

CAREER: Control of Acoustic Instabilities in Large Combustors

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A good traveler has no fixed plans, and is not intent on arriving.

–Lao Tzu

*ABSTRACT: This report describes the synergistic interactions that took place in summer 2008 between a team of investigators led by J. Majdalani from the University of Tennessee and a team of researchers at Peking University (PKU). This technical exchange was focused in the areas of acoustic wave propagation, unsteady fluid dynamics, and analytical methods for nonlinear problems. The value of the trip exceeded the researchers' expectations from both academic and cultural perspectives. Academically, it led to rich and fruitful exchanges that have spurred on new collaborations and opened up new avenues for research, not only with the team from PKU, but also with Prof. Liao's team who joined the group from Shanghai Jiao Tong University. The academic program included weekly research discussions, 18 presentations by the US team, 10 presentations by the PKU team, and two short courses that were offered by the US team to a broad audience at PKU. Among the scientific outcomes, four scientific articles have emerged in addition to two joint proposals and a Memorandum of Understanding (draft) between UTK and PKU. The research articles have included a valuable extension to Kelvin's minimum energy theorem that is applicable to fluid domains with open boundaries, and to studies that involve the Homotopy Analysis Method (HAM) developed by Prof. Shijun Liao for the treatment of nonlinear problems in injection driven chambers. The homotopy-based method proved to be invaluable to J. Majdalani's CAREER topic in which nonlinear mechanisms are paramount. The extension to Kelvin's theorem was hinted at by Professor J. Z. Wu. Its development alone would have justified the trip to Beijing. The investigators also discussed and produced a draft of a proposal that was later completed and submitted to NSF. A second proposal was also initiated during these discussions. Culturally, the US team greatly benefited from the hospitality extended to them by their gracious hosts. Related activities materialized in the form of outings and dinners that included both faculty and students. Members of the team were invited to partake in several extra curricular events organized by the host institution in addition to 5 sight-seeing tours that introduced them to the classical attractions in Beijing. Through these activities, the US team gained deeper appreciation for the broad history, daily wisdom, and laudable work ethics associated with the Chinese social etiquette. In fact, the participants left with the same conviction that Saint Augustine once held, specifically that **"The world is a book, and those who do not travel read only a page."***

INTRODUCTION

- *Name of awardee institution for current NSF award*
The University of Tennessee is the awardee institution. The primary NSF award for this grant is CMMI grant № 0353518. This grant is entitled, "CAREER: Control of Acoustic Instabilities in Large Combustors." The grant was awarded to Dr. Joseph Majdalani in the Mechanical, Aerospace and Biomedical Engineering Department (MABE).
- *A brief summary of work being carried out under current NSF Award*
The objectives of this award have been to investigate the physical mechanisms affecting instability, to develop models for both mean and unsteady flow fields in simulated combustors, and to promote the much needed expertise in this area. Presently, the team is ceaselessly exploring new strategies for describing unsteady wave propagation, bulk fluid motion, and instability

