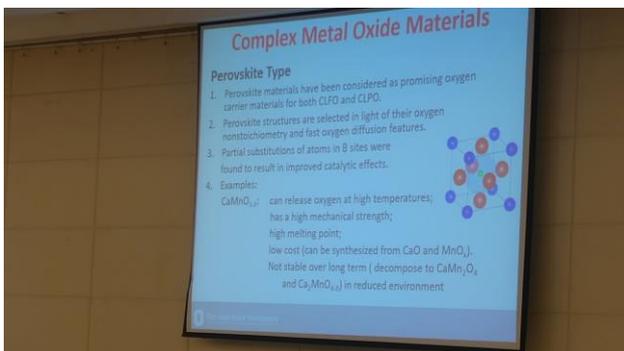


圖 15. Keynote Speech 1-9

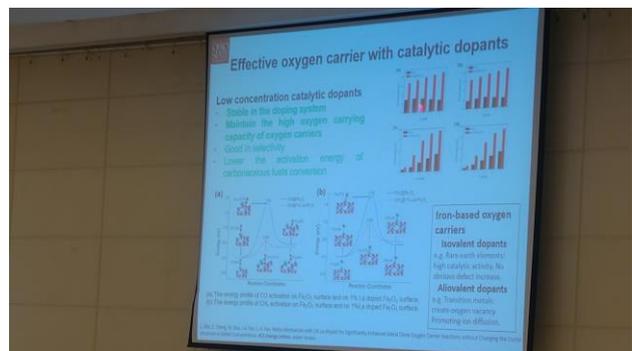


圖 16. Keynote Speech 1-10

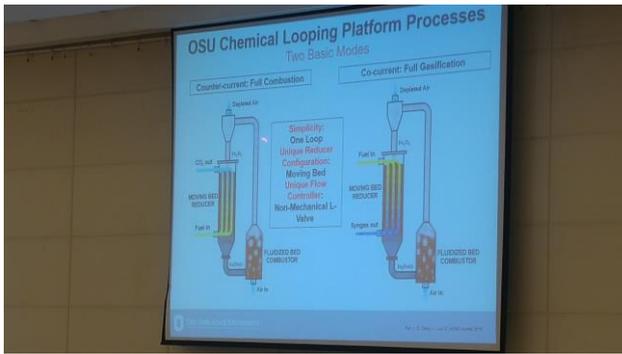


圖 17. Keynote Speech 1-11

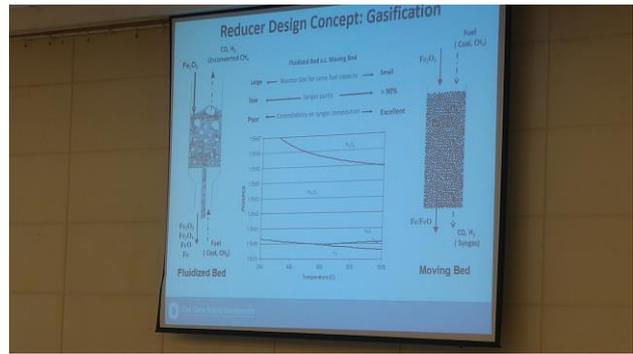


圖 18. Keynote Speech 1-12

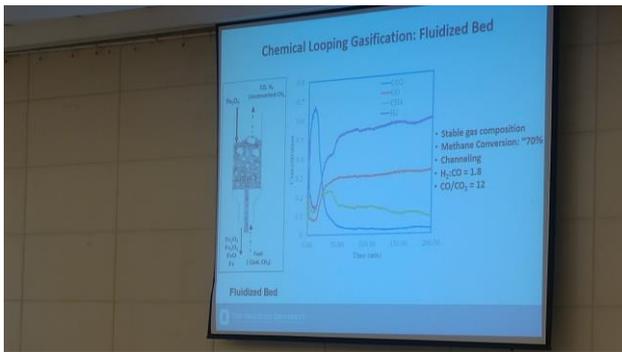


圖 19. Keynote Speech 1-13

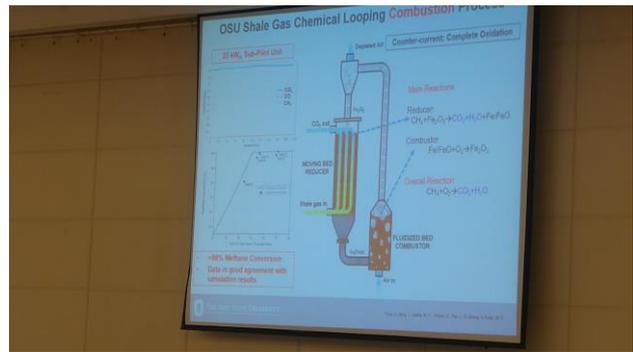


圖 20. Keynote Speech 1-14

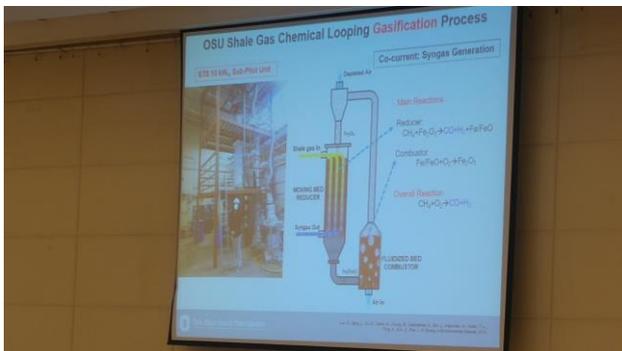


圖 21. Keynote Speech 1-15

(2) Reactor for Chemical-Looping Combustion of Solid Fuels

演講者為 Prof. Lai-Hong Shen，沈教授為大陸東南大學教授，同時為本次大會主席，演講中提到時至今日固態燃料用於化學迴圈技術已有不少研究，主要實驗研究主題為載氧體、空氣反應器、燃料反應器、以及燃料餵料方法等等。沈教授提到了一種將固態燃料用於具有氣泡式塔的燃料反應器，並且展示了研究團隊目前用於觀察流場的化學迴圈冷流模型，用以研究顆粒循環與流化現象，也提到塔式燃料反應器對壓降的影響。塔式燃料反應器的想法是在下方床體中引入固態燃料，其中固態燃料被氣化後大部分轉化為氣態燃料。在上方床體中，由下方床體夾帶的可燃氣體和固體將與載氧體接觸，如此將可提高轉化率，該演講之重要資料如圖 22~圖 43 所示。

