ANS LEGACY CIRCLE
PROFILE HONORING
Dr. William T. Sha

May 2019

American Nuclear Society

American Nuclear Society
555 N. Kensington Ave.
La Grange Park, IL 60526
708-352-6611

INTRODUCTION

Dr. William T. Sha is an honorary member of the American Nuclear Society, with a history dating back to 1964 when he first joined the Society. ANS can attest to the many accomplishments of our members within the nuclear science and technology fields – including Dr. Sha, as evidenced by his resume documenting a lifetime of achievement.

In 1984, Dr. Sha was nominated as an ANS Fellow, one of our Society's highest honors which led to Dr. Sha's advancement to Fellow.

In this biography, we have included the following information that highlights the successful – and inspiring – career of Dr. Sha:

1. Biographical Sketch
2. History with the American Nuclear Society
3. Westinghouse and Argonne National Laboratory
4. Publications

BIOGRAPHICAL SKETCH

About Dr. William T. Sha

The following biographical sketch is taken from ChiamOnline.com, a “unique source on and relating to Chinese Americans. It provides news about Chinese Americans in the United States and information of interest to reader. The web site is intended to foster understanding of the historical past of Chinese Americans and appreciation of Chinese Americans' contributions to the American society.”

> Dr. William T. Sha is a nuclear scientist and an inventor. He was a mechanical engineer with the Combustion Engineering Inc., Fellow Scientist at the Westinghouse Atomic Power Division, and served at the Argonne National Laboratory as Director of Analytic Thermal Hydraulic Research Program, Director of Multiphase Flow Research Institute, and Special Consultant to the Laboratory Director. At Westinghouse, Dr. Sha participated in the final phase design of Yankee Nuclear Power Station which is the world first pressurized water reactor for power generation, and developed analytical methods for design and safety analysis of pressurized water reactor. While working at Argonne, he focused on theory and methods development for design and safety analysis of light water and fast reactors, developed the novel porous media formulation which is widely used in the international reactor community, and organized cooperative research programs with Midwest University Consortium to carry out projects. He is now President of Sha and Associates, Inc., a consulting firm in the power industry.
>
> Dr. Sha also taught at Tsinghua University, Xian Jiaotong University, and is a consultant to Heat Transfer Research Facility, Columbia University, Lungmen Nuclear Power Plant Project of Taiwan Power Company, and China Guangdong Nuclear Power Holding Company. He received many honors and awards, including American Nuclear Society (ANS) Fellow, Member of ANS Special Publication Committee, Member of Editorial Board of the *International Journal of Nuclear Engineering and Design*, Argonne Pacesetter Award for Exceptional Job Performance (1986), and Outstanding Asian American Award from the Asian American Heritage Council (1982).
>
> Dr. Sha received his doctorate from Columbia University in 1964. His unique expertise is the assessment, design and analysis for various energy systems in general and fossil and nuclear power plants in particular. A prolific writer, he has published one book, over 280 technical papers, and received two U.S. patents. His latest patent is a pressure control system to improve power plant efficiency.

HISTORY WITH THE AMERICAN NUCLEAR SOCIETY

About the American Nuclear Society

Dr. Sha has been a member of the American Nuclear Society since 1964. ANS was launched in the mid-1950s just 10 years or so before Dr. Sha joined. The mid-fifties were a time of growing interest in employing peaceful applications of nuclear science and technology for bettering the lives of people in the United States and around the world.

The Society has made, and continues to make, important contributions to the use of nuclear science and technology, and consequently to the larger society beyond ANS. It achieves this through its many products and services, including meetings, publications, standards, outreach, honors and awards, scholarships, teachers workshops, Organization Members, and representation in Washington, D.C.

ANS continues to be a professional organization of scientists, engineers, and other professionals devoted to the peaceful applications of nuclear science and technology. Its 11,000 members, from over 40 countries, come from diverse technical disciplines ranging from physics and nuclear safety to operations and power, and from across the full spectrum of the national and international enterprise, including government, academia, research laboratories, and private industry.

