PHIL LIGRANI

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PROFESSIONAL PREPARATION

University of Texas at Austin	Mechanical Engineering	Bachelor of Science, 1974
Stanford University	Mechanical Engineering	Master of Science, 1975
Stanford University	Mechanical Engineering	Doctor of Philosophy, 1980

APPOINTMENTS

2014 – present Eminent Scholar in Propulsion, Professor of Mechanical and Aerospace Engineering, Propulsion Research Center, Department of Mechanical and Aerospace Engineering, University of Alabama at Huntsville
2010 – 2014 Oliver L. Parks Endowed Chair, Professor of Aerospace and Mechanical Engineering, Parks College, Saint Louis University
2010 – 2013 Director of Graduate Programs, Parks College, Saint Louis University
2006 – 2009 Statutory Professor, Department of Engineering Science, University of Oxford, Donald Schultz Professor of Turbomachinery
2006 – 2009 Director, Rolls-Royce UTC (University Technology Centre) in Heat Transfer and Aerodynamics, University of Oxford
1997 – 2006 Professor, Department of Mechanical Engineering, University of Utah
2002 – 2006 Adjunct Professor, Department of Bioengineering, University of Utah
1992 – 1997 Associate Professor, Department of Mechanical Engineering, University of Utah

ARCHIVAL JOURNAL PUBLICATIONS AND RELATED ITEMS.

As of December 2018, Dr. Ligrani is author or co-author of more than 184 publications in archival journals, including the International Journal of Heat and Mass Transfer, the ASME Transactions-Journal of Turbomachinery, the ASME Transactions-Journal of Engineering for Gas Turbines and Power, the ASME Transactions-Journal of Heat Transfer, the ASME Transactions-Journal of Fluids Engineering, the Journal of Fluid Mechanics, the AIAA Journal, Experiments in Fluids, Physics of Fluids, the AIAA Journal of Heat Transfer and Thermophysics, the International Journal of Rotating Machinery, Separation Science and Technology, Sensors and Actuators A: Physical, and the Journal of Microcolumn Separations. He is also author of 9 book chapters, and about 138 conference presentations and publications. A number of these are invited conference presentations at international meetings, at locations which include Korea, France, the Ukraine, Croatia, Germany, England-United Kingdom, and Belgium. From 1994 to 2018, he has also presented approximately 180 lectures at different institutions and establishments, including many invited lectures. From 2010 to 2018, he presented 4 Invited Keynote Papers, 7 Invited Papers, and 7 Invited Plenary Keynote Papers at different international conferences. Current SCOPUS Reference Citation H-INDEX is 40. Current GOOGLE SCHOLAR Reference Citation H-INDEX is 44.

EDITOR ACTIVITIES.

From 1998 to 2000, Dr. Ligrani served as Guest Editor for a Special Topical Issue for Measurement Science and Technology. He has also served as Associate Editor for the ASME Transactions-Journal of Heat Transfer from 2003 to 2006, and from 2010 to 2014, and as Associate Editor for the ASME Transactions-Journal of Fluids Engineering from 2005 to 2008. Present editor duties include: (i) Member of the Distinguished Editorial Review Board for the Advances in Transport Phenomena, Book Series with Springer Publishing Corporation (since 2006), (ii) Editorial Board Member, Power and Thermal Engineering Processes and Equipment Journal, Published by the National Technical University "Kharkov Polytechnic Institute", Russia and Ukraine (since 2015), (iii) Editorial Board Member, International Journal of Innovative Works in Engineering and Technology (IJIWET) (since 2015), (iv) Associate Editor, Journal of Propulsion Technology (JPT) Journal, Published by CNPIEC, P. R. China (since 2015), (v) International Editorial Board Member, Industrial Thermal Engineering Journal, Published by Thermogasdynamics Department, National Academy of Sciences of Ukraine, Kiev, Ukraine (since 2018), (vi) Editorial Board Member, Advances in Aerodynamics (AIA) Journal. Published by the Chinese Society of Aerodynamics (CSA), and the China Aerodynamics Research and Development Center (CARDC), P. R. China (since 2018), (vii) Associate Editor, Energies Journal (since 2018), (viii) Associate Editor, ASME Transactions-Journal of Journal of Engineering for Gas Turbines and Power (2018-2021).