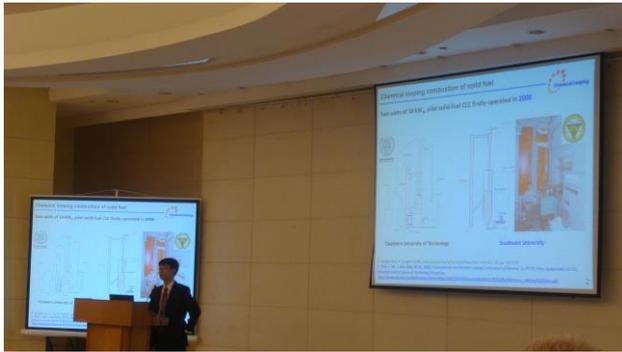


圖 22. Keynote Speech 2-1

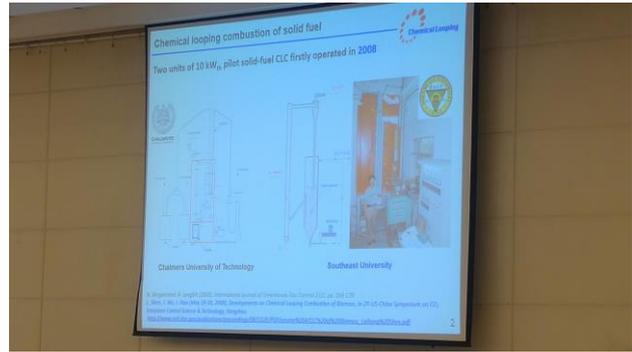


圖 23. Keynote Speech 2-2

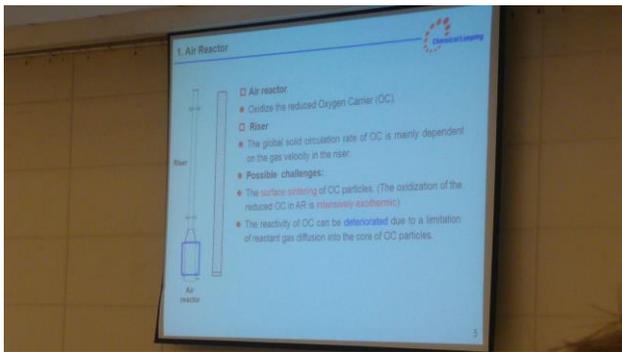


圖 24. Keynote Speech 2-3

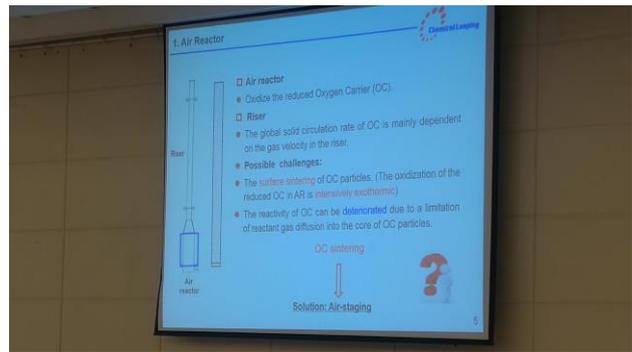


圖 25. Keynote Speech 2-4

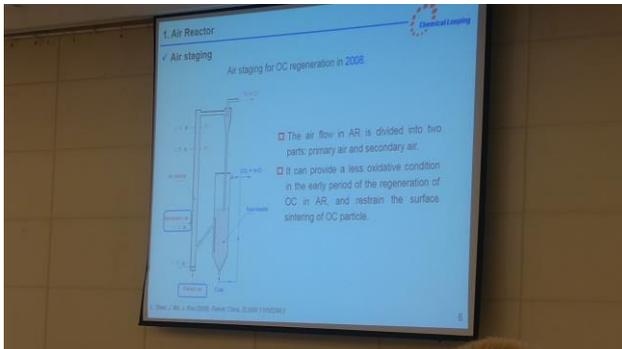


圖 26. Keynote Speech 2-5

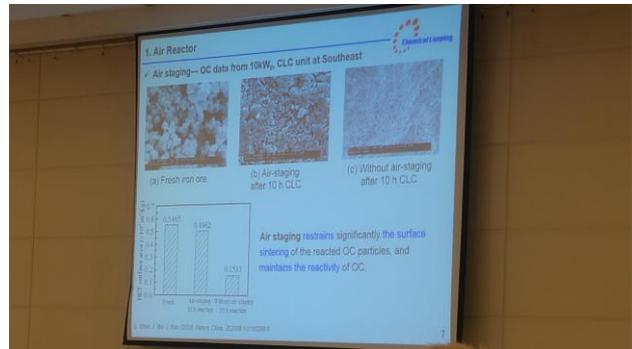


圖 27. Keynote Speech 2-6

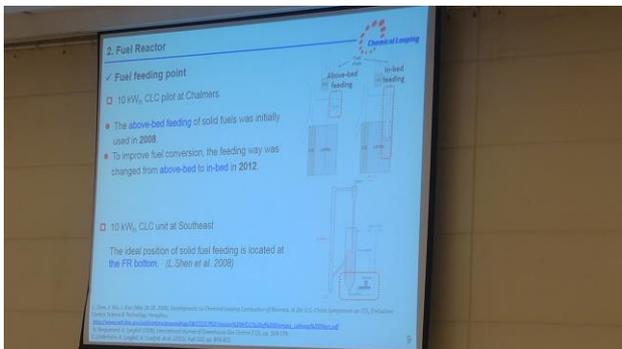


圖 28. Keynote Speech 2-7

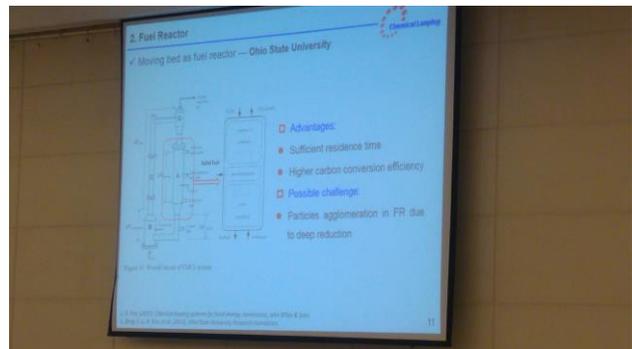


圖 29. Keynote Speech 2-8

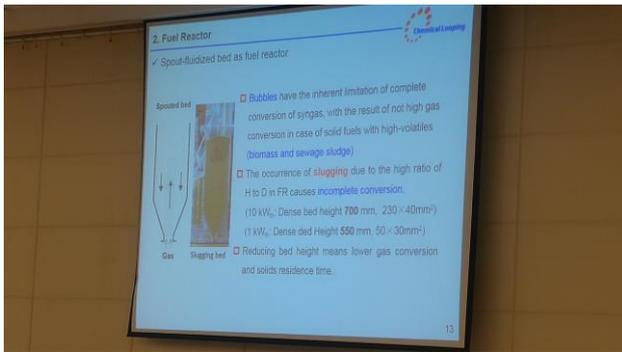


圖 30. Keynote Speech 2-9

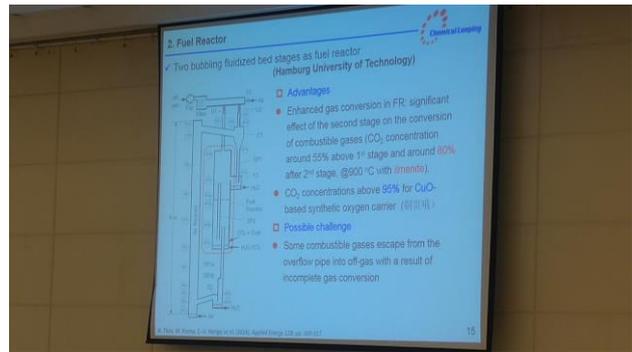


圖 31. Keynote Speech 2-10

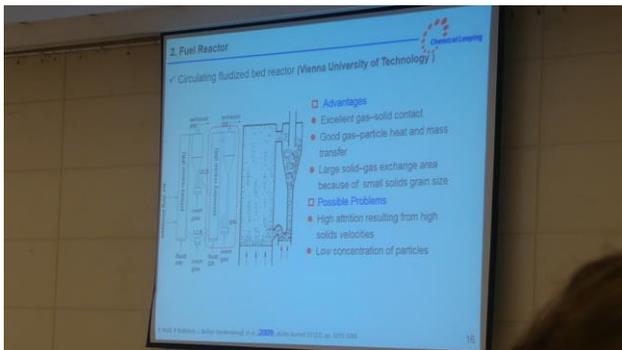


圖 32. Keynote Speech 2-11

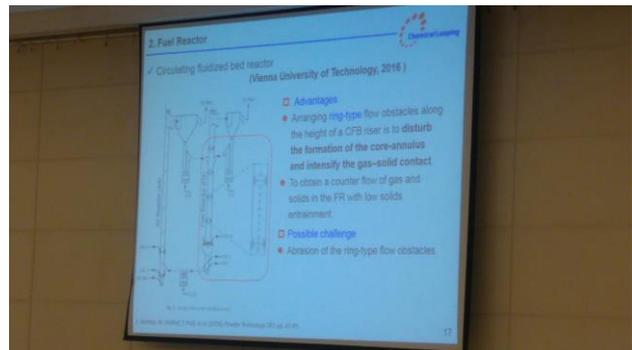


圖 33. Keynote Speech 2-12

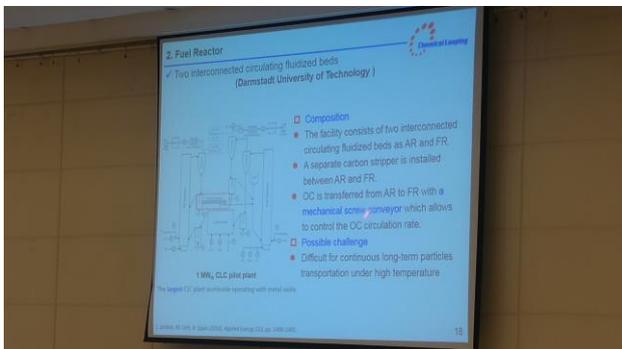


圖 34. Keynote Speech 2-13

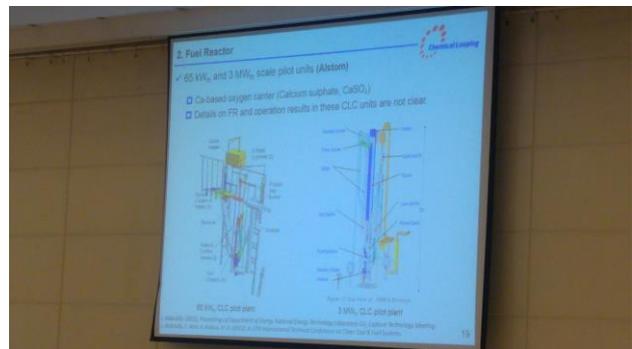


圖 35. Keynote Speech 2-14

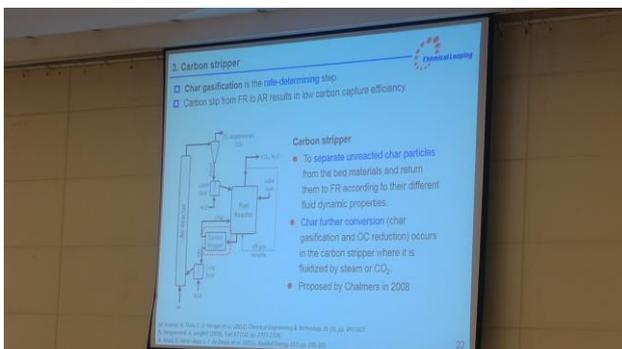


圖 36. Keynote Speech 2-15

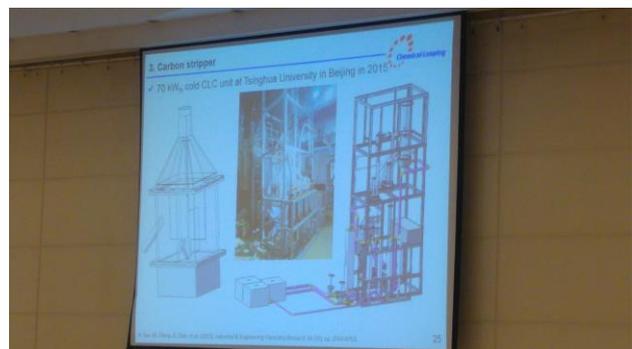


圖 37. Keynote Speech 2-16

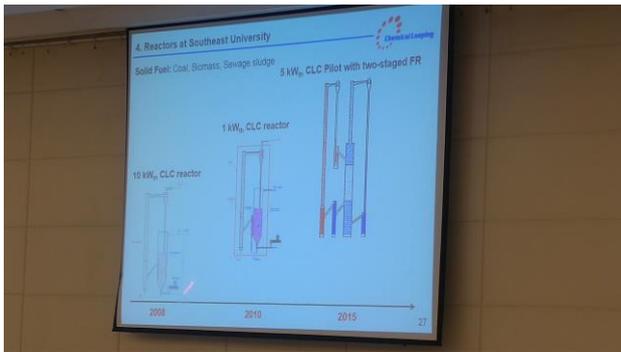


圖 38. Keynote Speech 2-17

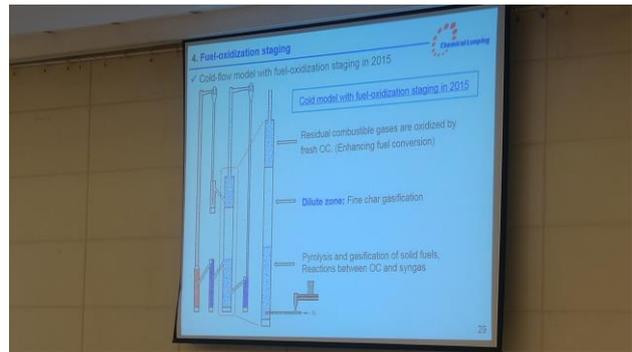


圖 39. Keynote Speech 2-18



圖 40. Keynote Speech 2-19

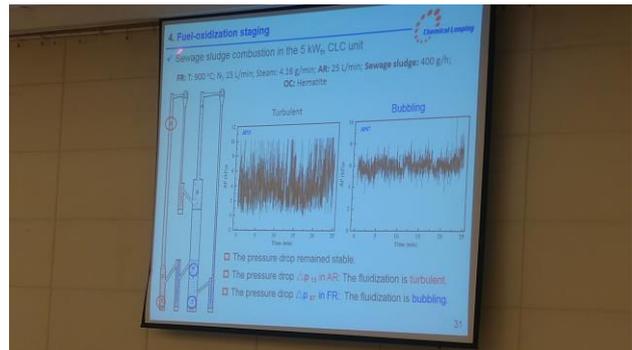


圖 41. Keynote Speech 2-20

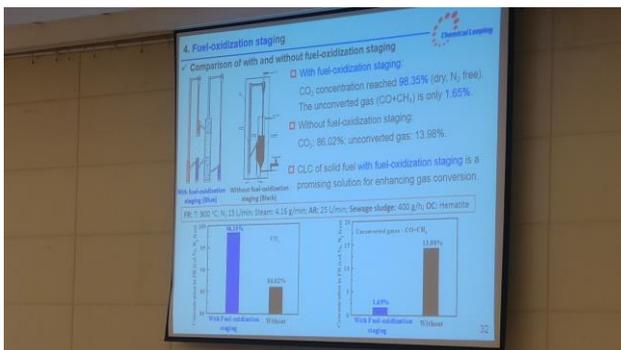


圖 42. Keynote Speech 2-21

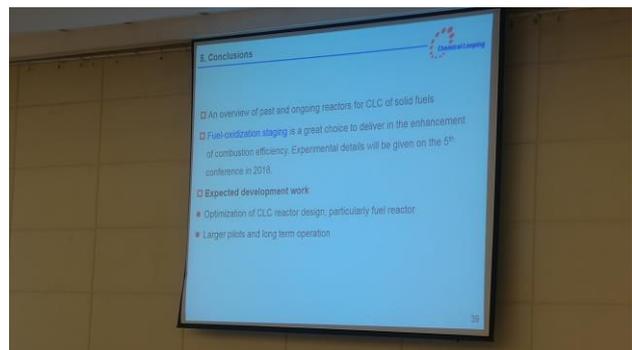


圖 43. Keynote Speech 2-22

2. Plenary Session

本次大會共安排三場次全體會議(Plenary Session)，本報告中摘錄第三場全體會議演講陳述，本篇大會演講排定於 9 月 28 日早上，演講主題為 “Zero Emissions Pressurized Chemical Looping Combustion for Heavy Oil Extraction”，演講者 Dennis Lu 來自加拿大的 CanmetENERGY。該演講之重要資料如圖 44~圖 67。

其內容以模擬與實驗方式於化學迴圈燃燒程序中增加壓力(Pressurized Chemical Looping Combustion, PCLC)，認為增加壓力將能夠增加系統效率，整個程序只需極少的額外電力，且能在燃料反應器的出口採集到高壓二氧化碳，如此二氧化碳捕獲率將提高，減少二氧化碳排放量。該研究也以實驗方法確認加拿大鈦鐵礦為 PCLC 的良好載氧體，且其成本低廉且對環境衝擊極小。另外，CanmetENERGY 計畫發展 PCLC 技術達成 200kW_{th} 目標，以產生氫氣、蒸汽、以及電力。