Making it all succeed are a Board of Directors, 20 standing committees, 19 professional divisions, one technical group and two working groups, 32 local sections, over 35 student sections, liaison agreements with over 30 non-U.S. nuclear societies, and a headquarters staff of about 50 people.

"Summary of Acknowledged Scientific and Engineering Attainments"

In 1983, ANS Fellows put forth a nomination to the ANS Honors and Awards Committee for consideration of Dr. Sha as an ANS Fellow. The nomination included a "Summary of Acknowledged Scientific and Engineering Attainments" that detailed Dr. Sha's work to-date. The summary ended with a statement that reflects Dr. Sha's importance to the field:

> "…Dr. Sha's nomination is based upon a distinguished record of achievements as the original thinker and developer of several advanced concepts and methods which served as the basis of development of several well-known computer codes for the numerical analysis of reactor heat transfer and fluid flow. His development of the VENUS, COMMIX, and BODYFIT codes represents a quantum jump for advancing the fundamental understanding of very complex physical processes and state-of-the-art of computational thermal hydraulics."

The following ANS Fellows drafted the original nomination – titles indicated here are the ones they held at the time of the nomination:

- **John J. Dorning**

- Nuclear Engineering Program, University of Illinois

- **Dr. Charles N. Kelber**
  - Deputy Director, Division of Accident Evaluation, Office of Nuclear Regulatory Research U.S. Nuclear Regulatory Commission

- **Dr. Walter B. Loewenstein** (ANS President 1989-1990)
  - Deputy Director, Nuclear Power Division, Electric Power Research Institute (EPRI)

- **Dr. Robert Avery**
  - Director, Reactor Analysis and Safety Division, Argonne National Laboratory

- **Dr. Paul A. Lottes**
  - Reactor Analysis and Safety Division, Argonne National Laboratory

The following text is taken verbatim from the summary:

> "To aid in the following elaboration of the specific set of contributions dealing with the development of advanced concepts/methods/codes in thermal hydraulics, a list of references is appended here, taken from Dr. Sha's total publications list.
>
> Dr. Sha is the original developer of the VENUS code [1,2], a coupled neutronic and hydrodynamic fast-reactor disassembly analysis code which serves internationally as basic framework for estimating energy yield during a hypothetical design-based accident. One of the unique contributions of the VENUS code is the effect of density change on material motion and thus on reactivity feedback during an accident. This effect was first recognized and modeled by Dr. Sha and was neglected in the original work of Professors H. A. Bethe and J. H. Tait in estimating the order of magnitude of the explosion when the core of a fast reactor collapses. As the result of the development of VENUS, the calculated energy yield during a maximum accident was decreased by one or more orders of magnitude as compared with previous estimates. Dr. Sha's work in this area had a very significant impact on setting the criteria for the design basis accident, and thus the reactor containment design. Dr. Sha was also the first to advocate the mechanistic approach of reactor accident analysis from the initiation to disassembly phase [3].
>
> Dr. Sha is the principal author of the COMMIX code [4], which provides significant advances in thermal-hydraulic analysis of a three-dimensional, transient multiphase system. The COMMIX code employs a new porous-media formulation [4], which provides significant advances in thermal-hydraulic analysis of a three-dimensional, transient multiphase system. The COMMIX code employs a new porous-media formulation [5,6,7,8] which was originally developed and derived by Dr. Sha. This new porous-media formulation uses the concepts of volume porosity, surface permeabilities, distributed resistance, and distributed heat source or sink. In the conventional porous-

media formulation, only volume porosity, distributed resistance, and distributed heat source are used. Volume porosity is defined as the ratio of the volume occupied by fluid in a control volume to the total control volume. Surface permeability is similarly defined as the ratio of area intersected by the fluid passing through a control surface to the total control surface area. The concept of surface permeabilities is new. In thermal-hydraulics analysis, resistance (friction factor) is in general not known precisely for most of the engineering applications; surface permeability is a function of geometry and is precisely known.

