ROOP L. MAHAJAN

Lewis A. Hester Chair Professor of Mechanical Engineering
Global Ambassador, Institute for Critical Technology and Applied Science (ICTAS)
Virginia Polytechnic Institute and State University, Blacksburg, VA 24061
Email: mahajanr@vt.edu

1. EDUCATION

Mahajan received a Ph.D. degree in Mechanical Engineering from Cornell University and his Bachelor of Science and Master of Science degrees in Mechanical Engineering from Punjab Engineering College, Chandigarh, India. His education has throughout been marked by distinction and superior academic performance.

2. CURRENT EMPLOYMENT: 2006-

Executive Director, Institute for Critical Technology and Applied Science, and **Lewis A. Hester Chair Professor** of Mechanical Engineering, Department of Biomedical Engineering and Mechanics, Virginia Tech, Blacksburg, VA 24061.

Mahajan served as the first permanent director of ICTAS for a decade from July 1, 2006 to June 25, 2016. Under his leadership, ICTAS has grown to be a premier institute for transformative research intersecting engineering, the sciences--physical, life, and social, and the humanities for a *sustainable future*. To this end, ICTAS research has been organized around converging technologies (nanotechnology, biotechnology, information technology, cognitive science), emerging technologies (Big Data, 3-D printing, pervasive communications, bio-inspired science and technology), and "black swan" high-impact disruptive innovations. Researchers from across the campus with expertise in their underlying disciplines but with a passion for interdisciplinary research and a vigilant eye for new, unprecedented discoveries have been pulled together to make advances in these areas, and develop and implement path-finding solutions for sustainable energy, sustainable water, renewable materials and national security.

The progress and growth have been phenomenal. From its modest beginnings in 2006 with a skeleton staff and a few rented offices at the Virginia Tech Corporate Research Center, the institute has grown to almost 200,000 square feet of footprint spread over three buildings on the main campus in Blacksburg, VT Research Center in Arlington, VA, and an Innovation Center in Chennai, India. It is home to fifty one state-of-the-art interdisciplinary research labs including a leading-edge Nanoscale Characterization and Fabrication Laboratory (NCFL).

At the time of his stepping down, ICTAS was home to twenty interdisciplinary research centers including the highly acclaimed *NNCI (National Nanotechnology Coordinated Infrastructure)* -Virginia Tech National Center for Earth and Environmental Nanotechnology Infrastructure (NanoEarth), Virginia Tech Center for Sustainable Nanotechnology (VT SuN), Discovery Analytics Center, Center for Engineering the

Human Exposome, Center for Multiscale Bio-engineered Devices and Systems, space@vt, Cognitive Radio Network (CogNet) testbed, the Hume Center for Cyber Security, Macromolecules Innovation Institute (MII), Center for Energy Harvesting Materials and Systems, and the Mid-Atlantic Aviation Program with Virginia Tech as the lead university for one of the six FAA UAS test sites. In fiscal year 2015, ICTAS-supported faculty, 355 from across the campus, secured over $112M in research grants from external agencies including NSF, NIH, DOE, DARPA, DOD and industrial sponsors. During the same period, it supported 182 doctoral students including 32 students from its elite ICTAS UK Soccer Tips Doctoral Scholars program.

3. PAST EMPLOYMENT

- **Professor, Department of Mechanical Engineering, University of Colorado at Boulder, 1991-2006.**

  Conducted and guided path-finding research in thermal sciences, artificial neural networks, nanotechnology, bio-MEMS and humanistic engineering, see Section 7.

- **Founding Director, Center for Advanced Manufacturing and Packaging for Microwave, Optical and Digital Electronics (CAMPmode): University of Colorado at Boulder, 1992-2006.**

  Founded as an interdisciplinary research center in 1992, CAMPmode became an NSF-Industry/University Cooperative Research Center in 1995 with a mission to define and conduct path-finding research and education programs for developing designs, components, packaging and process control technologies for manufacture of high quality, low cost microwave, optical and digital electronic systems. It slowly evolved into a leading center of research on MicroElectroMechanical Systems (MEMS), which later expanded to include an initiative on nanotechnology for engineering and life sciences. During its existence, the average annual budget for the Center was on the order of $2 millions/year.

- **Founding Co-Director, MicroElectronic Devices in Cardiovascular Applications (MEDICA), University of Colorado at Boulder, 1999-2006.**

  Founded in October 1999, MEDICA was an interdisciplinary center between CU-Health Sciences Center and the College of Engineering and Applied Sciences. Its mission was to foster excellence and scientific advancement in the study and application of MEMS (MicroElectroMechanical Systems) in cardiovascular applications. Significant contributions in pediatric cardiology including a company "Cardiac Assist" resulted from the efforts of the center.

- **Interim Dean, College of Engineering and Applied Science, University of Colorado at Boulder, 2001-2002.**

  After careful benchmarking and assessment of the strengths of the college, put a strategic plan in place for improving performance in research, instruction, diversity

and service to the community by a factor of 2 in 6 years. In the following years, the college leadership implemented the strategic plan I put in place and made national gains in reputation for its bold vision.

- **Research Leader, Thermal & Computational Engineering, AT&T Bell Laboratories, Princeton, NJ, 1979-1991.**

  Led and conducted research on transport processes in semiconductor manufacturing including silicon crystal growth, chemical vapor deposition, two phase flows, convective instability, and electronic cooling. Provided strong leadership and conducted high caliber research. Major contributions include development of closed single vapor- and in-line vapor phase heating technology for mass solder reflow applications, original expert football predictions work in silicon epitaxy, Czchrolaski crystal growth and thermal management in electronic switching systems.

- **Member Research Staff**, Thermal Energy Studies Department, Engineering Research Center, AT&T, Princeton, NJ, 1976-1979.

  Conducted research on two phase flows and chemical vapor deposition processes. During this short span of time, made significant advances in these fields of research, resulting in 2 U.S. patents and several publications.

4. ADDITIONAL PROFESSIONAL EXPERIENCE

United Nations Industrial Development Organization

Six-week assignment as an Expert Advisor to SAMEER (Society for Applied Microwave Electronics Engineering and Research in *Chennai*, India, leading lectures, workshops and setting up a state-of-the-art laboratory on thermal management, 12/1993-01/1994.

