

Clayton Crowe – The Legacy of a Teacher and Pioneer Researcher in Multiphase Flow



It is with profound sadness that we report the death of a much loved and greatly revered colleague and friend—Professor Dr. Clayton T. Crowe. To his students and colleagues in the multiphase flow community, he was both a father figure and mentor: someone you could turn to for advice and support, for insight and understanding on fundamental issues as well as difficult problems. In a career spanning nearly 50 years his contribution to the study of multiphase flow has been immense: he made seminal contributions to

practically all aspects of the subject from the deeply fundamental, to the industrial application. He was not only a brilliant scholar and engineer but also a gifted teacher. Throughout his career he devoted a great deal of his effort to the teaching of fluid mechanics and two phase flow. His book, *Engineering Fluid Mechanics* (co-authored with his Washington State University (WSU) colleague John A. Roberson and with D. F. Elger and B. C. Williams, who joined recently) has been one of the most popular undergraduate fluid mechanics textbooks for over 35 years. More recently his graduate textbook, *Multiphase Flows with Droplets and Articles* (co-authored with John D. Schwarzkopf, Martin Sommerfeld and Yutaka Tsuji) now into its 2nd edition has become a standard text book for teaching with its clear, concise and pedagogical approach, skillfully bridging fundamental theories and industrial applications. He was also the driving force and editor of the *CRC Multiphase Flow Handbook* that was published in 2006.

Clayton Crowe was born on July 6, 1933, in Kelowna, British Columbia, the only child of Goldie and Tom Crowe. His father was a blacksmith to whom Clayton owed much of his practical hands-on skills as an engineer, his propensity for hard work and his lifelong love of locomotives and steam engines.

He graduated from Salmo High School in 1951 and received his BSc degree in Aerospace Engineering from the University of Washington in 1956 and his MSc. from MIT in 1957. He followed this with his Ph.D. from the University of Michigan in 1962.

The first seven years of his career was spent as a rocket scientist at the United Technology Center in California where he worked on solid fuel combustion related to rocket launching applications. He and his co-workers identified four flow regimes a particle undergoes during its combustion process depending on the particle Knudsen number, kn : (a) continuum flow ($kn < 0.01$); (b) slip flow ($0.01 < kn < 0.2$); (c) transitional flow ($0.2 < kn < 5$); and (d) free molecular flow ($kn > 5$). They also suggested expressions for the drag coefficients of particles and droplets during the combustion processes.

In 1969, Clayton joined the Department of Mechanical Engineering at WSU, where he enjoyed a fruitful and creative 32-year career in teaching and research. During this period he worked with a number of collaborators and research students on numerous aspects of gas-particle and droplet flows. In the mid-1970s he

developed and applied the well-known Particle-in Cell Model in which the droplet phase as a source of mass, momentum, and energy to the gaseous phase is incorporated into a computational model. Applying the approach to a steady two-dimensional spray-cooling problem aptly illustrated the capability of the model to treat the complex phenomena associated with multiphase flows and it is now widely used as a computational modeling tool in studying industrial two phase flows. He then worked with his WSU colleague Dave Stock in developing computational schemes for predicting the performance of electrostatic precipitators and cyclone separators. He also collaborated with Sam Bernstein of Flow Industries (Kent, WA) in developing and patenting a range of multiphase flow devices from metering low-quality steam flows to a novel slurry jet pump.

Spray drying has been an enduring part of his research work and a motivation for developing a number of modeling and numerical procedures to capture the thermal and momentum coupling between the dispersed and carrier phases. He became the world authority on the subject and his advice and opinion were widely sought in industries as far away as Nestlé's in Switzerland. It was this aspect of his work that took him to the University of Bremen where he had a lasting collaboration with Udu Fritsching. In the course of those studies, he was one of the developers of the Euler-Lagrange approach which is widely used today in simulating the behavior of dispersed gas-droplet and particle suspensions.

Since the mid-1980s, Clayton was devoted to tackling some of the very fundamental issues of two phase dispersed flows. He was deeply interested in two-fluid modeling and how one obtained the 'continuum' equations in the case of large dispersed phase volume fractions from the various averaging procedures. He wrote very lucidly on this subject in a number of seminal papers and much of this formed the appendices in his *Multiphase Flows with Droplets and Particles* book. He was also interested in the carrier phase turbulence: in particular turbulence modulation (how suspended particles influence turbulence production and dissipation) and particle segregation (how turbulent structures can 'unmix' a suspension of particles). He and his students Gore and Giland demonstrated the significance of particle diameter/fluid length scale ratio in determining whether or not the addition of a dispersed phase would cause an increase or decrease in the carrier phase turbulence. Subsequently, Clayton developed a model for the carrier phase turbulence in a fluid-particle flow based on the volume-averaged equations for the kinetic energy of the carrier phase which reproduced the trends observed by experiment whereby small particles attenuate the turbulence while large particles enhance it. Most recently, he and his student John Schwarzkopf obtained equations that described the effect of particles on the carrier phase turbulence. They derived a transport equation for the energy dissipation rate ϵ ; in the k - ϵ model and the associated coefficients. The resultant model compared well with experimental data. During the revision of *Multiphase Flows with Droplets and Particles*, they also derived the volume-averaged Reynolds stress equations—a set of equations that Clayton wanted to include in the book.