This new porous-media formulation uses both distributed resistance and surface permeability for modeling velocity and temperature fields in anisotropic media. This is in contrast with the conventional porous media in which only the distributed resistance is used. Thus, any error in estimating resistance will not be entirely reflected in the results using the new porous-media formulation, but will be in the conventional porous-media formulation. The concept of surface permeability greatly facilitates modeling of velocity and temperature fields in anisotropic media and in general improves momentum transfer, resolution, and accuracy. This new porous-media formulation represents the first unified approach to thermal-hydraulic analysis. The COMMIX code has a wider range of applicability, and it is capable of solving thermohydraulic problems involving either a single component such as a rod bundle, reactor plenum, piping system, heat exchanger, etc. or a combination of these components.

Dr. Sha [9,10] developed a benchmark rod-bundle thermal-hydraulic analysis code called BODYFIT, using a boundary-fitted coordinate system. In this code, the complicated rod-bundled configuration is transformed to uniform mesh in either a rectangular or cylindrical coordinate system. Hence, because the physical boundaries of the rods coincide with coordinate lines, the boundary conditions can be accurately specified. The BODYFIT code enables a true rod-bundle benchmark calculation for the first time. For laminar flow, there is absolutely no assumption used in the analysis and only rod-bundle geometry must be specified, along with coolant thermal physical properties. For turbulent flow, the normal closure problem is encountered in the turbulence modeling, and empiricism is unavoidable. Lately, Dr. Sha has extended the boundary-fitted coordinate transformation applied to thermal-hydraulic analysis for 3D arbitrary geometries [11]."

References Included with the Summary

1. W.T. Sha and T. H. Hughes, "VENUS: A Two-Dimensional Coupled Neutronics Hydrodynamics Computer Program for Fast-Reactor Power Excursions," ANL-7701, October 1970.

2. W. T. Sha, T. A. Daly, A. J. Lindeman, E. L. Fuller, D. A. Meneley, and G. K. Leaf, "Two-Dimensional Fast Reactor Disassembly Analysis with Space-Time Kinetics," Proceedings of Conference on New Developments in Reactor Mathematics and Applications, Idaho Falls, Idaho, March 29-31, 1971.

3. W. T. Sha and A. F. Waltar, “An Integrated Model for Analyzing Disruptive Accidents in Fast Reactors,” Nuclear Science and Engineering, 44, 135-156, 1971.

4. W. T. Sha, H. M. Domanus, and R. C. Schmitt, “COMMIX-1: A Computer Program for Three-Dimensional, Transient, Single-Phase Thermal-Hydraulic Analysis,” NUREG-0415, ANL-77-96, January 1978.

5. W. T. Sha, “A New Approach for Rod-Bundle Thermal-Hydraulic Analysis,” Proceedings of the International Meeting on Nuclear Power Reactor Safety, Brussels, Belgium, October 16-19, 1978.

6. W. T. Sha and B. T. Chao, “Conservation Equations for Finite Control Volume Containing Single-Phase Fluid with Fixed, Dispersed Heat Generating (or Absorbing) Solids,” NUREG/CR-0945, ANL-CT-79-42, July 1979.

7. W. T. Sha, “An Overview of Rod-Bundle Thermal Hydraulic Analysis,” Special Issue on Liquid-Metal Fast Breeder Reactor Single-Phase Rod-Bundle Thermal Hydraulics of Nuclear Engineering and Design, Vol. 62, December 1980.

8. W. T. Sha, B. T. Chao, and S. L. Soo, “Local Volume Averaged Transport Equations for Multiphase Flow in Regions Containing Distributed Solid Structures,” NRUEG/CR-2354, ANL-81-69, December 1981.

9. W. T. Sha and J. F. Thompson, “Rod-Bundle Thermal-Hydraulic Analysis using Boundary Fitted Coordinate System,” NUREG/CR-0001, ANL-78-1, January 1979.

10. W. T. Sha, B. C-J. Chen, Y. S. Cha, S. P. Vanka, R. C. Schmitt, J. F. Thompson, and M. L. Doria, “Benchmark Rod-Bundle Thermal-Hydraulic Analysis using Boundary Fitted Coordinates,” ANS Transactions, November 1979.

