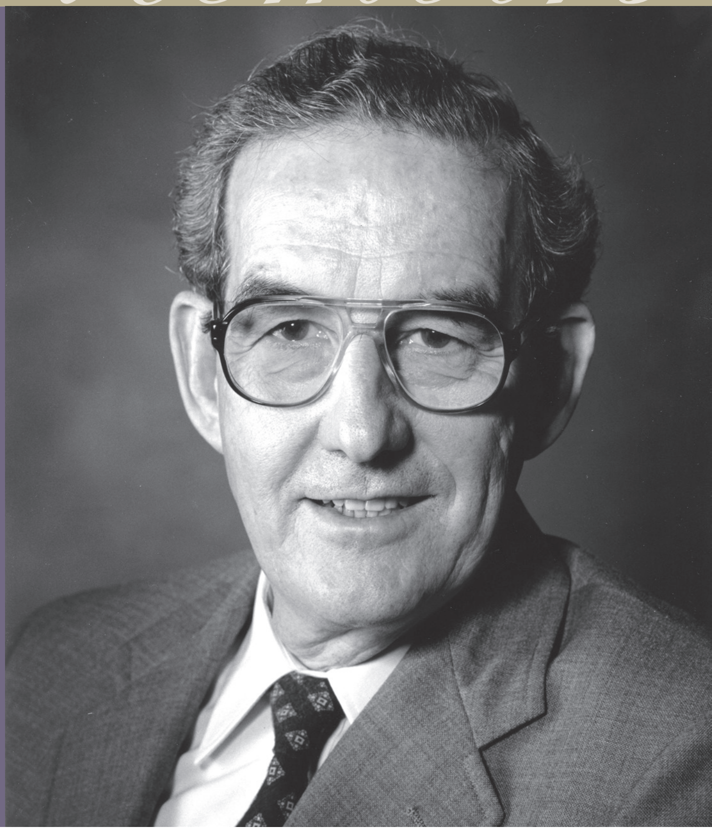
Thomas J. Hanratty

1926–2016

BIOGRAPHICAL *Memoirs*



A Biographical Memoir by
William R. Schowalter,
Mark J. McCready,
and Richard C. Alkire

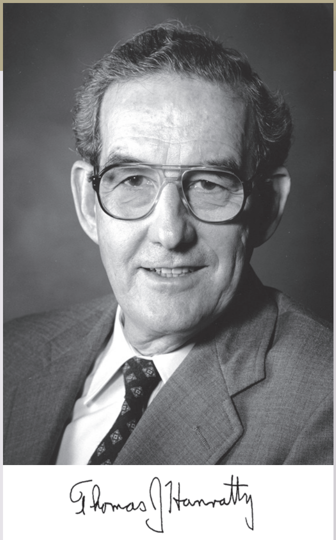
NATIONAL ACADEMY OF SCIENCES

THOMAS JOSEPH **HANRATTY**

November 9, 1926–August 24, 2016

Elected to the NAS, 1999

Thomas Joseph Hanratty was born on November 9, 1926, in Philadelphia, PA. He was the second of four children. His father, John Hanratty, was employed by the US Post Office. Tom attended Southeast Catholic High School in Philadelphia, graduating as valedictorian of his class in 1944. The Norbertine fathers at Southeast provided Hanratty with a sound foundation for his professional career. He was appointed editor of the school newspaper and yearbook and was a member of the debating team. He was given many opportunities at public speaking, including the valedictory address at graduation. These activities not only provided skills that Hanratty would use throughout his life but, as he later said, challenged him to distill essential ideas from large amounts of information.



By William R. Schowalter, Mark J. McCready, and Richard C. Alkire

In a 2007 memoir, Hanratty wrote that formal education beyond high school was not uppermost in his mind until he received a request to appear in the office of his high school principal, Father Michael J. Keough. Tom was surprised to learn he had received a four-year scholarship to attend St. Joseph, LaSalle, or Villanova College. He had been told that chemical engineering was a new high-tech field, one that was central to the production of many products used in daily life. An interest in chemistry and mathematics motivated him to enter the curriculum in chemical engineering at Villanova.

After graduating from Villanova in June of 1947, he accepted a position at Fischer & Porter Company in Hatsboro, Pennsylvania, where he worked on the metering of complicated fluids. In 1948, he was presented with an opportunity to work at the Battelle Memorial Institute in Columbus, Ohio, where he pursued an M.S. degree through the night program at the Ohio State University. At Battelle, he became involved with the development of a gas-phase catalytic process to manufacture the rocket fuel hydrazine. This gave him a taste for research that he never lost.