RESEARCH FUNDING AWARDS

Dr. Ligrani has a strong past and present record of performing sponsored, fundamental and applied research for a variety of funding agencies, including ones in the USA and Europe. As such, he has successfully managed a wide variety of research programs, for different industrial, foundation, and government sponsors. **As of December 2018, research funding awards have been received from the following organizations**: Alabama State Innovation Program Fund, University of Alabama in Huntsville Endowment for Eminent Scholar in Propulsion, University of Alabama in Huntsville Start-Up Funds, AEDC – Arnold Engineering Development Center of Arnold Air Force Base, National Science Foundation, Honeywell Aerospace Corp., The Boeing Company, IHI Corporation, the Henry Luce Foundation, South Carolina Institute for Energy Studies (SCIES-AGTSR) of the Department of Energy, U. S. Army Aviation Research and Technology Activity-AVSCOM, NASA-Ames Research Center, NASA-Lewis Research Center, Hispanic Research Center-Arizona State University, Turbo and Power Machinery Research Center-Seoul National University, Solar Turbines Incorporated, UCON U.S.-Japan Center-Weber State University, General Electric Corporate Research and Development Center, Pratt & Whitney Corporation-Florida, the North Atlantic Treaty Organization (NATO), Pratt & Whitney Corporation-Canada Corp., the Gas Technology Institute, Intel Corporation, HEET-High Efficiency Engines and Turbines Program - South Carolina Energy Research and Development Center, Invesys Corp. - Foxboro Company, Ceramatec Advanced Materials and Electrochemical Technologies Corp., CISCO Systems Inc., SEEDA-South East England Development Agency, EPSRC – Engineering and Physical Sciences Research Council of Great Britain, ISIS Innovation, John Fell Fund, European Community Sixth Framework Programme, Korea Institute of Geoscience and Mineral Resources - KIGAM, Lockheed Martin UK, The Royal Academy of Engineering, Rolls Royce PLC, Science and Engineering Research Council (SERC) Engineering Board of Great Britain, Office of Naval Research, Naval Postgraduate School Research Foundation, Aero-Propulsion Laboratory-Wright-Patterson Air Force Base, and Naval Postgraduate School Direct Funding.

CURRENT AND RECENT RESEARCH FUNDING AWARDS

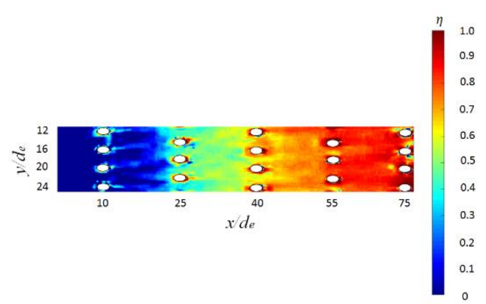
The total amount of funding, including grants contracts, and donations, since arriving at the University of Alabama in Huntsville as of December of 2018, is approximately $3.83 million. Current and recent research sponsors include: (1) Solar Turbines, Inc. of San Diego, California, USA (multiple research contracts), (2) IHI Corp. (Ishikawajma Harima Heavy Industries), of Tokyo, Japan (multiple research contracts), (3) National Science Foundation, CBET Thermal Transport Processes, Division of Chemical, Bioengineering, Environmental, and Transport (CBET) Systems, Arlington, Virginia, USA (multiple funding awards), (4) the Alabama Innovation Fund, Research Program, Montgomery, Alabama, USA, (5) Office of the Vice President for Research and Economic Development, University of Alabama in Huntsville, Huntsville, Alabama, USA, (6) AEDC – Arnold Engineering Development Center, Arnold Air Force Base, Tullahoma, Tennessee, USA, (7) State Administration of Foreign Expert Affairs, Federal Government of the P. R. China, Beijing, P. R. China (through the School of Aerospace Engineering, Beihang University, BUAA - Beijing University of Aeronautics and Astronautics, Beijing, P. R. China).

SELECTED RECENT HONORS, AWARDS, ACADEMIC RECOGNITIONS

● Outstanding Mechanical Engineer of the Year Award 2016, ASME – American Society of Mechanical Engineers, NAS - North Alabama Section, USA. ● Distinguished Advisory Professor, Inje University, South Korea, 2010 to 2020. ● Distinguished Lecture Award, 2011, CEAS Distinguished Lecture Series, College of Engineering, University of Wisconsin, Milwaukee, Wisconsin, USA. ● Distinguished Editorial Review Board membership for Springer Publishing Corporation. ● Carl E. and Jessie W. Menneken Faculty Award for Excellence in Scientific Research. ● NASA Space Act Tech Brief Award for "Development of Subminiature Multi-Sensor Hot-Wire Probes." ● Silver Winner for the Annual 26th Educational Advertising Awards for the Higher Education Marketing Report.

RESEARCH AREAS AND EXPERTISE.