11. W. T. Sha, “Boundary-Fitted Coordinate Transformation for Thermal Hydraulic Analysis in Arbitrary Three-Dimensional Geometries, “NUREG/CR-2313, ANL-81-54, September 1981.

American Nuclear Society Honors and Awards

ANS Fellow (1984)

Dr. Sha has received the honored membership grade of Fellow, awarded to ANS members for outstanding accomplishment in any one of the areas of nuclear science and engineering. Receiving the highest membership grade of the Society is reserved for senior members of good reputation who have compiled a professional record of experience marked by significant contribution to the advancement of one or more of the various disciplines served by the Society. The worthiness of a given candidate for advancement to Fellow is determined by critical review and assessment of submitted credentials and qualifications.

Technical Achievement Award (2005)

This is the highest award given by ANS's Thermal Hydraulic Division. It recognizes Dr. Sha's "many outstanding and unique contributions to the field of two phase flow and nuclear reactor design and safety analyses through the development and application of novel computational technique for analyzing thermal hydraulic behavior and phenomena, the development of NPMF of conservation equations used in the COMMIX code, development of boundary fitted coordinates transformation method used in BODYFIT code."

Glenn T. Seaborg Medal (2006)

The medal honors Dr. Sha's "outstanding contributions in understanding multi-dimensional phenomena of natural circulation and fluid stratification in reactor components and systems during normal and off-normal reactor operating conditions."

Samuel Untermyer II Medal (2007)

The medal is in recognition of Dr. Sha's "pioneering work in the development of significant improvements in NPMF for multiphase flow with far reaching implications and benefits for water cooled reactor components and systems."

Reactor Technology Award (2008)

The award recognizes Dr. Sha's "outstanding leadership and exceptional technical contribution for the U.S. Department of Energy's Industrial Consortium in developing computer codes for intermediate heat exchanges and steam generators of Liquid Metal Fast Breeder Reactors which are based on the NPMF."

American Nuclear Society Peer-Reviewed Journal Articles

1. "Boundary-Value Thermal-Hydraulic Analysis of a Reactor Fuel Rod Bundle"

William T. Sha, Robert C. Schmitt & P. R. Huebotter

Nuclear Science and Engineering, Volume 59, 1976 - Issue 2

2. "A Noniterative Method of Computing Neutron Flux Distributions and Coolant Density Profile in a Light-Water Moderated Reactor"

William T. Sha

Nuclear Science and Engineering, Volume 25, 1966 - Issue 4

3. “A Generalized Local Boiling Void Model for Light-Water Reactor System”
William T. Sha
Nuclear Science and Engineering, Volume 44, 1971 - Issue 3

4. “An Integrated Model for Analyzing Disruptive Accidents in Fast Reactors”
William T. Sha & Alan E. Waltar
Nuclear Science and Engineering, Volume 44, 1971 - Issue 2

5. “Transient Two-Phase Flow”
William T. Sha
Nuclear Technology, Volume 65, 1984 - Issue 2
“Effective Resonance Temperature Correlation of UO2”
William T. Sha
Nuclear Applications, Volume 1, 1965 - Issue 6

6. “Out-of-Pile Steam-Fraction Determination by Neutron-Beam Attenuation”
William T. Sha & Charles F. Bonilla
Nuclear Applications, Volume 1, 1965 - Issue 1

American Nuclear Society Presentation

“Multiphase Flow Conservation Equations are Differential-Integral Equations and are not a Set of Partial Differential Equations”
Special presentation by Dr. Sha at ANS Annual Meeting on June 25, 2007. Session: “Uncertainty Treatment in Nuclear Science and Engineering,” jointly sponsored by ANS’s Thermal Hydraulic Division and Mathematics and Computation Division.

Additional American Nuclear Society Activities

- Member of ANS’s Special Publication Committee (1975-1978)
- ANS’s Continuous Technical Contact for review of the book, “Thermal Analysis of Pressurized Water Reactors,” by Tong and Weisman (1979, 1995)

- Dr. Sha has many accomplishments outside of ANS. These are outlined in his resume and include his nearly 300 publications, longtime tenure at Argonne National Laboratory, and awards and recognitions.