- **United Nations Development Program**

  Four-week assignment as an Expert Advisor to the Indian Institute of Science in Bangalore, India, giving lectures and seminars on heat transfer in semiconductor processing, 09/1988.

5. SELECTED HONORS

- Recipient of the 75th Anniversary Medal of the ASME Heat Transfer Division, Minneapolis, Minnesota, July 15, 2013.
- Named **Fellow, Punjab Academy of Sciences**, honor bestowed at the 11th Punjab Science Congress, February 7, Thapar University, Punjab, India, 2008.
- The ASME **Ralph Coats Roe Medal Award** for lifelong contributions in communicating to the public the potential of engineering research for the betterment of society, and for contributions to engineering education as an inspirational teacher

and role model to students, 2007.

- The **ASME Charles Russ Richards Memorial Award** for outstanding achievement in mechanical engineering 20 years or more following graduation, 2003.
- The **ASME Heat Transfer Memorial Award** for outstanding contributions in Science and Practice of Heat Transfer, 2002.
- Subaru **Educator of the Year** Award, 2002.
- **Boulder Faculty Assembly Award** for Excellence in Research, Scholarship and Creative work, 1998-1999.
- Prestigious **Bell Labs Fellow,** 1989, "for outstanding technical contributions in advancing the manufacturing science of the thermally-based processes of condensation soldering and silicon epitaxial crystal growth in actual manufacturing practice."
- **ASME Fellow**, 1997.
- AT&T Technical Journal **Great Boss Award**, 1988; the award is based on the employees' nomination reflecting the selected manager's capabilities to motivate, lead, care and accomplish.
- The Journal of Electronic Packaging 1996 Peter A. Engel **Best Paper Award.**
- Listed in a number of Who's Who including "Most Admired Men and Women of the Year", "Who's Who among Asian Americans", "American Men and Women of Science".

6. SELECTED PROFESSIONAL ACTIVITIES

- Member Technical Advisory Board, Smith Group, 2011-
- Member, Editorial Board, International Journal of Engineering Sciences and Management, 2011-
- Editor-in Chief, CRC Press Advanced Series in Bioengineering, 2008-2010.
- Co-Editor-in Chief, CRC Press Mechanical Engineering Series, 2004-2008.
- Editor-in-Chief, International Journal of Microelectronics Packaging and Manufacturing, 1999-2000.
- Associate Technical Editor, ASME Journal Heat Transfer, 1997-2000.
- Associate Editor, Gordon and Breach book series on Electronic Packaging, 1994-2006.
- Member Editorial Board Journal of Electronics Manufacturing, 1994-2004.
- Member**,** Scientific Secretariat, ICS/UNIDO (International Center for Science and High Technology/United Nations Industrial Development Organization), Trieste, Italy, 2004-2006.
- Founding Member**,** CNTI (Colorado Nanotech, Inc", Member Board of Directors, 2004-2006.
- Member Board of Directors of CNTA (Colorado Nanotechnology Association), 2005.
- Member, National Steering Committee on Electronic Packaging Research and Education for the 21st Century, 1996-2006.
- Reviewer for Applied Mechanics Reviews, International Journal Heat & Mass Transfer, Journal Heat Transfer, IEEE Transactions on CPMT, Journal Semiconductor Manufacturing, AIAA Thermophysics and Heat Transfer, NSF,

Research Grants Council - Hong Kong, and many other journals and funding agencies.

7. MAHAJAN AS A RESEARCHER

Mahajan is a **prolific and outstanding researcher** with a stellar record and reputation in both traditional academic pursuits and industrial research. He is co-author of an advanced text/reference book on Buoyancy Induced Flows and Transport and has to his credit over 200 archival publications, several review articles and book chapters, over 170 invited talks and paper presentations at national and international conferences and a number of patents and invention disclosures. *A selected list of these is presented in the Appendices A and B.*

Mahajan's research can perhaps be best summarized by the following three characteristics: (i) high quality; (ii) a seamless transition from basic to applied research, and (iii) interdisciplinary. His greatest strength is as a forward-looking bold thinker, with the pulse on the latest trends in technology. He has proven to have an unerring instinct on new upcoming technologies and how to get there first, and the courage and confidence to pursue and implement his vision. This pioneering approach and passion for excellence has won Mahajan accolades from academics and practicing engineers alike, and has resulted in many awards and honors listed under section 5 above. His **areas of research** interest are:

- **Nanotechnology**: Synthesis and characterization of carbon nanotubes and their composites; design and fabrication of nanodevices
- **Thermal Sciences**: Buoyancy-induced flows and transport; transport in porous media; two phase flows; transport phenomena in semiconductor processing, electronic cooling
- **Biomedical engineering:** Biomedical applications of micro- and nano-scale systems including hyperthermia treatment and RF ablation of cancerous tumors
- **Humanistic Engineering**: Seamless integration of societal, ethical and environmental concerns in development of technology
- **Artificial Neural Networks**: Software development, neural nets for process optimization and control, neural nets for medical diagnostic and **electronic ear** for detecting heart murmurs in children.
- **Robust Sustainability:** Development of a platform of sustainable technologies including a novel melt blown process for fabrication of nanofibers for targeted delivery of medicine, fertilizer and pesticide for developing communities.

In each of these areas, he has made significant contributions, with many "firsts", in the fields, see Appendix A.

8. TEACHER/ADVISOR/MENTOR

Mahajan is an **inspirational and effective teacher** inside and outside of the classroom. He is visionary in his approach to curriculum and has been a strong

advocate of integrating societal and ethical aspects of technologies in engineering curriculum. He sets high standards of excellence for his students and motivates them to reach for the top. As a humanistic engineer, he is keenly aware of the unintended consequences of emerging technologies and has designed ways for engineers to *initiate and engage in effective dialogue with non-technical audiences* regarding the socio-humanistic critiques of engineering processes and products, and also encouraged them to perform their own critiques in the absence of such dialogue.

During his fifteen-year tenure at the University of Colorado, Boulder, he graduated twenty six doctoral and Masters (with thesis option) students. Placed in academia, the national laboratories, and industry, all of them are making strong contributions in their chosen fields. Loved by his students and respected by his peers, he was named *Subaru Educator of the Year in 2002.* At Virginia Tech, two of his advisees have graduated with MS degree (thesis option) in mechanical engineering, and one is on his way to graduate with Ph.D. in Industrial Systems Engineering in 2017.