Because of his interest in a teaching career, he decided to obtain a Ph.D. degree. He was attracted to Princeton, largely because of the work of Richard Wilhelm, one of the early masters who linked fundamental science to problems of everyday chemical engineering. Wilhelm studied the role of fluid mechanics in complex, large-scale reactors in which catalytic reactions took place on catalyst particles in either a stationary or fluidized state. Hanratty felt privileged to be one of the four people admitted to the PhD program.

Both Wilhelm and Hanratty saw that education in chemical engineering had been invigorated with the recognition that a large variety of chemical processes took place using a relatively small number of unit operations. At the time of Hanratty's arrival at Princeton the emphasis in the field was shifting to include an engineering-science approach which expanded basic knowledge about the principles underlying these unit operations. Hanratty's PhD thesis on mixing in fluidized beds was part of the broad research program on reactor design directed by Wilhelm.

During the years when Hanratty was conducting his thesis research on turbulent diffusion in fluidized beds, substantial advances in turbulence theory were being made. These were the researches of Kolmogoroff, Townsend, Batchelor, G. I. Taylor, and others. Hanratty's drive to put fundamental knowledge at the service of engineering applications differentiated his life's work from contemporaries who were more fundamentally oriented, but perhaps less bold in applying their discoveries to chemical process engineering.

Hanratty accepted an offer to join the faculty of the University of Illinois in February, 1953. At Illinois, chemical engineering was a division of the Department of Chemistry. The division's deep roots and its emphasis on engineering science were attractions for him. He remained at the University of Illinois for the rest of his career, formally retiring in 1997. He continued for nearly twenty more years as an emeritus professor with an active research program and frequent interaction with colleagues.

An important characteristic of Hanratty's persona was his unremitting focus on research and teaching, and his close associations with student colleagues. This is nowhere more evident than in a monumental summary of research published by Hanratty in 2014, in which he chronicles the work accomplished under his direction at the University of Illinois, where he supervised 78 MS students, 77 PhD students, and 23 postdoctoral associates over a 54-year period. Much of the description given here of Hanratty's work is taken from that document. In this work we see a man who had a keen sense of which measurements in complex systems would provide real understanding, a fearless attitude toward obtaining these data, and a sober perspective regarding what resulted so that he could differentiate the “signal” from the noise and take advantage of unexpected opportunities.

Tom was active and successful in many campus service contributions, but those who knew him well thought that he had no taste for, and perhaps no particular talent for, academic administration. This perception changed dramatically in 1999. At this time, the evolving research landscape in the life sciences caused the biochemistry department to reconsider its administrative affiliation with the departments of chemical engineering and chemistry within the School of Chemical Sciences (SCS). To avoid conflicts of interest, the College Dean sought an acting director of SCS who could provide wisdom and guidance for the impending divorce proceedings. Surprisingly, he found that Tom Hanratty was amenable to, and more than up to, this task. Through his diplomacy and calm demeanor, Tom brought good will and cordiality to what had by then become a heated and polarizing discussion. He presided over the disentanglement of the various financial and cultural conflicts, permitting the departments to develop shared visions that have since led to great success. The key to these successful negotiations was the trust and confidence from all parties in Tom, who was universally respected and perceived as fair.

In subsequent paragraphs we divide Hanratty’s research discoveries into five categories. Although they can be considered as an evolutionary progression, that is an oversimplification. In many respects he had a simultaneous interest throughout his career in all five, and he moved from one to another as experimental capabilities allowed him to do so.