WESTINGHOUSE AND ARGONNE NATIONAL LABORATORY

Westinghouse Atomic Power Division

As Fellow Scientist, Dr. William T. Sha participated in the final phase design of Yankee Rowe Nuclear Power Station, the world's first pressurized water reactor (PWR) for power generation only and developed the THUNDER code, the world's first 3D Nuclear-Thermal-Hydraulic Interaction Code (WCAP-7006, January, 1967) and other analytical methods for design and safety analysis of WWRs (1960-1967).

About Westinghouse

Dr. Sha worked at one of the founding companies in the nuclear industry, having a long history of innovation and technological expertise and we are sure Dr. Sha's time with Westinghouse had an impact on the company's work.

From the Westinghouse website, we learn of the company's mission and history, http://westinghouse.com/heritage/:

> Since 1886, Westinghouse has brought the best to life.
>
> "You can see it in the products we make. The power we create. The people we help. Today, our legacy lives on with technology that is transforming the human experience, from smart appliances for the home to energy solutions that are cleanly and safely powering us into the next generation."
>
> "Explore our history to discover how Westinghouse has been at work in our world:"

1846

George Westinghouse born in Central Bridge, New York.

1865

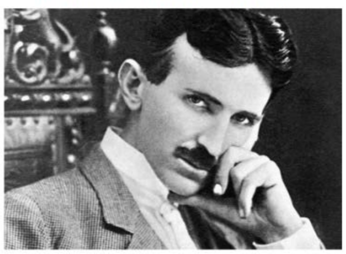
George Westinghouse patents the rotary steam engine.

1881

Westinghouse founds Union Switch and Signal Company to develop closed-track circuits and interlocking systems for railroads.

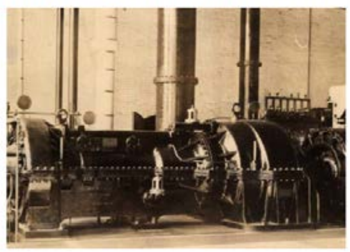
1888

Nikola Tesla receives a patent for the first alternating current motor and comes to work for Westinghouse Electric Company.



1901

First commercial Westinghouse steam turbine driven generator, 1,500 kW unit nicknamed the Mary-Ann, Hartford Electric Light Co.



1937

Westinghouse Electric constructs the first atom smasher to explore the potential of nuclear energy as a practical power source.

1941

Westinghouse begins producing power at Grand Coulee Dam.

1954

The USS Nautilus, the world's first nuclear submarine, was launched with a reactor built by Westinghouse.

1969

Westinghouse cameras capture the first moonwalk for viewers back on earth.

Westinghouse AP1000 Nuclear Power Plant Design

As noted above, Dr. Sha participated in the final phase design of Yankee Rowe Nuclear Power Station, the world's first pressurized water reactor (PWR). This lead to Westinghouse's AP1000 Nuclear Power Plant Design as described on their website, http://www.westinghousenuclear.com/New-Plants/AP1000-PWR.

"The AP1000 nuclear power plant is a two-loop pressurized water reactor (PWR) that uses a simplified, innovative and effective approach to safety. With a gross power rating of 3,415 megawatt thermal (MWt) and a nominal net electrical output of 1,110 megawatt electric (MWe), the AP1000 reactor, with a 157-fuel-assembly core, is ideal for new baseload generation.

<u>Simplified Plant Design</u>

Simplification was a major design objective of the AP1000 plant. Simplifications in overall safety systems, normal operating systems, the control room, construction techniques, and instrumentation and control systems provide a plant that is easier and less expensive to build, operate and maintain. Plant simplifications yield fewer components, cable and seismic building volume, all of which contribute to considerable savings in capital investment, and lower operation and maintenance costs. At the same time, the safety margins for the AP1000 plant have been increased dramatically over currently operating plants.

<u>The Technology</u>

The AP1000 PWR is comprised of components that incorporate many design improvements distilled from 50 years of successful operating nuclear power plant experience. The reactor vessel and internals, steam generator, fuel and pressurizer designs are improved versions of those found in currently operating Westinghouse-designed PWRs. The reactor coolant pumps are canned-motor pumps, the type used in many other industrial applications where reliability and long life are paramount requirements."

