出國報告（出國類別：其他）

參加第八屆應用能源國際研討會 (ICAE2016)出國報告

服務機關：核能研究所
姓名職稱：李灝銘　副工程師
派赴國家：中國大陸
出國期間：105 年 10 月 7 日~105 年 10 月 12 日
報告日期：105 年 11 月 4 日

摘　要

本次出國公差參加第八屆應用能源國際研討會(8th International Conference on Applied Energy, ICAE2016)，今年假大陸北京舉辦，全球各地 32 個國家與會，約 800 篇論文發表，研討會主題包括 1.潔淨能源轉換技術；2.能源管理、政策、經濟與永續；3.能源科學；4.能源貯存；5.智慧能源系統；6.減排技術；7.可再生能源。本次口頭發表核研所近兩年在工業節能的高效能熱管熱交換技術之部份研發成果，題目為 Stainless Steel Heat Pipe Fabrication, Performance Tests and Modeling。台灣地區的工業餘熱佔全國工業能源總需求量的 9.2%，相當於 3.9 百萬公秉油當量，其中溫度低於 250°C 的低階餘熱佔了 75% [1]，若上述低階餘熱完全回收，每年可以減少 8.4 百萬噸 CO_2 排放。熱管熱交換器具有高熱傳性能，適合應用於工業餘熱回收，但是面臨酸露點腐蝕的實務問題。為解決腐蝕問題，核研所開發不鏽鋼熱管，並研發抗腐蝕鍍層，讓腐蝕速率降低一至兩個數量級，有助延長工業應用時的使用壽命。另一方面，結合熱管與有機朗肯循環或超臨界 CO_2 朗肯循環的發電技術，可應用於地熱發電，因無需將地下熱水抽出，可以避免地層下陷的隱憂，也免除回補水所需的動力損失，我國具備地熱資源，此方法是值得我國發展的潛力技術。最後，許多講者在大會強調永續循環的重要，越來越多功能性複合材料被研發與應用，但最終將成為廢棄物的環保問題與資源回收再利用的資源永續問題，由於複合材料的回收再利用困難度高，新材料與新產品研發同時宜同時進行產品生命週期環境衝擊分析，且相關複合材料的回收再利用技術，也應及早研發。本次會中獲知多國研發趨勢，同時認識一些熱管與相關研發領域的國際友人，有益技術研發之提升與提速。

目次

（頁碼）

一、目　的

第八屆應用能源國際研討會(8th International Conference on Applied Energy, ICAE2016)乃Elsevier 雜誌下之知名期刊 Applied Energy 所主辦，每年舉辦一次，今年假大陸北京舉辦，全球各地 32 個國家與會，約 800 篇論文發表。研討會主題包括 1.潔淨能源轉換技術；2.能源管理、政策、經濟與永續；3.能源科學；4.能源貯存；5.智慧能源系統；6.減排技術；7.可再生能源。

為掌握國際在能源應用上的研究趨勢與現況，拓展國際人脈，核研所派李員參加此會議。李員目前在本所從事前瞻工業節能技術研發，本次口頭發表本所近兩年在工業節能的高效能熱管熱交換技術之部份研發成果，題目為 Stainless Steel Heat Pipe Fabrication, Performance Tests and Modeling。希冀藉由參與 ICAE 系列研討會，窺探國際研發趨勢，作為我國工業節能技術發展方向之參考；強化國際研發人脈，嘗試建立合作管道，加速科技研發進程。

二、過　程

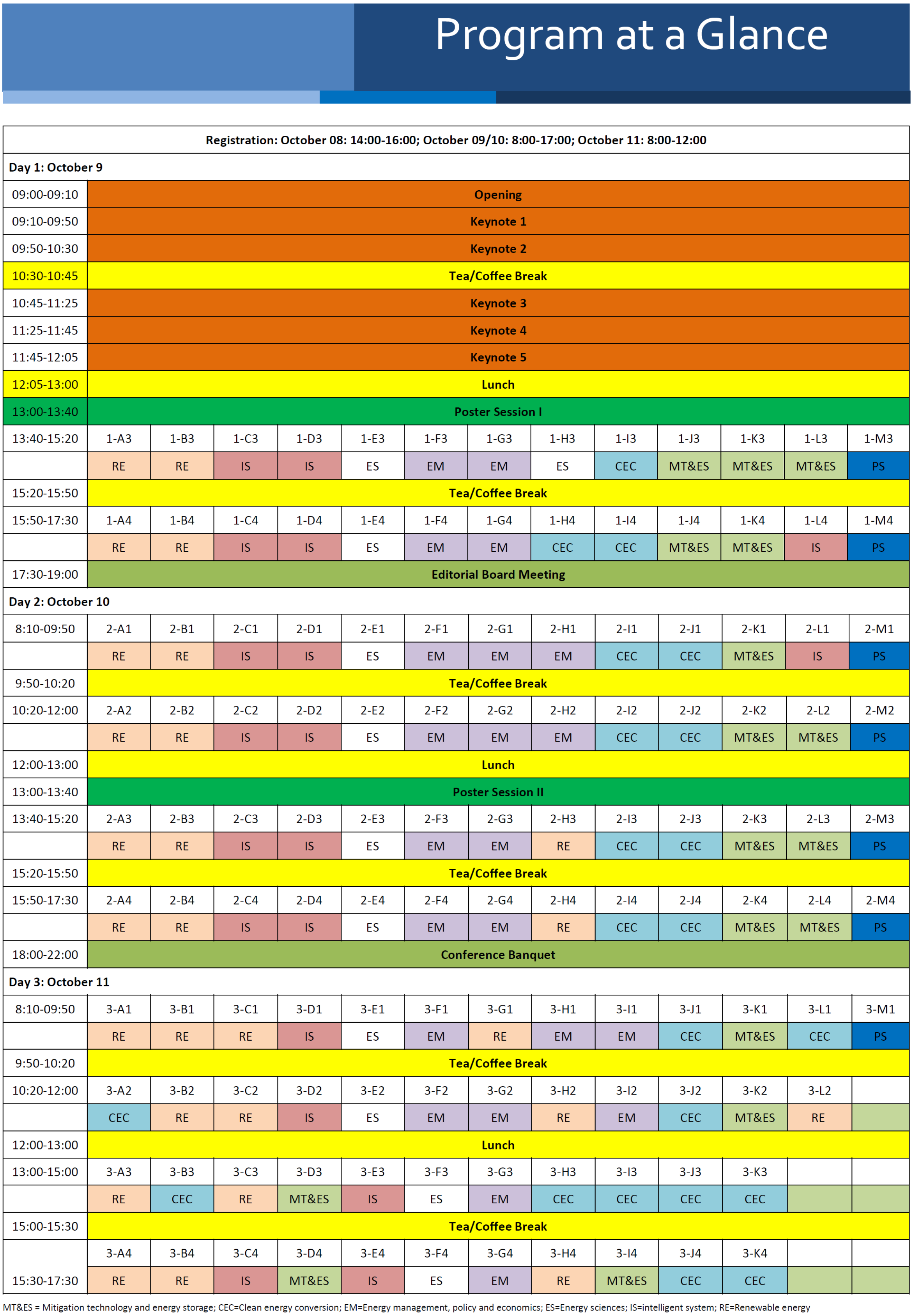
第八屆應用能源國際研討會(ICAE2016)，於 2016 年 10 月 8 日~11 日於中國北京舉行；該會議每年舉辦一次，國際主辦單位為 Applied Energy 期刊，地主主辦單位為北京理工大學，大會主席 Prof. Jinyue Yan 為 Applied Energy 期刊主編，乃國際上再生能源領域的知名學者。本次會議計有來自世界各地 32 個國家、近 800 位專業人士參加，共計近 1000 篇論文投稿，分成 118 場次口頭發表與 2 場海報發表，大會同時安排了 5 場專題演講與 7 場論壇，另外還有 3 場科技實地參訪行程。表 1 為大會議程簡表，細部議程由於頁數過多就不在本報告中列出，大會議程主要區分為 1.潔淨能源轉換技術；2.能源管理、政策、經濟與永續；3.能源科學；4.能源貯存；5.智慧能源系統；6.減排技術；7.可再生能源等類。李員口頭發表一篇論文，論文名稱為 Stainless Steel Heat Pipe Fabrication, Performance Tests and Modeling，屬於「熱管」領域，歸屬在「能源科學」項下的第 3 個子項目中，被安排在最後一天最後一場口頭報告，會場上多人給予肯定並提出相關建議，對研發工作有所幫助。