圖 44. Plenary Session 1-1



圖 45. Plenary Session 1-2

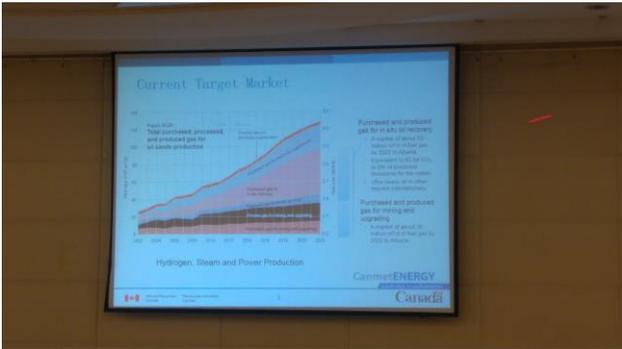


圖 46. Plenary Session 1-3



圖 47. Plenary Session 1-4



圖 48. Plenary Session 1-5

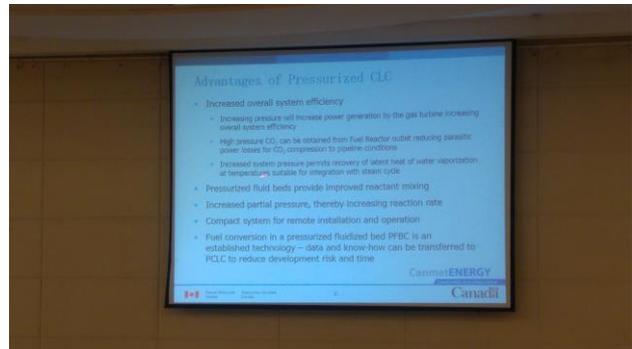


圖 49. Plenary Session 1-6

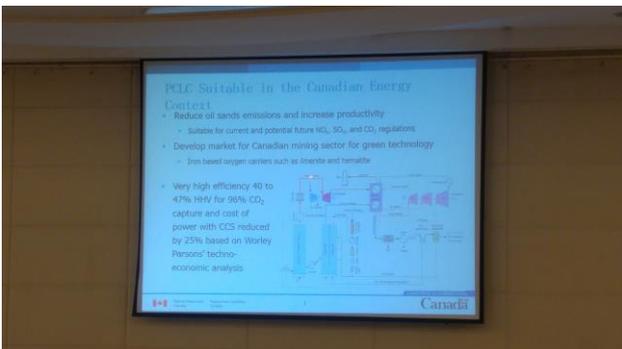


圖 50. Plenary Session 1-7

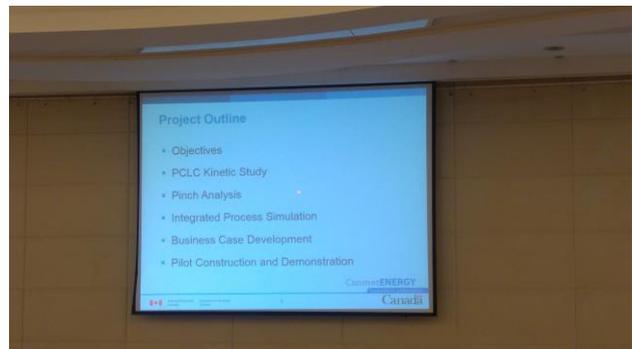


圖 51. Plenary Session 1-8

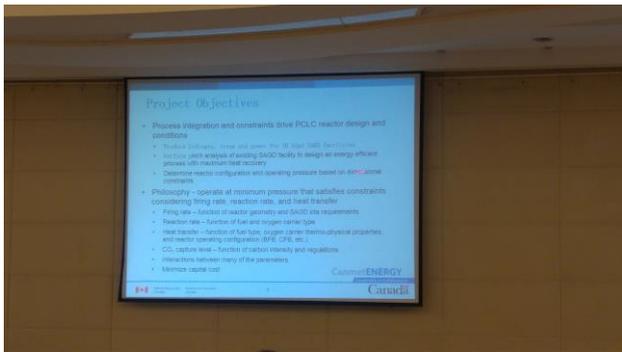


圖 52. Plenary Session 1-9

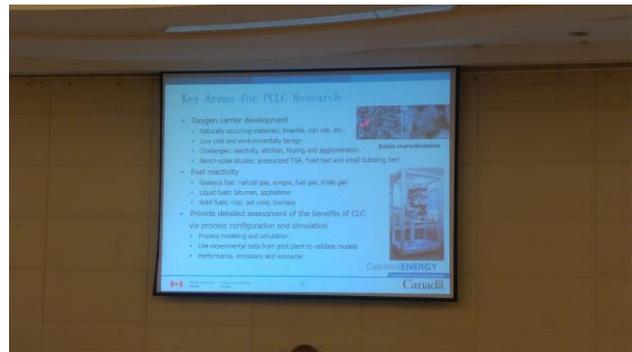


圖 53. Plenary Session 1-10

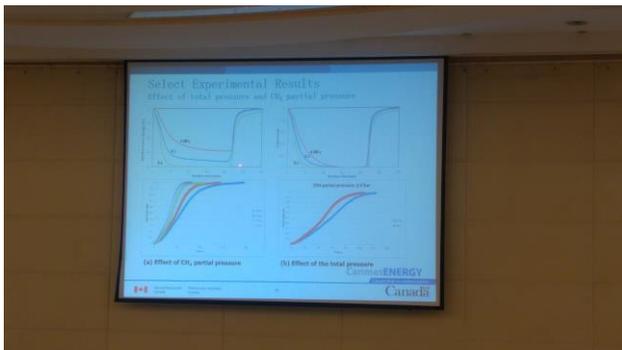


圖 54. Plenary Session 1-11

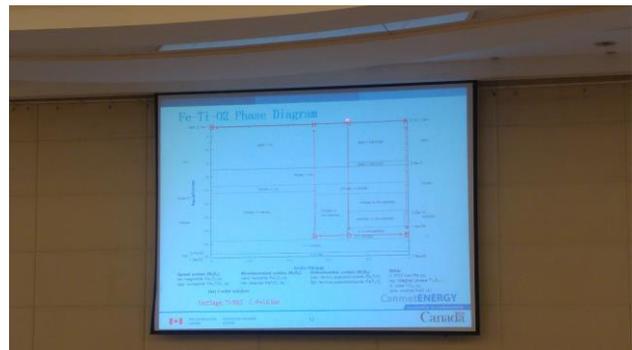


圖 55. Plenary Session 1-12

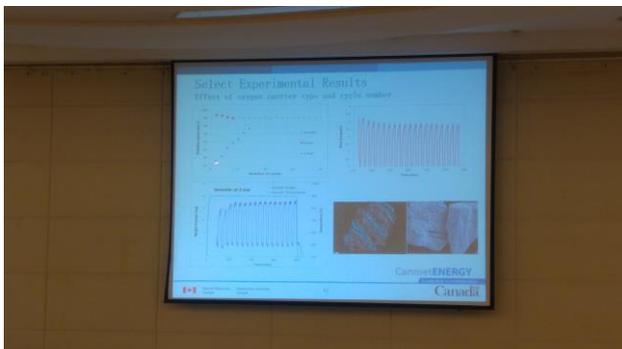


圖 56. Plenary Session 1-13

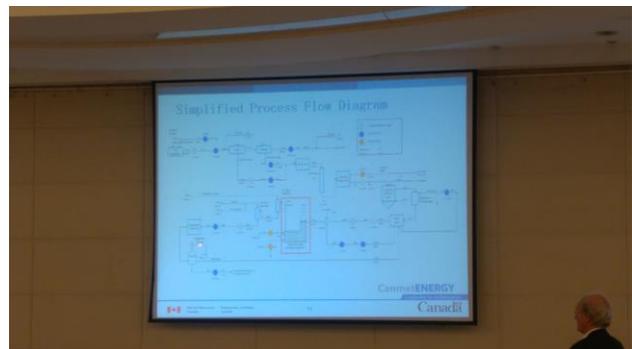


圖 57. Plenary Session 1-14

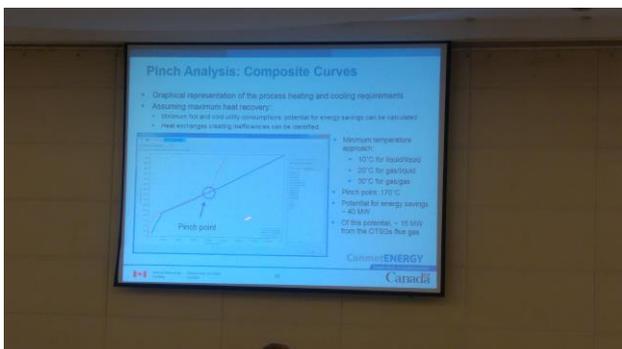


圖 58. Plenary Session 1-15

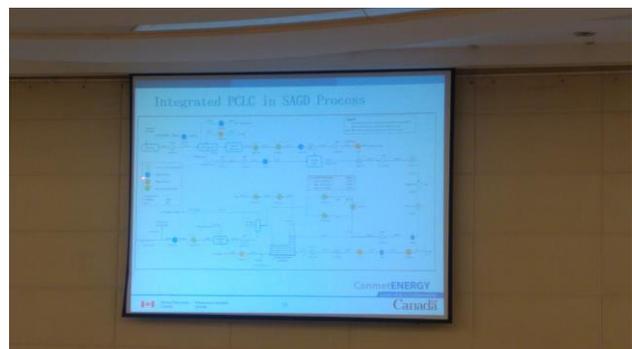


圖 59. Plenary Session 1-16

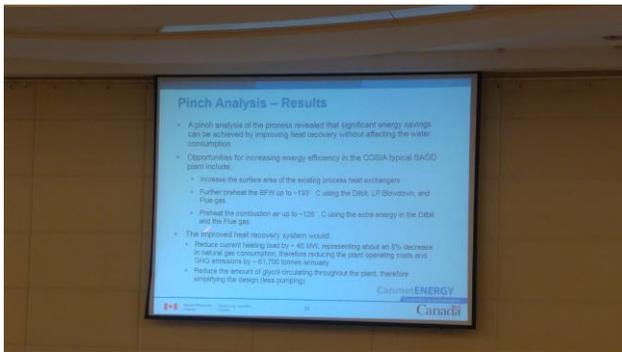


圖 60. Plenary Session 1-17

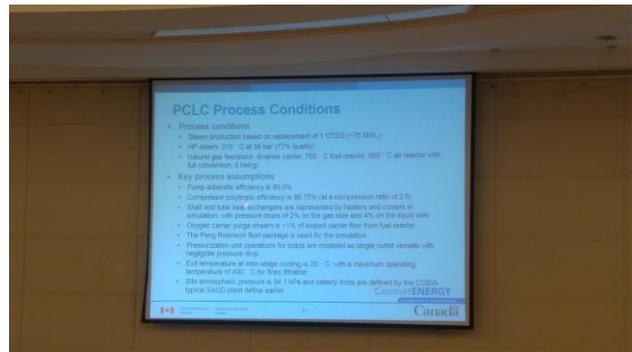


圖 61. Plenary Session 1-18

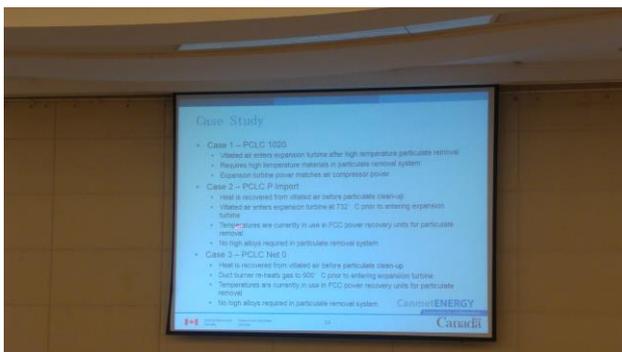


圖 62. Plenary Session 1-19



圖 63. Plenary Session 1-20

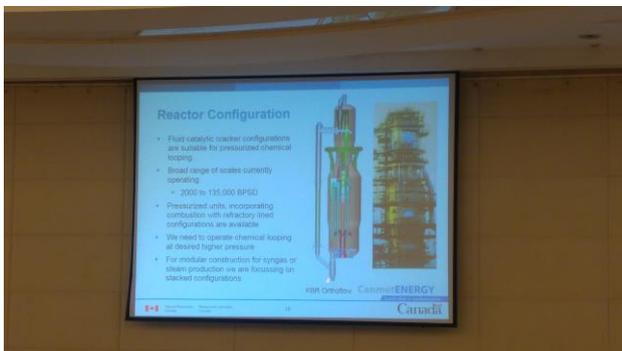


圖 64. Plenary Session 1-21

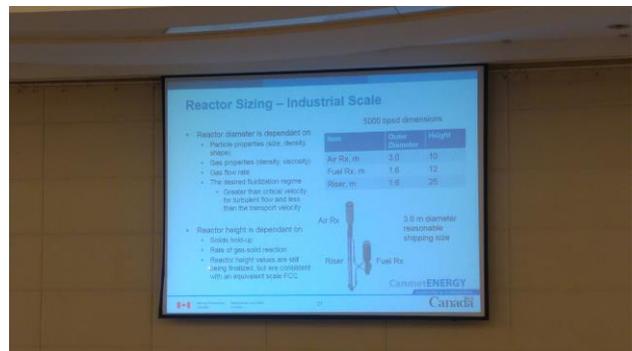


圖 65. Plenary Session 1-22

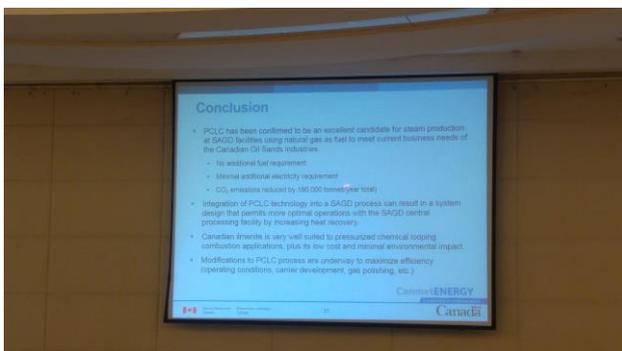


圖 66. Plenary Session 1-23



圖 67. Plenary Session 1-24

3. Oral Paper Sessions

ICCL 口頭論文發表議程每天大致分為四個時段，同時各有三個平行場次之口頭論文發表，每個時段至多安排五場專題演講，其間則有中場休息為區隔。技術議題涵蓋先導工廠測試、氫氣產物與氯化反應、載氧體分析與改質、化學迴圈模型建構，以及鈣迴圈技術討論，本次大會口頭論文篇數多達 94 篇。

(1) 本團隊在這次 ICCL 大會中發表之研究成果論文

筆者參與 2016 年第四屆化學迴圈國際研討會(4th International Conference on Chemical Looping)，發表研究成果論文“Study on Combustion-supporting Behavior of Ilmenite in Chemical Looping Combustion Process”，口頭演講時間安排於 9 月 26 日中午 12:10 ~ 12:30，但原本安排於筆者前一場的講者並未出席，所以論文發表演講提前開始，本場次會議主持人為台科大曾堯宣教授以及來自西班牙國家研究會的 Dr. Francisco Garcia Labiano。筆者演講內容之簡報如附錄所示。

筆者之簡報獲得在場與會者與會議主持人之熱烈回應討論(圖 68~圖 69)，原本安排問題時間為 5 分鐘，因該時段在筆者後並無安排其他演講，所以共討論了 10 分鐘，能與國際學者專家討論、分享本所近年來在化學迴圈燃燒程序應用在淨碳技術的研究成果，實為難得經驗。



圖 68. 筆者報告情形由會議工作人員所拍攝



圖 69. 報告後問題討論情形

(2) ICCL 大會中相關代表性口頭發表論文

基於篇幅及研究相關性考量，本報告摘錄前述主題「載氧體分析與改質」之代表性論文。

A. Reactivity of Oxygen Carriers after Recycling in Chemical Looping Combustion of Coal

此論文由 Japan Coal Energy Center, Japan 的研究人員所發表，內容呈現了鈦鐵礦以及 $\text{Fe}_2\text{O}_3/\text{Al}_2\text{O}_3$ 作為載氧體時，在經過 CO 和 CO/CO_2 還原氣氛下的化學迴圈燃燒，其反應性及形態的變化。演講內容摘錄如圖 70~圖 73 所示。

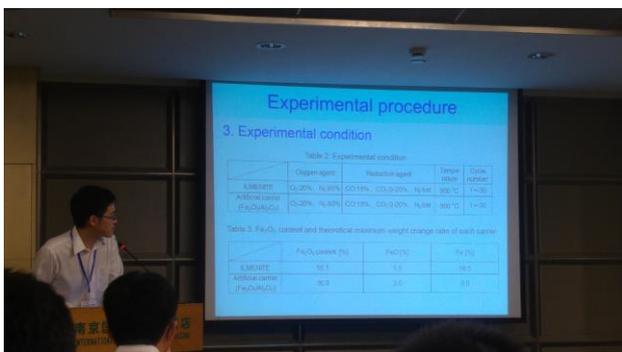


圖 70. Oral Paper 1-1

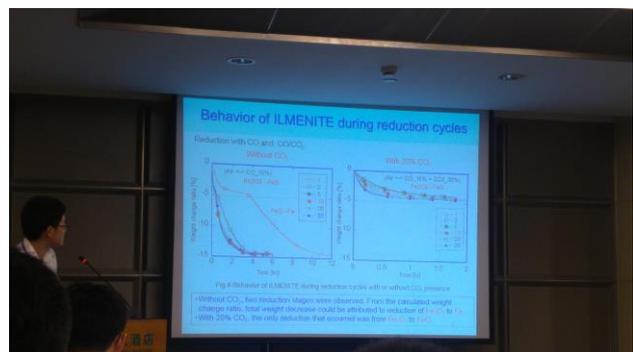


圖 71. Oral Paper 1-2

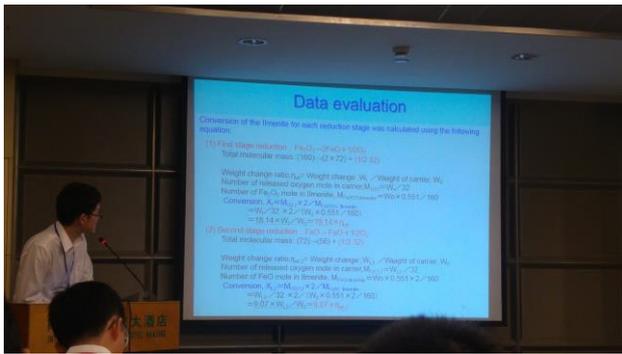


圖 72. Oral Paper 1-3

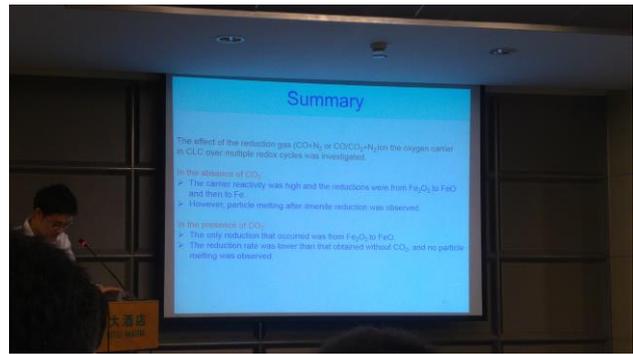


圖 73. Oral Paper 1-4

B. Selective Oxidations via Chemical Looping: Selective Combustion of Hydrogen in Hydrocarbon Mixtures

此論文由 University of Cambridge, UK 的研究團隊所發表，他們將顆粒狀載氧體改質，並研究它們在 C₂H₄ 存在下選擇性燃燒 H₂ 的活性、選擇性和儲氧能力。研究發現載氧體在 H₂ 存在下對 C₂H₄ 較具惰性，但在缺少 H₂ 的條件下，載氧體對 C₂H₄ 更具反應性。演講內容摘錄如圖 74~圖 80 所示。