As a pioneer of the concept of humanistic engineering, he has led efforts on integrating humanistic content in engineering curriculum. Most recently, he has developed a four year Mechanical Engineering curriculum (ME 2029), that is a unique blend of human and social sciences, applied sciences, communication and leadership besides the required math and core mechanical courses. These concepts have been firmly integrated into his research enterprise. For example, he had an embedded humanist as a doctoral student in his nanotechnology research laboratory, whose presence and interactions with the classical engineering students led to innovative and holistic approaches to problem solving.

9. HE IS AN ORGANIZATION BUILDER PAR EXCELLENCE.

At all the three major institutions he has worked over the past 38 years (Bell labs, Cu-Boulder and Virginia Tech), he founded or redirected existing organizations with a clear vision to be among the top three in the nation. Leading by example and with an uncanny ability to recruit strong achievers around him, he has been able to build world-class organizations. *AT&T Technical Journal Great Boss Awarded to him in 1988* perhaps best captures his leadership capabilities. This award is based on the employees' nomination reflecting the selected manager's capabilities to motivate, lead, care and accomplish.

10. *HUMANITARIAN*

Mahajan is a **humanitarian** at heart and is committed to community service. For over thirty years, he has organized, established and taught at Bal Vihars –Sunday schools for children of Indian origin to promote values, confidence, leadership through awareness and knowledge of their roots and cultural heritage. Recently, his wife and he have also established a charitable foundation fund to serve under-served communities locally and globally.

APPENDIX A
A Brief Description Of Major Research Accomplishments With An Emphasis On "Firsts".

A. Convective flows and transport

1. *A new physics-based criterion for the onset of transition for buoyancy-induced vertical flows in gases was proposed that departed from the conventional wisdom of using Grashof number as an indicator of transition from laminar to turbulence.*

   It was argued that the Grashof number as indicated by the linear instability theory cannot accurately be a predictor of turbulence, which is essentially characterized by a non-linear growth of high amplitude disturbances. A new parameter—a modified Grashof number related to the kinetic energy of the flow was proposed. It was shown that the wide range of transition Grashof number reported in past studies collapsed around a single value of the new parameter with remarkable consistency [4, 7].

2. Demonstrated that *vertical buoyancy-induced boundary layer flows sharply filter naturally-occurring disturbances imposed on the flow at a single characteristic frequency, which, in turn, is a function of only the Prandtl number [1].*

3. In yet another important piece of research, he showed through an elegant analysis that for terrestrial flows, *the viscous dissipation effect is always smaller than the pressure effect for all values of Prandtl number [9].*

4. In a landmark *first-ever experimental study of laminar-film-condensation heat transfer for fluids with Stefan or Jakob number greater than 1*, the important role played by the property variation and non-condensable gases was delineated [34]. In a complementary study [35], *it was shown the text book heat transfer correlations over a bank of tubes are in error for these fluids. For example,* the heat transfer rate from a tube in the lower rows is higher and not lower than from a tube in the top row. In a practical application of such fluids to condensation soldering, this finding translates to compact condenser designs.

B. Transport Phenomena in High Porosity Metal Foams

This work was motivated by preliminary experiments [23] which showed that high porosity metal foam heat sinks can outperform state-of-the-art pin fin heat sinks by a factor of 2-3. However, not much was known about the underlying transport mechanisms in such high porosity media. A decade-long research led to:

1. *Experimentally validated analytical models to predict the effective thermal conductivity, permeability, and inertia coefficient of different high porosity metal foams [24-27]. The model for permeability, K, included a new correction for tortuosity of the foam [26].*
2. *A first-principles model for energy transport in forced and buoyancy-induced flows for such foams, including thermal dispersion conductivity, interstitial heat transfer coefficient and without invoking the assumption of local thermal equilibrium was developed [27-29].* Flow regimes under which the assumption of local thermal equilibrium may produce significant

errors were delineated. Validated by a significant body of experimental data, the results revealed some interesting flows and pointed out directions for optimization of these heat sinks.

3. *Mahajan's research led to a new generation of finned metal foam heat sinks [30]. It has been demonstrated that these new heat sinks can potentially better the thermal performance of the first generation high porosity metal foam heat sinks by a factor of as high as 6. The performance of these novel heat sinks in natural and forced convection has also been quantified [31, 32].*

4. More recently, the research has led to the design of novel phase change electrodes with metal foams for irreversible electroporation therapy [95].

C. Chemical Vapor Deposition

1. *A first systematic study of the role played by buoyancy, Soret Dufour, and variable property effects on silicon epitaxial deposition.*

   He showed that the agreement between the experimental data and simplified transport analyses in the past studies was fortuitous—the Soret and variable property effects simply cancelled each other!! While this coincidence worked for silicon systems, it failed for other deposition systems [44].

2. *Demonstrated multiple steady states and hysteresis effect in vertical metal-organic chemical vapor deposition reactors, resulting in guidelines for operating these systems in practice.*

   A comprehensive review article [52] on **Transport Phenomena in CVD systems, Advances in Heat Transfer, 1996 V. 28, pp. 339-427** captures most of this work and those of others in the field.

3. *Radiation- Molecular Flow Analogy for High Vacuum Deposition Systems*

   In a departure from past work on conventional continuum flow reactors, his team investigated the deposition process in high vacuum physical vapor deposition processes used in the manufacture of stable thin-film photovoltaic devices. The work showed conclusively that the geometry modeling and radiation analysis capabilities of commercial finite element software can be successfully deployed for optimizing high vacuum deposition processes by applying the radiation-molecular flow analogy. In a recent paper presented at the 29th International Symposium on Rarefied Gas Dynamics, Xi'an, China in 2014 [96], the analogy between thermal radiation and molecular flow to model the flow of a gas in a 2D channel was extended across all regimes of rarefaction.

D. Artificial Neural Networks

Another area of research in which Mahajan has made strong contributions relates to the development and application of artificial neural networks. Since his initial entry into this field in 1992, his work has led to the following major contributions:

1. *Development of a new approach to building economical and more accurate artificial neural*

network models. This work resulted in a new, powerful and accurate software called CU-ANN [53].