李員全程參加會議。未參加實地科技參訪行程(BAIC BJEV、Collaborative Innovation Center of Electric Vehicles、及 Shenwu Group)，乃因大會的參訪議程直到開會前幾天才公告，機票與公務行程早已安排；參訪日期不是安排在會議舉辦日期內，竟是排在結束後一天(10 月 12 日)；實地參訪主題為電動車，也與李員研發題目相關性低，因此未克參加。

本次公差行程如下：7 日啟程至北京。8 日至大會註冊，熟悉大會附近交通與環境，同時研讀大會手冊預習相關論文。9 日參加研討會。10 日白天參加研討會，晚上參加大會晚宴。11 日參加研討會，並於下午 15:30~15:50 口頭論文發表。12 日中午搭機返國。

本次公差恰遇大陸的十一長假(10 月 1~7 日)，導致 7 日前往北京的機票異常難買，李員雖然提早一個月就開始訂機票，但足足花了一個星期才幸運訂到。提醒相關人員前往大陸地區，若遇到大陸長假，宜提早數月就訂機票較為安全。但本次大會直到開會前一個月才公告暫訂議程，使得本次公務出國的安排非常倉促與限制，能順利完成任務實屬幸運。

表 1：ICAE2016 研討會議程[2]



Program at a Glance

Registration: October 08: 14:00-16:00; October 09/10: 8:00-17:00; October 11: 8:00-12:00													
Day 1: October 9													
09:00-09:10	**Opening**												
09:10-09:50	**Keynote 1**												
09:50-10:30	**Keynote 2**												
10:30-10:45	**Tea/Coffee Break**												
10:45-11:25	**Keynote 3**												
11:25-11:45	**Keynote 4**												
11:45-12:05	**Keynote 5**												
12:05-13:00	**Lunch**												
13:00-13:40	**Poster Session I**												
13:40-15:20	1-A3	1-B3	1-C3	1-D3	1-E3	1-F3	1-G3	1-H3	1-I3	1-J3	1-K3	1-L3	1-M3
	RE	RE	IS	IS	ES	EM	EM	ES	CEC	MT&ES	MT&ES	MT&ES	PS
15:20-15:50	**Tea/Coffee Break**												
15:50-17:30	1-A4	1-B4	1-C4	1-D4	1-E4	1-F4	1-G4	1-H4	1-I4	1-J4	1-K4	1-L4	1-M4
	RE	RE	IS	IS	ES	EM	EM	CEC	CEC	MT&ES	MT&ES	IS	PS
17:30-19:00	**Editorial Board Meeting**												
Day 2: October 10													
8:10-09:50	2-A1	2-B1	2-C1	2-D1	2-E1	2-F1	2-G1	2-H1	2-I1	2-J1	2-K1	2-L1	2-M1
	RE	RE	IS	IS	ES	EM	EM	EM	CEC	CEC	MT&ES	IS	PS
9:50-10:20	**Tea/Coffee Break**												
10:20-12:00	2-A2	2-B2	2-C2	2-D2	2-E2	2-F2	2-G2	2-H2	2-I2	2-J2	2-K2	2-L2	2-M2
	RE	RE	IS	IS	ES	EM	EM	EM	CEC	CEC	MT&ES	MT&ES	PS
12:00-13:00	**Lunch**												
13:00-13:40	**Poster Session II**												
13:40-15:20	2-A3	2-B3	2-C3	2-D3	2-E3	2-F3	2-G3	2-H3	2-I3	2-J3	2-K3	2-L3	2-M3
	RE	RE	IS	IS	ES	EM	EM	RE	CEC	CEC	MT&ES	MT&ES	PS
15:20-15:50	**Tea/Coffee Break**												
15:50-17:30	2-A4	2-B4	2-C4	2-D4	2-E4	2-F4	2-G4	2-H4	2-I4	2-J4	2-K4	2-L4	2-M4
	RE	RE	IS	IS	ES	EM	EM	RE	CEC	CEC	MT&ES	MT&ES	PS
18:00-22:00	**Conference Banquet**												
Day 3: October 11													
8:10-09:50	3-A1	3-B1	3-C1	3-D1	3-E1	3-F1	3-G1	3-H1	3-I1	3-J1	3-K1	3-L1	3-M1
	RE	RE	RE	IS	ES	EM	RE	EM	EM	CEC	MT&ES	CEC	PS
9:50-10:20	**Tea/Coffee Break**												
10:20-12:00	3-A2	3-B2	3-C2	3-D2	3-E2	3-F2	3-G2	3-H2	3-I2	3-J2	3-K2	3-L2	
	CEC	RE	RE	IS	ES	EM	EM	RE	EM	CEC	MT&ES	RE	
12:00-13:00	**Lunch**												
13:00-15:00	3-A3	3-B3	3-C3	3-D3	3-E3	3-F3	3-G3	3-H3	3-I3	3-J3	3-K3		
	RE	CEC	RE	MT&ES	IS	ES	EM	CEC	CEC	CEC	CEC		
15:00-15:30	**Tea/Coffee Break**												
15:30-17:30	3-A4	3-B4	3-C4	3-D4	3-E4	3-F4	3-G4	3-H4	3-I4	3-J4	3-K4		
	RE	RE	IS	MT&ES	IS	ES	EM	RE	MT&ES	CEC	CEC		

MT&ES = Mitigation technology and energy storage; CEC=Clean energy conversion; EM=Energy management, policy and economics; ES=Energy sciences; IS=intelligent system; RE=Renewable energy

三、心　得

ICAE2016 共安排 5 場 keynotes 演講，如表 2 所示。就講者國籍來看，美國與英國各一場，中國地主有三場。就領域而言，太陽光電、CO_2 封存再利用、與能源政策各一場，電動車兩場。

表 2：ICAE2016 的五場 keynotes 演講

主講人	職位	Keynote 題目	領域
Prof. Lawrence L. Kazmerski	Science and Technology Partnerships, NREL (National Renewable Energy Laboratory)執行長(since 2009)	Photovoltaics Technology: Where we are, how we got here, and where we are going	太陽光電
Prof. Heping Xie 及 Prof. Bin Liang	四川大學校長及化工系主任	Mineralization, a Profitable and Prosperous CCUS Route	CO_2 封存再利用
Prof. Goran Strbac	Imperial College, London, UK	Role and Value of Flexibility in Future Low Carbon Energy Systems	能源政策
Dr. Chengyin Yuan	• Deputy General Manager of Beijing Electric Vehicle Co. Ltd • VP of Beijing Pride Power SystemTechnology Ltd	Electric Vehicle and Battery Pack Development in China	電動車
Mr. Gaopeng Li	• Chief Engineer of National Engineering Technology Research, Center for Electric Bus Control and Safety • Deputy Technical Director of Zhengzhou Yutong Bus Co., Ltd	Research, Development and Industrialization of the Electric Bus in China	電動車

第一場是太陽光伏領域世界知名的 Prof. Lawrence，他自 2009 年開始即擔任 Science and Technology Partnerships, NREL (National Renewable Energy Laboratory)執行長，講題主要內容是 NREL 在太陽能研發趨勢的調查與預測，類似內容在全世界演講已逾百場，介紹了太陽光伏自 1950 年代至現在的發展歷史與趣事，Prof. Lawrence 口條風趣使得會場上笑聲不斷。太陽光伏主要技術路徑趨勢如圖 1 所示。近年來的趨勢沒有太大變化，整體市場被矽晶太陽能獨佔，壓縮了其他技術的發展空間，卻也促使太陽能發電成本的大幅下降與產業化。

大陸能源政策採取補貼政策，因為此舉使得太陽能電池成本降至市場電價水平，但國家級補貼也引起全球各國在經濟上指責。不可諱言，補貼政策有助新技術進入市場，有利節能

與減碳目標的達成。然而補貼政策會侵蝕國家財政，削弱既有技術市場廠商的獲利，有其後座力。因此我國若要加速新能源與再生能源的政策實踐，適當的補貼政策有其必要，但應周詳考慮，訂立時間表計畫性施行，推行新政目標的同時給既有廠商適當的緩衝期。