- characteristics in injection and swirl-driven chambers. To date, the work has produced 3 MS projects, 2 PhD dissertations, and 57 publications. These include 19 journal papers [1-19], 3 book chapters [1-3], and 32 conference papers [4-35]. The most notable are (a) an award winning review article presenting a procedure for the analytical treatment of compressible flow problems [36], (b) a review article with an undergraduate student [37], and (c) AIAA Paper № 2004-4054 [35], recipient of the 2005 Solid Rockets Best Paper Award, now in the *Physics of Fluids* [38].
- *Reasons/rationale for international cooperation carried out under IREE*
Dr. Majdalani stands as a strong proponent of international collaboration. Prior to his IREE award, he had cultivated several international partnerships with faculty members at the Eindhoven Institute of Technology (NL), SUPAERO (France), and PKU (China). His efforts are reflected in several joint publications coauthored with international scientists. However, the work performed in the past was limited to email communications and telephoning. Through this IREE supplement, Dr. Majdalani and one research assistant were not only able to meet their research counterparts in person, but also initiate technical exchange protocols between their home institution and PKU, thus paving the way for a longer term relationship.
 - *Anticipated research and education outcomes*
The technical exchange with PKU faculty was intended to help in developing refined core flow formulations for combustors that are driven by wall injection or swirl. One of the key objectives was to investigate the possibility of deriving new solutions to the Navier-Stokes equations for injection driven porous chambers (this was indeed achieved through collaboration with a team of applied mathematicians from Shanghai Jiao Tong University). Another objective was geared toward the establishment of a new line of research inquiry in the field of multi-process theory. Accordingly, acoustic, pressure-driven disturbances would be accounted for at the same order as rotational, vorticity-driven, and thermal, entropy-driven oscillations. Among the concepts to be researched was a plausible explanation for the sudden acoustic pressure excursion, known as DC shift, that usually accompanies the onset of nonlinear, limit cycle oscillations. Researchers had hypothesized that excess acoustic energy from the unsteady field could be transferred to the mean flow, thus causing it to steepen. A mathematical model toward this paradigm was therefore pursued. The educational objectives consisted of offering two short courses on unsteady wave propagation and core flow modeling of injection driven chamber gas dynamics in addition to informative presentations related to recent work carried out under this grant. This research-educational effort proved to be truly integrated. For example, during one of the instructional presentations, the need for extending Kelvin's classic theorem to fluid domains with open boundaries was realized. It then became a primary object of research that was tackled by the researchers both in China and later in the US. This particular experience reminded us of Seneca's proverbial quote that
"Travel and change of place impart new vigor to the mind."
 - *Information about host laboratory*
Dr. Majdalani and his student were hosted on the second floor of PKU's State Key Laboratory for Turbulence and Complex System, PKU, Beijing 100871, China. The PKU College of Engineering is quite unique. The ME faculty are almost entirely devoted to thermofluid science (which encompasses the theory of acoustics); the faculty are supported by a cadre of highly-talented graduate students that seem to complement the strengths of faculty at the grantee's home institution. Among them are international experts in stability, vorticity dynamics, turbulence (LES, DNS), computational physics, combustion, heat transfer, etc. Their unit comprises four major groups, each led by a distinguished faculty member. These are: (1.) Professor Zhen-Su She and his team (his Physical Review Letter with Dr Levesque is acclaimed for being the most cited paper in the field of turbulence); (2.) Professor Shi-Yi Chen's team (CoE Dean Chen was previously Chair of ME at The John Hopkins University); (3.) Professor Cun-Biao Lee and his experimental team; and, finally, (4.) Professor Jie-Zhi Wu and his team (with expertise in vorticity aerodynamics).
 - *Name of travelers and dates*
The trip was scheduled from June 20, 2008 to July 31, 2008. Dr. Majdalani and his student, Tony Saad, left from Nashville, TN to Washington and then straight to Beijing.

RESEARCH ACTIVITIES AND ACCOMPLISHMENTS OF THE INTERNATIONAL COOPERATION

- *Program of research carried out during international research experience*

The primary research tasks performed during this exchange program were to: (1.) develop a mathematical model that can capture wave steepening and hydrodynamic stability processes, (2.) denote the assumptions that are required to produce a solution, and (3.) determine all of the necessary inputs required to perform the analysis. The wave steepening analysis stems from the work of Crocco and Mitchell [39]. Hydrodynamic stability analysis has originated from several years of theoretical work at the French *Centre National d'Etudes Spatiales* (CNES), ONERA, and, recently, at UTSI [19,25,26]. The UTSI effort is presently funded through a CAREER award. The technical exchange with PKU has focused on the following subtasks:

 - Devise a system of equations that elucidates both linear and nonlinear interactions between unsteady vortical and acoustic fields [40-48].
 - Develop the system of equations to incorporate wave steepening effects and hydrodynamic stability corrections into the existing vortico-acoustic framework. This task was carried out in conjunction with Professor Jian-Jun Tao.
 - Engage and refine Professor Jie-Zhi Wu's Multiprocess Theory for Complex Viscous Compressible Flows.
 - Establish a set of sample problems to evaluate the new analysis. Since an analytic solution can be used for the mean flow [30,49-51], evaluate its suitability for use as a benchmark in numerical studies.
 - Develop and offer courses in acoustic wave propagation and instability to help in revitalizing and developing similar courses domestically. These courses incorporate the latest findings in the field such as those shown in Figs. 1-2.
 - After returning from China, integrate all technical findings into a discussion of the work carried out; express useful recommendations showcasing the predictive capabilities of our models. Prepare a report that conveys the experiences gained from the trip.