2. *A new approach called physical-neural network was developed that combines the power of both physical modeling and artificial neural networks; the approach was shown to be successful in a number of applications ranging from modeling of electronic manufacturing assembly processes to predicting reliability of soldering joints [54,58,60].*

3. *The development of a new knowledge-based transfer technique that allows easy and economical transfer of a model from one design/process to another [55]*

This research has resulted in a number of publications for application to different fields in electronic packaging and manufacturing [59-69], and *demonstrates again the versatility of Professor Mahajan's work and his ability to make solid contributions in a new field for him in a relatively short period of time.*

E. Microsystems for Biomedical Applications

Venturing into a yet another new area of research of BioMEMS, Mahajan and his research team developed an integrated experimental-analytical program to study the behavior of single cells under mechanical forces, with an eye on producing an *in vitro* diagnostic tools for understanding the underlying cause of disease and its treatment [70-79]. The following major contributions resulted.

A novel MEMS platform for studying the behavior of cells under uniaxial and biaxial stimulations was developed[71, 75-76] demonstrating that such a device can be used to understand the force - displacement behavior of healthy and malignant cells leading to its utility as an in *vitro* diagnostic device. Parallel research resulted in a rigorous, generalized model that described the behavior of micromachined electrostatic actuators in conducting liquids and provided a guideline for designing such actuators to operate in aqueous electrolytes such as biological media [77-78].

F. Nanotechnology and Humanistic Engineering

From microsystems, Mahajan's interest evolved to engineering devices, fibers, and coatings at the nanoscale [80-89]. As is characteristic of his research, a number of key publications resulted including:

1. *The first-ever fabrication of a carbon nanotube-based nanoknife that generated a lot of media interest.*
2. *The first demonstration of bubble formation on individual multiwalled carbon nanotubes initiated using a 1064 nm wavelength laser and a very low 100mW power.*

Perhaps, the most noteworthy dimension of this research is his focus on societal and ethical considerations of nanotechnology. Collaborating with his graduate student, Erik Fisher-- the first-ever embedded humanist in a nanotechnology laboratory, he developed a keen interest in a holistic approach to technology development, in general, and emerging technologies, in particular. A number of highly cited publications resulted [90-94].

1. **Mahajan, R.L.** and Gebhart, B (1975). "Characteristic disturbance frequency in natural convection vertical flows", **Int. J. Heat Mass Transfer**, vol. 18, pp. 143-148.

2. **Mahajan, R.L.** and Gebhart, B (1978), "Leading edge effects in transient natural convection flow adjacent to a vertical surface", **J. Heat Transfer**, vol. 100, pp. 731-733.

3. **Mahajan, R.L.** and Gebhart, B. (1978), "Higher order approximations to the natural convection flow over a uniform flux vertical surface", *Int. J. Heat Mass Transfer*, vol. 21, pp. 549-556.

4. **Mahajan, R.L.** and Gebhart, B. (1979), "An experimental determination of transition limits in a vertical natural convection flow adjacent to a surface", *J. Fluid Mechanics*, vol. 91, Part 1, pp. 131 – 154.

5. **Mahajan, R.L.** and Gebhart, B. (1980), "Higher order boundary layer effects in plane horizontal natural convection flows", *J. Heat Transfe***r**, vol. 102, pp. 368-371, 1979.

6. **Mahajan, R.L.** and Gebhart, B. (1980), "Hot wire anemometer calibration in pressurized nitrogen at low velocities", *J. Physics, E. Sci. Instrum*., vol. 13, pp. 1110-1118.

7. "Instability and Transition in Buoyancy Induced Flows", with B. Gebhart, **Advances in Applied Mechanics**, vol. 22, pp. 231-315, Academic Press, New York, NY, 1982.

8. **Buoyancy Induced Flows & Transport**, with B. Gebhart, Y., Jaluria, and B. Sammakia, Hemisphere, 1988, 1000 pages (in both Reference and Text versions).

9. **Mahajan, R.L.** and Gebhart, B. (1989), "Viscous dissipation effects in buoyancy induced flows", Int. J. Heat Mass Transfer, vol. 32, no. 7, pp. 1380-1382.

10. Angirasa, D. and **Mahajan, R.L.** (1993), "Natural convection from L-shaped corners with adiabatic and cold isothermal walls", *J. Heat Transfer*, vol. 115, pp. 149-157.

11. Angirasa, D., Chinnakotla, R.B. and **Mahajan, R.L.** (1994), "Buoyancy-induced convection from isothermal L-shaped corners with symmetrically heated surface", *Int. Journal Heat and Mass Transfer*, vol. 37, pp. 24392463.

12. Angirasa, D. and **Mahajan, R.L.** (1995), "Combined forced and buoyancy-induced convective heat transfer in a partially closed vertical channel", *Numerical Heat Transfer*, Part A, pp. 579-594.

13. Chinnakotla, R.B., Angirasa, D. and **Mahajan, R.L.** (1996), "Parametric study of buoyancy-induced flow and heat transfer from L-shaped corners with asymmetrically heated surfaces", **Int.** *Journal Heat and Mass Transfer*, vol. 39, no. 4, pp. 851-855.

14. Lohe, R. Bhattacharya, A. and **Mahajan, R.L.** (2001), "Longitudinal finned heat sinks with unheated and heated shrouds in buoyancy induced convection", Proceedings # IPACK 2001-15588, *InterPACK 2001*, HI.
15. Bhattacharya, A. and **Mahajan, R.L.** (2001), "Effects of leading edge clearance in buoyancy-induced flows in longitudinal finned and finned metal foam heat sinks", *International Journal of Microelectronics Packaging*, vol. 4, Issue 1, pp. 253-268.

16. **Mahajan, R.L.** and Angirasa, D. (1993), "Combined heat and mass transfer by natural convection with opposing buoyancies**",** *J. Heat Transfer*, vol. 115, pp. 606-612.

17. Angirasa, D. and **Mahajan, R.L.** (1993), "Combined heat and mass transfer by natural convection over a horizontal surface", *Int. Communications in Heat and Mass Transfer*, vol. 20, pp. 279-293.

18. Phanikumar, M.S. and **Mahajan, R.L.** (1998), "Numerical analysis of unsteady thermosolutal convection over a horizontal isothermal circular cylinder", *Num. Heat Transfer*, Part A, vol. 3, pp. 673- 700.

19. Lau, K. S. and **Mahajan, R.L.** (1989), "Convective heat transfer from longitudinal fin arrays in the entry region of turbulent flow", *ASME J. Electronic Packaging*, vol.111, no. 3, pp. 213-219.