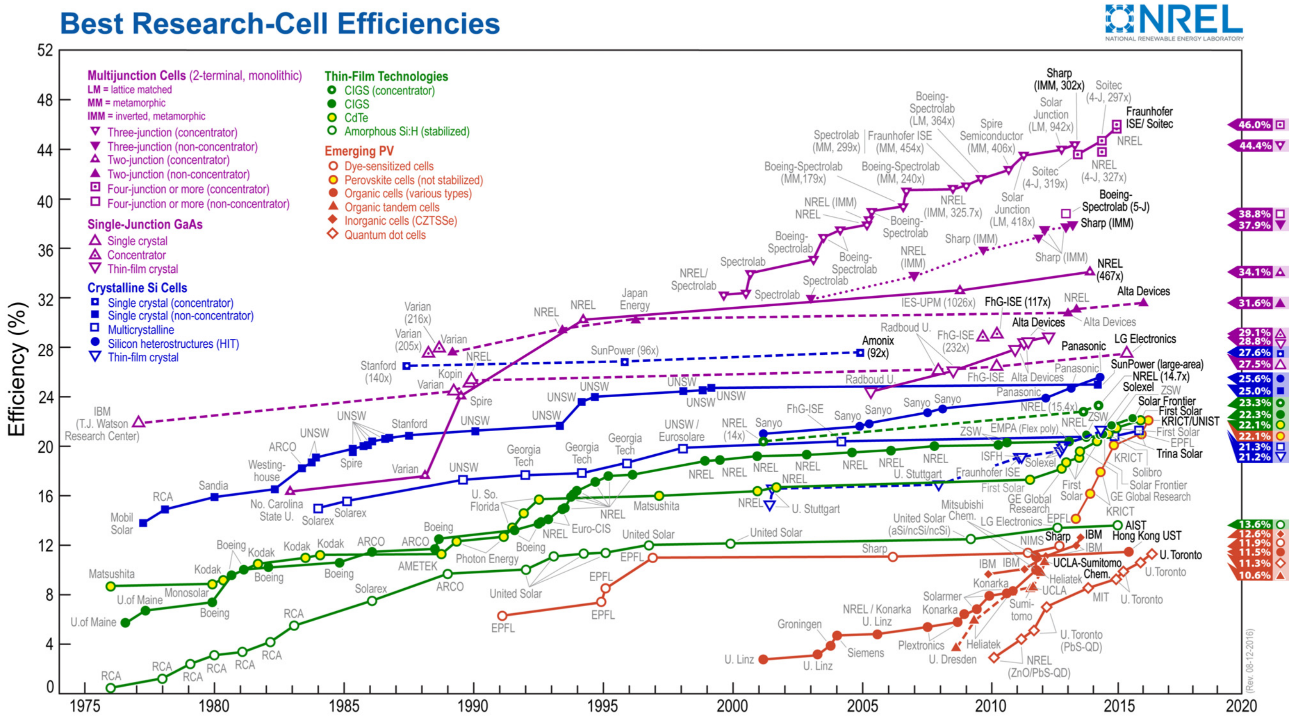


圖 1：國際太陽光伏發電效率發展路徑與趨勢[3]

第二場專題演講是關於二氧化碳封存再利用，講者為四川大學校長謝和平教授(Prof. Heping Xie)及化工系主任梁斌教授(Prof. Bin Liang)，講題為“Mineralization, a Profitable and Prosperous CCUS Route CO_2”。碳酸鈣($CaCO_3$)是一種常用的化工產品，中國 2012 年碳酸鈣產量>2000 萬噸，消費量>1600 萬噸，消費量每年~15%成長[4]。沉澱碳酸鈣的工業生產方法主要透過煅燒石灰石、消化後再用 CO_2 碳化得到產品。由於石灰石高溫煅燒過程能耗較大，即使製程精進後每噸石灰石仍需消耗約 110 kg 的煤炭。石灰石多是露天開採，開採過程容易破壞植被與山林等環境問題。

乙酸低溫酸解石灰岩造腔是一種可控制的石灰岩開採過程。若在石灰岩地質的地層，以地下井注入酸液溶解石灰岩，再將鈣鹽溶液泵出，直接井下開採程序可以降低開採時的環境破壞問題。另一方面，通過石灰岩腔的控制性溶解，可以得到能夠作為封存 CO_2 的地下岩腔儲庫。泵出的乙酸鈣溶液在加壓 CO_2 氣體作用下生成沉澱碳酸鈣與乙酸，過濾分離後可回收

乙酸及沉澱碳酸鈣。回收的乙酸可重複用於石灰岩的溶解，沉澱碳酸鈣是化工產品。此技術同時達到石灰岩開採造腔和生產沉澱碳酸鈣之目的。相關化學反應如下：

$CaCO_3$ (石灰岩) + 2 CH_3COOH (乙酸) ←→ $Ca(CH_3COO)_2 + CO_2 + H_2O$

$Ca(CH_3COO)_2 + CO_2 + H_2O$ ←→ $CaCO_3$ (產品:沉澱碳酸鈣) + 2 CH_3COOH

乙酸酸解石灰石造腔是一種新技術，可以環保開採石灰岩製備沉澱碳酸鈣，同時建造地下 CO_2 儲存庫。另外也有一些相似可行的二氧化碳再利用技術，如利用氯化鎂礦化 CO_2 聯產碳酸鎂及鹽酸、利用固體廢棄物的磷石膏礦化 CO_2 聯產硫基複合肥等，均被視為具有大規模工業應用的可能。也因此四川大學與中國石化集團在 2013 年簽署協議，共同設立 CCU 及 CO_2 礦化利用研究院，致力發展 CO_2 捕集及 CO_2 礦化利用等技術。

筆者認為，CO_2 再利用同時解決廢棄物問題並產出有價實體的技術，是值得發展與令人期待的，我國能源國家型計畫第二期(NEP-II)也支持相關技術的發展，看來英雄所見略同。上述 CO_2 再利用技術雖有多重效益，但筆者認為發展前須考量以下問題：終端產品需求量與 CO_2 去化量。雖然 CO_2 可作為其他產品的原料，但是每一種產品都有市場需求飽和量，不可能無限制生產；換言之，產品市場需求飽和量限制了 CO_2 的使用量或消化量。就筆者的印象，所有可以 CO_2 為原料的化學品，均以 CO_2 為原料進行生產，所消耗的 CO_2 量仍遠低於全球排放的 CO_2 量；換言之，以 CO_2 為原料是不可能完全去化 CO_2 排放。即使現實如此，筆者認為 CO_2 再利用技術仍值得發展，但必須在具經濟效益或具其他邊際效益的前提。

第三場專題演講的主題是能源政策，由英國倫敦 Imperial College 的 Prof. Goran Strbac 講說 Role and value of flexibility in future low carbon energy systems。低碳能源系統牽涉內容複雜，每個人的觀點不會相同，不同產業關心的面向也不一致，如何系統性量化與分析，擬出合適政策乃一重要但艱難的課題。Prof. Goran Strbac 強調全面性系統分析的重要性，鼓勵國際合作致力相關技術的發展與數據的交流，促進低碳生活的落實。能源政策是本次 ICAE2016 會議中的大宗，在 118 場口頭發表 sessions 中佔了 22 場(19%)，顯示此方面的研究頗受重視。

第四場及第五場專題演講的主題關於電動車，演講內容大多在介紹公司營運與產品，推測之所以成為專題演講的原因是兩家公司為大會的贊助商。但值得注意的有兩點：(一)電動車在大陸地區成長非常快速，原因與大陸政策補貼有關，目前電動車的補助金約 50%，使得電動車價格與一般車輛相當，因此電動車的環保，單位行駛里程成本較化石燃料車輛便宜等因素，使得電動車的銷售量每年以雙位數成長。目前大陸具規模的電動車廠商有十來家，算是百家齊放的戰國市場。本次大會展示了電動汽車及實際上路的電動公車，如圖 2 所示。(二)電動車製造商已經開始留意廢電池的問題，廠商估計電池壽命約 8 年，因此未來幾年就會面臨廢電池固體廢棄物的環保問題，因此如何妥善再利用相關廢電池，達到資源循環與永續，必須提早因應。話雖如此，但會場上未說明可行技術與方法。國內電動車與 3C 產品如筆電與手機，也使用大量的電池，如何妥善處理也值得思考與發展。