- *A substantive description of the general interaction between researcher and host laboratory*

Our small delegation closely interacted with PKU faculty and students. We were hosted by Prof. Jie-Zhi Wu and Prof. Zhen-Su She, the Director of the State Key Turbulence Laboratory at PKU (a national laboratory).

We have identified research areas of mutual interest and drafted plans to foster collaboration in science, proposal writing, and teaching. We have also met with a small delegation from Shanghai Jiao Tong University; this group was involved in truly cutting-edge theoretical work in flow field modeling. Several productive discussions and presentations followed. We were introduced to the theory of Homotopy Analysis which is a powerful method for solving nonlinear problems. We applied this new technique to a problem involving a simulated combustor with sidewall injection.

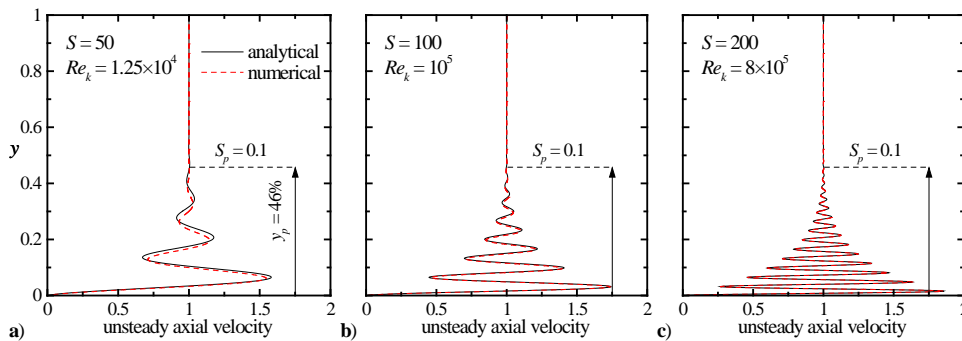


Fig. 1. Analytical and numerical solutions for the axially travelling wave in a simulated cylindrical motor driven by sidewall mass injection obeying the Taylor-Culick model [41]. Oscillations and corresponding depth of penetration y_p are shown for the first fundamental mode and three specific values of the Strouhal (S) and kinetic Reynolds numbers (Re_k). The agreement between numerics and asymptotics improves with successive increases in S despite the highly dispersive (oscillatory) and dissipative (damped) nature of the solution and the reduction in spatial wavelength between (a) and (c).

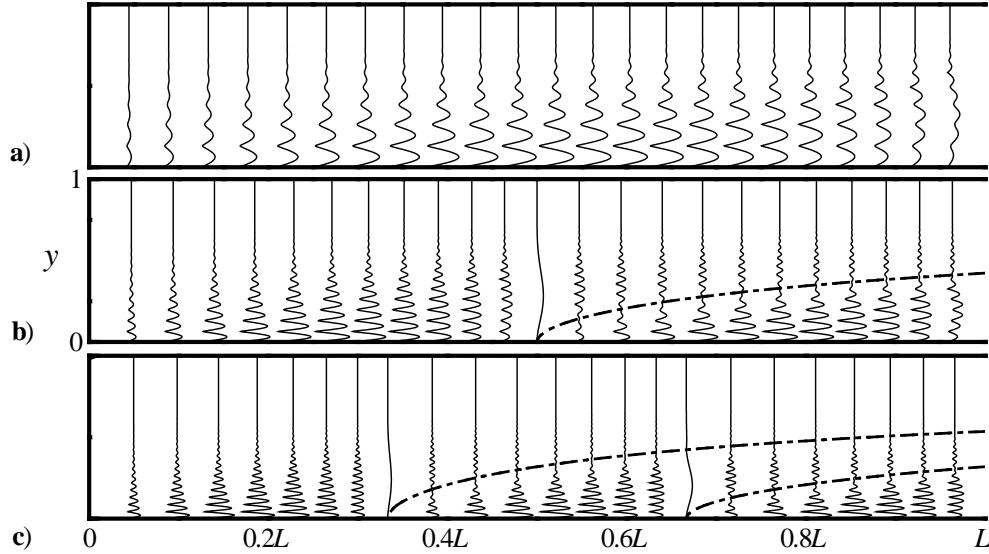


Fig. 2. Modulus of the unsteady longitudinal wave in an injection driven porous tube at several axial locations and for the first three oscillation modes (a-c). Results are shown for $S=50m$ and $S_p=16/m^2$, where m is the acoustic mode number. A pattern correlation with classic acoustic mode shapes is apparent. Maximum rotational amplitudes occur near acoustic pressure nodes and diminish in the direction of velocity nodes.