20. Lau, K.S. and **Mahajan, R.L.** (1989), "Effects of tip clearance and fin density on the performance of heat sinks for VLSI packages**",** *IEEE Trans. Components Hybrids, and Manufacturing Technology*, vol. 12, no. 4, pp. 757-765.

21. Calmidi, V.V. and **Mahajan, R.L**. (1998), "Mixed convection on a horizontal surface in a partial enclosure", *International Journal of Heat and Fluid Flow*, vol. 19, pp. 358-367.

22. Calmidi, V.V. and **Mahajan, R.L.** (1994), "Combined forced and buoyancy induced convection over a heated horizontal surface", *Proceedings of the 6th AIAA/ASME Thermophysics and Heat Transfer Conference*, June 20-23, published in the ASME-HTD, vol. 274, p. 41, Colorado Springs CO, 1993.

23. Lee, Y. C., Zhang, W., Xie, H., and **Mahajan, R.L.** (1993), "Cooling of a FCHIP package with a 100 watt, 1 sq. cm. chip", *Proceedings ASME Int'l. Electronics Packaging Conference*, Sept. 29, Binghamton, NY.

24. Calmidi, V.V. and **Mahajan, R.L.** (1999), "Thermal conductivity of high porosity metal foams: experimental measurements and analysis", *ASME Journal of Heat Transfer*, vol. 121, pp. 466-471.

25. Bhattacharya, A., Calmidi, V.V. and **Mahajan, R.L.** (1999), "An analytical-experimental study of the determination of the effective thermal conductivity of high porosity fibrous foams", A*SME International Mechanical Engineering Congress and Exposition*, AMD vol. 233, pp. 13-20.

26. Bhattacharya, A., Calmidi, V.V. and **Mahajan, R.L.** (2001), "Permeability and inertial coefficient of high porosity metal foams", Paper #NHTC 01-1474, *Proceedings ASME National Heat Transfer Conference*, Anaheim, CA.

27. Calmidi, V.V. and **Mahajan, R.L.** (2000), "Forced convection in high porosity metal foams", *ASME J. of Heat Transfer*, vol. 122, pp. 557-565.

28. Phanikumar, M. S., and **Mahajan, R.L.** (2000), "Non-Darcy convection in a high porosity medium heated from below: Effects of thermal dispersion and local thermal non-equilibrium-Part 1. Problem Formulation", *Proceedings ENCIT 2000*, Brazilian Congress of Thermal Engineering and Science, October 2-5, Porto-Allegre, Brazil.

29. Phanikumar, M. S., and **Mahajan, R.L.** (2000), "Non-Darcy convection in a high porosity medium heated from below: Effects of thermal dispersion and local thermal non- equilibrium -Part 2. Numerical and experimental results", *Proceedings ENCIT 2000*, Brazilian Congress of Thermal Engineering and Science, October 2-5, Porto-Allegre, Brazil.

30. Patent pending "Novel finned metal foam heat sinks", patent Application Serial No. 09/497,821.

31. Bhattacharya, A. and **Mahajan, R.L.** (2000), "Finned metal foam heat sinks for electronic applications in forced convection", *Proceedings ASME Heat Transfer Division*, Paper #NHTC 2000,12256, 11 pages, Pittsburgh, PA., Aug. 20-22.

32. Bhattacharya, A. and **Mahajan, R.L.** (2000), "Metal foams and finned metal foam heat sinks for electronic cooling in buoyancy induced flows in horizontal configuration", *Proceedings ASME Heat Transfer Division, HTD*, vol. 366-4, pp. 391-398, ASME IMECE 2000 Conference.

33. **Mahajan, R.L.**, Arbelaez, F. and Sett, S. (2000), "An experimental study on pool boiling of saturated FC-72 in highly porous aluminum metal foams", Paper # NHTC 2000-12192, *Proceedings 34th National Heat Transfer Conference*, Pittsburgh, PA, Aug. 20-22.

34. **Mahajan, R.L.**, Chu, T.Y. and Dickinson, D.A. (1991), "An experimental study of laminar film condensation with Stefan number greater than unity", *J. Heat Transfer*, vol. 113, pp. 472-478.

35. Sharma, R. and **Mahajan, R.L.** (2000), "Experimental study of laminar film condensation on horizontal and vertical cylinders with Stefan number greater than unity", ***Proceedings ENCIT 2000,*** Brazilian Congress of Thermal Engineering and Science, October 2-5, Porto-Allegre, Brazil 1999.

36. **Mahajan, R.L.** (1979), "Determination and control of heater surface temperature in condensation soldering", *Proceedings of the Technical Program*, NEPCON West, Anaheim, CA.

37. Wenger, G.M. and **Mahajan, R.L.** (1979), "Condensation soldering technology - Part I: Condensation soldering fluids and heat transfer**",** *Insulation/Circuits*, Sept. issue, p. 131.

38. Wenger, G.M. and **Mahajan, R.L.** (1979), "Condensation soldering technology - Part II: equipment and production", *Insulation/Circuits*, Oct. issue, pp. 15-19.

39. Wenger, G.M. and **Mahajan, R.L.** (1979), "Condensation soldering technology - Part III: installation and application**",** *Insulation/Circuits*, Nov. issue, pp. 13-16.

40. **Mahajan, R.L.,** * "An overview of condensation soldering technology", *International Soc. Hybrid Microelectronics*, Tokyo.

41. Mahajan, R.L., *, (1980) "Improving condensation soldering facility operations", **1980 Vapor Phase Soldering Workshop**, New York, invited paper.

42. Wright, A.W. and **Mahajan, R.L.** (1984), "An overview of condensation reflow soldering",

METADEX and AMS's Eng. J1, 12 pages (invited paper), 1980.

43. Sharma, R., Hassani, V. and **Mahajan, R.L.** (1999), "Forced convective condensation of pure steam and ammonia-steam vapor mixtures in a shell-tube condenser", *Proceedings ASME IMECE,* HTD vol. 364-2, pp. 11-28.

44. **Mahajan, R.L.** and Wei, C. (1991), "Buoyancy, Soret, Dufour and variable property effects in silicon epitaxy", *J. Heat Transfer*, vol. 113, pp. 688-695.

