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With the Wizard of the Unit Circle – an appreciation of T.Y.Wu*

Christopher Earls Brennen
Richard and Dorothy Hayman Professor of Mechanical Engineering, Emeritus,
California Institute of Technology, Pasadena, California 91125

Abstract: An account of my interactions with Professor Theodore Yao-Tse Wu of the California Institute of Technology.

Key words: Caltech, fluid mechanics, cavitation

1. A Chance Encounter with T.Y. Wu

After my DPhil at Oxford I failed to adequately explore subsequent employment and so I was fortunate to be appointed a junior research fellow at the National Physical Laboratory (NPL) just west of London, England. Actually it transpired that this was a a very lucky turn of events for that lab had built several large high-speed water tunnels for the study of the phenomenon of cavitation and these facilities were being underutilized. Indeed I was urged to use the large high-speed water tunnel for experiments that I was interested in. Those experiments led to several sole-author papers in the prestigious Journal of Fluid Mechanics over the next year. In the process of that research I became aware of the outstanding work of Professor Theodore Yao-Tse Wu of the California Institute of Technology on free streamline flows particularly fully-developed cavity flows. His remarkably elegant application of complex mapping techniques to acquire solutions to these flows made a great impression on me. I did feel, however, that my experimental observations could be useful in enhancing and validating those theoretical results.

Now it so happened that in the summer of 1968, Ted, as he became known to me, visited the Lab primarily to interact with George Gadd, my mentor at NPL. I doubt that Ted had any prior knowledge of my presence there but during his visit George urged him to visit with me. I anticipated a brief courtesy visit to my tiny office next to the water tunnel. But, to my surprise, Ted seemed remarkably interested in the experimental results I had obtained and spent well over an hour listening to me and asking questions. As things would transpire that hour changed my life and made me a life-long admirer of this great man not only for his mathematical genius but also for his humanity and kindness. At the time I did not, of course, have any idea of what was about to transpire but three weeks later, much to my surprise and delight, I received a letter from Ted inviting me to come to Caltech for a year to work in his group on cavitation and other fluid mechanical problems of interest to him. It was the chance of a lifetime for I was also aware of the very fine work of other Caltech faculty, particularly Allan Acosta, Milton Plesset and Anatol Roshko. In the years to come all of these would have an impact on my career, particularly Allan.

Corresponding author: Brennen, C.E.,
E-mail: Brennen@caltech.edu

2. And So To Caltech

Just a few months later on New Years Eve of 1968/69, my wife Doreen and I and our two young daughters embarked on a flight across the Atlantic and on to California. We had cashed in all our assets to purchase the tickets and wondered what on earth we would do without adequate resources for food and rent when we reached Pasadena. But Ted had anticipated all of our needs. Two of his graduate students Michael Wilson and Art Whitney were waiting for us when we disembarked at LAX and drove us to the apartment in Pasadena that Ted had arranged for us. Moreover, he and Cecilia Lin had stocked the refrigerator with food for the first few days and he had made arrangements for an advance on my first month salary. How lucky was I to have encountered such a brilliant but also incredibly kind man that day in my tiny NPL office!

Thus began a fabulous first year at Caltech. In the lab

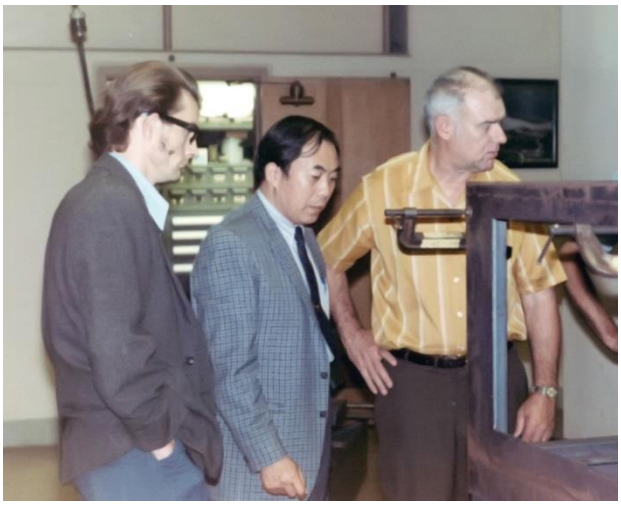
I became deeply involved with the research projects of Wu's group. We examined non-linear effects and devised numerical methods to investigate tsunami waves. In addition I was drawn into Ted's new investigation of the locomotion of small organisms, prokaryotic (bacteria) and eukaryotic (large organisms). Among other discoveries we were involved in showing how and why bacteria use flagella that continuously rotate relative to their heads - unlike eukaryotic propulsion in which a similar propulsive effect is produced by propagating waves along the flagella. In addition to all of these new adventures, I continued my interest in cavitation and conducted experiments on cavitating wedges in the Caltech High-Speed Water Tunnel. All this led to a renewal of my research fellowship for a second year.