最後一提的是，目前電池的發展趨勢是比容量越大越好，即單位體積電容量越大越好，許多研發致力於新電池材料開發，其中複合材料的表現尤佳；但是相較單一或簡單材料而言，複合材料的回收再利用，困難度高出非常多，這是未來電池開發時必須事先考量的，研發同時進行產品生命週期環境衝擊分析應有其必要。

圖 2：ICAE2016 會場展示的電動汽車(左)與電動公車(右)

大會論文近千篇，同一時間有 12~13 場 sessions 平行進行，無法聆聽所有論文。筆者考量自身專業背景與目前研究工作內容，因此鎖定節能、熱管、生質能等主題。

本次會議中生質能的文章相當多，在 118 場 sessions 中佔了 13 場(11%)，口頭發表論文約 65 篇，主題大致可分為焙燒、裂解、氣化、燃燒、微藻、生質燃油、觸媒等。可能因為生質能發展已久也相當成熟了，本次大會發表論文並未見突破性的技術，多針對更細的科學現象與問題進行探討。

在節能部分，本次大會共有 18 篇論文與有機朗肯循環(ORC, Organic Rankine Cycle)技術有關，在眾多能源技術論文中，數量算相當高，顯示此刻 ORC 研究在國際間頗受重視。表 3 為 ORC 相關的 18 篇論文，有興趣的讀者可至 Energy Procedia 期刊免費下載論文全文；依發表國而言，中國佔大宗；有 6 篇論文為跨國合作，占三分之一比例，顯示跨國研究合作非常盛行，此趨勢值得我國學研界參考，整合國際研究資源與人員經驗交流，對於加速與深入科學技術發展定有幫助。

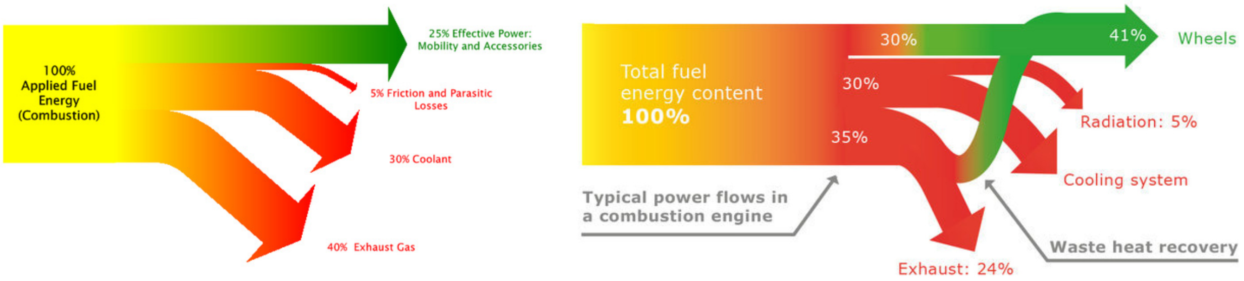
表 3：ICAP2016 會議中與 ORC 相關之 18 篇論文

論文名稱	單位	作者	國別
1. A critical analysis on performance of ORC through a modified thermodynamic model based on fluid property	Key Laboratory of Efficient Utilization of Low and Medium Grade Energy, Tianjin University Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences	Wang et al.	中國
2. An assessment of subcritical and supercritical organic Rankine cycles for waste-heat recovery	Clean Energy Processes Lab., Dep. of Chem. Eng., Imperial College London Department of Flow, Heat and Combustion Mechanics, Ghent University	Oyewunmi et al.	英國 比利時
3. Analysis of an alternative method to optimize the combined model of engine and organic Rankine cycle	State Key Laboratory of Engine, Tianjin University	Shu et al.	中國
4. Comparative investigation on thermo-economic performance between ORC and LiBr absorption refrigerating cycle in waste heat recovery	Key Laboratory of Low-grade Energy Utilization Tech. and Systems, Chongqing University College of Power Engineering, Chongqing University	Wu et al.	中國
5. Design and parametric study of an Organic Rankine cycle using a scroll expander for engine waste heat recovery	Sir Joseph Swan Centre for Energy Research, Newcastle University Department of Energy Engineering, Zhejiang University	Lu et al.	英國 中國
6. Dynamic modeling of CO_2 transcritical power cycle for waste heat recovery of gasoline engines	State Key Laboratory of Engines, Tianjin University	Li et al.	中國
7. Dynamic response performance comparison of ranking cycles with different working fluids for waste heat recovery of internal combustion engines	State Key Laboratory of Enignes, Tianjin University	Wang et al.	中國
8. Economic feasibility of organic Rankine cycles (ORC) in different transportation sectors	Institute for Energy Systems, Technische Universität München School of Mechanical & Aerospace Eng., Nanyang Technological University	Pilia et al.	德國 新加坡
9. Effects of the ORC Operating Conditions on the Engine Performances for an Engine-ORC Combined System	School of Mechanical Eng., Beijing Institute of Technology School of Mechanical and Automotive Eng., Hubei University of Arts and Science School of Mechanical and Power Eng., North University of China	Zhao et al.	中國
10. Experimental study on a small-scale R245fa organic Rankine cycle system for low-grade thermal energy recovery	RCUK National Centre for Sustainable Energy Use in Food Chains, Institute of Energy Future, Brunel University London	Li et al.	英國

11. Integration of organic Rankine cycle with lignite flue gas pre-drying for waste heat and water recovery from dryer exhaust gas: thermodynamic and economic analysis	State Key Laboratory of Multiphase Flow in Power Eng., Xi’an Jiaotong University Laboratory of Steam Boilers and Thermal Plants, National Technical University of Athens	Han et al.	中國 希臘
12. Performance evaluation and comparison of experimental organic Rankine cycle prototypes from published data	Université Grenoble Alpes CEA CNRS ADEME	Landelle et al.	法國
13. Potential of low temperature organic Rankine cycle with zeotropic mixtures as working fluid	Beihang University	Dong et al.	中國
14. Preliminary experimental results of an 11 kWe organic Rankine cycle	Department of Flow, Heat and Combustion Mechanics, Ghent University Clean Energy Processes Laboratory, Department of Chemical Engineering, Imperial College London	Lecompte et al.	比利時 英國
15. Simulation study of an ORC system driven by the waste heat recovered from a trigeneration system	Sir Joseph Swan Centre for Energy Research, Newcastle University Guangxi Electrical Power Institute of Vocational Training Institute of Engineering Thermophysics, Chinese Academy of Sciences	Ji et al.	英國 中國
16. System design and thermodynamic analysis of a sintering-driven organic Rankine cycle	Key Laboratory of Thermo-Fluid Science and Engineering, School of Energy and Power Engineering, Jiaotong University	Liu et al.	中國
17. Supercritical CO_2 Rankine cycle system with low-temperature geothermal heat pipe	Energy Conversion Research Center, Department of Mechanical Engineering, Doshisha University Graduate School of Life and Environmental Sciences, Osaka Prefecture University ACE System Co. Ltd.	Pumaneratkul et al.	日本
18. Thermodynamic analysis of organic rankine cycle with hydrofluoroethers as working fluids (Poster)	Key Laboratory of Renewable Energy, Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences Guangdong Key Laboratory of New and Renewable Energy Research and Development University of Chinese Academy of Sciences	Wang et al.	中國

筆者對於 ORC 有兩點感受較深刻：(一)應用 ORC 於大客貨車，提升整體燃料使用效率，(二)法國 Landelle 等人發表 ORC 原型機的統計分析，分述於下與大家分享。