45. Yang, L., Farouk, B., and Mahajan, R.L. (1992), "Three-dimensional prediction of silicon deposition in a barrel type CVD reactor", *J. Electrochemical Society*, vol. 159, no. 9, pp. 2666-2673.

46. **Mahajan, R.L.,** Schichtel, B.E. and Wang, X.A. (1993), "Liquid crystal thermographic measurements of transport in a CVD-barrel reactor", *Proceedings ASME National Heat Transfer Conference*, Aug. 8- 11, HTD, vol. 252, pp. 31-38, Atlanta, GA.

47. Kelkar, A.S. and **Mahajan, R.L.** (1997), "Two-and three-dimensional transport models for MOCVD reactors: effect of boundary conditions", *Proceedings of the 32nd National Heat Transfer Conference*, HTD, vol. 347, p. 261.

48. Wang, X.A. and **Mahajan, R.L.** (1995), "CVD epitaxial deposition in a vertical barrel reactor: Process modeling and optimization using neural network models", *J. Electrochem. Soc.*, vol. 142, no. 9, pp. 3123-3132.

49. **Mahajan, R.L.***, Hopper, P. and Atkins, W. (1995), "Neural nets and fuzzy logic for semiconductor manufacturing**",** *Semiconductor International*, July issue, Part I: Basic Concepts, pp. 217-224 (invited paper).

50. Kelkar, A.S., **Mahajan, R.L.** and Sani, R.L. (1996), "Real-time physico-neural solutions for MOCVD", ASME Journal of Heat Transfer, vol. 118, pp. 814-821.

51. Wang, X. A. and **Mahajan, R.L.** (1996), "Artificial neural network model-based run-to-run process controller", *IEEE Trans. CPMT-Part A*, vol. 19, no. 1, pp. 19-26.

52. Review Article on "Transport Phenomena in Chemical Vapor Deposition Systems", **Advances in Heat Transfer**, vol. 28, pp. 339-415, Academic Press, San Diego, CA, 1996.

53. Malhotra, C.P., **Mahajan, R.L**., Sampath, W.S., Barth, K.L., Enzenroth, R.A., (2006), "Control of temperature uniformity during the manufacture of stable thin-film photovoltaic devices", *Int. J. Heat and Mass Transfer*, v. 49, pp 2840-2850.

54. Malhotra, C.P. and **Mahajan, R.L.**, (2007). "High Knudsen Number Physical Vapor deposition: Predicting Deposition Rates and Uniformity", *ASME J. Heat Transfer* v. 129, Issue 11, pp. 1546-1553.

55. Marwah, M., **Mahajan, R.L.** and Li, Y. (1996), "Integrated neural network modeling for electronics manufacturing", *J. Electronics Manufacturing*, vol. 6, no. 2, pp. 79-91.
56. **Mahajan, R.L.** and Wang, X.A. (1993), "Neural network models for thermally based microelectronic manufacturing processes", *J. Electrochem. Soc.*, vol. 140, no. 8, pp. 2287-2293.

57. Marwah, M. and **Mahajan, R.L.** (1999), "Building neural network equipment models using model modifier techniques", *IEEE Transactions on Semiconductor Manufacturing*, vol. 12, no. 3, pp. 377-381.

58. Bhatikar, S.R. and **Mahajan, R.L**. (1999), "Neural network based diagnosis of CVD barrel reactor", Proceedings InterPack'99, June 13-19, Maui, Hawaii, *ASME EEP*-vol 26-1, Advances in Electronic Packaging, pp. 621-640.

59. Bhatikar, S., **Mahajan, R.L.,** Wipke, K.B. and Johnson, V.H., "Neural network based battery modeling for hybrid electric vehicles", presented at the *2000 Future Car Congress*, April 2-6, Arlington, VA.

60. Calmidi, V.V. and **Mahajan, R.L.** (1998), "Optimization for thermal and electrical performance for a flip-chip package using physical-neural network modeling", *IEEE Trans. on Components, Packaging and Manufacturing Technology*, Part C, vol. 21, no. 2, pp. 111-117.

61. Li, Y., **Mahajan, R.L.** and Nikmanesh, N. (1996), "Fine pitch stencil printing process modeling and optimization", *ASME Journal of Electronic Packaging*, vol. 118, pp. 1-6.

62. Subbarayan, G., Li, Y. and **Mahajan, R.L.** (1996), "Reliability simulations for solder joints using stochastic finite element and artificial neural network models", *ASME Journal of Electronic Packaging*, vol. 118, no. 3, p. 148-156. Received The ASME Journal of Electronic Packaging 1996 Peter A. Engel Best Paper Award.

63. Watson, P.M., Gupta, K.C. and **Mahajan, R.L.** (1999), "Applications of knowledge-based artificial neural network modeling to microwave components", *International Journal of RF and Microwave Computer-Aided Engineering,* vol. 9, no. 3, pp. 254-260.

64. Li, Y., **Mahajan, R.L.** and Tong, J. (1994) "Design factors and their effects on PCB assembly yield: statistical and neural network predictive models", *IEEE-CPMT*, vol. 17, no. 2, pp. 183-191.

65. **Mahajan, R.L**, Hopper, P. and Atkins, W. (1995), "Neural nets and fuzzy logic for semiconductor manufacturing**",** *Semiconductor International*, July issue, Part I: Basic Concepts, pp. 217-224 (invited paper).

66. **Mahajan, R.L.**, Hopper, R and Atkins, W. (1995), "Neural nets and fuzzy logic for semiconductor manufacturing**",** *Semiconductor International*, August issue, Part II: Process Optimization and Control, pp. 111-118 (invited paper).

67. Li, Y. and **Mahajan, R.L.** (1998), "CBGA solder fillet shape prediction and design optimization", *ASME J. Electronic Packaging*, vol. 120, pp. 118-122, also appeared in *Proceedings SMTA-BGA Conference*, May 20, Minneapolis, MN.

68. Mahajan, R. L. "Electronics Manufacturing: Processes, Optimization and Control", **CRC Handbook of Mechanical Engineering**, Second Edition, Eds. F. Kreith and D. Yogi Goswami, **Chapter 13.7**, pp. 13.114 – 13.153, 2004.

69. R. L. Mahajan, **Book Chapter** on "Process Modeling, Optimization and Control in

Electronics Manufacturing", **Manufacturing Challenges in Electronic Packaging**, eds. Y. C. Lee and W. T. Chen, Chapman and Hall, 1998, pp. 185-221.