Structure and mechanisms of wall turbulence and scalar transport

Hanratty’s early work grew from a desire to understand heat, mass, and momentum transfer in real systems. Consequently, wall effects, particle motion and interactions, and temperature inhomogeneities were all important subjects for inquiry. Hanratty began addressing these subjects as soon as he arrived at Illinois. It is significant that he published three single-author papers on the complex subject of coupled turbulent transport at or before the time a paper coauthored with his Princeton advisor appeared. One of the things that especially intrigued Hanratty during his early ventures into this complex area was the development of unambiguous experiments in “real” systems, such as pipes, wall regions, and enclosed beds of particles; and the explanation of the resulting data using theoretical results drawn from highly idealized systems. He was impressed with G. I. Taylor’s results for diffusion of mass from a point source into a turbulent field and he sought to apply those results to some extraordinary data he and his students collected to show how heat or mass diffused from a wall into the interior of fluid in turbulent flow through a pipe. Among other things, the design and execution of the required experiments demonstrated Hanratty's skills as an experimentalist who could deal with engineering-scale laboratory equipment, e.g., blowers capable of achieving Reynolds numbers > $70x10^3$, 8-inch pipes with vertical runs greater than 60 feet, a 70-foot long gas-liquid flow system that could be precisely inclined or declined a fraction of a degree, and minute probes equivalent to hot-wire anemometers with wires of approximately $1.5x10^{-3}$ in. in diameter! A key to Hanratty's analysis was his interest in following histories of packets of fluid (Lagrangian viewpoint) rather than looking at fixed points in a test section (Eulerian viewpoint). Following Taylor's analysis one can then compute spatial variations of eddy diffusion coefficients, and this is what Tom did. The results showed how a Lagrangian approach, in which the diffusion of heat from a packet of moving fluid to its surroundings, explained variations in eddy diffusivities over the cross section of a pipe in which heat is transferred from the wall to its interior. Hanratty's early work on this subject was responsible for his receipt of the Colburn Award of the AIChE in 1957. This is the most prestigious award for research performed by someone under the age of 35, bestowed annually by the Institute. It was the first of many major professional honors received by Hanratty.

Hanratty and student with gas-liquid flow system.

Tom realized that to understand thoroughly the generation of turbulence and how turbulence controls mass and heat transfer to a pipe wall, it would be necessary to make measurements that could be resolved in both space and time in the region very close to the wall. To accomplish this, Tom and a some of his students experimented with the idea of using an electrochemical reaction on a small electrode, to produce a chemical species as a "point source" at the wall or within the near-wall region. As they began this work, they noticed significant current fluctuations in the (constant voltage) polarized electrodes and concluded (a point that could not have been obvious), that these devices could be used as a means for direct measurement of instantaneous mass transfer rates and wall shear stress. These probes are arguably the most innovative diagnostic invention of Hanratty's career. One of the first papers on this work, "An experimental study of the unsteady nature of the viscous sublayer," from 1963, is Hanratty's most cited paper at the time of this writing (2018). Of course, this technique could not have been fully exploited without an accompanying theoretical analysis showing how the electrochemical probe could be used to measure separately a local, instantaneous wall shear stress or a local instantaneous mass transfer coefficient. In addition it was necessary to know the physical probe sizes needed to resolve specific features of the turbulence, and how to avoid calibration of the probes. Another important early result from the use of these wall probes was to interrogate the boundary layer for the classic problem of flow past a circular cylinder and to locate the separation point to within 1 degree.

A "rake" with seven electrochemical probes to measure time-varying velocity close to a wall.

Hanratty and coworkers exploited the electrochemical probes and theoretical analysis to determine spatial and temporal scales of wall turbulence and to understand mass transfer at high Schmidt numbers. The ability to measure simultaneously fluctuations in both velocity and concentration revealed in 1969 that concentration fluctuations were of much lower frequency than velocity fluctuations and that this frequency decreased as the Schmidt number increased. While there was no reason to doubt the measurements, could an explanation be had? The Colburn analogy for mass, momentum and heat transfer was not completely correct and the filtering behavior would not easily result directly from eddy diffusivity arguments. Tom, with Kam Sirkar, turned to the governing advection-diffusion equation, applied some physical insight to aid in the simplification, and produced the result that fluctuations in the mass transfer coefficient should drop off as the cube of the frequency and that the magnitude of the mass transfer coefficient spectrum should drop off with the inverse of the Schmidt number—exactly what is observed experimentally.

A third very surprising and important result of Hanratty's studies of turbulent mass transfer were the steady-state measurements of the mass transfer coefficient as a function of Schmidt number S_c. These experiments, done with Dudley Shaw and published in 1977, showed that the mass transfer coefficient varies as $S_c^{-0.704}$ over the range S_c = 631-37,200. These measurements, done using two different electrochemical systems, iodine/iodide and ferric-ferro cyanide and by varying the viscosity of the liquid using sugar, are accurate enough to definitively rule out the -2/3 or -3/4 powers that would result from scaling theory based on mass-momentum analogies or a simple eddy diffusivity model. While the reason for the exact power value is still not clear, the filtering of some of the energy is consistent with a mass transfer coefficient falling faster than the -2/3 power. Essentially, much of the energy in the turbulence was not contributing to mass transfer and a greater fraction was lost as the Schmidt number increases. These data are a "gold standard" and thus this work is continually cited to verify the correctness of current-generation computer solutions of the Navier-Stokes equations coupled to the advection-diffusion equation.