圖 74. Oral Paper 2-1

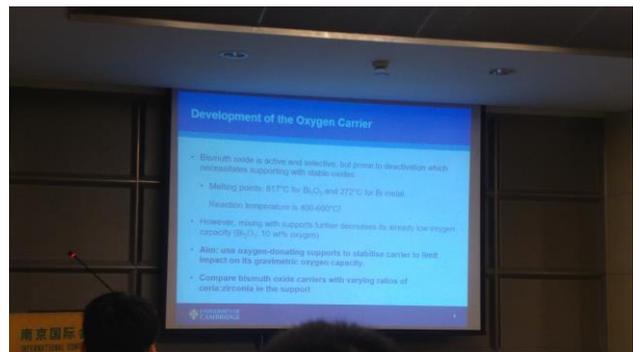


圖 75. Oral Paper 2-2

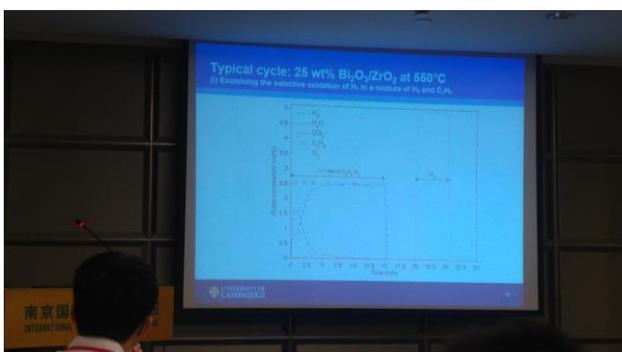


圖 76. Oral Paper 2-3

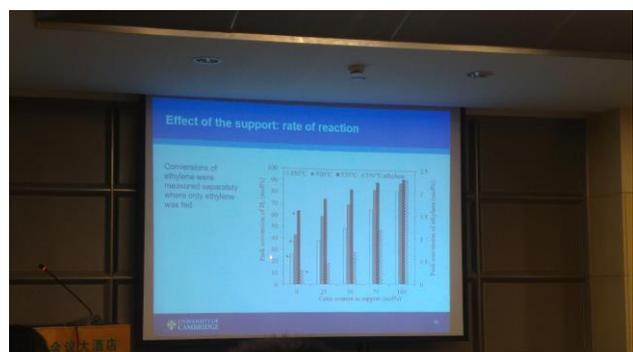


圖 77. Oral Paper 2-4

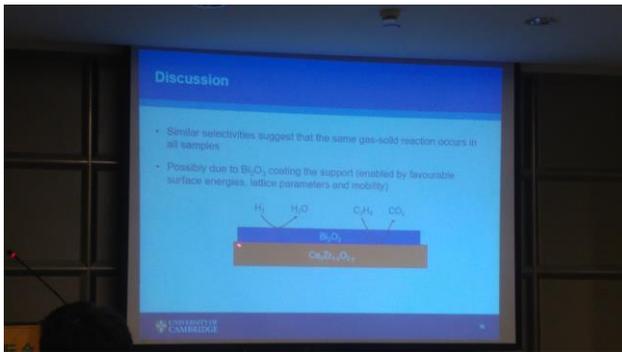


圖 78. Oral Paper 2-5

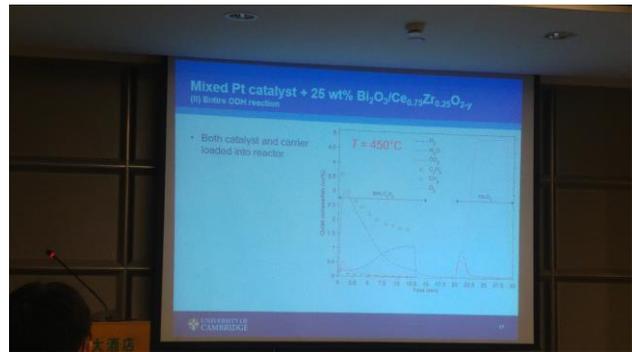


圖 79. Oral Paper 2-6



圖 80. Oral Paper 2-7

4. Poster Session

大會在壁報論文區備有咖啡、茶水及點心，供與會者於中場休息時可在此區聚集，參觀壁報論文展示，並互相討論(圖 81~圖 83)。

依大會議程安排，壁報論文自第一天起開始張貼，即從早上 8:30 開始到傍晚 18:00，持續展示至會議結束。筆者亦抽空參閱了解壁報論文發表，以了解各研究機關團體之研究成果與現況。本次會議壁報論文共有 49 篇，本報告摘錄數篇具相關性之論文展示於後，概分為下列五大領域(圖 84~圖 90)。

(1) Pilot Plants

- A. “Enhanced Fuel Conversion by Staging Oxidization in a Continuous Chemical Looping Reactor based on iron ore oxygen carrier” (圖 84), Nanjing Institute of Technology & Southeast University, China

(2) Hydrogen Production & Gasification

- A. “Process Simulation of a Hydrogen Production Chemical Looping Process with Various Coal Sources” (圖 85), National Taiwan University of Science & Technology, Taiwan

(3) Oxygen Carrier

- A. “Chemical Looping Combustion of Coal by Using Limestone with In-Situ Desulfurization” (圖 86), Instituto de Carboquímica, Spain
- B. “Characterization and Evaluation of Prepared TiO₂ and Al₂O₃ Supported Fe₂O₃ Oxygen Carriers for CLC” (圖 87), National Taiwan University of Science & Technology, Taiwan

(4) Modelling

- A. “Numerical Simulation for Chemical Looping Combustion of Circulating Fluidized Bed Reactor” (圖 88), National Taiwan University of Science & Technology, Taiwan
- B. “Computational Fluid Dynamics Simulation of a Cold Model of an Interconnected Fluidized Bed for Chemical Looping Combustion” (圖 89), CSIRO, Australia

(5) Calcium Looping

- A. “Characteristic of CoTiO_3 as Oxygen Carrier” (圖 90), Chonbuk National University, Korea



圖 81. 大會中場休息於壁報發表場所景象-1

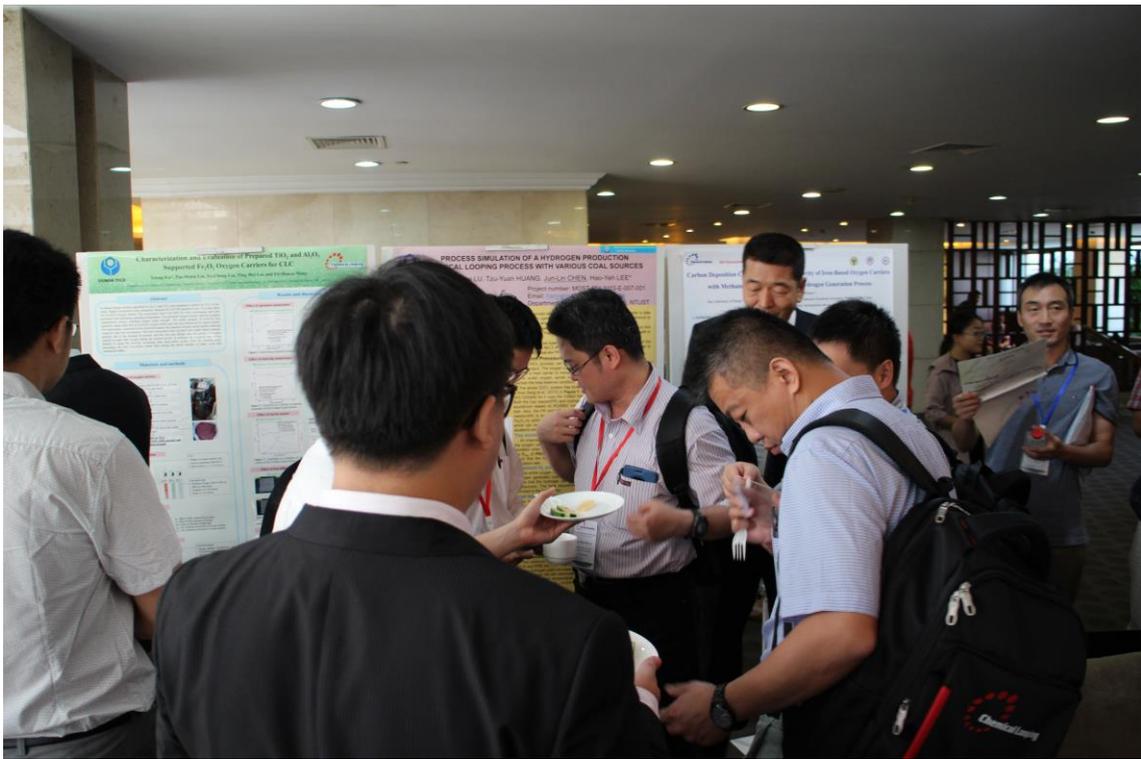


圖 82. 大會中場休息於壁報發表場所景象-2

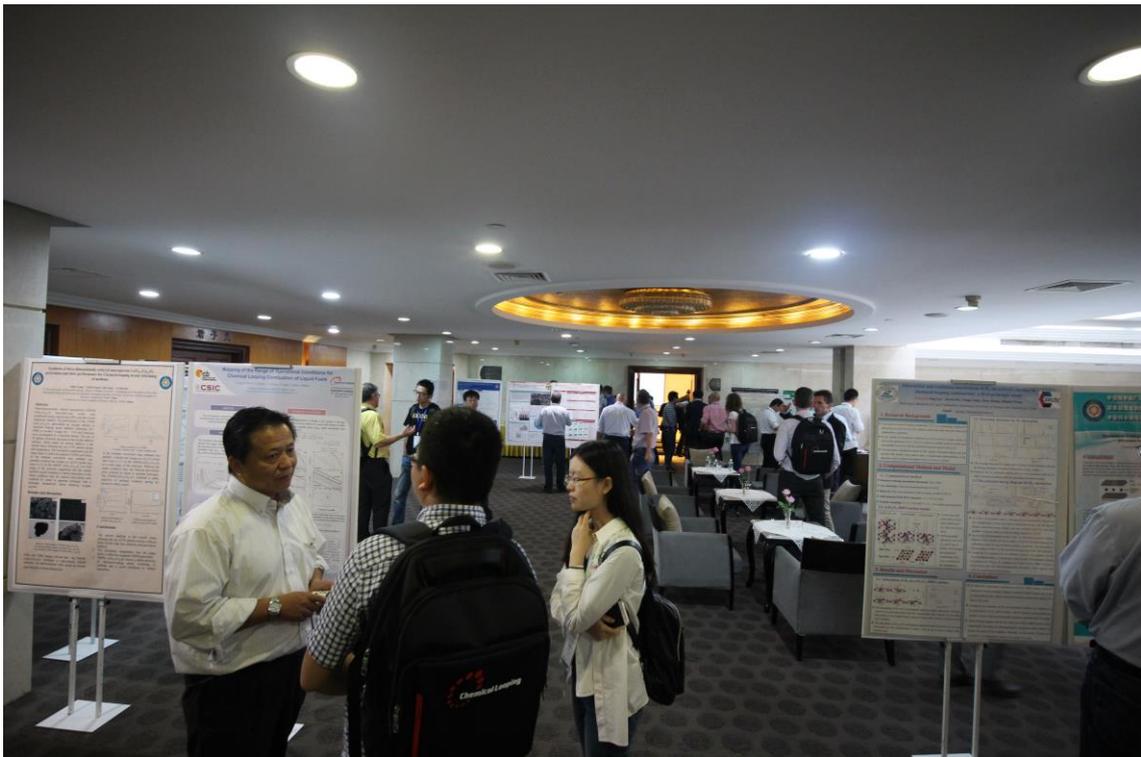


圖 83. 大會中場休息於壁報發表場所景象-3

Enhanced Fuel Conversion by Staging Oxidization in a Continuous Chemical Looping Reactor based on Iron ore Oxygen Carrier

Haiming Gu^{1,2*}, Laihong Shen², Siwen Zhang¹, Weidong Liu², Xin Ni², Huijun Ge¹, Shouxi Jiang², and Lulu Wang²

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INTRODUCTION

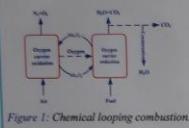


Figure 1: Chemical looping combustion.

Chemical looping combustion is an emerging combustion technology with inherent separation of CO₂. Natural iron ore as an oxygen carrier for chemical looping combustion (CLC) has recently attracted increasing attention. However, low fuel conversion is the major issue for the CLC process based on iron ore. In order to promote the fuel conversion in CLC process, staging oxidization of fuel in the fuel reactor was proposed in this paper. A new 2 kW CLC system of interconnected fluidized bed was constructed with a two-stage fuel reactor. The fuel oxidation primarily occurs in the 1st stage fuel reactor and then, the unconverted combustible gas is further oxidized in the 2nd stage fuel reactor. This CLC reactor was tested using an Australian iron ore as oxygen carrier and syngas and CH₄ as gaseous fuels, respectively. Results indicate that the staging oxidization in the fuel reactor is an efficiently method to improve the fuel conversion. For the syngas test, fuel conversion efficiency for the 2 kW reactor maintained at 96.2%-99.2% while that for the 1 kW reactor maintained at only about 80%. The elevated temperature also played a positive effect on fuel conversion. For the CH₄ tests with thermal input of 0.9- 1.8 kW, up to 88.2% CH₄ was converted and the CO₂ yield reached around 83% at 980 °C.

METHODS

(1) Oxygen carrier

An Australia iron ore, after calcination at 950 °C for 3 h, was used as the oxygen carrier material. According to the XRF analysis, the oxygen carrier was composed of 83.21% Fe₂O₃, 7.06% SiO₂ and 5.37% Al₂O₃. The particles were sieved to a size range of 0.1-0.3 mm.

(2) Gaseous fuel

Both syngas and natural gas were used as fuel for the CLC tests. The corresponding varied from 1 kW to 2 kW. The fuel reactor temperature maintained at 900- 940 °C.

(2) Experimental setup and procedure

A new 2 kW CLC reactor was constructed, and the layout is shown in Figure 2. The prototype is based on the concept of interconnected fluidized bed reactors. The system consists of a fast fluidized bed as air reactor, a cyclone, a two-stage spout fluidized bed as fuel reactor, and an outside loopseal. The riser provides driving force for the circulation of oxygen carrier. The separation of gas-solid flow was realized by a cyclone, which is connected with a downcomer. By gravity, the oxygen carrier is transferred to the 2nd stage fuel reactor. Through the overflow pipe, the oxygen carrier reached the 1st stage fuel reactor. By loopseal, the oxygen carrier could be transported to the air reactor.

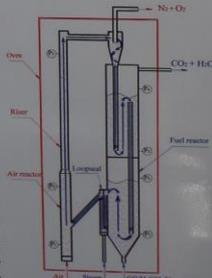
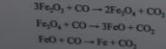


Figure 2: The layout of the 2 kW interconnected fluidized bed for CLC.