Professor Wu's group in 1969: CEB, Allen Chwang, Mike Wilson, Art Whitney, Prof. Wu and Ed James.

Ted Wu with Georg Weinblum in 1970.

3. Onwards

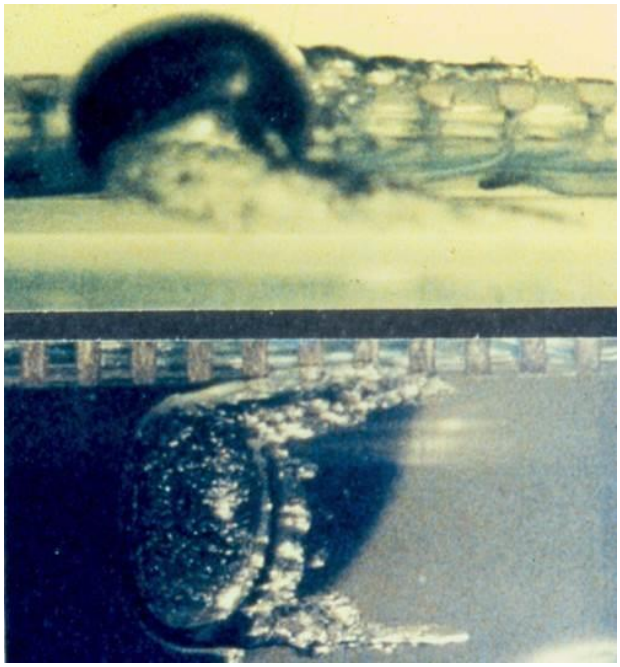
In the 40 years that followed I feel I was privileged to enjoy a truly special career at Caltech. The initial appointment as a Research Fellow expanded into a total of seven years on the research faculty as a Research Fellow (1969-1972), Senior Research Fellow (1972-75) and Research Associate (1975-76). When I look back I recognize that those years allowed me to establish a sound foundation for my scientific career without the obligations of teaching and administration that young tenure-track faculty face. During the first few years I not only worked closely with Ted but also formed close collegial and research bonds with Allan Acosta. When I first arrived at Caltech, I was given an office in the Karman Building that adjoined Allan's office. We rapidly became friends and that friendship led to a career-long collaboration in cavitation and turbomachinery research.



Constructing a water tank for fish swimming study.

In the 1930s Caltech had begun many decades of leading-edge research into high-speed liquid flows and particularly the phenomenon of cavitation. The very first high-speed water tunnel was designed and built at Caltech by Robert Knapp with the support of Theodore von Karman. Moreover, observation of these high-speed flows was made possible through the development by Albert Ellis and others of remarkable cameras with framing rates as high as a million frames per second. These observations motivated pioneering programs of experimental and theoretical research into cavitation by Blaine Parkin, Milton Plesset, Allan Acosta and Ted Wu among others. It was inevitable that I would become entrained into this inspiring effort and in the years that followed I was able, with the support of the US Office of Naval Research, to pursue many of the leading research questions

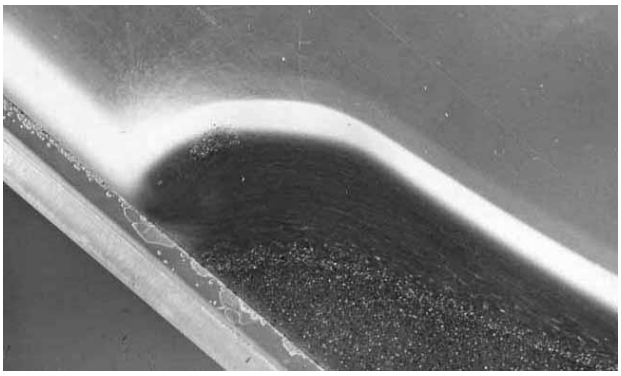
associated with cavitation. Specific projects included (1) studies of the interactions between cavitation bubbles and the flow and the implications for cavitation noise and damage[1,2,3] (2) the population dynamics of cavitation nuclei of microbubbles and the relation to cavitation event rates[4] (3) studies of the dynamics and acoustics of clouds of cavitation bubbles[5,6,7,8] (4) the dynamics of cavitating propellers[9]. The results of these studies and much more were incorporated in my books "Cavitation and Bubble Dynamics[10] " and "The Fundamentals of Multiphase Flow[11] ". But it had all begun with Ted's support; indeed chapters of those books were taken almost directly from Ted's Annual Review of Fluid Mechanics paper on Cavity Flows[12] (of course with his consent).