Along with his WSU co-workers Chung and Troutt, he was the first to identify experimentally the phenomenon of particle clustering in the large scale coherent structures found in turbulent shear flows. They performed a number of simulations and experiments on particle dispersion in mixing layers, free shear and wake flows in which they characterized the segregation according to the particle Stokes number and found the segregation to be a maximum when the Stokes number is ~ 1 . They put forward the now traditional view that particles are flung out of regions of high vorticity into the straining regions between them. The importance of this phenomenon in enhancing collisions and particle agglomeration/droplet coalescence in a number of environmental and industrial flows has been the subject of intensive research in the last 20 years.

Students remember Clayton as an enthusiastic, creative and entertaining teacher with a teaching style based on 'learning by discovery'. He engaged his students, involved them in the subject, lead them gently by the hand by asking them interesting questions and engaging them in open discussions. He was both amusing and entertaining while at the same time his lectures were always a model of clarity combined with mathematical rigor. One of us well remembers his master class in teaching at a summer school on Two-fluid Modeling at CISM in Udine (Italy). His classes were in a class by themselves.

Clayton's in-depth and all round knowledge of fluid mechanics combined with his caring personality made him a wonderful mentor for graduate students and junior colleagues. He showed his students that there is never a right or wrong method, only a logical method. He encouraged them to pursue their individual research ideas, all the while guiding them by gently asking questions. He had a wealth of knowledge and always seemed to know the correct research path prior to the final outcome. He built and maintained an environment for everyone to exchange and express their ideas. With donuts and treats, he routinely organized group meetings for all graduate students in the department who were interested in two-phase flows and reviewed research papers together to help students identify open research issues. He loved to hold holiday parties at his house for graduate students with his personal crafted fun activities. He treated students as individuals with unique personal characteristics and abilities and often followed students' progress for many years afterwards.

The Editorship of the *CRC Handbook on Multiphase Flow* which preoccupied him for the latter part of his career was a monumental task. The book covered all aspects of multiphase flow: the fundamentals, the modeling, the simulation, the numerical methods and the experimental measurements and techniques. The book is not only a testament to his vast knowledge of the subject but to his ability to organize and bring together such diverse material, to engage and commit so many experts in the fields to make contributions as well as making his own numerous contributions to the book. It will undoubtedly be his legacy to Multiphase Flow Research and a testament to the enormous contribution he has made to the subject.

Throughout his long career, he won many awards for both his research and teaching. Perhaps of all of these, he treasured most the International Multiphase Flow Award which he received in

2001 at the ICMF in New Orleans. He was a Fellow of ASME and supported the society in many of its activities, both as an Associate Editor for JFE and in organizing technical sessions at FED meetings. In 2009, Clayton gave a keynote lecture at the ASME FED conference in Vail, CO which those who attended will always remember for its lucidity and clarity of exposition. He had clearly not lost his ability to communicate and engage with an audience. There he received the ASME Fluids Engineering Division Certificate of Appreciation for his continued work in the area of fluids engineering.

Clayton, although retired, chose to mentor his last student from 2002–2008. While doing this, he also found time to travel (to several countries), write books, publish journal articles, give keynote lectures, teach children's Sunday school, sing in the church choir, and serve as director of the local Prostate Cancer Support Group in his hometown. He often joked about going back to work just so that he could take a break—he once said "...being retired can be exhausting! One of these days I will have to retire from being retired."

Many of our colleagues have referred to Clayton as a scholar and a gentleman. Certainly he was both of these. He had what many call an intellectual curiosity. But he was also a brilliant engineer who could solve problems; someone who has made an immense contribution to fluid mechanics and multiphase flow; the author of two classic text books on the subject; a brilliant teacher who inspired his students, encouraged them and supported them. But, above all, in spite of all his achievements, the prizes and awards, he showed modesty, humility and a compassion for those less well off than himself. He had indeed 'much of the milk of human kindness'. He knew good manners, courtesy, respect and warmth and an empathy and measured consideration; a great wit with a whacky sense of humor and an infectious laughter which could 'set the table on a roar'. He always saw the funny side of things. With his outstanding interpersonal skills, his sense of humor and his impeccable scientific credentials, he was an excellent ambassador for the multiphase flow community. He lived every day to the full; he was always full of life and in good spirits. He loved science, religion, his family, his friends and his students

To some of us fortunate to have known him well, he was not just an admired and respected colleague but a great friend who influenced and changed our lives, one for whom it has been a privilege to know. Clayton Crowe was indeed a unique and special human being and we all share with his family and friends their great sense of loss.

Stathis Michaelides

Michael Reeks

John D Schwarzkopf

David Stock

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