RESULTS

Fuel Reactor

1st stage fuel reactor:



2nd stage fuel reactor:

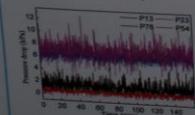
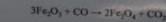


Figure 3: Time series of bed pressure drop of both reactors during continuous operation at fuel reactor temperature of 940 °C.

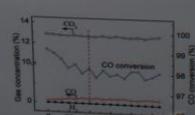


Figure 4: Gas composition of the fuel reactor versus time at the fuel reactor temperature of 940 °C.

References:

- [1] Kubota Y, Kaneko K. Reusability of combustion process. *Separation Science*, 1983, 23(1): 71-86.
- [2] Langrish A, Lockart R, Matteson T. A Fluidized-Bed Combustion Process with Inherent CO₂ Separation. *Application of Chemical Looping Combustion*. Chemical Engineering Science, 2005, 10(20): 5141-5153.

Announcement: This research was supported by the National Natural Science Foundation of China (Grant No. 51406053, 51276077, 51476029)

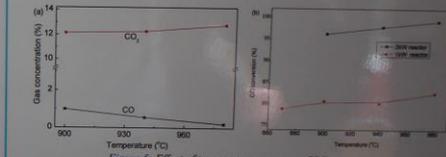


Figure 5: Effect of temperature on syngas CLC process: (a) Gas concentration, (b) CO conversion efficiency.

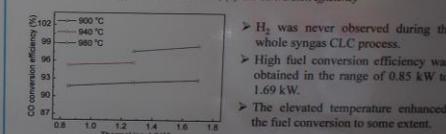


Figure 6: Effect of thermal input on CO conversion efficiency at typical temperature.

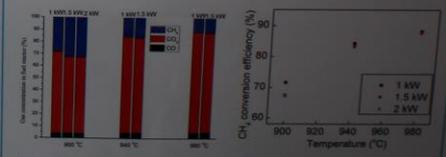


Figure 7: Gas concentration during CH₄ CLC at typical temperature.

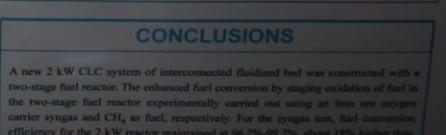


Figure 8: CH₄ conversion efficiency versus temperature at typical thermal input.

CONCLUSIONS

A new 2 kW CLC system of interconnected fluidized bed was constructed with a two-stage fuel reactor. The enhanced fuel conversion by staging oxidization of fuel in the two-stage fuel reactor experimentally carried out using an iron ore oxygen carrier syngas and CH₄ as fuel, respectively. For the syngas test, fuel conversion efficiency for the 2 kW reactor maintained at 96.2%-99.2%, about 18% higher than the result from the 1 kW reactor. The elevated temperature also played a positive effect on fuel conversion. For the CH₄ tests with thermal input of 1 - 2 kW, up to 88.2% CH₄ was converted and the CO₂ yield reached around 83.1% at 980 °C. The results indicate the success feasibility of the new facility with two-stage fuel reactor.

圖 84. 海報論文展示- Pilot Plants



PROCESS SIMULATION OF A HYDROGEN PRODUCTION CHEMICAL LOOPING PROCESS WITH VARIOUS COAL SOURCES

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Motivation and Purpose:

The coal-direct chemical looping (CDCL) process is a promising process concept which efficiently converts coal using the oxygen carrier to take place reduction-oxidation. In the experimental system, the fuel reactor generally operates through an external heater in a constant temperature to maintain reactor temperature. Only a little papers explore the heat balance of the whole CDCL process.

To continuously run this kind of process, the energy should be self-sufficiency between these process. Also, it would spend a lot of cost to find all of the optimal operating conditions by trial and error method in the experiment. Therefore, to develop a simulation method is a major benefit to find maximum H₂ production rate under heat balance condition.

In this study, the whole process is established by Aspen Plus simulator. The coal types may be changed in the CDCL process because of the coal prices or the production rate. In this study, three kinds of coal, Pocahontas NO.3 (PN3), Illinois NO.6 (IN6), and PRB, are investigated to demonstrate the fluctuation of fuel sources. The highest and lowest moistures of coal are PRB and Pocahontas NO.3.

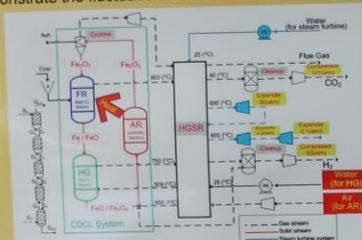


Figure 1: Process flow diagram for CDCL process

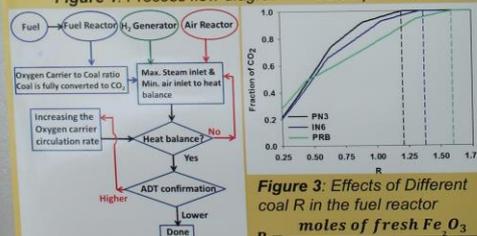


Figure 2: Methodology

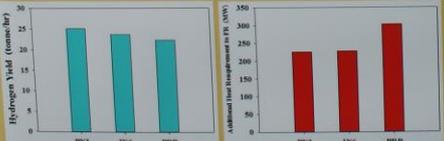


Figure 3: Effects of Different coal R in the fuel reactor

$$R = \frac{\text{moles of fresh Fe}_2\text{O}_3}{\text{moles of carbon in coal}}$$

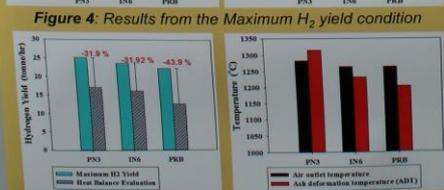


Figure 4: Results from the Maximum H₂ yield condition

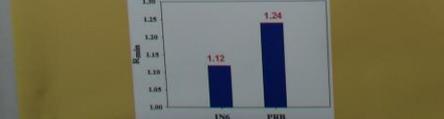


Figure 5: Results from the heat balance evaluation condition



Figure 6: Results from the increasing the OC rate condition

Simulation Procedure:

The CDCL process can obtain highly purity of CO₂/H₂ and energy in the process output. The oxygen carrier is not only serves as the solid phase reactant but also a heat carrier to transport the energy in the entire loop. When the air reactor outlet oxygen carrier can transport enough energy to fuel reactor, it reaches the heat balance condition.

The whole CDCL system has three main reactors and the basic CDCL model is from Zeng et al. (2012) in Figure 1. The reaction of oxygen carrier with fuel is very complex so it uses the GIBBS free energy to predict the reaction behavior. Both the fuel reactor (FR) and hydrogen generator (HG) are set as the five-stage equilibrium based on RGIBBS module to describe the countercurrent moving bed. Also, the FR and HG is operated isothermal at 900 and 750 °C. The air reactor (AR) is an adiabatic system. The oxygen carrier is fully regenerated to Fe₂O₃ by adding air in AR. Furthermore, the reaction releases a significant heat which can be transferred back to the fuel reactor by the oxygen carrier. Three situations are discussed and Figure 2 shows the method in this study.

The minimum oxygen carrier circulation rate

An important factor of R which is the oxygen carrier to coal fuel ratio, it implies the oxygen carrier circulation rate in the whole system. Also, it reaches the R_{min} condition when the carbon in coal totally converted to CO₂. Figure 3 shows that the R_{min} of PN3, IN6, and PRB are 1.21, 1.38, and 1.6, respectively. Also, it is found that the higher moisture of coal should operate at high oxygen carrier circulation rate.

Maximum H₂ yield

The entire oxygen carrier serves as the hydrogen production; it implies that the hydrogen generator outlet oxygen carrier is totally oxidized to Fe₃O₄. Figure 4 shows that the hydrogen yield is inversely proportional to the moisture of coal. Furthermore, The heat requirement which is the additional energy should be provided to the fuel reactor.

Heat balance evaluation

By reducing the hydrogen generator (HG) steam inlet, the partial oxygen carrier sends to the air reactor to oxidize, it would increase the heat release to compensate the heat needed in the fuel reactor. Comparing with the maximum H₂ yield case, Figure 5 show that the hydrogen yield decrease about 32 % to 44 %. However, the air outlet temperature of the IN6 and PRB are higher than the ash deformation temperature (ADT). It may cause the ash melting, so the temperature should be decreased.

Increase the oxygen carrier circulation rate

By increasing the oxygen carrier circulating rate, the air outlet temperature can be decreased. Figure 6 shows the IN6 and PRB should be operated at 1.12 R_{min} and 1.24 R_{min} to prevent the ash melting.

$$\Delta H_{CDCL} = Q_{FR} + Q_{AR} \leq 0 = M_{OC} C_p (T_1 - T_2)$$

Conclusions:

The minimum oxygen carrier circulation rate R_{min} of Pocahontas No.3, Illinois NO.6 and PRB are 1.21, 1.38 and 1.6. The whole system reaches heat balance but the hydrogen yield decrease about 32 % to 44 % from the maximum H₂ yield case. However, the ash deformation takes place if the temperature is higher than the ash deformation temperature. The Illinois NO.6 and PRB should be operated at 1.12 R_{min} and 1.24 R_{min} to prevent the ash melting.

Acknowledgement:

The authors thank the National Energy Program-II of Taiwan for supporting this research under the grant of MOST 104-3113-E-007-001.

圖 85. 海報論文展示- Hydrogen Production & Gasification

Chemical Looping Combustion of Coal by using Limestone with in situ desulfurization

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The **OBJECTIVE** of this work was to get an insight into the Limestone Chemical Looping (LCL-CTM) process, where sulfated limestone in the CLC system is used as an oxygen carrier. Mass and enthalpy balances for the CLC system were carried out in order to show that the LCL-CTM process is a promising and energy efficient option to carry out the coal combustion with CO₂ capture and in situ desulfurization.

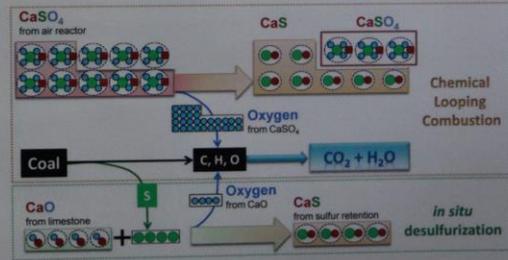
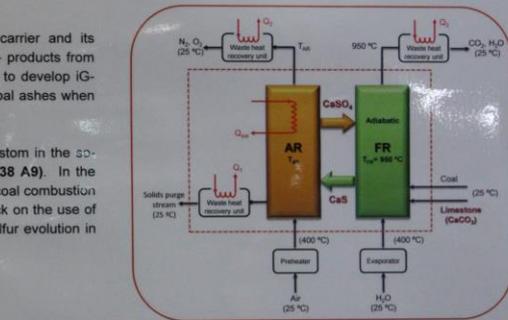
LIMESTONE CHEMICAL LOOPING COMBUSTION (LCL-CTM) PROCESS

In *in situ* Gasification Chemical Looping (IG-CLC) with solids, the cost of the oxygen carrier and its environmental friendly behavior are very relevant characteristics. The use of natural ores or by-products from industrial processes, which are inexpensive and easily obtainable, could be a promising option to develop IG-CLC technology since it is inevitable that some oxygen carrier particles are extracted with the coal ashes when they are removed from the system.

Recently, sulfated limestone has been used as an oxygen carrier in a 3 MW_{th} CLC unit by Alstom in the so-called Limestone Chemical Looping Combustion process (LCL-CTM (Patent WO 2010/014938 A9)). In the LCL-CTM process, CaSO₄ formed in situ by the limestone reaction with sulfur from coal or ash from coal combustion in a circulating fluidized bed (CFB) is proposed as an oxygen carrier material. The main drawback on the use of CaSO₄ as oxygen carrier is the sulfur release from CaSO₄/CaS during redox processes. But sulfur evolution in gases is suppressed in the LCL-CTM process because of the use of CaCO₃ as sulfur sorbent.

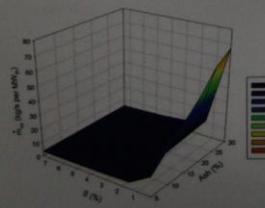
Table 1: Chemical reactions involved in IG-CLC using CaSO₄ as oxygen carrier.

CLC related to chemical reactions	
FR	CaSO ₄ + 4 CO → CaS + 4 CO ₂
	CaSO ₄ + 4 H ₂ → CaS + 4 H ₂ O
	CaSO ₄ + CH ₄ → CaS + CO ₂ + 2 H ₂ O
AR	CaS + 2 O ₂ → CaSO ₄
	CaSO ₄ + CO → CaO + SO ₂ + CO ₂
	CaSO ₄ + H ₂ → CaO + SO ₂ + H ₂ O
	4CaSO ₄ + CH ₄ → 4CaO + 4SO ₂ + CO ₂ + 2 H ₂ O
	3 CaS + CaSO ₄ → 4 CaO + 4 SO ₂
	CaSO ₄ → CaO + SO ₂ + 1/2 O ₂
	CaS + 3/2 O ₂ → CaO + SO ₂
Reactions involving limestone and sulfur from coal	
	CaCO ₃ → CaO + CO ₂
	CaO + H ₂ S → CaS + H ₂ O
	CaSO ₄ + 4/3 H ₂ S → CaS + 4/3 SO ₂ + 4/3 H ₂ O
	CaO + SO ₂ → CaSO ₃
	CaSO ₃ + CO ₂ → CaSO ₄ + CO
	CaSO ₃ + H ₂ O → CaSO ₄ + H ₂



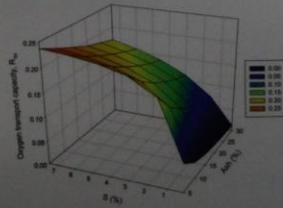
RESULTS: EFFECT OF COAL COMPOSITION (SULFUR & ASH CONTENT) ON MASS AND ENTHALPY BALANCES

Solids circulation rate



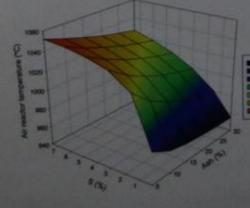
The solids circulation rate decreased by decreasing the ash and/or by increasing the sulfur content. The amount of oxygen carrier is more concentrated in the solids stream as the ash content is lower and/or the amount of CaSO₄ formed is higher.

Oxygen transport capacity



The oxygen transport capacity of the circulating solids increased by increasing the sulfur and by decreasing the ash content of the coal, thus decreasing the required flow of recirculated solids.

Air reactor temperature



The temperature in air reactor increased by decreasing the ash and by increasing the sulfur content of the coal. This is because a decrease in the solids circulation rate is associated with a higher difference of temperature between fuel and air reactor.