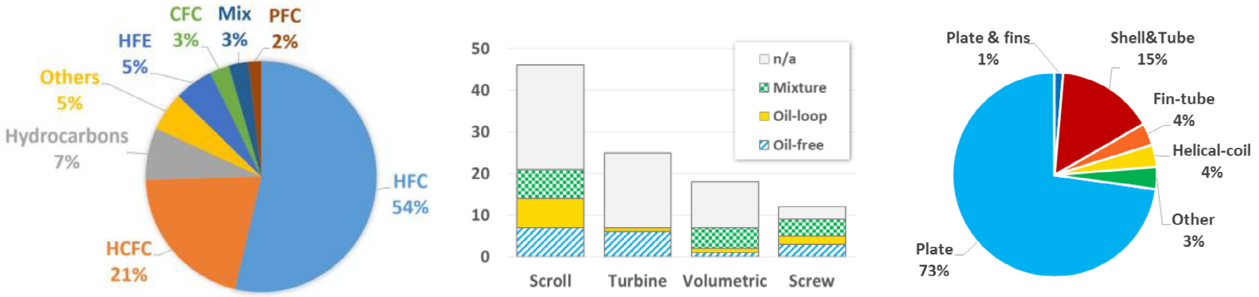
(一)應用 ORC 於大客貨車，提升整體燃料使用效率。根據 IEA 統計，全世界有 14%能源用於運輸工具。然而車輛的燃料使用效率只有約 25%，有近 40%以廢熱方式排出，如圖 3a 所示，除了能源利用率不佳外，也加劇了都會地區的熱島效應，並增加了隧道升溫及其風險。因此國外一些運輸巨擘如 Volvo 及 Renault 等汽車公司，均投入於廢熱再利用的研發工作。ORC 可將熱轉為電能，因此被視為將廢熱回收的可行技術之一。圖 3b 為汽油內燃機引擎燃燒燃料能源分流的未來情境展望，隨著引擎科技進步，燃料效率可望由 25%提升至 30%，可利用廢熱由 40%降至 35%；透過廢熱回收後，燃料效率可望由 30%再提升至 41%，廢熱則由 35%降至 24%；換言之，每公升汽油里程數是目前的 1.64 倍。ORC 看似可以大幅提升效率，但是個人卻對 ORC 實務應用存有兩個疑慮：(1) ORC 體積與重量龐大能否符合實務需求？(2)交通載具的速率(功率)變動頻繁，ORC 運轉能否匹配？但不諱言的是，市場有需求，科技進步提供解決方案，希望未來可以看到路上有 ORC 省油汽車。



(a)現有引擎[5] (b) 未來預期目標[6]

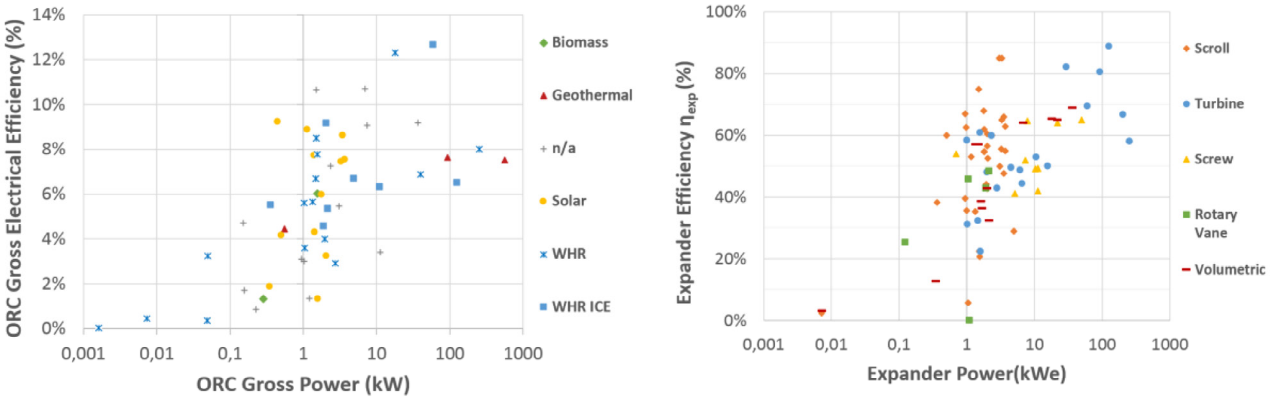
圖 3：典型汽油內燃機引擎燃燒燃料能源分流圖

(二)法國 Landelle 等人發表 ORC 原型機的統計分析。論文名稱為 Performance evaluation and comparison of experimental organic Rankine cycle prototypes from published data，作者們蒐集 ORC 論文，刪除不可靠或不完整者，以百來篇論文的數據為資料進行統計分析，包括 ORC 種類、工作流體(working fluid)、膨脹器(expander)、潤滑方式(lubrication)、熱交換器(heat exchanger)，如圖 4 所示，讀者可以了解 ORC 技術的選用趨勢。圖 5 為 ORC 功率大小與效率之關聯性，圖 5a 顯示 ORC 功率與 ORC 效率的關係，圖 5b 呈現膨脹器功率對膨脹器效率的影響，與筆者預期相符，大致而言功率愈大效率越高；圖 5 同時區分不同熱源供應型式，讀者可進一步掌握 ORC 研發相關趨勢與細節。上述統計分析乃相當繁瑣耗時的工作，筆者心感敬佩。



(a) Working fluid categories (b) Expanders and lubrication (c) Heat exchangers types

圖 4：法國 Landelle 等人對 ORC 種類統計分析結果[2]



(a) ORC efficiency function of power output (b) Expander efficiency function of power output

圖 5：ORC 功率大小與效率之關聯性[2]

筆者本次發表一篇文章，論文題目為 Stainless Steel Heat Pipe Fabrication, Performance Tests and Modeling，介紹核研所近兩年在熱管(heat pipe)製造、性能測試、數值模擬的研發成果，論文全文列於附錄供大家參考。本次會議中關於「熱管」的文章共 6 篇，由國籍來看，中國 4 篇、日本與我國各 1 篇：(1) Experimental research of a thermoelectric cooling system integrated with gravity assistant heat pipe for cooling electronic devices、(2) Experimental study of energy saving performances in chip cooling by using heat sink with embedded heat pipe、(3) Performance analysis of an integrated solar-assisted heat pump system with heat pipe PV/T collectors operating under different weather conditions、(4) Heat transfer simulation and analysis of ice and snow melting system using geothermy by super-long flexible heat pipes、(5) Supercritical CO_2 Rankine cycle system with low-temperature geothermal heat pipe、(6) Stainless steel heat pipe fabrication, performance tests and modeling。

前兩篇為熱管應用於電子設備的冷卻散熱，這方面應用在台灣已經商品化了。第三篇以熱管應用於太陽熱能，是熱管的常見應用。第四篇較特殊，以超長熱導塑膠熱管作為路面解凍用途，其中超長軟性熱管(super-long flexible heat pipe, SFHP)是其新穎之處，如圖 6 所示。熱管材質一般都會選用高熱傳材料，而塑膠的熱傳係數比銅或其他金屬低了 2~3 個數量級，理應不該作為熱管材質；但作者表示 SFHP 以塑膠為外管可免除腐蝕問題，使用年限較長且容易維護。根據作者模擬結果，建議採用 70 m 長的 SFHP，蒸發段、絕熱段與冷凝段分別為 40 m、10 m 與 20 m，採用 Φ32×2 mm 管徑，以氨為熱管的工作流體，熱傳量可達約 1.15 kW。他們也在研發熱傳係數較高新式熱導塑膠，是個找到特定應用對象、研究方向反向思考的好案例。融雪應用研究主題在寒帶國家有需求；台灣屬於亞熱帶國家，融雪需求不大，但可以思考相關可行應用。

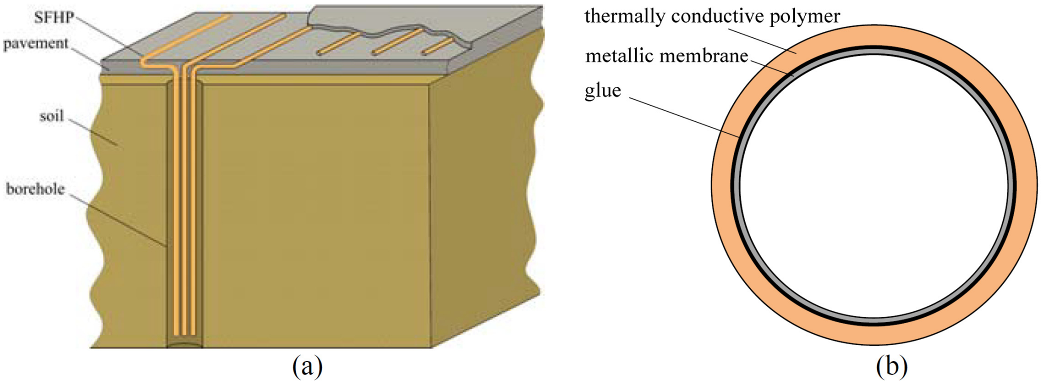


圖 6：(a)超長軟性熱管(super-long flexible heat pipe, SFHP)應用於(b)路面解凍[2]