Dr. Ligrani has a strong past and present record of working with many different collaborators and co-workers, from many locations throughout the world. Additional information on selected, currently active research projects is provided within sections which follow. **(i) Traditional Heat Transfer and Fluid Mechanics Investigations** involving electronics cooling, heat transfer augmentation, drag reduction, turbulent boundary layers, flows in channels with dimpled surfaces, flows in curved channels, elastic turbulence, slot impingement cooling, and macro-scale pumps and pump flows. Also included are **aerodynamics investigations with *high-speed, compressible flows at transonic and supersonic Mach numbers***, including SWBLI – Shock Wave Boundary Layer Interactions. Related projects involve **transonic and supersonic experimental testing**. Research interests also include experimental diagnostics in high speed flows, and air breathing propulsion. **(ii) Air Breathing Engines - Gas Turbine Heat Transfer, Cooling, and Aerodynamics Losses,** including internal cooling, film cooling, impingement cooling, cooling of extremities, aerodynamic performance including aerodynamic losses, and transonic turbine flows and heat transfer. This subject area includes the effects of uses of bio-fuels, synthetic fuels, and renewable energy sources in relation to gas turbines and gas turbine heat transfer and cooling technologies. Note that an important area of turbomachinery research interest involves heat transfer and aerodynamics investigations with *high-speed, compressible flows at transonic and supersonic Mach numbers*, including linear cascade studies. **(iii) Micro-Fluidics and Millimeter-Scale-Fluidics**, including micro-pump flows, and the effects of slip phenomena on gas and liquid flows in micro-scale passage flows with and without surface roughness, including the effects of hydrophobic surfaces and elastic turbulence. **(iv) Experimental Techniques**, including development of millimeter-scale multiple-hole pressure probes, subminiature hot-wire anemometry, and infrared thermography.

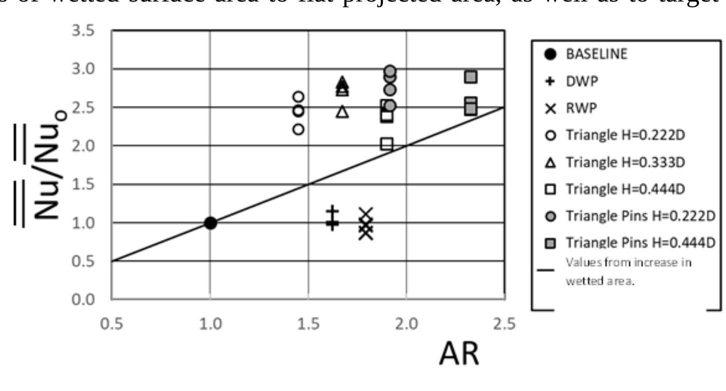


DOUBLE WALL COOLING RESEARCH INVESTIGATIONS

Provided are new effusion cooling data for both surfaces of full coverage effusion cooling plate. For the effusion cooled surface, measured are spatially-resolved distributions of surface adiabatic film cooling effectiveness, and surface heat transfer coefficients (measured using transient techniques and infrared thermography). For the impingement cooled surface, measured are spatially-resolved distributions of surface Nusselt numbers (measured using steady-state liquid crystal thermography). To produce this cool side augmentation, impingement jet arrays at different jet Reynolds numbers, from 2720 to 11100, are employed. Experimental data are given for a sparse effusion hole array, with spanwise and streamwise impingement hole spacing such that coolant jet hole centerlines are located midway between individual effusion hole entrances. Considered are initial effusion blowing ratios from 3.3 to 7.5. The velocity of the freestream flow which is adjacent to the effusion cooled boundary layer is increasing with streamwise distance, due to a favorable streamwise pressure gradient. Such variations are provided by a main flow passage contraction ratio CR of 4. Overall, the present results show that, for the same main flow Reynolds number, approximate initial blowing ratio, and streamwise location, significantly increased thermal protection is generally provided when the effusion coolant is provided by an array of impingement cooling jets, compared to a cross flow coolant supply. An example of hot-side surface, local adiabatic film cooling effectiveness variation (measured using infrared thermography) for an initial blowing ratio of 7.5 and a mainstream Reynolds number of 147000 is presented within the attached figure.