A final point on turbulence and mass transfer cycles back to our characterization of Hanratty as fearless. To measure fluctuations in wall mass transfer and the transverse scales of turbulence with desired accuracy, low wall curvature and a Reynolds number > 20,000, with as low a velocity as possible, are required if one is to achieve physical dimensions of the turbulence scales sufficiently large to enable measurements with the electrodes. To satisfy these constraints Tom built a vertical pipe loop that had a rise of more than 60 feet with access points on 5 levels of a newly-constructed building addition. The test section had an inside diameter of 7.6 in. and required over 150 gallons of electrolyte solution! The new experiments from this rig removed the effect of spatial averaging over the electrodes, producing a new value for the strength of the mass transfer coefficient fluctuations at 30% of average. They further confirmed that the dominant transverse turbulent eddies have a scale of about 100 dimensionless "wall" units.

Turbulent flow over wavy surfaces

Hanratty published over 30 papers on the subject of turbulent flow over solid wavy surfaces. While the obvious motivation could be supposed as gas flow over water waves, and Hanratty admitted this was his original intention, it turns out that even for wave amplitudes small enough to produce a linear response to the shear stress, the details of the turbulence are very sensitive to the undulation and the shear stress and pressure variation can exhibit considerable shift in phase angle. Hence these measurements would produce a sensitive test of turbulence models. A question of particular interest at the time (1970's) was whether the "quasilaminar" model (or "frozen turbulence models"), in which the effect of the turbulence was included only through changes in the mean velocity profile, and the "equilibrium turbulence" model, which used an eddy diffusivity closure, could be reconciled. These two limiting models had a distinct mismatch in the predicted phase angle for the wall shear stress at moderate wavenumbers. To resolve this discrepancy, Hanratty found it would be necessary to perform experiments at a much higher Reynolds number. Tom was undaunted, and along with Jonathan Abrams he purchased a new pump that was designed as an emergency pump to supply water for fighting fires in tall buildings. He also required a new electrical source dedicated to his laboratory. The resulting data showed a sharp peak in the phase angle of the shear stress for intermediate wave numbers even more dramatic than was suggested by the mismatch of the limiting theories. In addition, Tom and Jon Abrams provided a theoretical explanation for the behavior using a "relaxation" model. These data are another "experimental standard" that continues to be cited by researchers to verify the correctness of solutions obtained by direct numerical simulation (DNS) of the Navier-Stokes equations.

It was through his examination of turbulent flow in rectangular channels and over wavy surfaces that Tom began a lifelong collaboration with Professor Ronald J. Adrian, who was at the time at the University of Illinois. Professor Adrian is an expert in the use of laser-Doppler velocimetry and a pioneer in the development of particle image velocimetry (PIV). These laser techniques enabled imaging of flow fields close to the surface of a wavy wall and could provide detailed, instantaneous flow structures over length scales of the entire wave trough where flow reversal could be occurring. The rectangular geometry (as opposed to a circular pipe) enabled elegant optical experiments. A particularly important result from this fruitful collaboration is a paper from 2001 in which PIV enabled discernment of large-scale flow structures and directly demonstrated that momentum is carried to the wall not by turbulent fluctuations but by large-scale (i.e., size of the channel) motions.

Gas-liquid flows

Studies of turbulent transport to a fluid from a solid boundary soon evolved into moving boundaries, such as gas-liquid flows. Tom explored these systems, starting in 1959 with the simple configuration of a gas blowing over a liquid in a rectangular channel. In a series of papers with Engen, Hershman, and Cohen, he developed equipment to provide meaningful measurements of the intricacies of an air/liquid interface and its dependence on flow rates of each phase. As important as the detailed experiments was the use of mathematical analysis to investigate the nature of the instability that led to formation of the different types of waves. The relation between roll waves, which cause significant mixing and atomization, and the smaller-amplitude 2-D and 3-D waves that merely roughen the surface and cause modest increases in the pressure drop, was clearly distinguished by experiments and theory. Hanratty's experiments showed that a long-wavelength approximation and suitable spatial averaging, (which is distinctly different from the classic Kelvin-Helmholtz analysis used by other researchers in this field) could describe the turbulent gas flow, the increased stress at the gas-liquid interface, and provide prediction of the conditions where roll waves and ultimately slugs would occur. This latter work has had particular technological impact in the petroleum process industries because slugs (intermittently occurring, fast moving plugs of high liquid fraction that can be many pipe diameters long) can overwhelm the processing equipment on off-shore platforms if that equipment is designed for average liquid flow conditions.