Our time spent in Beijing was packed with scientific exchanges, presentations, and plans for collaboration. We have identified several scientific projects that we would like to continue to pursue collaboratively. These cover a range of topics including thermal and vorticoacoustic wave propagation, homotopy analysis, hydrodynamic instability, and LES modeling.

Initially, our activities were mostly focused on the tasks delineated in our NSF International Research and Education in Engineering (IREE) program. In this vein, our efforts included research and teaching activities. Teaching activities included offering two short courses (1 full day each), giving 10 additional presentations (approximately 18 hours of presentations apart from the short courses), and several open discussions of scientific problems of mutual interest. The initial wave of courses and presentations was widely advertised and posters were sent to several major universities in the area. This plan was later augmented by various presentations requested by PKU faculty. Fulfilling this plan required preparing hundreds of slides and working round the clock, 24/7, for several weeks in a row.

- *Discuss the research accomplishments of student(s) during the trip*

During the entire course of this trip, the graduate student actively assisted Dr. Majdalani in carrying out both research and teaching initiatives. In addition to preparing and offering one 2 hour presentation, he offered two short presentations at follow-up meetings. He initially focused on the problem involving energy-based steepening of the core flow in an injection driven enclosure. This study was completed and then submitted to the Proceedings of the Royal Society. This paper was entitled “On the Lagrangian optimization of wall-injected flows: from the Hart-McClure potential to the Taylor-Culick rotational motion.” The team also began working on Kelvin’s minimum energy theorem extended to fluid domains with open boundaries. The ensuing work is presently under review in the Journal of Fluid Mechanics under the title, “Is Kelvin’s minimum energy theorem valid for compressible fluid motions and regions with open boundaries?” Broadening the scope of Kelvin’s classic theorem led to the introduction of a new definition of a so-called *Kelvin surface* and the derivation of an extended form of Kelvin’s theorem. To be more specific, Kelvin’s minimum energy theorem holds for steady incompressible fluids and offers a uniqueness characteristic for single-valued velocity potentials in simply connected regions. Accordingly, the irrotational component of motion is expected to carry the least kinetic energy of other flow profiles that may be kinematically established in the fluid domain and which satisfy the same normal velocity conditions prescribed on its boundaries. A fundamental question that our work has addressed is whether the theorem may be extended to

regions with open boundaries on which the normal velocity requirements are relaxed. To this end, Kelvin's analysis was reconstructed for compressible motions and regions that comprised open boundaries (see Fig. 3). An extended form of the theorem was then presented such that the incompressible analogue in a simply connected region might be returned as a special case. Kelvin's theorem was found to remain generally valid as long as a well defined criterion for the surface integral over the open boundary was observed. We then considered specific cases to illustrate the applicability of this criterion and test its validity in the context of a problem involving axisymmetric rotational motion in a porous cylinder.

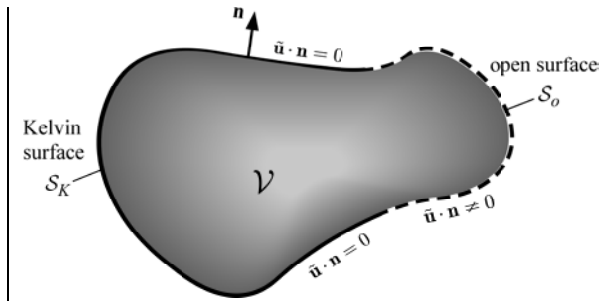


Fig. 3. Volume of fluid showing both Kelvin and open surfaces with corresponding velocity requirements at the boundaries.