第五篇 Supercritical CO_2 Rankine cycle system with low-temperature geothermal heat pipe 為日本學者的報告，結合了甲醇熱管與超臨界 CO_2 朗肯循環的地熱發電，如圖 7 所示，以甲醇熱管對地熱與 CO_2 進行熱交換，再透過超臨界 CO_2 朗肯循環來發電。研究指出若甲醇流率為 2 kg/s 時，發電量約 30 kW。台灣具有地熱潛力，此地熱發電方面的研發值得我國參考。

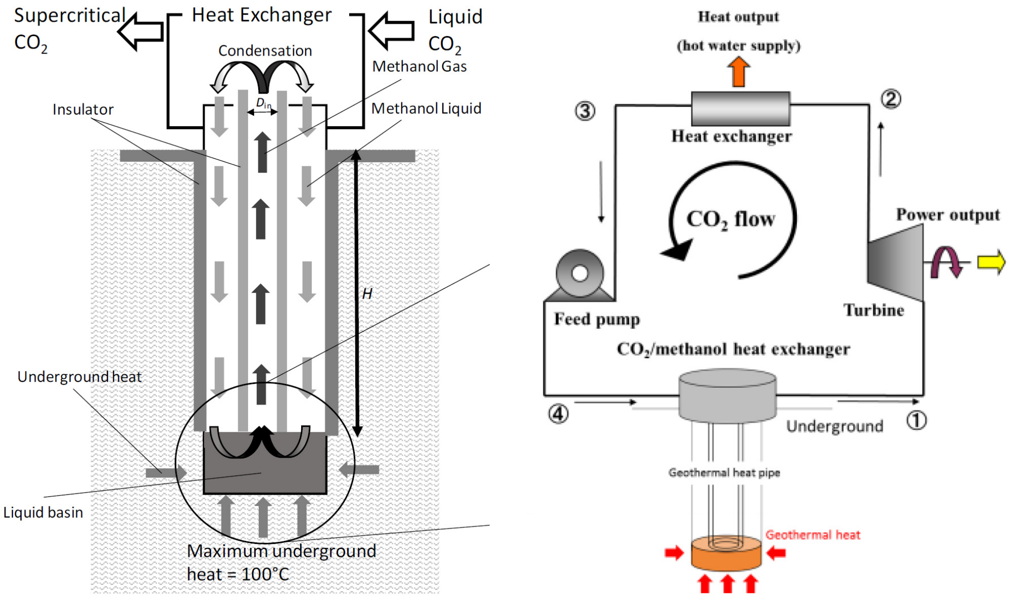


圖 7：超臨界 CO_2 朗肯循環地熱發電示意[2]

最後一篇為筆者發表文章，題目為 Stainless steel heat pipe fabrication, performance tests and modeling。會議上筆者說明熱管用於工業廢熱回收的價值與機會，台灣地區的工業餘熱佔全國工業能源總需求量的 9.2%，估計有 3.9 百萬公秉油當量，其中溫度低於 250°C 的低階餘熱佔了 75% [1]；若上述低階餘熱可以完全回收，每年可以減少 8.4 百萬噸 CO_2 排放。熱管熱交換器具有高熱傳性能，具備實務應用潛力，但是面臨酸露點腐蝕的實務問題。為解決腐蝕問題，核研所開發不鏽鋼熱管(如圖 8)，並研發抗腐蝕鍍層(包括 TiN、CrC 及 NiCr)進一步提升抗腐蝕性，結果顯示抗腐蝕鍍層可以降低腐蝕速率一至兩個數量級，有助延長工業應用時的使用壽命。本次會議中獲知國際研發趨勢，結識一些研發相關的國際友人，有益我國研發之提升與提速。

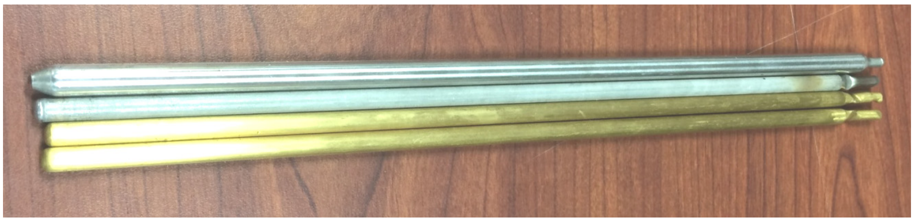


圖 8：核研所研發自製的不銹鋼熱管(上二)及 TiN 不銹鋼熱管(下二)

四、建議事項

(一) 台灣地區溫度低於 250^{o}C 的低階工業餘熱估計有 2.9 百萬公秉油當量，若完全回收每年約可減少 8.4 百萬噸 CO_2 排放。熱管熱交換器具有高熱傳性能，具備實務應用潛力，但是面臨酸露點腐蝕的實務問題，因此抗腐蝕熱管熱交換技術值得發展。

(二) 台灣具有地熱潛力，結合熱管與有機朗肯循環或超臨界 CO_2 朗肯循環的發電技術，如此不必將地下熱水抽出，可以避免地層下陷的隱憂，也免除回補水所需的動力損失，是值得我國發展的潛力技術。

(三) 新產品開發最重視者莫過於高效能與低成本，因此越來越多複合材料被廣泛研發與使用。由於所有產品均有其壽命，最終將面對廢棄物處理的環保問題與資源回收再利用的永續問題。由於複合材料回收再利用的困難度高，建議未來新材料與新產品研發同時，應進行產品生命週期環境衝擊分析，促進資源循環經濟社會的落實。相關複合材料的回收再利用技術的開發，也應及早進行。

五、附　錄

參考文獻：

[1] 經濟部能源局，「讓能源充分發揮效益–工業廢熱回收」，能源報導，2014.09。

[2] Proceedings of the 8th International Conference on Applied Energy (ICAE2016), Beijing, China, Oct. 8-11, 2016.

[3] NREL, http://www/nrel.gov/pv/, downloaded at 2016.11.02.

[4] 楊政、岳海榮、周向葛、梁斌、謝和平，「CO_2碳酸化石灰岩酸解產物回收乙酸及副產沉澱碳酸鈣」，化工學報，第 65 卷，第 9 期，2014 年 9 月。

[5] http://www.greencarcongress.com/2005/02/doe_cofunds_12_.html, downloaded at 2016.11.03.

[6] https://tmcemployeneurship.com/projects/power-plant-on-every-truck, downloaded at 2016.11.03.

發表論文如下共 **6** 頁。

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Energy Procedia 00 (2016) 000–000

Energy Procedia

www.elsevier.com/locate/procedia

The 8th International Conference on Applied Energy – ICAE2016

Stainless Steel Heat Pipe Fabrication, Performance Testing and Modeling

How-Ming Lee, Meng-Chang Tsai, Hsin-Liang Chen, Heng-Yi Li

Institute of Nuclear Energy Research (INER), 1000 Wenhua Rd., Longtan District, Taoyuan City 32546, Taiwan

---

Abstract

A set of stainless steel tabular heat pipes are successfully fabricated, for the purpose of the low-grade heat recovery applications in a corrosion exhaust environment. The fabrication, the thermal performance testing systems, and modeling are presented in the paper. Experimental results show that the water filling ratio plays a significant role in the thermal performance of heat pipes. A numerical model is developed and the model prediction is trustworthy in comparison with experimental data. The model reveals that a better heat pipe thermal performance could be achieved by selecting a material with higher thermal conductivity coefficient. However, it should be compromised in terms of the thermal performance and the application concerns like corrosion.

Keywords: Heat pipe, waste heat recovery, heat pipe simulation, stainless steel heat pipe, fabrication of heat pipes.

---

1. Introduction

The low-grade heat, especially the waste heat from exhausts of factories with a gas temperature lower than 250°C, is relatively difficult to be recovered to date. A heat pipe is a good heat transfer device on the field of heat exchange applications, and is one of possible engineering solutions to the purpose of low-grade heat recovery. However, a corrosive problem on the acid dew point in flue gases at 100~150°C is deemed necessary to be solved for such challenging application.