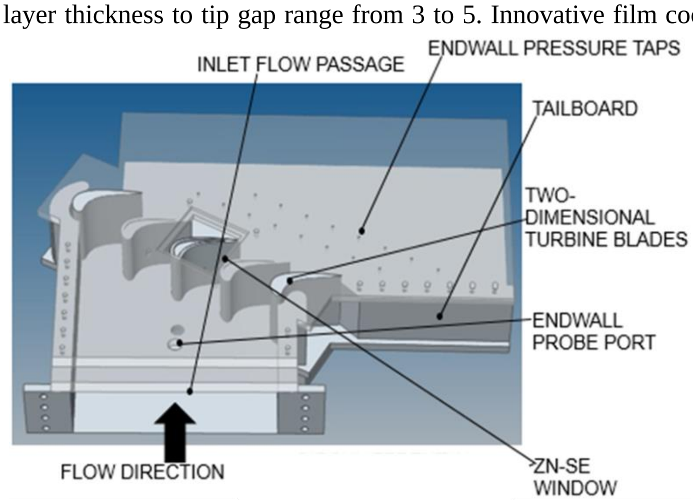
IMPINGEMENT JET ARRAY COOLING RESEARCH USING TARGET SURFACES WITH SPECIAL TEXTURES AND SURFACE ROUGHNESS DISTRIBUTIONS

The target surface experimental results are obtained with target surfaces with a variety of different surface roughness and surface texture arrangements. One arrangement employs arrays of small triangle roughness elements, with different roughness heights, both with and without the addition of large pin roughness elements. The impingement plate employed contains round holes, such that holes in adjacent streamwise rows are staggered with respect to each other. As such, data are provided for different impingement jet Reynolds numbers (based on impingement jet hole diameter) of 900, 1500, 5000, and 11000. Resulting variations in performance are then related to different roughness element arrangements, with different ratios of wetted surface area to flat projected area, as well as to target surface internal conduction, and to the increased three-dimensional transport and mixing produced by arrays of target surface roughness elements. Shown within the attached figure are Nusselt number ratio values as dependent upon AR, ratio of wetted surface area to flat baseline area, wherein configurations with different surface roughness arrangements are compared for impingement jet Reynolds numbers of approximately 11000. Note that the values associated with solid line are associated with an increase in wetted surface area. Within the figure, data are given for different magnitudes of roughness height H, where impingement hole diameter is denoted D.



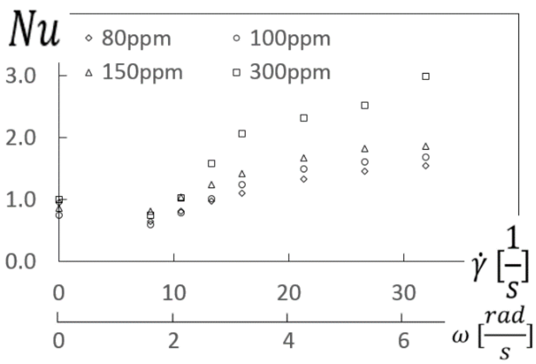
TURBINE BLADE HEAT TRANSFER RESEARCH WITH INNOVATIVE FILM COOLING CONFIGURATIONS

Currently, there is a deficit of experimental data for surface heat transfer characteristics and thermal transport processes associated with tip gap flows, and a lack of understanding of performance and behavior of film cooling as applied to blade tip surfaces. As a result, many avenues of opportunity exist for development of creative tip configurations with innovative external cooling arrangements. Overall goals of the present investigations are to reduce cooling air requirements, and reduce thermal loading, with equivalent improvements of thermal protection and structural integrity. Of interest is development of a two-dimensional linear cascade with appropriate cascade airfoil flow periodicity. Included are boundary layer flow bleed devices, downstream tailboards, and augmented cascade inlet turbulence intensity. The present linear cascade approach allows experimental configuration parameters to be readily varied. Tip gap magnitudes are scaled so that ratios of tip gap to inlet boundary layer thickness, ratios of tip gap to blade axial chord length, and ratios of tip gap magnitudes to blade true chord length match engine hardware configurations. Ratios of inlet boundary layer thickness to tip gap range from 3 to 5. Innovative film cooling configurations are utilized for one blade tip configuration, and scaled engine components are modelled and tested with complete external cooling arrangements. Blade tip and geometry characteristics are also considered, including squealer depth and squealer tip wall thickness. Results are obtained with engine representative transonic Mach numbers, Reynolds numbers, and film cooling parameters, including density ratios, which are achieved using foreign gas injection with carbon dioxide. Transient, infrared thermography approaches are employed to measure spatially-resolved distributions of surface heat transfer coefficients, adiabatic surface temperature, and adiabatic film cooling effectiveness. Presented within the attached figure is a three-dimensional view of the turbine blade cascade which is employed for the investigation.