Success and insights from the (idealized) horizontal rectangular configuration led Hanratty to make many important contributions to our knowledge of multiphase flow behavior in vertical and horizontal pipes. Tom was actually a little late (1960's) getting into this area as people such as Abe Dukler at the University of Houston and Geoff Hewitt in the UK (Harwell and Imperial College) were already using novel experiments to produce seminal findings about the detailed mechanisms of the very complex gas-liquid flows. However, even within this elite group, Tom made significant contributions—his coupling of experiments that were directly analyzed theoretically enlivened the entire field. For these situations, the first problem of interest is the flow regime—that is the dynamic and time-average geometric location of the gas and liquid. Even though this had been a much-studied problem before Hanratty began considering it, he produced a series of new understandings about the formation mechanism for slugs (the expected formation directly from wave growth is augmented by coalescence), but perhaps more important, he found that the visual identification of flow regimes could be wrong. In another very impressive flow facility, an 80-foot-long horizontal pipe loop, he discovered "pseudo slugs." These "look" exactly like regular slugs from the outside of the pipe but they have a hole through them and hence don't create a very large pressure fluctuation. This finding called into question much of the existing literature on flow regimes in gas-liquid flows.

In vertical flows, a photographic examination of the mechanism of atomization came with theoretical analysis and ultimately useful engineering correlations. Perhaps Hanratty's most interesting and important work on vertical two-phase flows involved measurement of drop size distributions and diffusion in annular flows. As much as 50% of the liquid flowing in a vertical two-phase annular flow occurs within the gas as a drop phase—a critical result for heating conditions where the pipe is subjected to the high temperatures of combustion gases and the liquid film must be present to provide cooling.

Or, if "burnout" were to occur, the drops in the core would provide the only recourse to prevent pipe damage. As with all of his work, theory was augmented with engineering intuition, resulting in several engineering correlations that are currently in use.

A final thread on this topic was the work to image the concentration boundary layer close to a gas-liquid interface. Since the most interesting problem occurs only when waves are present, and the concentration boundary is very thin, this is a particularly challenging task. However, Hanratty and his students were successful at measuring the 2-D wave field and imaging the concentration boundary layer. These results provided confirmation of the link between short wavelength waves, interacting with the gas flow, and the control of mass transfer. This explained why the mass transfer coefficient, made dimensionless with the (wind) friction velocity, has an almost universal value across air-water flow facilities that differ by two orders of magnitude in water depth and flow length.

A pioneer of computer simulation of turbulence and turbulent transport.

In light of his succession of stunning experimental achievements it should not be overlooked that Tom Hanratty continually employed the best theoretical and (later) numerical methods, both in concert with his experiments and (as appropriate) separately. Thus it is not surprising that by the middle of the 1980's Tom realized that computers had reached a performance level at which it was becoming possible to solve the Navier-Stokes equations "exactly" rather than with closure relations and phenomenological models. Hence he could do "experiments" on the computer. He jumped at this chance, adding a new collaborator, Professor John B. McLaughlin, a computational expert who likewise had interest in computational simulations using the governing equations of fluid mechanics. This fruitful collaboration lasted for the rest of Tom's life. Their work advanced rapidly in the 1990's producing new insights into wall turbulence structure and the mechanism of turbulent heat and mass transfer. In fact, as with others in the field, he verified the veracity of some of these theoretical calculations by comparison with his own classic experiments, (e.g., Shaw and Abrams)! Of course, the value of simulations is that all variables are known at every time across the entire flow field—which is not possible in laboratory measurements. The most important findings were specific insights into how the main flow feeds energy into the wall region and sustains the turbulence generation and a better mechanistic understanding of the filtering (of high frequencies) effect that occurs for high Schmidt number turbulent transport to the wall.