Heat pipes are generally made of copper, however it is weak in corrosion resistance point of view. In the study, therefore, a set of heat pipes are fabricated of stainless steels. It is expected that the heat transfer performance of stainless steel heat pipes should be lowered compared to copper one, because the thermal conductivity of stainless steel (k = 16 W/m/K) is much lower than that of copper (k = 400 W/m/K). Experimental tests are carried out to evaluate the influence of materials on the heat transfer performance.

In addition, a numerical model is developed to better understanding of heat pipes as well as the influence of materials.

2. Heat Pipe Fabrication and Thermal Performance Test

A number of heat pipes are fabricated in the study. The tubular heat pipes are made of unpolished SUS316 stainless steel tubes, of a diameter of 6 mm and a length of 300 mm. The thickness of tubes is 0.5 mm. When a wick structure inside stainless steel tubes is fabricated, the heat pipe is carefully flushed, deeply cleaned, and completely dried. The one end sealed tube is then vacuumed and filled with deionized water as the working fluid. The volumetric ratio of the filling water to the internal heat pipe volume ranges from 4% to 11%. The end cap is clamped and welded in a vacuum environment. A photo of the homemade heat pipes is presented in Figure 1.

Fig. 1. Photo of homemade SUS316 stainless steel heat pipes.

The thermal performance measurement of heat pipes is carried out with two testing systems, as shown in Figure 2. The thermal performance measurement shown in Figure 2(a) is designed for fast evaluation of a heat pipe. A heat pipe is placed inside a thermal insulation chamber with a slope inclined at 45° to horizontal. An electric heater directly contacts with the bottom half side of a heat pipe. The power of the heater is gradually stepped up from 0 to 200 W. A circulating water bath is adopted as the heat sink. Both heating and cooling sides are of a contact length of 30 mm. Two thermocouples locate at the center of heating and cooling sections, respectively. Accordingly, an effective length for the thermal performance measurement of heat pipes is about 270 mm.

Figure 2(b) illustrates the high temperature testing system used in the study. The lower half part of a testing heat pipe is placed in an electric oven. The other half part is inserted into an enclosed water/steam chamber, containing one third of water. Outside the chamber, fiber glass is used as a thermal insulation from the ambient air. Four thermocouples are installed. Three of the four thermocouples locate separately, vertically and evenly on the surface of heat pipe inside the oven, and the last one locates around the top of the head space of the water/steam chamber.

3. Results and Discussion

3.1. Thermal performance tests with the fast testing system

Figure 3 shows the thermal performance of heat pipes, tested with the fast testing system, for three different water filling ratios of 4%, 7%, and 11%. The x-axis is the input power of the oven or the heat source. T1 and T3 represent the temperatures at heating and cooling sections, respectively. The temperature difference between T1 and T3 is also plotted. The y-axis on the left hand side is the thermal resistivity, which is calculated by the temperature difference divided by the input power.

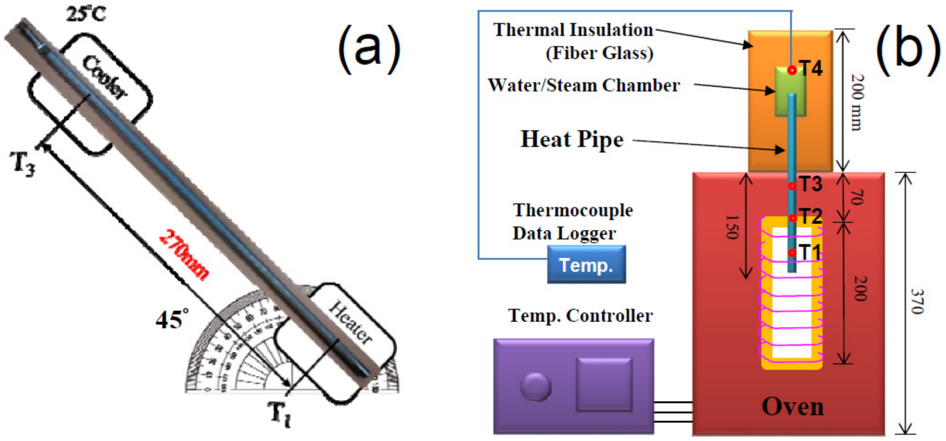


Fig. 2. Illustration of two thermal performance measurements used in the study, (a) fast testing system; (b) high-T testing system.

For the water filling ratio of 4%, in Figure 3(a), the temperature T1 is always greater than T2, and both temperatures increase with the increase of the input power. The temperature difference also increases with the increase of the input power when the power is lower than 50 W. Beyond that, the temperature difference reaches stable at about 45 W. The temperature difference and the thermal resistivity are both high in the range of all powers tested. It indicates a poor thermal performance, which is expectedly resulted from water dry out due to low water amount inside the heat pipe.

Figure 3(b) shows results for the water filling ratio of 7%. The temperatures increase with the increase of the input power, as similar as the trend shown in Figure 3(a). However, an eventful feature is observed that there is a temperature drop between the power of 50 W and 60 W. One can also observed that the temperature difference is high as $P<50$ W, and the temperature difference becomes relatively small as $P>60$ W. It experimentally indicates that a 7%-water-filled heat pipe should be operated at a startup temperature greater than 60°C. As $P>60$ W, the temperature difference and the thermal resistivity are reduced and stably kept to 40°C and 0.07 K/W, respectively.

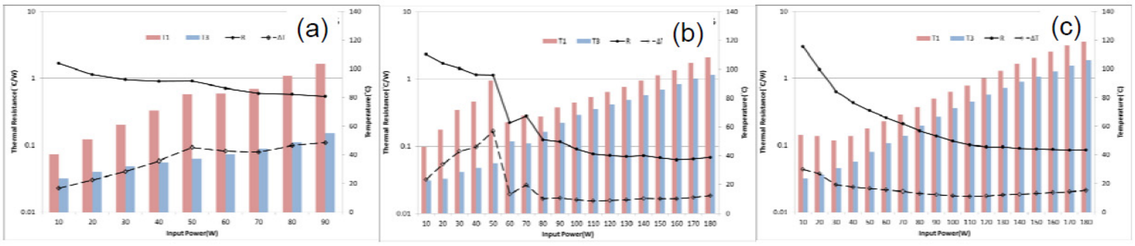


Fig. 3. Thermal performance of heat pipes for three water filling ratios of (a) 4%, (b) 7%, and (c) 11%.

Figure 3(c) presents experimental data for the water filling ratio of 11%. The temperature difference monotonically decreases with the increase of the power. The temperature drop observed in Figure 3(b) cannot be observed. It indicates that an 11%-water-filled heat pipe can be easily started up, even at a low input power or a low temperature. As P>60 W, the temperature difference and the thermal resistivity stabilize to 45°C and 0.09 K/W, respectively. The thermal resistivity for the 11%-water heat pipe is higher than that for 7%-water one. It means that a 7%-water heat pipe is relatively excellent in heat transfer rate, and an 11%-water heat pipe is relatively suitable to be used at lower temperatures (i.e., T<60°C).

3.2. Thermal performance tests with the high-temperature testing system

Figure 4 displays the temperature variation with the time for four thermocouples measured in the high-T testing system. The channels 1 to 4 represent the temperatures of thermocouples T1 to T4 illustrated in Figure 2(b), respectively. The temperatures on the heat pipe surface in the heating section are in the order of T1 > T2 > T3, but frankly speaking the three temperatures are very close quantitatively. T1, T2 and T3 reach a stable temperature of 233°C in t = 1,800 s (0.5 h). In a longer time t = 5,400 s (1.5 h), T4 approximately reaches a stable temperature of 152°C. It corresponds to a steam pressure of about 5 kg/cm^2. The test is lasted for 25,200 s (7 h) and no damage occurred to the heat pipe.