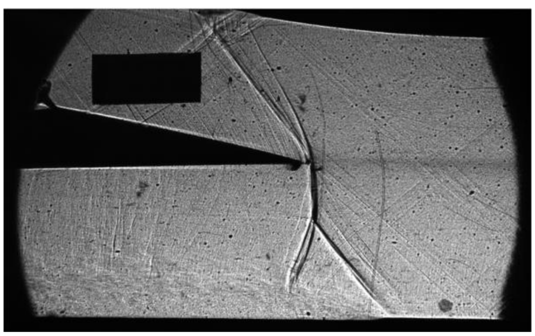
THERMAL TRANSPORT ENHANCEMENT FROM ELASTIC TURBULENCE

The influences of elastic turbulence on convective heat transfer, within a rotating Couette flow arrangement are experimentally determined using viscoelastic fluids, and Boger fluids, which are constant viscosity solvents. Different concentrations of polyacrylamide in 65 percent sucrose solutions are used, along with solutions with 65 percent sucrose only, as different magnitudes of shear stress and strain rate are imposed upon the flow field. Transition and development of elastic turbulence are characterized, along with convective heat transfer enhancements. The resulting increased levels of mixing, transport, and diffusion from elastic turbulence give convective heat transfer coefficient enhancements which are as large as 240 percent, relative to Boger fluids at the same shear rate, rotation speed, flow passage height, and flow temperature. Variations of spectra of static temperature fluctuations, and mean-square magnitudes of fluctuating static temperature provide evidence of increased flow irregularities and unsteadiness (relative to Boger solution flows), which are believed to result from elastic turbulence induced polymer twisting, unsteadiness, and convolutions. Shown within the attached figure are Nusselt number variations with shear rate and disk rotational speed for different polymer concentrations (ppm), for the 2/3 radial location within the rotating Couette flow environment.



INVESTIGATIONS OF SHOCK WAVE UNSTEADINESS

Despite over fifty years of research on shock-wave-boundary-layer-interaction unsteadiness, the source, origin, and propagation direction of the unsteadiness remains controversial and a debated topic. The present research effort is designed to address normal shock wave unsteadiness characteristics, using a newly-developed, supersonic wind tunnel, which is located at the University of Alabama in Huntsville, USA. The wind tunnel test section includes a two flow passage arrangement, where each passage is separated by a shock wave holding plate. The top wall for the top passage is contoured relative to the streamwise flow direction, and a choking flap is located at the downstream portion of the bottom flow passage. With this arrangement, the Mach number at the test section inlet is 1.54, and total air mass flow rate is approximately 12.5 kg/s. Of particular interest are spatially- and temporally-varying flow structural characteristics, which are quantified using shadowgraph flow visualization images, grayscale value spectral energy variations, magnitude squared coherence variations with frequency, and time lag magnitude variations with frequency, where these last two quantities are determined for different flow locations relative to shock wave locations. Two-point correlation functions, as they vary with frequency, indicate that perturbations at a Strouhal number Str of 0.0144 originate downstream of the shock wave and propagate upstream. At a Strouhal number Str of 0.0057, perturbations originate near the shock wave and propagate both upstream and downstream. Coherence functions, determined between different flow locations within the present investigation, show strong correlation between the shock wave and the downstream boundary layer exists at Str = 0.0029. Overall results thus demonstrate that perturbations associated with unsteadiness do not all originate in the same location, nor travel in the same direction. The attached figure shows a shadowgraph flow visualization image from recent research efforts, which illustrates the presence of a normal shock wave, lambda foot, and separated turbulent boundary layer within the lower flow passage, and an oblique shock wave system within the upper flow passage. Note that flow direction is from right to left.



DEAN FLOW DYNAMICS IN LOW-ASPECT RATIO SPIRAL MICROCHANNELS

A wide range of microfluidic cell-sorting devices has emerged in recent years, based on both passive and active methods of separation. Curvilinear channel geometries are often used in these systems, due to presence of secondary flows, which can provide high throughput and sorting efficiency. Most of these devices have been designed on the assumption that there are two counter rotating Dean vortices, present in the curved rectangular channels, which exist in the state of steady rotation and amplitude. Investigated are associated secondary flows in low aspect ratio spiral rectangular microchannels, in order to define their development with respect to the channel aspect ratio and Dean number. This work is the first to experimentally and numerically investigate Dean flows in microchannels for *Re* > 100, and show presence of secondary Dean vortices beyond a critical Dean number. Also demonstrated is the impact of these multiple vortices (>2) on particle and cell focusing. Ultimately, this work offers new insights into secondary flow instabilities for low-aspect ratio, spiral microchannels, with improved flow models for design of more precise and efficient microfluidic devices for applications such as cell sorting and micromixing. The included figure shows a schematic diagram of the positions where the confocal images were taken to determine the position of trapped 10 µm particles.