BROADER IMPACTS OF THE INTERNATIONAL COOPERATION

- *How the supplement award helps expand the original scope of the current award*
 This travel supplement has considerably helped in expanding the original scope of the award. For example, the HAM technique was not known beforehand. Being a recent technique developed in the nineties, it was not included in the original research plan. However, through this supplement, several new studies have emerged. In addition to Kelvin's extended theorem which we have already applied to two distinct problems, we have completed an important sequel through the use of Prof. Liao's powerful homotopy technique. This article is entitled, "Homotopy Based Solutions of the Navier-Stokes Equations for a Porous Channel with Orthogonally Moving Walls," now under review in the Physics of Fluids. We have also completed and submitted an NSF proposal that involves Prof. Jie-Zhi Wu and Prof. Majdalani. Several additional unit problems have been identified and initiated. These include [Collaborative Targets -Tentative Titles/Faculty Involved]:
 - Homotopy analysis of the regressing channel flow problem -Xu/Wu/Liao/ Majdalani. Done.
 - Vorticoacoustic and hydrodynamic wave energy: Part 1-Formulation -Majdalani/Tao.
 - Vorticoacoustic and hydrodynamic wave energy: Part 2-Evaluation -Majdalani/Tao.
 - Instability of the Mean Flow with Particle Interactions -Majdalani/Tao.
 - Instability of the Bidirectional Vortex -Tao/Majdalani.
 - Modeling of the water hammer problem -Wu/Majdalani.
 - Homotopy analysis of a new exact solution of the Navier-Stokes Equations -Xu/Wu/Liao/Majdalani.
 - LES Simulation of the Cylindrical Bidirectional Vortex -Majdalani, Wu, Yipeng Shi.
 - Simulation of the Conical Cyclone -Majdalani/Wu/Yipeng Shi.
 - LES model based on the generalized scaling technique -Shi/Su/Majdalani.

At the end of the exchange period, our team received encouraging feedback from various participants. Below is a photograph that depicts Prof. Majdalani thanking his host, Prof. Wu, for handing him the Pei-Yuan Chou commemorate plaque. Dr. Chou was the founding father of PKU's College of Engineering and considered by many the Thomas



Fig. 4. Prof. Majdalani receiving the Pei-Yuan Chou plaque from Prof. J. Z. Wu at the conclusion of one of the series of presentations offered at Peking University.

Jefferson of China. It is said that he was the first to introduce the concept of a *Visiting Scholar*. More on this can be found at

http://www.utsi.edu/news/News_2008/release9-16-08professorgrasummerchina.htm

It may be worthy to note that, in the Annual Review of Fluid Mechanics, John L. Lumley of Cornell University wrote,

“In this generation there were at least four giants in fluid mechanics from four countries; men who had, each in his own way, tremendous influence inside and outside his country, certainly by contributing to the development of areas of fluid mechanics, but also by providing intellectual and personal leadership; men of such stature that substantial numbers of distinguished workers in fluid mechanics in each country could trace their academic lineage to that great man. I have in mind von Karman in the United States, Kolmogorov in the (then) Soviet Union, G .I. Taylor in the United Kingdom, and Pei-Yuan Chou of China.”

- *How the travel fosters closer future interaction between awardee institution and host institution*
This trip left the investigators with such a positive impression that they have decided to plan for an encore. They have initiated a Memorandum of Understanding with PKU that should help to regulate and promote future exchanges. This MOU is presently under review by the Compliance Department of the University of Tennessee.
- *How the visit has helped to enhance international perspective for the US researchers*
The investigators were quite impressed by the outstanding work ethics displayed by both faculty and graduate students at PKU. They not only worked long hours, but did not exclude weekends and holidays. Moreover, the level of respect and reverence expressed by students toward faculty was inimitable. This trip was quite helpful in experiencing firsthand how life in the vast land of China is actually sustained. While Dr. Majdalani did not focus on language acquisition, his student studied the language to the extent of understanding the cashier at Wu-Mei (Wal-Mart).

DISCUSSION AND SUMMARY

- *Summary of the most significant accomplishments of the international research experience*
The most significant accomplishments of this trip include:
 - Receiving constructive criticism and guidance from experts in the field who share mutual research interests.
 - Forging new friendships with world-class researchers at PKU, the “Harvard of China.”
 - Gaining deeper understanding of modeling strategies used by a group of experts.
 - Learning a new tool for research, the Homotopy Analysis Method (HAM).
 - Establishing new lines of research inquiry that are complementary to ongoing investigations.
 - Establishing new themes for collaborative research at an international level.
 - Touching the lives of a large group of highly competitive graduate students who could be potentially recruited at the doctoral or post-doctoral levels.
 - Initiating an MOU to facilitate the exchange of faculty and GRAs.
 - Appraising that hard work and sharing are the secret to success irrespective of available infrastructure.
 - Savoring the likes and dislikes of a foreign culture.
 - Helping to improve the communication skills of a foreign group of investigators.
 - Promoting US leadership and visibility in one’s area of concentration.
 - Increasing research productivity through networking.
 - Establishing new sources for funding.
 - Finding simple and natural answers to longstanding problems. As elegantly worded by Anatole France, “*Wandering re-establishes the original harmony which once existed between man and the universe.*” This statement is certainly true when research is considered and the manner by which the chips seem to naturally fall into place.
- *Recommendation for “Best Practices” in future operation of the IREE Program*
Prior to his trip to China, Dr. Majdalani participated in the 2008 IREE Conference, Washington, DC, May 2-3, 2008. This pre-travel conference proved quite valuable in learning more about what