Argonne National Laboratory

At Argonne National Laboratory, Dr. Sha served as Senior Nuclear Scientist (equivalent to the rank of full professor at the University of Chicago), Director of Analytic Thermal Hydraulic Research Program, Director of Multiphase Flow Research Institute (MFRI), and Special Consultant to the Laboratory Director.

According to Dr. Sha's resume, he worked on a variety of projects, including developing single phase multi-components and two phase flow theoretical and predictive methods for design and safety analysis of LMBR and LWR with special emphasis on porous media formulation, modeling closure relations, and code development.

About Argonne National Laboratory

The importance of Argonne National Laboratory is readily apparent from the following snapshot of their history (https://www.anl.gov/our-history).

> "Argonne traces its birth from Enrico Fermi's secret charge — the Manhattan Project — to create the world's first self-sustaining nuclear reaction.
>
> 
>
> Code-named the "Metallurgical Lab," the team constructed Chicago Pile-1, which achieved criticality on December 2, 1942, underneath the University of Chicago's Stagg football field stands. Because the experiments were deemed too dangerous to conduct in a major city, the operations were moved to a spot in nearby Palos Hills and renamed "Argonne" after the surrounding forest.
>
> An illustration depicting Chicago Pile-1, the site of the world's first controlled, self-sustaining nuclear reaction. (Image copyright Chicago Historical Society)
>
> This drawing depicts the historic event on December 2, 1942, when a group of 49 scientists led by Enrico Fermi created the world's first controlled, self-sustaining nuclear chain reaction.
>
> On July 1, 1946, the laboratory was formally chartered as Argonne National Laboratory to conduct "cooperative research in nucleonics." At the request of the U.S. Atomic Energy Commission, it began developing nuclear reactors for the nation's peaceful nuclear energy program. In the late 1940s and early 1950s, the laboratory moved to a larger location in Lemont, Illinois, and established a remote location in Idaho, called "Argonne-West," to conduct further nuclear research.
>
> In quick succession, the laboratory designed and built Chicago Pile 3, the world's first heavy-water moderated reactor, and the Experimental Breeder Reactor I, built in Idaho, which lit a string of four light bulbs to produce the world's first nuclear-generated electricity in 1951. Knowledge gained from the Argonne experiments formed the foundation for the designs of most of the commercial reactors currently used throughout the world for electric power generation, and continue to inform designs of liquid-metal reactors for future commercial power stations.

Conducting classified research, the laboratory was heavily secured; all employees and visitors needed badges to pass a checkpoint, many of the buildings were classified, and the laboratory itself was fenced and guarded. Such alluring secrecy drew visitors both authorized — including King Leopold III of Belgium and Queen Frederica of Greece — and unauthorized. Shortly past 1 a.m. on February 6, 1951, Argonne guards discovered reporter Paul Harvey near the 10-foot (3.0 m) perimeter fence, his coat tangled in the barbed wire. Searching his car, guards found a previously prepared four-page broadcast detailing the saga of his unauthorized entrance into a classified “hot zone.” He was brought before a federal grand jury on charges of conspiracy to obtain information on national security and transmit it to the public, but was not indicted.

Not all nuclear technology went into developing reactors, however. While designing a scanner for reactor fuel elements in 1957, Argonne physicist William Nelson Beck put his own arm inside the scanner and obtained one of the first ultrasound images of the human body. Remote manipulators designed to handle radioactive materials laid the groundwork for more complex machines used to clean up contaminated areas, sealed laboratories or caves. In 1964, the “Janus” reactor opened to study the effects of neutron radiation on biological life, providing research for guidelines on safe exposure levels for workers at power plants, laboratories and hospitals. Scientists at Argonne pioneered a technique to analyze the moon’s surface using alpha radiation, which launched aboard the Surveyor 5 in 1967 and later analyzed lunar samples from the Apollo 11 mission.

