

Reflection on 50 Years of Friendship and Collaboration on Aerosol Science and Technology

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Abstract

I have the great fortune to work with many exceptional aerosol pioneers (iara.org/AerosolPioneers.htm) and outstanding students/post-docs/scholars over the past 50 years. I am very grateful that our friendship and collaboration have continued today. All these activities are fun and most satisfying while contributing to the aerosol science and technology.

Decade of 1970's

I started my master's degree in 1971 and completed Ph.D. degree in 1976 under the mentorship of Professor Benjamin Liu. During these years, we worked on bipolar charging and established the criterion to neutralize charged aerosols. An electrical aerosol analyzer (EAA) was developed to measure atmospheric particle size distributions, and led to the successful commercialization of TSI 3030 EAA. Professor Kenneth Whitby and Dr. William Wilson of EPA invited me to participate in the LA smog measuring campaign which provided results, together with other field measurements, to help EPA set up the PM_{2.5} standard. A differential mobility analyzer (DMA) was developed to provide monodisperse aerosols of primary and absolute standard to calibrate aerosol size analyzers and condensation particle counters. This has attracted many aerosol pioneers to bring their instruments to Minnesota for calibration. Prof. Jean Bricard and Dr. Michele Pourprix brought the French Continuous Flow counter which led to the commercialization of TSI Condensation Particle Counter. Dr. David Sinclair of DOE came with his Diffusion Battery and together we performed experiments to verify the Einstein equations using aerosol techniques. Prof. Othmar Preining invited us to the first international condensation particle counters workshop in Vienna with all the existing counters. At the time, Wladyslaw Szymanski was completing his Ph.D. degree and we remain good friends over all these years. With Prof. Yasuo Kousaka, Prof. Kikuo Okuyama, and Professor Peter McMurry, we also conducted CPC calibration workshop in Minnesota. Throughout, we have a long history of collaborating with TSI, with Gilmore Sem during the early years and more recently, with Brian Osmondson. Following the successful introduction of the commercial EAA, there were intense collaborations among Liu-Pui-Fissan-Sem to make continued improvement. The replacement of the integral mobility analyzer in EAA with the differential mobility analyzer and the replacement of electrometer with the condensation particle counter led to the development of DMPS. The adoption of Prof. Rick Flagan's scanning voltage mode allowed rapid particle size distribution measurement, leading to the successful commercial development of SMPS.

Decade of 1980's

After serving as a post-doctoral research associate and the PTL manager for several years, I was promoted to Associate Professor in the Mechanical Engineering Department at the University of

Minnesota in 1984. My first three Ph.D. students were Chair Professor Chuen-Jinn Tsai, Dr. Yan Ye and Dr. Francisco Romay – we are still collaborating and publishing joint papers. Chuen-Jinn was my first Ph.D. student who has good analytical mind and writes well – qualities of a good academic. Yan was a senior director of Applied Materials and held 100 patents before his early retirement. During this period, I have started intense collaboration with Prof. Heinz Fissan, not only on research but also on organizing aerosol associations, IARA, IAC, and several major conferences and workshops. Our collaboration has built a strong basis that led us to receive the Max Planck Research Award – the highest award for Engineers and Scientists in Germany, Humboldt Research Award for Senior U.S. Scientists (Pui), and the establishment of the Fissan-Pui-TSI Award for International Collaboration presented every 4 years during the International Aerosol Conference. Our families are close friends. In fact, together with Fissan, Kousaka, Pourprix, Szymanski, we sent our daughters to each other's families every summer for several years. We now meet every two years to continue our friendships in Kyoto (2013), Burgundy (2015), Vancouver (2017), Berlin (2019). In 1988, I took a sabbatical leave at Caltech working with Prof. John Seinfeld, Prof. Rick Flagan and Prof. Chak Chan. At that time, Chak was a Ph.D. student helping me in the lab, and he is now a Dean at the City University of Hong Kong.