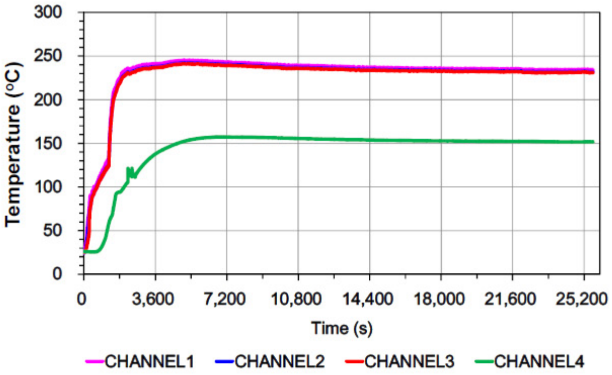


Fig. 4. Temperature variation with the time for four thermocouples measured in the high-T testing system. The channels 1 to 4 represent the temperatures of thermocouples T1 to T4 in Figure 2(b), respectively.

3.3. Model results

To better understanding of heat pipes, a numerical model for heat pipe simulation is conducted with a commercial finite element package, COMSOL Multiphysics.

Due to page limit, only selected information and simulation results are presented in the paper. The detail fundamentals of heat transfer equations in COMSOL and heat transfer in general can be found elsewhere [1–5]. The model is 2D axisymmetric. Figure 5 illustrate the model's physical geometry, which can be referred to that shown in Figure 2(b). The boundary conditions for the heat source and for the heat sink are set to 233°C and 25°C, as the same as the experimental data shown in Figure 4. The time dependent model is run and the results are summarized in Figures 6 and 7.

Figure 6 displaces the temperature distribution of the heat pipe testing system model for selected times at 0, 60, 600, 1200, 2400, and 3600 s. At t=0, all temperatures are as the same as the initial value of T=25°C. At t=60 s, the heat pipe quickly reaches thermal steady state thanks to its high thermal conductivity. After t=600 s, the temperature variations are visually and difficultly distinct, although temperatures are still slightly increased somewhere.

Figure 7 shows the time dependence of temperatures at selected points. All temperatures are obviously quite close except for the temperatures at two points, R_b_air and R0_boiler_top. The former locates outward the surface of the insulation and the temperature therefore equals to the ambient temperature of

25°C. The latter locates near the top inside the boiler (i.e., the water/steam chamber), and the temperature represents the steam temperature, which is important in heat exchange and waste heat recovery applications. The steam temperature is stepped up and reaches to a stable temperature of 155°C after *t*=2,400 s (40 min).

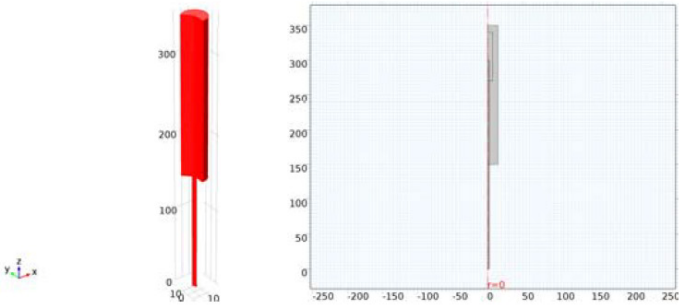


Fig. 5. A 2D axisymmetric physical geometry for the heat pipe high-T testing system. The unit is in mm.

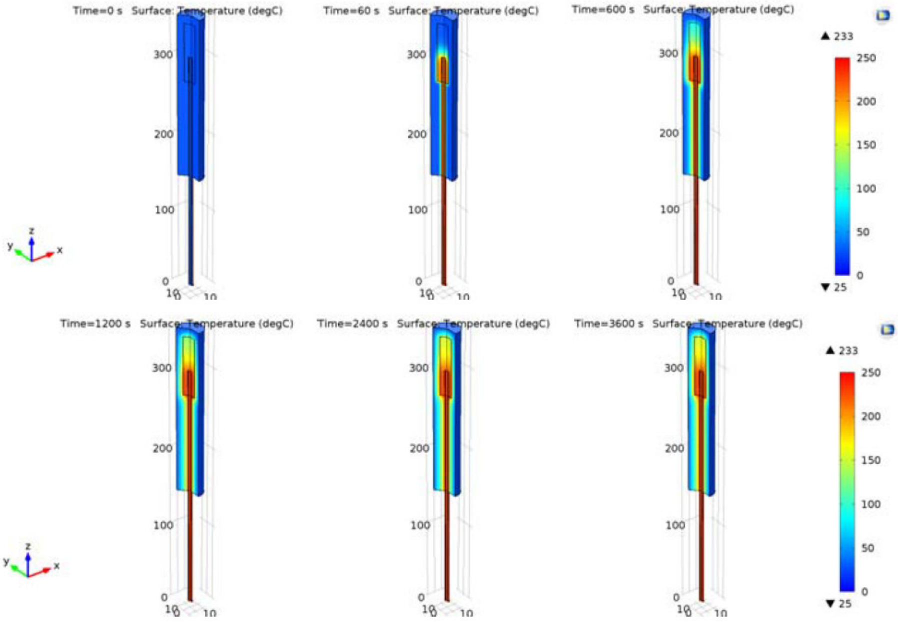


Fig. 6. Temperature distribution for selected time from 0 to 3600 s.

Comparing the experimental data and the model output, the steady-state temperatures are essentially close (152°C vs. 155°C, respectively). There is a time lag between the experimental data and model results (Figures 4 vs. 7). Authors believe that the time lag is due to variation of heating rate automatically controlled by the oven used in the experiment. Overall speaking, the model prediction should be trustworthy.

In addition, 300-mm heat pipes made of SS316 stainless steel and copper are compared by using the developed model. The surface temperatures of the heat source and the heat sink are 250 and 150°C, respectively. The steady state time needed for a cooper heat pipe is approximately 0.15 s and 0.45 s for SUS316 one. It reveals that a better heat pipe thermal performance could be achieved by selecting a material with higher thermal conductivity coefficient. It should be compromised in terms of the thermal performance and the application concerns like corrosion. The model could be a useful tool for the development of heat pipes as well as a heat pipe waste heat recovery system henceforth.

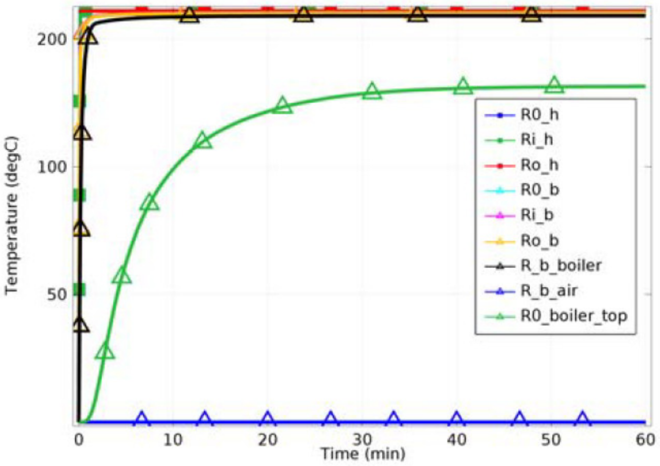


Fig. 7. Temperature variation for selected points in the high-T heat pipe testing system. The symbols used in the legend are defined as follows, "0" stands for $r=0$, "i," for r=the inner radius of the heat pipe tube, "o" for r=the outer radius of the heat pipe tube, "h" for z=the half height of heat pipe in the heating region, "b" for z=the half height of heat pipe inside the boiler (i.e., the water/steam chamber), "boiler" for r=the radius of the boiler, "air" for r=the radius of the insulation, respectively. "R0_boiler_top" locates close to the top of the boiler at $r=0$.

Acknowledgements

Funding by MOST and INER is acknowledged. Those who participated in the project are appreciated.

References

[1] Incropera FP, DeWitt DP, Bergman TL, Lavine AS. *Fundamentals of heat and mass transfer*. 6th ed. John Wiley & Sons; 2006.

[2] Bejan A. *Heat Transfer*. John Wiley & Sons; 1993.

[3] *Heat Transfer Module User's Guide*. COMSOL, http://www.comsol.com/; 2013.

[4] Hussain MN, Janajreh I. Numerical simulation of a cylindrical heat pipe and performance study. *Int. J. of Thermal & Environ. Eng.* 2016; **12**:135–41.

[5] Faris MA, Ghafori S, Hamza A, Windi OE. Analysis of the performance and phase change inside the heat pipes. *IJMRA*. 2015; **3** 76–87.