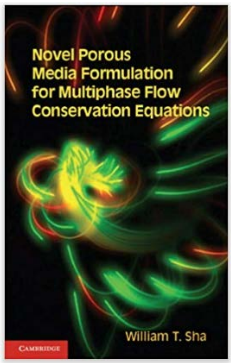
In addition to nuclear work, the laboratory maintained a strong presence in the basic research of physics and chemistry. In 1955, Argonne chemists co-discovered the elements einsteinium and fermium, elements 99 and 100 in the periodic table. In 1962, laboratory chemists produced the first compound of the inert noble gas xenon, opening up a new field of chemical bonding research. In 1963, they discovered the hydrated electron.”

PUBLICATIONS

Novel Porous Media Formulation for Multiphase Flow Conservation Equations

Dr. Sha’s book “Novel Porous Media Formulation for Multiphase Flow Conservation Equations” was published by Cambridge University Press in September, 2011. The following provides an overview of its contents (https://www.amazon.com/Porous-Formulation-Multiphase-Conservation-Equations/dp/1107012953).

“William T. Sha first proposed the novel porous media formulation in an article in Nuclear Engineering and Design in 1980. The novel porous media formulation represented a new, flexible and unified approach to solve real-world engineering



problems. It uses the concept of volume porosity, directional surface porosities, distributed resistance and distributed heat source and sink. Most practical engineering problems involve many complex shapes and sizes of solid internal structures whose distributed resistance is impossible to quantify accurately. The concept of directional surface porosities eliminates the sole reliance on empirical estimation of the distributed resistance of complex-shaped structures often involved in the analysis. The directional surface porosities thus greatly improve the resolution and modeling accuracy and facilitate mock-ups of numerical simulation models of real engineering systems. Both the continuum and conventional porous media formulations are subsets of the novel porous media formulation."

The concept of directional surface porosities was first suggested by Sha and it greatly improved resolution and modeling accuracy.

In the book, Wm. Howard Arnold, National Academy of Engineering, attests to the value of Dr. Sha's work (https://www.cambridge.org/core/books/novel-porous-media-formulation-for-multiphase-flow-conservation-equations/foreword/48CF79EEF08FBD66D3DC1428AB3A9218).

Summary

"When I was the manager of reactor physics in the Westinghouse Atomic Power Division [later called the Pressurized Water Reactor (PWR) Division], Dr. William T. Sha worked for me and was instrumental in our development of the first multi-dimensional integral calculation of nuclear-thermal-hydraulic interaction named THUNDER code for the commercial PWRs. The reactivity feedbacks due to thermal-hydraulics, including local subcooled and bulk boiling, control rod insertion, dissolved boron poison in the moderator, and fuel pellet temperature (Doppler effect) were explicitly accounted for. We were then designing Yankee Rowe, Connecticut Yankee, Edison Volta, and Chooz 1. He was clever, indefatigable, and a great asset in our development of the THUNDER codes (WCAP-7006, 1967) and designing these reactors. Plants based on this design are now found in more than half of the world's nuclear power plants. This code represented a quantum jump in design and performance of PWRs when it was successfully completed in 1967.

Once again, Dr. Sha demonstrates innovation and lays the theoretical foundation to develop the novel porous media formulation for multiphase flow conservation equations. The starting point of the novel porous media formulation is Navier-Stokes equations and their interfacial balance equations; the local-volume averaging is performed first via local-volume-averaged theorems, followed by time averaging. A set of conservation equations of mass, momentum, and energy for multiphase systems with internal structures is rigorously derived via time-volume averaging. This set of derived conservation equations has three unique features: (1) the internal structures of the multiphase system are treated as porous media formulation – it greatly facilitates accommodating the complicated shape and size of the internal structures; (2) the concept of directional surface porosities is introduced in the novel porous media formulation and greatly improves modeling accuracy and resolution; and (3) incorporation of spatial deviation for all point dependent variables make it possible to evaluate interfacial mass, momentum, and energy transfer integrals. The novel porous media formulation represents a unified approach for solving real world multiphase flow problems."