MASS BALANCE

- Coal feeding = 1 MW_{th}
- [H₂O/C] feeding ratio = 1
- Oxygen carrier to fuel ratio, φ = 10
- Sulfur Retention (SR) = 100%
- O₂ excess = 10%
- Ca/S molar ratio = 3
- CaCO₃ fed into the fuel reactor is a function of the [Ca/S] molar ratio
- Complete regeneration of CaS to CaSO₄ in air reactor
- Ashes extracted from the CLC system through purge stream

ENTHALPY BALANCE (HSC 6.1 Program)

- Fuel reactor is adiabatic, T_{FR} = 950 °C
- Regeneration of the oxygen carrier by supplying preheated air (400 °C)

CONCLUSIONS

- Mass balances showed that a solids stream with high CaSO₄ content can be circulated from air to fuel reactors without any hydrodynamic restriction. So, these solids have a high enough oxygen transport capacity to transfer oxygen from air to fuel.
- The IG-CLC process using CaSO₄ as oxygen carrier is efficient from an energy point of view. No drawback referred to the integration of both reactors

圖 86. 海報論文展示- Oxygen Carrier - A



Characterization and Evaluation of Prepared TiO₂ and Al₂O₃ Supported Fe₂O₃ Oxygen Carriers for CLC

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Abstract

Fe-based oxygen carriers supported by Al₂O₃ and TiO₂ were prepared as pellets for CLC in this study. Higher conversions were constantly obtained for FeTi320 operated in the TGA than those for FeAl320 oxygen carrier. The conversions were over 80% for most experiments and were promoted with increasing operating temperature. The prepared oxygen carriers sintered at higher temperatures always exhibited higher crush strength. The crush strength of FeTi320 was generally higher than that of FeAl320 oxygen carrier and was less influenced by starch content. For experiments conducted in the fixed bed reactor, the prepared oxygen carrier pellets exhibited relatively high fuel conversions. The fuel conversions were elevated with higher starch contents possibly due to the increase of porosity and the iron ions diffuse onto the surface of oxygen carriers to react with oxygen during the reaction period. In addition, the vacancies and porous formed to cause the porosity increasing after multi-redox cycles. With the reaction cycle increasing, the fuel conversion varied little during the whole number of redox cycle and maintained stable.

Materials and methods

Preparation of oxygen carriers

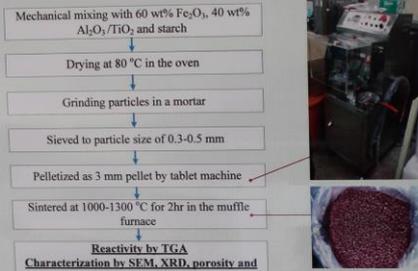
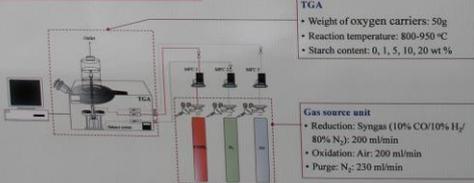


Diagram of TGA system



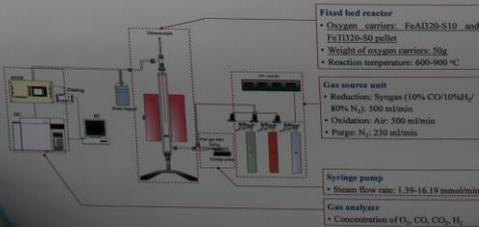
Calculation of conversion

$$X_{red} = \frac{m_o - m(t)}{m_o - m_r}$$

$$X_{ox} = \frac{m(t) - m_r}{m_o - m_r}$$

m_o : Mass of fully oxidized Fe₂O₃ (mg)
 m_r : Mass of fully reduced to Fe (mg)
 $m(t)$: Mass as function of time (mg)
 X_{red} : The reduction conversion of oxygen carriers
 X_{ox} : The oxidation conversion of oxygen carriers

Diagram of fixed bed reactor system



Results and discussion

Effect of operation temperature

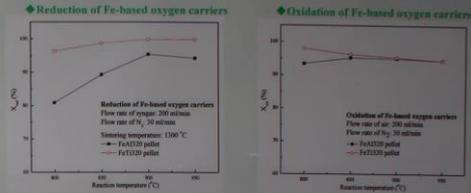


Figure 1 Conversion as a function of reaction temperature for the Fe-based oxygen carriers.

Effect of sintering temperature

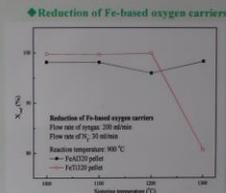


Figure 2 Conversion as a function of sintering temperature for the Fe-based oxygen carriers.

Table 1 Crush strength of Fe-based oxygen carriers in various sinter temperature.

Oxygen carriers	Crush strength (N)				
	Sintering temperature (°C)	1000	1100	1200	1300
FeAl320		218.42	466.68	>550	>550
FeTi320		250.99	340.58	>550	>550

* Tested by ASTM D4179-01 (2006), the value is over instrument limited which is the 550 N.

Effect of starch content

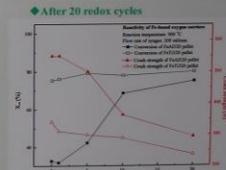


Figure 3 Conversion as a function of starch content for the Fe-based oxygen carriers

Table 2 Porosity of Fe-based oxygen carriers in various starch content.

Starch (wt%)	FeAl320		FeTi320	
	20 redox cycles	20 redox cycles	20 redox cycles	20 redox cycles
0	19.57	21.26	23.97	51.60
1	19.63	23.97	24.90	51.94
5	25.59	29.48	27.29	52.38
10	29.95	34.82	30.94	53.47
20	39.61	41.18	35.51	54.52

* Tested by ASTM C373-88 (2006).

Effect of iron diffusion

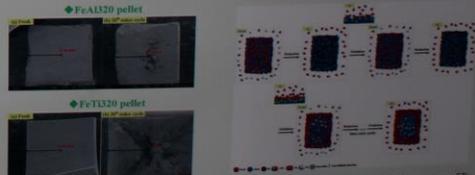


Figure 4 SEM images of cross-sectional area of Fe-based oxygen carriers (a) fresh; (b) 20th redox cycle.

Figure 5 A scheme of iron cations diffusion process of Fe-based oxygen carriers between reduction and oxidation progress.

Application of H₂ production in fixed bed reactor

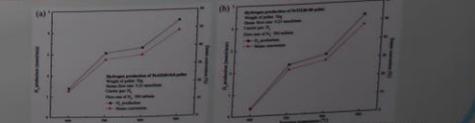


Figure 6 Concentration and conversion as a function of various reaction temperatures for oxygen carriers in fixed bed reactor system for H₂ production (a) FeAl320-S10 pellet; (b) FeTi320-S0 pellet.

Conclusions

- The conversion for the reduction and oxidation both in FeAl320 pellet and FeTi320 pellet exhibited great reactivity at 900 °C by syngas reduction.
- It could be inferred that in the sintering temperature of 1300 °C and 1100 °C were proper sintering condition for FeAl320 pellet and FeTi320 pellet, respectively.
- Iron cations may diffuse onto the surface of oxygen carriers and react with oxygen anions during the oxidation.
- It could be summarized that the FeAl320-S10 pellet has low cost, proper crush strength and sintering than FeTi320-S0 pellet and it would be a suitable candidate for combustion and H₂ production in CLC.

圖 87. 海報論文展示- Oxygen Carrier - B

Numerical Simulation for Chemical Looping Combustion of Circulating Fluidized Bed Reactor



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Abstract

Chemical looping combustion (CLC) process is combined two reactors to be a circulating combustion process which contained the air and fuel reactor, and the oxygen carriers were used to provide the oxygen demand through the redox reaction process. In a CLC process, a vivid design of the flow field inside the circulating process is required to optimize the redox reaction. To get detail fluid dynamics of the system, building a cold flow model or using the computational fluid dynamics (CFD) simulation are functional ways that many researchers published elsewhere. In this study, a specific circulating fluidized bed (CFB) cold flow model is designed and constructed to investigate the pressure and solid circulation. To identify a gas-solid mixing flow structure in the CFB cold model, a three-dimensional (3D), transient time, two fluid dispersed flow model and kinetic theory of granular flow model are used to describe the flow regimes to build a functional CFD predictive method by Ansys Fluent software. Results showed that the model is validated by comparing the predictions with the experiment data of solid volume fraction, but the pressure distribution and solid circulation rate were over predicted by using the generic drag model. The user defined drag model might be indicated to get a more comparable results.

Chemical Looping Combustion

Chemical Looping Combustion (CLC) is the results of two main reaction steps which occurred in separated reactors. The oxygen carriers were circulated in reactor for the redox reaction to generated power and was resulted in a high concentration of CO₂ directly as shown in figure 1.

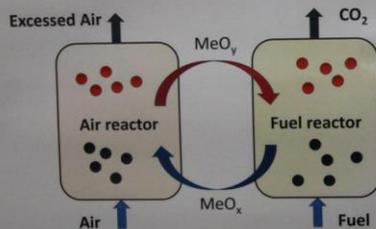


Figure 1. CLC scheme.

Air reactor

Oxidation reaction: $MeO_y + O_2 (air) \rightarrow MeO_x$

Fuel reactor

Reduction reaction: $MeO_x + CH_4 (fuel) \rightarrow MeO_y$

where $(y < x)$

Methods and Boundary Conditions

The commercial CFD software code Fluent 15.0 was employed in this study. A comprehensive 3D numerical model was developed to simulate the behavior of iron ore with air as gas. The Eulerian-Eulerian multiphase flow method and kinetic theory granular flow (KTGF) were used to simulate the gas-solid flow with mass and momentum conservation equations, and the k-epsilon turbulence models were selected. Table 1 lists the main conditions applied to flow quantifications. The whole simulation process is as shown in figure 2. The time step was set as 0.0001s for total 20 seconds simulation.

Table 1 - CFD simulation settings.

Properties	Setting
Air Density [kg/m ³]	1.225
Air Viscosity	1.8x10 ⁻⁵
Solid Density [kg/m ³]	4741
Diameter [m]	2.37x10 ⁻⁴
Granular temperature	Phase property
Granular viscosity	Syamlal-O'Brien
Granular bulk viscosity	Lun et al.
Frictional viscosity	Schaeffer
Frictional angle [degrees]	30
Granular temperature	Algebraic
Solids pressure	Lun et al.
Radial distribution	Lun et al.
Drag coefficient	Gidaspow
Distribution coefficient	0.9
Spontaneity coefficient	0.8
Initial peak fraction	0.4513
Packing limit	0.45



Figure 2. CFD process.

Results and discussion

Currently, the results of preliminary analysis showed that the solid volume fraction of the oxygen carriers are comparable to the experiment flow field as shown in figure 3. The oxygen carriers were started to transport within the corresponding air flow induced into the system. The design of geometry made the fuel reactor, loop seal and the bottom of air reactor formed bubbling fluidized regime, and made the riser formed fast fluidized regime during operation. But the pressure distribution were over predicted in the air reactor which may caused by the present drag model or the neglect of the energy loss in the system as shown in figure 4.

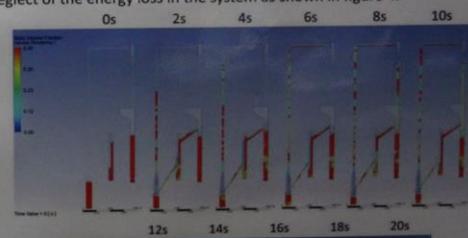


Figure 3. Solid volume fraction in the CLC system during 20 seconds operation.

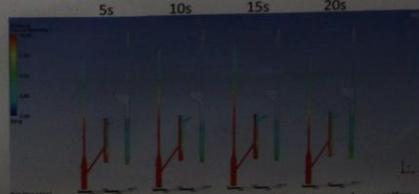


Figure 4. Pressure distribution in the CLC system during 20 seconds operation.

Conclusion

In this study, We have presented a model that describes a multiphase hydrodynamics applied to whole reactor for CLC process. The results showed that the flow pattern of solid volume fraction was well predicted, but the pressure pattern was over predicted by using the current drag model. To get more accurate prediction, the suitable parameters may required in the future.

Acknowledgement

This work was supported through National Energy Program Phase II. Project number: MOST 104-3113-E-007-001

圖 88. 海報論文展示- Modelling - A

Computational fluid dynamics simulation of an interconnected fluidized bed for chemical-looping combustion

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¹Energy Business Unit, ²Mineral Resources Business Unit, CSIRO, Clayton, VIC, 3168, Australia

Model

The public domain computer code, Multiphase Flow with Interphase eXchanges (MFIx), was used to conduct the CFD simulations [1]. The model is based on Euler-Euler model coupled with kinetic theory of granular flows.

A 2D geometry of an interconnected fluidized bed, including AR, FR, LS and cyclone, was used for the simulation (Fig. 1). The geometry is similar to the experimental configuration reported by Lyngfelt et al. [2] with minor modification.

Reaction kinetics network for Ni based OC suggested by Zhou et al. [3] was adopted, which include 4 OC reduction reactions (R1-R4) and 6 reactions catalyzed by Ni (R5-R10).

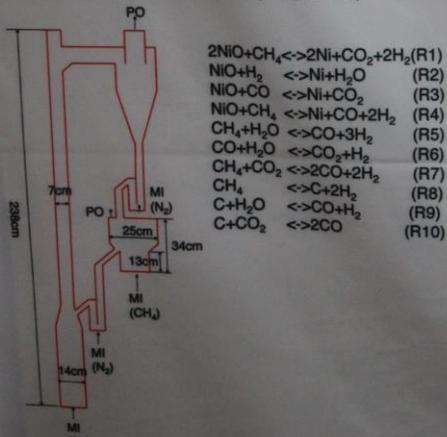


Figure 1: Layout and geometry of the interconnected fluidized bed for CLC

Pressure profile
 Model predicted that the two loop seals can balance the pressure difference between the FR and AR. Pressure of FR is lower than that of AR, which avoids leakage of CO₂ into AR.

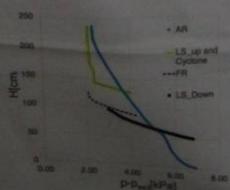


Figure 2: Simulated pressure profile of the whole loop

Void fraction

The time evolution of void fraction is shown in Figure 3. The OC circulation is evident. Cluster is formed in high velocity AR. The bed high of FR is decided by the outlet height of the down-pipe.



Figure3: Time evolution of gas void fraction in CLC reactor

Solid circulation flux
 The solid flux is dynamic fluctuating with time. With the increase of velocity of AR, the solid flux is increasing.