Strange Cavitation Bubbles[1]

Cavitating model of the Low Pressure Liquid Oxygen Pump in the Space Shuttle Main Engine[13]

As the years went on I naturally explored other fluid mechanical research projects, most notably a decades-long effort to understand and document how cavitation in high-speed turbo pumps like those in the Space Shuttle Main Engine respond to unsteady conditions[13] and how the cavitation drives critical instabilities in liquid-propelled rocket engines. How similar instabilities arise in water-cooled nuclear reactors[14]. I also became very interested in the fluid mechanics of particle flows[15] and was able to advance that science with a combination of experiments and computer simulations.



Granular material hydraulic jump[15]

But it had all begun with Ted. I learnt from him not only research strategies and techniques but also a simple humanity that encouraged me to become the Master of Student Houses at Caltech, then the Dean of Students and finally the Vice-President of Student Affairs. His example influenced my guidance of several generations of both undergraduates and graduate students. About 35 young people obtained their PhDs under my supervision and most of them have gone on to outstanding careers. Quite a few are now professors at institutions around the world including MIT, Brown University, Princeton, University of Michigan, University of Southern California, Purdue University, Cambridge University, University of Pisa, Yeditepe University in Istanbul, National Cheng Kung University in Taiwan, National Autonomous University of Mexico, and Keio University in Tokyo. Others have become movers and shakers in companies like Chevron, Schlumberger, Boeing, TRW, Exxon Mobil and Dow Chemical. Others have made major contributions to small companies. One is now an orthopaedic surgeon and two became NASA astronauts and walked in space. I have kept in touch with almost all of these academic children and take great pride in their accomplishments - but Ted needs to be attributed some of the credit.

Ted and Chin-Hua about 1993 (Doreen and I beyond Ted's shoulder)

Ted and I on at his 90th Birthday celebration in September, 2014, and 46 years after we first met.

3. Postscript

Looking back I cannot help but wonder why Ted's contributions to fluid mechanics were not more widely recognized and honored. To those like me whom he guided he will always be a mathematical wizard able to integrate around the unit circle with magical results. But he will also be remembered as a humble, kind and gentle man whose heritage will be widely spread through those, like myself, whom he guided and encouraged. Perhaps his humility and lack of self-promotion had the effect in the short-term of limiting that recognition. But not by those of us who were so honored to have known this special man.

References

[1] Ceccio, S.L. and Brennen, C.E. (1991). Observations of the dynamics and acoustics of travelling bubble cavitation. J. Fluid Mech., 233, 633-660. Corrigenda, 240, 686.

[2] Kuhn de Chizelle, Y., Ceccio, S.L. and Brennen, C.E. (1995). Observations and scaling of travelling bubble cavitation. J. Fluid Mech., 293, 99-126.

[3] Brennen, C.E. (2002). Fission of collapsing cavitation bubbles. J. Fluid Mech., 472, 153-166.

[4] Liu, Z. and Brennen, C.E. (1998). Cavitation nuclei population and event rates. ASME J. Fluids Eng., 120, 728-737.

[5] d'Agostino, L., and Brennen, C.E. (1988). Acoustical absorption and scattering cross-sections of spherical bubble clouds. J. Acoust. Soc. of Amer., 84, No.6, 2126-2134.

[6] d'Agostino, L., Brennen, C.E., Acosta, A.J. (1988). Linearized dynamics of two-dimensional bubbly and cavitating flows over slender surfaces. J. Fluid Mech., 192, 485-509.

[7] d'Agostino, L., and Brennen, C.E. (1989). Linearized dynamics of spherical bubble clouds. J. Fluid Mech., 199, 155-176.

[8] Brennen, C.E., Reisman, G.E. and Wang, Y.-C. (1996). Shock waves in cloud cavitation. Proc. 21st ONR Symp. on Naval Hydrodynamics, 756-771.

[9] Duttweiler, M.E. and Brennen, C.E. (2002). Surge instability on a cavitating propeller. J. Fluid Mech, 458, 133-152.

[10] Brennen, C.E. (1995). Cavitation and Bubble Dynamics. Oxford University Press.

[11] Brennen, C.E. (2005). Fundamentals of Multiphase Flow. Cambridge University Press.

[12] Wu, T.Y. (1972). Cavity and wake flows. Ann. Rev. Fluid Mech., 4, 243--284.

[13] Brennen, C.E. (2013). A review of the dynamics of cavitating pumps. ASME J. Fluids Engineering, 135, No. 6 : 061301-1 to -11.

[14] Brennen, C.E. (2016). Thermohydraulics of Nuclear Reactors. Cambridge University Press.

[15] Brennen, C.E., Sieck, K. and Paslaski, J. (1983). Hydraulic jumps in granular material flow. Powder Tech., 35, 31-37.

[16] Campbell, C.S. and Brennen, C.E. (1984). Computer simulation of granular shear flows. J. Fluid Mech., 151, 167-188.

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