to expect and hearing it directly from former IREE participants. In what follows some recommendations are offered to future travelers.

Bruce Lee is quoted for stating that **“In every passionate pursuit, the pursuit counts more than the object pursued.”** This thought simply reiterates the longstanding belief that the “journey is more important than the destination.” Such a frame of reference certainly applies to the IREE program, regardless of the outcome. In the present case, the academic return on the investment was substantial, far exceeding the investigators’ expectations. However, even in the absence of a significant result in research, participants can rest assured that the visit to a foreign country will be well worth their time. The exposure to a foreign culture only enhances one’s appreciation for the tools and opportunities that are available back home. It will impart the participants with a boost of energy and a renewed passion for achieving their research and teaching goals. Moreover, the level of visibility and potential for dissemination and recruiting that are possible through the IREE program are second to none. Travelers need not fear nor hesitate, for the benefits of IREE far outweigh the risks involved.

Another suggestion to future travelers is to plan (moderately) ahead of time. It is useful to contact the person in charge and make sure that suitable accommodations are available. In the work environment, it would be helpful to request in advance a computer, a printer, internet privileges (in some countries, these require a clearance), a scanner, and a good size monitor. As for personal belongings and traveling tips, it may be best to follow Susan Heller’s advice:

“When preparing to travel, lay out all your clothes and all your money. Then take half the clothes and twice the money.”

Essentially, “Travel light and enjoy yourself!”

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Joseph C. Majdalani received his PhD degree from the University of Utah, Department of Mechanical Engineering, in 1995. Between 1997 and 2003 he served as an Assistant and then Associate Professor in the Department of Mechanical Engineering at Marquette University, Milwaukee. He then joined the Mechanical, Aerospace and Biomedical Engineering Department at the University of Tennessee in Fall 2003.

Dr. Majdalani's research devotes itself to the theoretical and numerical modeling of injection and swirl induced flow fields. He is a strong proponent of sound physical and mathematical modeling at the foundation of investigative analysis. His interests span several disciplines that entail unsteady fluid dynamics, thermo-acoustic instability theory, engine core flow modeling, particle mean flow interactions, singular perturbations, electronics cooling, and swirl induced heat transfer. He is also keen on problems connected with peristaltic and bifurcating biological flows.

Dr. Majdalani received the 1998 College of Engineering Research Award in addition to the 1999 and 2000 Outstanding Teaching Awards from Marquette University. Subsequently, he received NASA's 2002 and 2003 Faculty Research Infrastructure Awards, the 2002 Higher Education Incentive Award and, from the National Science Foundation, the CAREER Award in 2003. In the Aerospace category, he received the 2007 Ralph R. Teetor Educational Award from SAE International, and the H. H. "Hap" Arnold Award administered by the American Institute for Aeronautics and Astronautics in conjunction with the Air Force for "outstanding personal contributions to the advancement of compressible flow theory and rocket internal ballistics." He is presently a Fellow of ASME, appointed Member of the External Advisory Board, Center for Simulation of Advanced Rockets, University of Illinois, and designated AIAA Chair of Education and Technical Expert in Analytic Approaches to Hybrid Rocket Flowfields.

Tony Saad is a doctoral candidate in Mechanical Engineering at the University of Tennessee, working with Dr. Majdalani. His undergraduate degree is also in Mechanical Engineering from Notre Dame University, where he graduated second in his class. His work involves the formulation of innovative core flow models in an injection driven chamber. Mr. Saad was the recipient of the Lloyd Crawford Fellowship both in 2005 and 2007. He also received the UTSI Outstanding Graduate Research Assistant award in 2007. He has co-authored 5 journal and 8 conference papers since 2005.