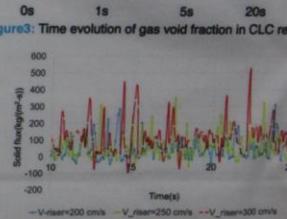


Figure4: Effect of riser velocity on the time evolution of solid flux

Gas composition

No gas leakage from FR to AR is evident from Fig 4. A typical dry gas composition is given in Table 1. Fine tune the kinetic parameters obtained from TGA is necessary in matching experimental data.

Table 1: Predicted dry gas composition at FR outlet

FR temperature	800 °C	850 °C	900 °C
CO ₂	91.4	91.5	91.7
CO	1.33	1.26	1.15
H ₂	7.22	7.20	7.13
CH ₄	0.04	0.01	0.01

Figure 4: CO₂ distribution in the FR

Conclusion

Open source code MFIx has been applied in modeling the full-loop CLC reactor. Loop seals can balance the pressure of two reactors. Solid flux was primary depended on velocity of AR. Kinetic parameters obtained from TGA needs to be tuned in CFD simulation.

1) Spalding, D., Rogers, W., 2005. T.J. MFIx Documentation: Theory Guide, M.I.T., U.S. Department of Energy DOE, Editor: 1990. Morganston.
 2) Lyngfelt, S., Thunman, A., Leion, H., Johansson, H., and Berg, D., 2001. Chemical Engineering Journal, 82(2001), 331-344.
 3) Zhou, L., 2001. Chemical Engineering Journal, 82(2001), 331-344.



圖 89. 海報論文展示- Modelling - B

Characteristic of CoTiO_3 as Oxygen Carrier

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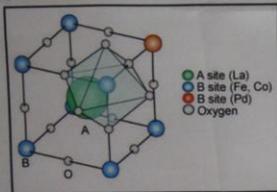
Introduction

- Oxygen carrier has an important role in chemical looping.

- Perovskites have a cubic structure with general formula of ABO_3 .

- It is well known that the perovskite groups maintain the stable crystal structure and can show the activity for specific reaction.

- Perovskites can be diversified because it is possible to dope the a or b site.

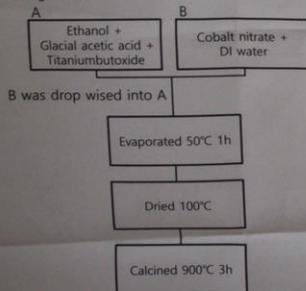


Objectives of the study

- Investigate CoTiO_3 oxygen carrier for chemical looping combustion using hydrogen and methane gas.

Experiment

- CoTiO_3 oxygen carrier preparation
Sol-gel method

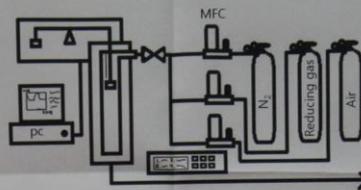


Characterization of reduction and oxidation

Loaded mass	Reaction temp.	Reduction gas	Oxidation gas	Detector
50 mg	100 - 900°C (heated 5°C/min)	5% H_2/Ar	5% O_2/He	TCD

TGA

Loaded mass	Reaction temp.	Reduction gas	Oxidation gas	Purge gas
30 mg	900°C (iso thermal)	15% H_2/N_2 (10min)	high purity Air (5min)	N_2 (3 min)



Results and discussion

- TGA data analysis method

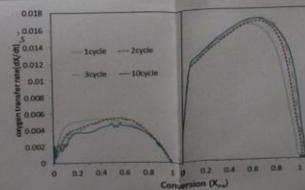
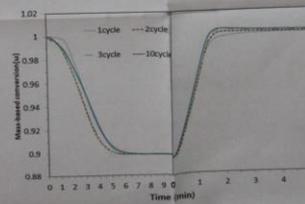
$$R_o(\text{oxygen capacity}) = \frac{m_{\text{ox}} - m_{\text{red}}}{m_{\text{ox}}}$$

$$\omega(\text{mass based conversion}) = \frac{m}{m_{\text{ox}}} = 1 + R_o(X - 1)$$

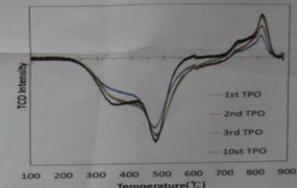
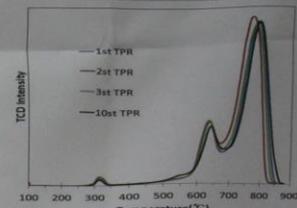
m_{ox} = mass of completely oxidized state
 m_{red} = mass of completely reduced state

- In this study, m_{ox} and m_{red} was determined at first cycle.

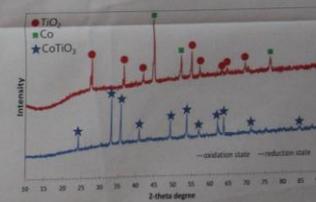
Redox reaction with cycle using TGA



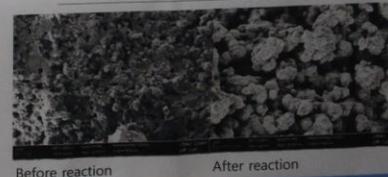
TPR analysis using TCD



XRD analysis



FE-SEM analysis



Conclusion

- In this study, CoTiO_3 particles were carried out TGA and TPR for reactivity test.
- XRD data showed CoTiO_3 phase in oxidation state and $\text{Co} + \text{TiO}_2$ phase in reduction state.
- The oxygen capacities within 15% H_2/N_2 .
- The maximum oxygen transfer rate of reductions reached around 0.005/s in 15% H_2/N_2 .
- The result showed that CoTiO_3 particles have a potential as a oxygen carrier.

Eco-friendly Alternative Energy Laboratory



圖 90. 海報論文展示- Calcium Looping

(二) Lab Visit：參訪大陸東南大學沈來宏教授實驗室

大會於 9 月 27 日下午安排參訪大陸南京東南大學沈來宏教授實驗室，東南大學位於南京市玄武區，距離會議場館南京國際會議大酒店大約 7 公里，車程約 30 分鐘。東南大學參訪過程如圖 91~圖 99 所示。

沈來宏教授團隊已有多年氣化燃燒技術與化學迴圈技術相關研究經驗，本次參訪主要看到沈教授研究團隊的大型流體化床氣化爐以及化學迴圈冷模實驗設備，各實驗相關設備皆有實驗室負責人講解，說明該團隊對於氣化與化學迴圈實驗技術概況，根據講解人員說法：此次看到的氣化爐為該團隊於 2011 年建立之 50kW_{th} 流體化床氣化爐反應器，實驗燃料轉化率可接近 100%，二氧化碳捕獲率可達 94%，該團隊也規劃在未來四年內於東南大學新校區建立更大的反應器系統。由於本所尚未建置大型化學迴圈與氣化爐結合之設備，講解過程令筆者印象深刻，未來本所若持續化學迴圈相關技術研究，或可參考大陸東南大學相關研究成果，甚至可進一步洽談相關合作之方向。