70. Scuor, N., Gallina, P., Sbaizero, O. and **Mahajan, R.L.** (2005), "Design of a microfluidic device in the presence of an electrostatic induced cross-flow", Biomedical Microdevices, Sept.; 7(3), pp.231-242.

71. Scuor, N., Gallina, O., Panchawagh, H.V. and **Mahajan, R.L.,** Sbaizero, P. and Sergo, V., (2006), "Design of a novel MEMS platform for the biaxial stimulation of living cells", *Biomedical Devices,* 8(3), pp. 239-246.

71. Sharp, A.A., Panchawagh, H.V., Ortega, A., Artale, R., Richardson-Burns, S., Finch, D., **Mahajan, R.L.** and Restrepo, D., (2006), "Towards a self-deploying memory polymer neuronal electrode", *J. Neural Engineering***,** v 3, pp. L 23-L 30.

73. Panchawagh, H.V., Serrell, D.B., Faheem, F.F., Hermann, C.F., Finch, D.S. and **Mahajan, R.L**., (2006). "Packaging of in-plane thermal microactuators for bioMEMS applications", *J. Sensors and Actuators: A (Physics)*, vol. 134, Issue 1, pp. 11-19.

74. Scuor, N., Gallina, P., Sbaizero, O., Panchawagh, H.V. and **Mahajan, R L**. (2006), "Dynamic *characterization of MEMS cantilevers in liquid environment using a low-cost optical system", Measurement Science and Technology***,** V. 17, pp 173-180.

75. Serrell, D. Oreskovic, T.L., Slifka, A.J., **Mahajan, R.L.**, and Finch, D.S., (2007). "A Uniaxial BioMEMS Device for Quantitative Force-Displacement Measurements", *Biomedical Microdevices,* v. 9, no.2, pp. 267-275.

76. Serrell, D.B., Law, J., Slifka, A.J., **Mahajan, R.L.** and Finch, D.S. (2008), "A Uniaxial BioMEMS Device for Imaging Single Cell Response during Quantitative Force-Displacement Measurements", *J. Biomedical Microdevices,* v. 10, Issue 6, pp. 883-889.

77. Panchawagh, H, Sounart, T.L. and **Mahajan, R.L.** (2009). "A model for electrostatic Actuation in Conducting liquids", *J. of Microelectromechanical Systems*, v.18, no. 5, 1105-1117.

78. Sounart, T. L., Panchawagh, H. V., and **Mahajan, R.L.** (2010). "Frequency-dependent stability of parallel-plate electrostatic actuators in conductive fluids". *Applied Physics Letters,* v 96, n 20, p 203505 (3 pp.).

79. Maggiolino, S., Scuor, N., **Mahajan, R.L.**, Sbaizero, O. (2010), "MEMS-DSC: A new device for microcalorimetric analysis in the biological field", *Microsystem Technologies,* v 16, n 6, pp. 967-971.

80. Ramadurai, K., Lewis, L. Cromer, C., **Mahajan, R.L.**, Hurst, K E. and Lehman, J.H., (2007). "Carbon based coatings for thermal detectors: Laser damage and thermal efficiency", *Proc. SPIE V. 6403 64031G-4, pp.1-8.*

81. Singh, G., Priya, S., Hossu, M., Shah, S.R., Grover, S., Koymen, Ali R., and **Mahajan, R.L.** (2009). "Synthesis, electrical and magnetic characterization of core-shell carbon nanotube – SiCN nanowires", *Materials Letters,* 63 (28), Pages 2435-2438.

82. Singh, G., Rice, P., **Mahajan, R.L.** and McIntosh, J.R. (2009). "Fabrication and Characterization of a carbon nanotube-based-nanoknife", *Nanotechnology,* 20, 095701.

83. Bedekar, V., Singh, G., **Mahajan, R.L.**, and Priya, S. (2009). "Synthesis and Microstructural Characterization of Barium Titanate Nanoparticles Decorated SiCN-MWCNT Nanotubes—"nanoNecklace", *Ferroelectrics Letters,* Volume 36 (5-6). Pages 133-140.

84. Karmarkar, M., Singh, G., Shah, S., **Mahajan, R.L.** and Priya, S. (2009). "Large piezoresistivity phenomenon in SiCN – (La, Sr) MnO3 composites", *Applied Physics Letters,* 94, 072902; also *the Virtual Journal of Nanoscale Science & Technology.* *(http://www.vjnano.org).*

85. Slifka, Andrew J., Singh, Gurpreet, Lauria, Damian S., Rice, Paul, and **Mahajan, R.L.** (2010). "Observations of Nanobubble Formation on Carbon Nanotubes". *Applied Physics Express* (formerly Japanese journal of applied physics -2,), v. 3, issue no. 6, article no. 065103.

86. Vishwas Bedekar, Mitsu Murayama, **Roop L. Mahajan**, Shashank Priya, (2010), "Controlled Synthesis of BaTiO3-Coated Multiwall Carbon Nanotubes", v. 93,issue 11, pp. 3618–3623.

87. V. Bedekar, G. Singh, **R.L. Mahajan** and S. Priya (2010),"Barium titanate and Cobalt ferrite nano-particles decorated SiCN/MWCNT nanotubes: synthesis and microstructural characterization", *Ceramic Transactions,* v 221, pp. 19-28, Advances in Electro-ceramic Materials II.

88. Singh, G., Slifka, A. J., Rice, P., Lauria, D. and **Mahajan, R.L.** (2012), "Optical trapping in air using an individual nanotube-sphere device", *Applied Physics Express* 5 (9) Art: 095001, Published online, August 10.

89. Haasounah, Ibrahim Anwar, Shehata Nader Abdelmonem, Kimsawatade, Gade Carolyn, Hudson, Amanda Gayle, Srirnagnanathan, Nammalwar, Joseph, Eugene Gregory and Mahajan, Roop L., "Studying the effect antitubercluosis drugs inside electrospun polyvinyl alcohol, polyethylene oxide, and polycaprolecton nanofibers", J. Biomed Mater Res. Part A 2014.

90. Fisher, E. and **Mahajan, R.L.** (2003), "Humanistic enhancement of engineering: liberalizing the technical curriculum", *Proceedings International Conference on Engineering Education,* July 21-25, Valencia, Spain, 2002.