Decade of 1990's

Chair Professor Da-Ren Chen started his Ph.D. study in early 1990's. During his dissertation research and post-doctoral years and subsequent tenure as the PTL Manager, we together developed many exciting new aerosol technologies. Our two seminal papers on Electrospray, which have received nearly 1,000 citations. We also explored the technology for aerosolizing nanoparticles in the aerosol form for measuring liquid-borne particles using the more sophisticated aerosol instruments. Following the development of a technique to produce nanoparticle medicines, we co-founded a start-up Nanocopoeia in St. Paul, Minnesota. Da-Ren also modeled and designed the Nano-DMA, the workhorse for making nanoparticle measurements. Professor Fissan and his student Dr. Detlev Hummes also were involved in this important development. Prof. Ben Liu and I also started the Center for Filtration Research (CFR) in 1991, which is still going strong with 20 leading international filter manufacturers and end users. During the early years, we also worked with Dr. Wilson Poon (WL Gore), Dr. Scott Earnest (NIOSH Associate Director), and Dr. Shintaro Sato (Hitachi) on a variety of filtration projects. Besides Scott, we have 3 other CFR Ph.D.s, Drs. Chaolong Qi, Liming Lo, and Seungkoo Kang, working at NIOSH, an affiliated member of CFR and a good resource for our research. Other CFR early graduates included Dr. Ming Ouyang (Cummins), Dr. Bruce Forsyth (Boston Scientific), and Dr. Hee-Siew Han (TSI). A master's student Xiang Zhang that I mentored is now the President of the University of Hong Kong. I also enjoyed helping Prof. Chuen-Jinn Tsai on Taiwan TAAR, Prof. Kangho Ahn on Korea KAPAR, and Prof. Junji Cao on CAAR during the startup of their respective aerosol associations.

Decade of 2000's

One of the major programs during this period was funded by Intel on Extreme UV Lithography (EUVL) Mask Study. The objectives were to develop methods to evaluate and control particulate contaminant generation, transport and deposition in a mask handling system. Prof. Fissan was a key investigator, and his student Dr. Christoph Asbach as a CFR post-doctoral research associate. Dr. Asbach is now the President of GAeF (Gesellschaft fuer Aerosolforschung) – the oldest aerosol

association in Europe. Other students/post-docs working on the project included Prof. Se-Jin Yook, Prof. Jung-Hyeun Kim, Prof. Jing Wang and others. We have developed thermophoretic technique to protect the masks, and injection system to evaluate particle deposition under vacuum conditions. We also deposited known size nanoparticles on the masks as calibration masks. In all, we published 16 peer reviewed journal papers. Many of the techniques we have developed are now industry practice for EUVL system. I also had the opportunity of mentoring Dr. Seungki Chae who became VP and Sr. VP of Samsung Electronics and Samsung Display. During this period, long-time collaborator Dr. George Mulholland worked with us on certifying NIST 60 nm and 100 nm standard particles using the DMA technique. He worked with Jung-Hyeun to obtain the slip correction in the large Knudsen number regime and published a series of papers with Prof. Weon-Gyu Shin on agglomerate particles characterization. In 2006, I attended Prof. Jing Wang's Ph.D. Final Defense in Aerospace Engineering and Mechanics (AEM). I was so impressed with his thesis research in fluid mechanics that I immediately recruited him to join my group as a post-doctoral research associate to work on aerosol and filtration research. In just a few years, he published a series of 35 papers focusing on EUVL and filtration research. He also helped to mentor junior students, Dr. Tze Yan Ling (Intel) and Weon Gyu. He has continued to contribute a great deal to CFR, even after his departure to ETH Zurich in 2010.