An editorial review from Amazon also attests to the value of the book (https://www.amazon.com/Porous-Formulation-Multiphase-Conservation-Equations/dp/1139003402)

> "In the reviewer's opinion, this book provides a fundamental and comprehensive presentation of the mathematical and physical theory of multiphase flow, pointing out several important practical applications. [It] is excellently written and readable. Numerical solutions are given graphically and in tabular form. A large list of 66 papers and books is included at the end of the book. The book will be useful to a wide range of specialists working in the area of flows in porous media, such as design engineers, physicists, chemical engineers, and also to researchers interested in the applied mathematical theory of flows in porous media. It can be also recommended as a text for seminars and courses, as well as for independent study. Some chapters of the book present the state-of-the-art reviews, and they provide a solid background for future research." Ioan Pop, Zentralblatt MATH

The book's abstract is found on Science Direct's website: https://www.sciencedirect.com/science/article/pii/S0029549307000234.

<u>Abstract</u>

"Multiphase flows consist of interacting phases that are dispersed randomly in space and in time. An additional complication arises from the fact that the flow region of interest often contains irregularly shaped structures. While, in principle, the intraphase conservation equations for mass, momentum, and energy, and their initial and boundary conditions can be written, the cost of detailed fluid flow and heat transfer analysis with explicit treatment of these internal structures with complex geometry and irregular shape often is prohibitive, if not impossible. In most engineering applications, all that is required is to capture the essential features of the system and to express the flow and temperature field in terms of local volume-averaged quantities while sacrificing some of the details. The present study is an attempt to achieve this goal by applying time averaging after local volume averaging.

Local volume averaging of conservation equations of mass, momentum, and energy for a multiphase system yields equations in terms of local volume-averaged products of

density, velocity, energy, stresses, and field forces, together with interface transfer integrals. These averaging relations are subject to the following length scale restrictions:

$d \ll \ell \ll L$,

where d is a characteristic length of the pores or dispersed phases, ℓ a characteristic length of the averaging volume, and L is a characteristic length of the physical system.

Solutions of local volume-averaged conservation equations call for expressing these local volume-averaged products in terms of products of averages. In nonturbulent flows, this can be achieved by expressing the "point" variable as the sum of its intrinsic volume average and a spatial deviation. In turbulent flows, the same can be achieved via subsequent time averaging over a duration T such that

$\tau_{HF} \ll T \ll \tau_{LF}$,

where τ_{HF} is a characteristic time of high-frequency fluctuation and $\tau_{LF}$is a characteristic time of low-frequency fluctuation. In this case, and instantaneous "point" variable ψ_k of phase k is decomposed into a low-frequency component ψ_{kLF} and a high-frequency component ψ'_k, similar to Reynolds analysis of turbulent flow. The low-frequency component consists of the sum of the local intrinsic volume average ${}^{3i}\langle \psi_k \rangle_{LF}$ and its local spatial deviation $\tilde{\psi}_{kLF}$. Time averaging then reduces the volume-averaged products to products of averages plus terms representing eddy and dispersive diffusivities of mass, Reynolds and dispersive stresses, and eddy and dispersive conductivities of heat, etc. These terms arise from both high-frequency fluctuations and local spatial deviations. This procedure of time averaging after local volume averaging leads to a set of differential–integral equations of conservation for multiphase flow. This set of multiphase flow conservation equations is particularly suitable for numerical analysis with staggered grid computational systems.

Attention is focused on multiphase flow in a region containing fixed and dispersed heat-generating and absorbing solid structures. The novel porous media formulation employs the concept of volume porosity, directional surface porosities, distributed resistance and distributed heat source and sink which is derived through local volume averaging of conservation of mass, momentum and energy equations. The directional surface porosities are defined as a fraction of free flow surface area to control surface area in three principal directions which are readily calculable quantities. The conventional porous media formulation employs the concept of volume porosity, distributed resistance and distributed heat source and sink. Most of engineering problems involve many complex shapes and sizes of structures which are impossible to quantify their distributed resistance accurately. The concept of directional surface porosities reduced the reliance of empirical estimate of distributed resistance and improved the resolution and modeling accuracy. The novel porous media formulation represents a significant advance for solving real engineering problems."

American Nuclear Society