91. Fisher, E. and **Mahajan, R.L.** (2006), "Contradictory intent? US federal legislation on integrating societal concerns into nanotechnology research and development", *Science and Public Policy***,** V. 33, number 1, pp. 516.

92. Fisher, E., **Mahajan, R.L.** and Mitcham, C., (2006). "Midstream modulation of technology: Governance from within", **Bulletin of Science, Technology and Society, V. 26, No.6, pp. 485-496.**

93. Fisher, E. and **Mahajan, R.L**., (2006). "Midstream modulation of nanotechnology research in an academic environment", *ASME International Mechanical Engineering Congress & Exposition*, Nov. 5-10, Chicago, IL.

94. **Book Chapter** on "Embedding the Humanities in Engineering: Art, Dialogue, and a

Laboratory" with Erik Fisher, in a book "Creating new kinds of collaboration: Trading Zones and interactional expertise", **MIT Press, Inside Technology Series**, Eds. Michael Gorman and Robert Evans, 2010, pp. 209-231.

95. Nithyanandam, K. and **Mahajan, R.L**., "Development of Novel Phase Change Electrodes with Metal Foams for Irreversible Electroporation Therapy", 2014 BMES Annual Meeting, October 22-25, San Antonio, Texas.

96. Malhotra, C.P., and **Mahajan, R.L.** (2014), "Use of finite volume radiation for predicting the Knudsen minimum in 2D channel flow", 29th International Symposium on Rarefied Gas Dynamics, Xi'an, China, July 13-18.

APPENDIX B

Book/Book Chapters/Patents/Invention Disclosures

- **Text and Reference Book: "Buoyancy Induced Flows & Transport"**, with B. Gebhart, Y., Jaluria, and B. Sammakia, Hemisphere, 1988, 1000 pages; translated in other languages.

- **Book Chapters**

  - "Societal Convergence for Human Progress: Beyond Convergence of Nano-Bio-Info-Cognitive Technologies" **NSF Report**, Editor, M. Roco, 2013.

  - "Embedding the Humanities in Engineering: Art, Dialogue, and a Laboratory" with Erik Fisher, in a book "Creating new kinds of collaboration: Trading Zones and interactional expertise", **MIT Press, Inside Technology Series**, Eds. Michael Gorman and Robert Evans, 2010, pp. 209-231.

  - "Electronics Manufacturing: Processes, Optimization and Control", **CRC Handbook of Mechanical Engineering**, Second Edition, Eds. F. Kreith and D. Yogi Goswami, **Chapter 13.7**, pp. 13.114 – 13.153, 2004.

  - "Process Modeling, Optimization and Control in Electronics Manufacturing", **Manufacturing Challenges in Electronic Packaging**, eds. Y. C. Lee and W. T. Chen, Chapman and Hall, 1998, pp. 185-221.

- **Review Article**s

  - "Transport Phenomena in Chemical Vapor Deposition Systems", **Advances in Heat Transfer**, vol. 28, pp. 339-425, Academic Press, San Diego, CA, 1996.

  - "Instability and Transition in Buoyancy Induced Flows", with B. Gebhart, **Advances in Applied Mechanics**, vol. 22, pp. 231-315, Academic Press, New York, NY, 1982.

- **U. S. PATENTS/COPYRIGHTS/INVENTION DISCLOSURES**

  - U.S. Patent 8747402B2, June 10, 2014, "Electrical conductivity probes for measuring attributes of tissues", Inventors: **Roop L. Mahajan**, Ming Yi, Ronald J. Podhajsky, and Hrishikesh V. Panchawagh.

  - U.S. Patent 7,951,144B2, May 31, 2011, "Thermal and electrical conductivity probes and methods of making the same", Inventors: **Roop L. Mahajan**, Ming Yi, Ronald J. Podhajsky, and Hrishikesh V. Panchawagh. University of Colorado.

  - Patent No. 4,421,786, Dec. 1983, "Chemical Vapor Deposition Reactor for

Silicon Epitaxial Process". Inventor: **Roop L. Mahajan**

- Patent No. 4,187,974, Feb. 1980, "Condensation Soldering Facility", Inventor: **Roop L. Mahajan**

- "Heat Storage Systems for Non-Thermal Pulsed Electric Field Based Therapies", VTIP Invention Disclosure No: 12-118 filed in April 2012; Provisional Patent filed in June 2012. Inventors: **Roop L. Mahajan**, Rafael V. Davalos and Christopher B. Arena. Virginia Tech.

- Patent Application, Serial Number 61/623,621 filed on 04/13/2012, "Melt-Blown Nanolayer Fibers and Webs", Inventors: Eugene Joseph, William Christopher Rowland and **Roop L. Mahajan.** Virginia Tech.

- Provisional Patent Application 61/178, 224; May 14, 2009; "A minimally-invasive tool for locating, sampling and treating diseased cells and methods for its use". Inventors: **Roop L. Mahajan**, Ming Yi and N. Sriranganathan. Virginia Tech.

- Invention Disclosure, April 2009, "Spray Coatings of polymer derived SiCN particles", Inventors: Gurpreet Singh and **Roop L. Mahajan.** Virginia Tech.

- Invention Disclosure, 2004, "A novel Micro-System platform to study biomechanics of single cells". Inventors: D. Serrel, H. Panchawagh, D. Finch and **Roop L. Mahajan,** U. of Colorado.

- Invention Disclosure, 2004,"Integrated Electrical and thermal Conductivity micromachined probe for biomedical applications". Inventors: H. Panchawagh, M. Yi, **Roop L. Mahajan** and N. Goldberg. U of Colorado.

- Invention Disclosure, 2004, "Double-Spiral Antenna for Hyperthermia Treatment of Cancer". Inventors: H. Zhang, M. Yi and **Roop L. Mahajan.** U. of Colorado

- Invention Disclosure, 2001,"Web Based Monitor for Innocent and Pathological Murmurs", Inventor: S. Bhatikar and **Roop L. Mahajan.** University of Colorado.

- Invention Disclosure, 1998, "Super- Efficient Finned Metal Foam Heat Sink", Inventor: **Roop L. Mahajan**, University of Colorado.

- Copyright: CU-ANN Software for Artificial Neural Network Modeling; 1996, Owner: **Roop L. Mahajan,** U. of Colorado