Turbulent drag reduction due to low concentrations of dissolved polymer

It was inevitable that Hanratty would eventually turn his attention to a phenomenon that has intrigued the international community of rheologists for 75 years. We refer to the remarkable reduction of drag that can occur in turbulent flow when dissolved polymer is present at concentrations as low as parts per million.

It is interesting that while Hanratty made an initial experimental foray into the subject as early as 1972, he did not return to the subject in any focused way until the final phase of his career (perhaps because he was venturing out of his fluid-mechanics comfort zone), when the subject became central to his research. During the period 1995-2005 he produced more than a dozen papers related to turbulent drag reduction.

In the 1972 work Hanratty and his students exploited their electrochemical probe technique. From their measurements they concluded that the presence of polymer substantially altered the structure of the wall region. Specifically, they found a significant increase in the length of longitudinally oriented eddies in the viscous sublayer, and they hypothesized that this structure could reduce viscous resistance in the flow direction. When he returned to the subject 20 years later he was in a position to adapt his experiences with DNS to a polymer solution. By using a well-recognized model for long-chain molecules (the FENE-P bead-chain model) his group had quantitative mechanics for bead extension that could be incorporated into DNS calculations of shear fields. This permitted simulation of the coiling and uncoiling of a polymer molecule in the viscous sublayer, as well as farther into the buffer and outer flow regions. In essence, this was a numerical experiment yielding insights at a more detailed level than would be possible in the laboratory. They postulated that drag reduction was achieved through energy transfer at the molecular level, thus altering eddy structure and hence the magnitude of Reynolds stresses. Unfortunately, a drawback to these calculations, fully appreciated by the authors, was the restriction to single polymer molecules. Subsequent laboratory measurements, using laser-Doppler velocimetry (LDV) methods, led to the consistent conclusion that polymer stresses are a significant contribution to the turbulent energy balance.

In summary, the Hanratty work on turbulent drag reduction did not offer a final and complete explanation of the phenomenon any more than one exists for Newtonian turbulence. However, it was a major accomplishment to confirm the importance of interactions between mechanical properties of polymer-chain dynamics and the customary mechanics of Reynolds stress of the solvent.

Concluding comment

In composing this Memorial the authors were reminded how much we benefitted from Tom Hanratty's keen technical insight and from the warm personal interactions we had with him over a period spanning between 40 and 60 years of his career as a faculty colleague, a PhD advisor, a professional counselor, and a friend. Our request for some thoughts by Professor John McLaughlin came back with an all too modest admission that his best research had been achieved with Tom and Tom's students, and that he had particularly enjoyed their personal interactions. Professor Ronald Adrian remarked that even after a joint publication, he and Tom did not always achieve a complete meeting of the minds (it was turbulence after all!), but that Tom always drove the collaboration to determine the precise conclusions that were justified by the experiments and calculations. A final word from Professor Geoffrey Hewitt is perhaps an appropriate closure. In addition to lauding Tom's research accomplishments, noting his pleasure at discussing mutual interests and recalling their rewarding personal relationship, he described Tom as a True Gentleman. No one could disagree!

SCHOLASTIC AND PROFESSIONAL HONORS

Allan P. Colburn Award, American Institute of Chemical Engineers, 1957

National Science Foundation Senior Postdoctoral Fellowship, 1962

Curtis W. McGraw Award, American Society for Engineering Education, 1963

William H. Walker Award, American Institute of Chemical Engineers, 1964

Professional Progress Award, American Institute of Chemical Engineers, 1967

Member, National Academy of Engineering, 1974

Honorary Doctorate Degree, Villanova University, 1979

Senior Research Award, American Society of Engineering Education, 1979

Shell Distinguished Professorship, 1981-1986

Distinguished Engineering Alumnus Award, Ohio State University, 1984

Ernest Thiele Award, Chicago Section AIChE, 1986

University of Illinois Senior Scholar, 1987

American Academy of Arts and Sciences, 1997

Lamme Medal, The Ohio State University, 1997

First winner of The Multiphase Flow International Prize, 1998

Member, National Academy of Sciences, 1999

Docteur Honoris Causa, de l'Institut National Polytechnique de Toulouse, 1999

Recognition as one of the influential chemical engineers of the modern era (post World War II)at the AIChE Centennial Celebration, Philadelphia, 2008

J. Stanley Morehouse Award, Villanova College of Engineering, October 2, 2009

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