Decade of 2010's and beyond

We have explored industrial applications of filtration research during this period. Three major contributors during this period are Prof. Sheng-Chieh (Shawn) Chen, Dr. Seong Chan Kim and Dr. Qisheng Ou. They all have served a term as the manager of PTL/CFR. Shawn was Chuen-Jinn's Ph.D. student and came as a post-doc. He has worked on several topics: 1. evaluating membrane filter efficiency using sub-10 nm quantum dots – a collaboration with Prof. Doris Segets, a post-doc at U of Erlangen-Nuremberg with Prof. Wolfgang Peukert; 2. co-authoring a PM2.5 review paper which has received 600 citations in a few years; 3. exploring the Electret filter applications – collaborating with Prof. Ziyi Li of the University Science and Technology Beijing on Zeolite coated Electret Media. Seong Chan spent 15 years at CFR separated by 5-year stay at Entegris as a contamination engineer. He came as a post-doc from Prof. J.K. Lee at Pusan National University. He worked on agglomerates generation and characterization, health effects of nanoparticles (performed in-vitro studies with Prof. Gunter Oberdorster at University of Rochester), and many filtration applications projects, particularly in respirators/masks and contamination transport problem to mitigate covid spreading. I am pleased that Seong Chan has now started to work as a defect/contamination specialist at ASML, a major manufacturer of EUVL systems. Dr. Qisheng Ou started as a post-doctoral research associate from the Washington University of St. Louis (with Da-Ren as his Ph.D. advisor) and is now manager of CFR/PTL. He has performed research on filtration topics, and developed systems to: 1. produce high temperature agglomerates; 2. develop methods for coating nanoparticle membrane on wall filters to improve efficiency; and 3. evaluate respirator/masks and droplet dispersion in dental tools. He mentored several Chinese scholars who became professors in Chinese universities, including Prof. Xinjiao Tian, Prof. Qiang Lv, and Prof. Cheng Chang, and recent students Dr. Chenxing Pei (Midea group), Weiqi Chen and Dongbin Kwak. Dr. Ou is currently focusing on starting an indoor air quality program.

There were many former students/post-docs/scholars who have contributed to my career and I will prepare a table listing all of them for the conference proceedings. Recent Korean graduates include Prof. Changhyuk Kim at Pusan National University and Prof. Handol Lee at Inha University.

I appreciated the collaboration I have with Professor Emeritus Tom Kuehn and Professor David Kittelson who have co-advised and mentored several Ph.D. students with me. Dr. Hoo Young Chung has served as a resource person since retirement from Donaldson Company as a Technical Fellow. I am particularly pleased that Professor Kuehn, Prof. Shawn Chen, Charles Lo, and Dr. Qingfeng Cao are currently working with me on designing and operating 2 Air Cleaning Towers in Delhi, India, for the health and wellbeing of the residents. The Delhi Towers are the third generation Air Cleaning Tower. Starting in 2015, Qingfeng and I published 5 papers on developing solar-assisted large scale cleaning system (SALSCS) to removed PM_{2.5} in urban atmosphere. We collaborated with Prof. Junji Cao of Chinese Academy of Sciences (IEECAS) and Prof. Wenquan Tao of Xi'an Jiaotong University, together with Dr. Ningning Zhang of CAS, to construct the first generation SALSCS in Xi'an which has attracted worldwide attention. Professor Junji Cao is now Director General of Institute of Atmospheric Physics (IAPCAS). The second generation SALSCS was constructed in Yancheng Science Park, in collaboration with Prof. Jing Sun and Dr. Xiaofeng Xie of CAS (SICCAS), and has the capability of removing CO₂ for carbon neutrality study. The third generation Air Cleaning Tower in Delhi makes use of a set of fans to blow clean air to the surrounding area at the ground level to benefit the residents nearby.

I was on the scientific committee and chairing sessions on several International Conference on NanoSafe in Grenoble, France. During the 2008 NanoSafe Conference, I met Professor Yuliang Zhao of CAS. His research interests are in nanobiomedicine and nanosafety, and is currently the Director-General of National Center for Nanoscience and Technology of China. He introduced me to Prof. Chunying Chen at the Center, who is now the mentor of Dr. Nanying (Leo) Cao. As part of his Ph.D. thesis, Leo worked with me and Professor Heinz Fissan in the development of the Nanoparticle Surface Area Monitor, TSI NSAM. Other notable collaborators in China include Prof. Jingxian Liu of Northeastern University, Prof. Jingkun Jiang of Tsinghua University, and Prof. Hong He of CAS (RCEES). During the past three years, I also taught at the Chinese University of Hong Kong, Shenzhen (CUHKSZ) under a joint agreement between UMN and CUHKSZ and established friendship with many faculty and students. We welcome the arrival of post-doc Zhengyuan Pan in January 2022 who received his Ph.D. from a long-time collaborator Prof. Yun Liang of South China University of Technology. Dr. Pan also completed 1.5 years stay at ETH Zurich with Prof. Jing Wang.

I am deeply gratified that AAC organizers set up the commemorative session to honor my 50 years of service to the aerosol discipline. I hope that this will start other commemorative sessions for many other deserving colleagues who have made major contributions to the aerosol discipline.

Sincerely,



David Y.H. Pui
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