圖 91. 東南大學流體化床氣化爐-1



圖 92. 東南大學流體化床氣化爐-2



圖 93. 東南大學流體化床氣化爐-3



圖 94. 東南大學流體化床氣化爐現場講解

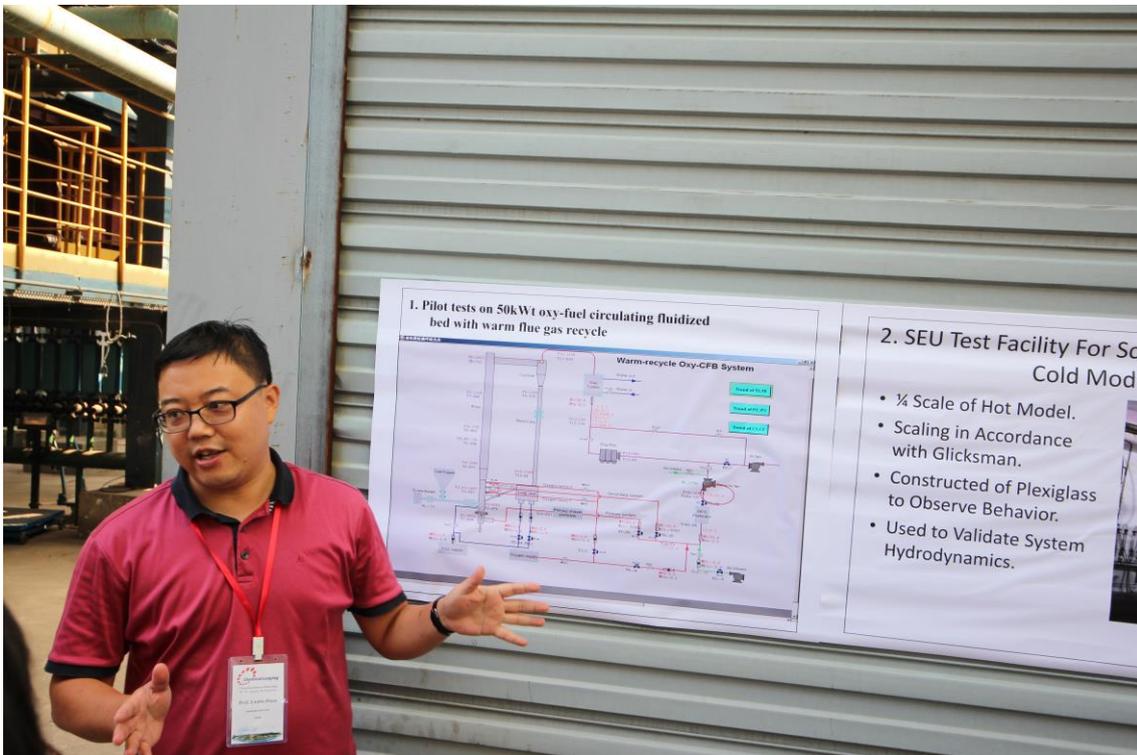


圖 95. 東南大學流體化床氣化爐概念海報解說-1

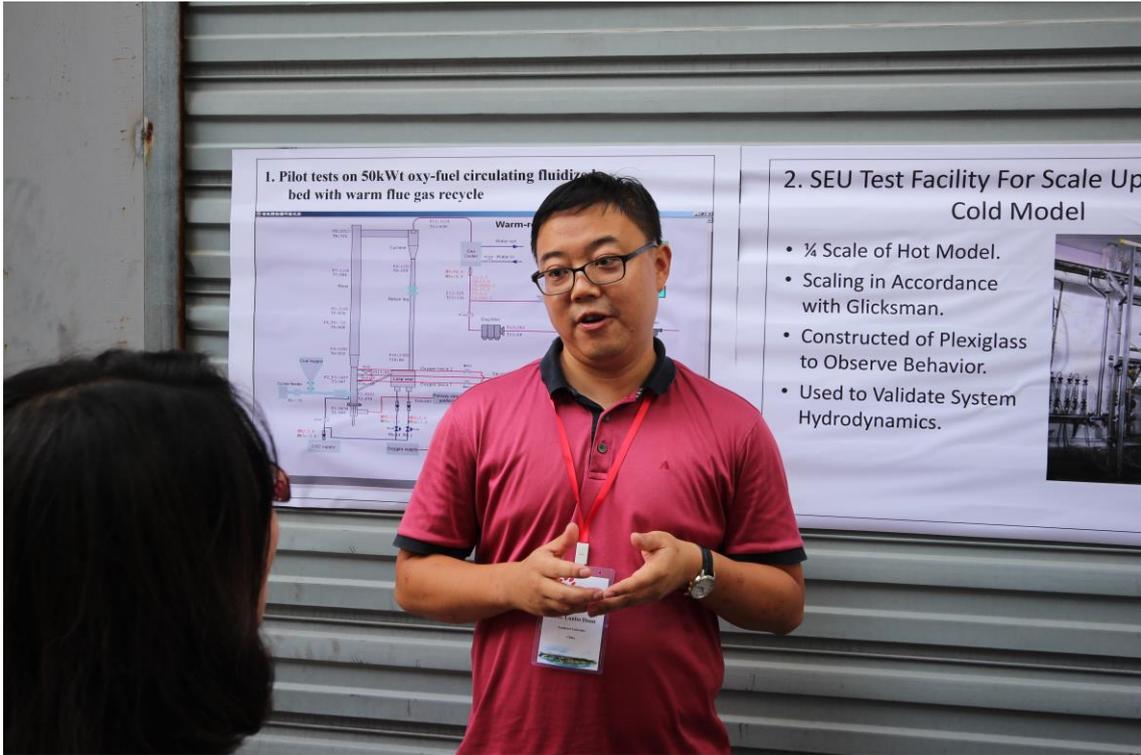


圖 96. 東南大學流體化床氣化爐概念海報解說-2

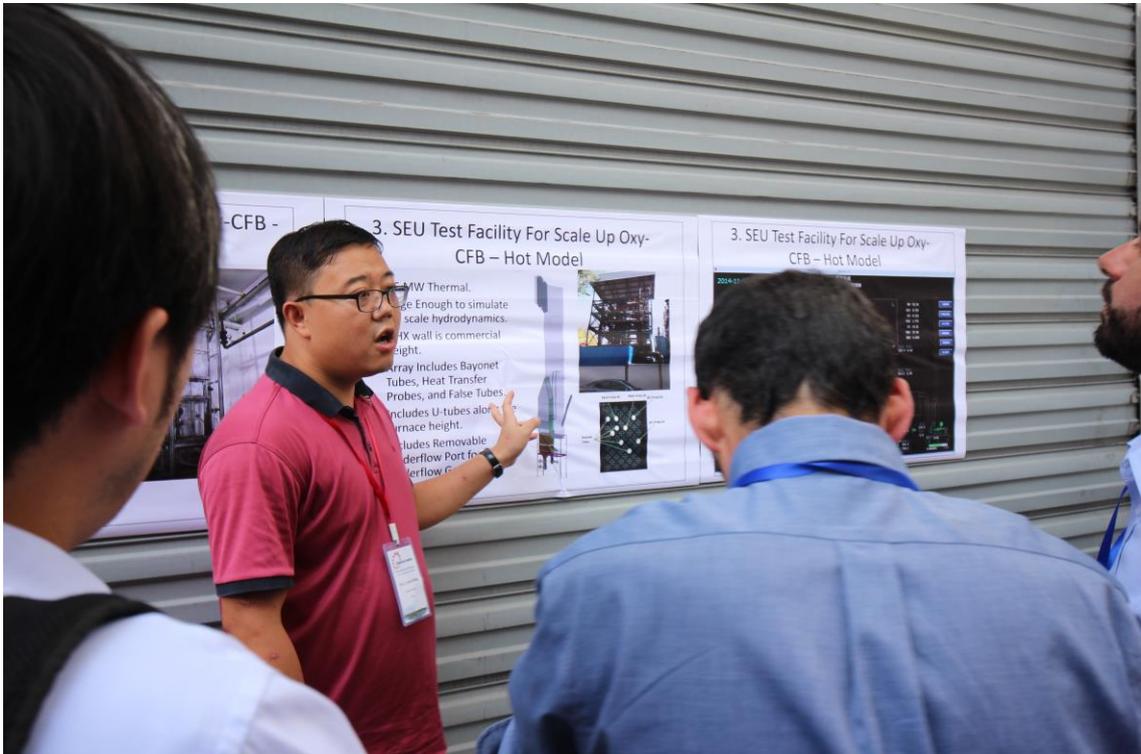


圖 97. 東南大學流體化床氣化爐概念海報解說-3



圖 98. 東南大學化學迴圈冷模系統

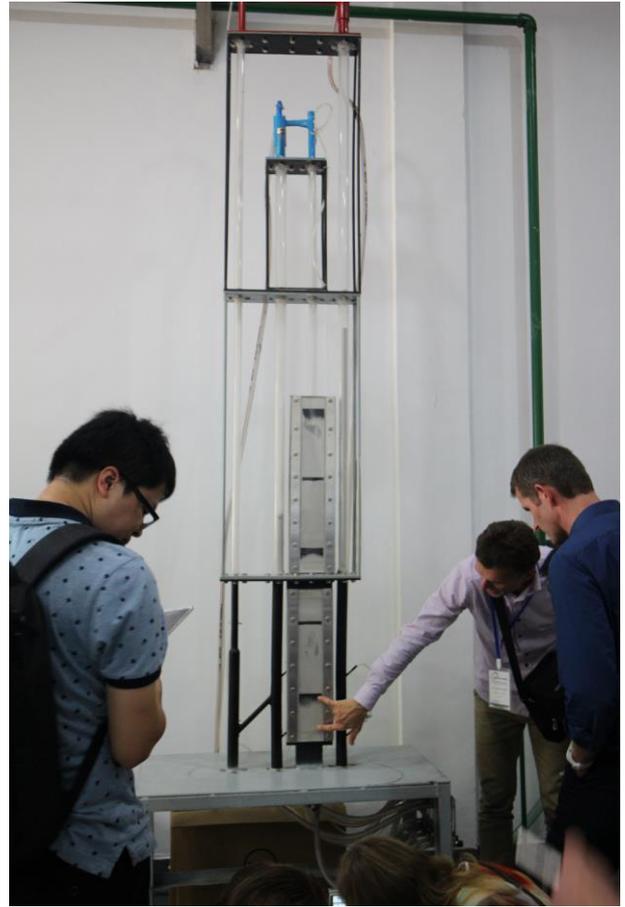


圖 99. 東南大學化學迴圈冷模系統現場講解

四、建議事項

近年來，全球氣候議題持續升溫，各方研究顯示人為溫室氣體排放對於全球溫室效應有關鍵性的影響。根據國際能源總署（IEA）報告，能夠直接減少工業碳排放的最有效技術即為碳捕獲技術。化學迴圈燃燒(chemical looping combustion, CLC)是一項新穎的富氧燃燒技術，化學迴圈燃燒程序幾無 NO_x、SO_x 等污染物排放，具有能源效率高與二氧化碳分離之特性，成為有效降低 CO₂ 排放的甚佳途徑，因此，吸引國際研究機構投入開發，例如奧地利 Vienna 科技大學、瑞典 Chalmers 大學、美國 OHIO 州立大學、猶他大學等，另外，本屆化學迴圈國際研討會的主辦單位：大陸東南大學，近年也具有相當豐碩的相關研究成果。

在本屆國際研討會的各项會議中，除了可以看到研究機構與專家近期的研究現況，也看到不少廠商在朝技術的實際應用發展，諸如此類大型國際研討會所交流訊息及獲取經驗必定對國家產業發展及落實推廣計畫有一定影響力，建議如下：

- 實際參與此國際性研討會議後，看到世界各國研究單位對於化學迴圈燃燒技術的投入，本所若能充分掌握相關研究方向，將有助於國內提升能源技術之水平，除建立國內自主能源技術外，亦能與國際合作擴展能源技術之海外市場。
- 化學迴圈燃燒技術是 ICCL 大會的討論主軸，被歐盟與美國能源部評估為最具前瞻性的二氧化碳捕獲技術，亦顯示本所淨碳技術開發計畫之推動符合國際主流趨勢，值得繼續推動。
- 藉由多參與大型研討會及利用投稿方式，一方面提高核研所的曝光度，一方面更能達到宣導本所研究的效果，有助拓展與國際學者專家之關係及國際合作，並提升本所化學迴圈研究人員的視野與強化本職的學識與技能。

五、附 錄

附錄一、本次會議研究論文發表摘要

Study on Combustion-supporting Behavior of Ilmenite in Chemical Looping Combustion Process

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Abstract – Chemical looping combustion (CLC) which divides the combustion process into an air reactor and a fuel reactor has been regarded as an effective method to facilitate carbon dioxide sequestration. Between the two reactors, specific metal-oxide particles, called Oxygen Carrier (OC), are used for oxygen transport. Because OC is the main additional cost of the whole process, it is proposed that low-cost minerals such as ilmenite can be a candidate with great potential to work.

The first part of this study is to characterize the properties of the selected material. Consecutive reduction-oxidation cycles of ilmenite were carried out in a thermogravimetric analyzer (TGA) with the main gases from coal gasification, i.e., H₂, CO, and CH₄. The TGA analysis results show that the ilmenite have the best oxygen transfer capacity with hydrogen as fuel gas, followed by simulated syngas (10 vol% H₂ and 10 vol% CO) and methane. The oxygen transfer capacities of ilmenite with H₂ and syngas as fuel gas were close to the theoretical oxygen transfer capacity (12.67%). When using CH₄ as fuel gas, carbon deposition occurred on the surface of ilmeite and decreased the oxygen transfer capacity. During the 10 redox cycling tests, the reactivity of ilmenite increased with increasing the number of redox cycles under the syngas environment.

The Ilmenite was further examined in a bubbling fluidized-bed column with methane as fuel. The trend of conversion ratio of fuel shows that a low flow rate of 6 lpm (liter per minute) outperforms for most of the time the counterpart of the case with higher flow rate (10 lpm). Also, for the low flow rate with preheating to 400°C, the conversion ratio does not rise significantly, or rather is very close to that for the case of 10 lpm without preheat process. Finally, under different concentration, the results show that the reduction of concentration can improve the conversion ratio of methane.

附錄二、本次會議研究論文演講簡報

Study on Combustion-supporting Behavior of Ilmenite in chemical looping combustion (CLC) process

Yau-Pin Chyou*, Der-Ming Chang, Ching-Ying Huang, Hsuan-Hua Chang#

Hsuan-Hua Chang
2016/09/26

Outline

- Introduction
- Material & Method
- Results
- Conclusions



Introduction

➤ **Clean Coal Technologies:**

- Gasification
- Post-combustion process
- Pre-combustion process
- Oxy-combustion process
- **Chemical Looping combustion**
-

Introduction

➤ **Chemical looping combustion (CLC)**

- a two-step combustion process
- combined two interconnected fluidized bed reactor

- highly concentrated stream of CO₂ for sequestration

Oxygen Carrier

- In CLC process, choosing an **adequate oxygen carrier** is the major challenge.
- **Characteristics of a good oxygen carrier**
 - high oxygen transport capacity
 - high reactivity
 - high mechanical strength
 - low production costs
- In this work, **ilmenite** is used as OC.

- a natural iron-containing mineral
- cyclic stability during repeated cycles of oxidation and reduction
- reactivity increase with the number of cycles
- ilmenite is a good candidate of oxygen carrier in terms of the economical and environmental issues



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- > **Fluidized bed reactor:**
 - 2 inches Ø X 4 feet height
 - the flow rates of the feed gases were controlled by three mass flow meters
- > **On-line gas analyzer:**
 - Molecular analysis 6000 for CH₄, O₂, CO₂ and CO
- > **TGA system:**
 - Weight of oxygen carrier: ~20mg
 - Reaction temperature: 900 °C

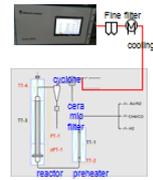


Fig. Fluidized bed reactor



Fig. TGA system



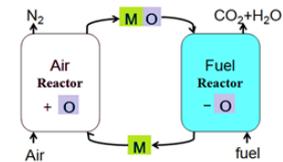
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- > **Oxygen carrier: ilmenite mineral**
- **Apparent density:** ~3.9 g/cm³
- **Composition:**
 - 42.2% Fe₂O₃ · 54.86% TiO₂ · 2.94% others
- **Particle size:** 170 μm
- **u_{mf}:** 1.75 cm/s @900°C
- > **Fuel: methane**
 - 20 vol% CH₄ · 80 vol% N₂



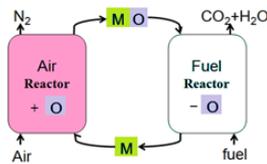
9

- > **Fuel reaction**
 - the oxygen release rate from OC
 $\dot{r}_{O_2} = \dot{n}_{in} M_{O_2} (y_{CO_2} + 1.5 y_{CO})_{out}$
 - the weight change of OC
 $\Delta W_{CO} = \frac{\int \dot{r}_{O_2} dt}{W_{CO,0}}$
 - the fractional conversion of fuel
 $X_{CH_4} = \frac{(\dot{n}_{CO} + \dot{n}_{CO_2})_{out}}{(\dot{n}_{Total C})_{out}} = \frac{(y_{CO} + y_{CO_2})_{out}}{(y_{CO} + y_{CO_2} + y_{CH_4})_{out}}$



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- > **Air reaction**
 - the oxygen recovered rate on OC
 $\dot{r}_{O_2} = \dot{n}_{in} M_{O_2} \left(y_{O_2, in} - \frac{\dot{n}_{out}}{\dot{n}_{in}} (0.5 y_{CO} + y_{CO_2} + y_{O_2})_{out} \right)$
 - where $\frac{\dot{n}_{in}}{\dot{n}_{out}} = \frac{y_{N_2, out}}{y_{N_2, in}} = \frac{1 - (y_{CO} + y_{CO_2} + y_{O_2})_{out}}{y_{N_2, in}}$
- the weight change of OC
 $\Delta W_{CO} = \frac{\int \dot{r}_{O_2} dt}{W_{CO,0}}$

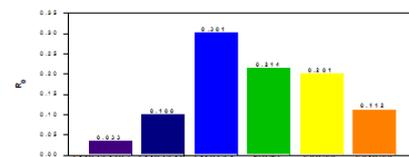


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> Oxygen ratio (R_o):

It describes the maximum oxygen of the oxygen carrier could be transferred during between the air and the reducing (fuel) reaction.

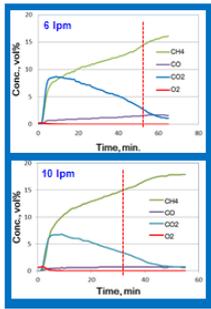
$$R_o(\text{oxygen ratio}) = \frac{m_{ox}}{m_{red}} \quad m_{ox}: \text{mass of metal-oxide}; \quad m_{red}: \text{mass of reduced metal-}$$



Theoretical oxygen ratio, Ro, for the different pairs of metals/metal oxides



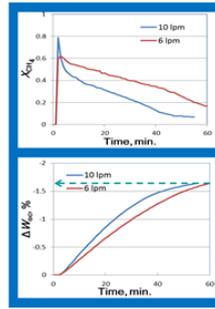
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- **Test Conditions :**
 flow rate are set to 6 and 10 lpm respectively, at 900°C with 4kg ilmenite
- higher flow rate case, *the combustion of methane is less complete*
 - the time for outlet concentration of remaining methane to reach 80% of inlet concentration is shorter.*



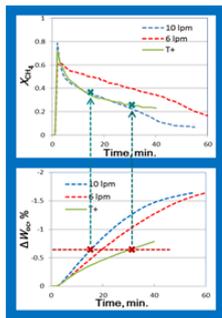
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- 10 lpm case :
 - the fractional conversion is close to 80% at initial stage
 - drop dramatically later with gradually decreasing slope.
- 6 lpm case :
 - the ratio went more smoothly
 - outperform the 10 lpm most of the time
- Weight change of the OC :
 - the rate to release the oxygen is higher in 10 lpm case, but not in direct proportion
 - the final reduction weight of the carrier for the both cases is close to 1.8%



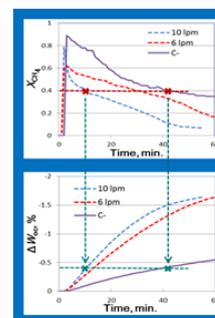
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- **Test Conditions :**
 fuel is preheated to 400°C at a flow rate of 6 lpm
- Fractional conversion :
 - does not rise significantly with the increasing temperature, but close to the 10 lpm case
 - Weight change of the OC :
 - the higher temperature demonstrates worse result as the counterpart at normal temperature



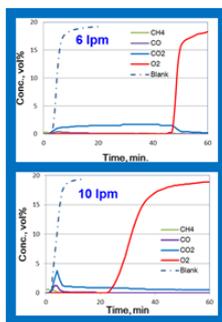
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- **Test Conditions :**
 mix the fuel with nitrogen to reduce the concentration to 1/5 of the original level (@ 6 lpm, non-preheated)
- The reduction of concentration can improve the fractional conversion.
 - The tendency of weight reduction of the OC is slower.



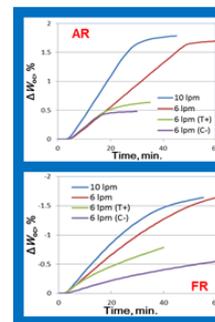
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- **Test Conditions :**
 flow rates of 6 and 10 lpm respectively, at 900°C without preheat process with 4kg ilmenite
- oxygen will be consumed completely after initiation
 - A portion of oxygen is used for the oxidation of carbon residue.
 - The low flow rate case required a longer time to oxidize the used OC with air.



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- Weight change of the OC :
 - the rising slope with 10 lpm is steeper than that with 6 lpm
- For all 6 lpm cases, the weight change rates are all the same in the beginning.
- In case that the time is sufficient, oxygen carrier for reduction can be recovered by oxidation, and usually take a shorter time.



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1. The **flow rate**, **temperature**, and **concentration** are all important parameters when designing a reactor.
2. Based on the results of temperature and concentration, it is conjectured that **the speed of the mass transfer** is the dominating factor to control the reaction.
3. The **reduction of fractional conversion** of methane occurs when increasing reaction **temperature**, due to shorter residence time.
4. The oxidation reaction rate of ilmenite is much faster than its reduction reaction rate.



T H A N K Y O U

Any question?

