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# AES

## Advanced Energy Systems Division Newsletter

Srinivas Garimella, Editor

Fall 2001

## Chair's Message

*Jerzy Fiszdon*

I've been involved with various ASME activities for a number of years, and now I have the honor and the responsibility to chair the Advanced Energy Systems Division (AESD). As chair, I hope to continue to conduct the business of the Division in a professional manner, to enhance the benefits of participation in Division activities, and to keep up the excellent professional standing of the Division. I am very fortunate in having an excellent team of executive committee members. I count on their guidance and support. We have attracted over 900 primary members to our Division. Division activities center on coordinating two technical conferences annually, the International Mechanical Engineering Congress and Exposition (IMECE) and the Intersociety Energy Conversion Engineering Conference (IECEC). Because of tighter funding, we see a decrease in attendance at conferences where we meet and get our work done, and have to find new ways to increase participation.

The Division co-sponsors several conferences held in countries all around the world. The Division also participates in a once-a-year AESD dedicated issue of Mechanical Engineering, journal articles, and recognizes technical accomplishments in Division related areas through an active awards program.

The Division has seven Technical Committees, although not all committees are fully active. The technical committees, which involve people from industry, government, and academia, work hard to create very high quality technical programs. Working to develop technical conferences, members of the committees come together under circumstances different from their typical work relationships. Authoring a technical paper or encouraging others to do so, presenting a paper or making general announcements, organizing a technical session or coordinating activities with a conference organizer, budgeting time and resources, and gaining exposure to other engineers with different technical specialties and different management levels, are all excellent means of professional development. As chair of AESD, I welcome this opportunity to thank all who have volunteered their time and talents to make the Division a success and to invite the rest of you to participate in these activities.

Currently, Dr. S.A. Sherif, the Vice-Chair of the Division, is preparing a new Strategic Plan, and would be glad to share this document with anyone requesting it.

I would like to welcome our new incoming executive committee member, Dr. Robert Boehm from the University of Nevada, Las Vegas. Dr. Boehm has been active in the area of Energy Systems for a long time. I also want to welcome our new representative to the US CADDET National Team Dr. Michael von Spakovsky, Pro-

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## Publication Opportunities for AESD Authors

Several opportunities are available for AESD authors to publish their technical articles. These include symposia, the monthly Mechanical Engineering, and archival journals. AESD authors are cordially encouraged to give a tangible expression of their ASME affiliation by considering these publication outlets for their work.

Periodically, AESD has a special section in the monthly *Mechanical Engineering*. Special sections are comprised of articles submitted by various AESD technical committees on a rotating basis. Members interested in participating in this activity should contact the AESD chair and/or their technical committee chairs.

Opportunities for publishing technical papers are provided by the symposium volumes of papers presented at the IMECE AESD technical sessions. Normally one or more such volumes are prepared annually, comprising the two dozen or more papers presented at IMECE. Such papers may be eligible for consideration for the prestigious *E. F. Obert Award*.

Symposium volumes are available for purchase at IMECE and also may be ordered directly from ASME technical publications. Abstracts are generally due in January for papers to be presented at the following IMECE. Authors wanting to participate at the 2001 or 2002 IMECE should check the calls for papers in the monthly meetings calendar of *Mechanical Engineering*.

Many AESD authors participate in the

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## Chair's Message

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fessor and Director of the Energy Management Institute at Virginia Tech.

Finally, the 2001-2002 Executive Committee thanks the previous Executive Committee, particularly the leadership of Dr. Salvador Aceves of Lawrence Livermore National Laboratory, for a job well done. Major highlights are:

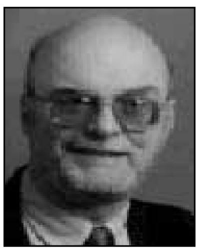
- Increase in AESD membership by 7%
- Restoring the AESD issue of Mechanical Engineering
- Increasing the number of technical committees organizing sessions at the 2001 IMECE, and the number of planned technical sessions.

I would also like to thank Dr. Gordon M. Reistad for his years of service in various areas of the Division. I hope he will still participate in the Division activities on an informal basis.

In closing, I would like to urge anyone with an interest in the Division or Committees activities to participate.

*Jerzy Fiszdon*

## Boehm Named to Executive Committee



*Robert Boehm*

Dr. Robert Boehm is the new Executive Committee Member for the Division. He is Professor of Mechanical Engineering at the University of Nevada, Las Vegas and Director of the Energy Research Center there. His principal work has been in the fields of energy conversion, heat transfer and thermal system simulation, with applications in diverse areas such as renewable energy and biology. He is a Fellow of the ASME.

He received his BSME and MSME degrees at Washington State University. He was then with the General Electric Atomic Power Equipment Department in San Jose, California. After completion of the PhD work at the University of California at Berkeley (1968), he joined the Mechanical Engineering Department at the University of Utah. He has served twice as Chairman of the Department.

He has been on the faculty at UNLV since 1990, where he came as Chair to develop the newly formed Department of Mechanical Engineering. He also served as Senior Technical Liaison to the US Department of Energy from the University and Community College System of Nevada. The Center for Energy Research, in which he is now active, focuses on renewable energy technologies, alternative fuels, and energy conservation issues. He is the author or co-author of 10 books and over 300 technical publications.

In addition to the Advanced Energy Division, he is active in the Heat Transfer and Solar Energy Divisions of ASME. He is a member of the national Energy Committee of ASME.

## New CADDET-EETIC Representative

*Michael von Spakovsky*

Dr. Michael von Spakovsky replaces Jerzy K. Fiszdon as the representative from The American Society of Mechanical Engineers to the CADDET - EETIC (Centre for the Analysis and Dissemination of Demonstrated Energy Technologies - Energy and Environmental Technologies Information Centres) United States National Team. He has over 13 yrs of teaching and research experience and over 17 yrs of industry experience in mechanical engineering, power utility systems, aerospace engineering and software engineering. He received his B.S. in Aerospace Engineering from Auburn University and his M.S and Ph.D. in Mechanical Engineering from the Georgia Institute of Technology. He has held prior positions at NASA, the power utility industry, and the Swiss Federal Institute of Technology. Since 1997, he has been Professor of Mechanical Engineering and Director of the Energy Management Institute at Virginia Tech and has taught courses in thermodynamics, industrial energy systems, fuel cell systems, and energy system design. His research interests include computational methods for modeling and optimizing complex energy systems, methodological approaches for the integrated synthesis, design, operation and diagnosis of such systems (stationary power as well as high performance aircraft systems), theoretical non-equilibrium and equilibrium thermodynamics, and fuel cell applications for both transportation and distributed power generation.

The CADDET program was first set up to promote the international exchange of information on energy-efficient technologies. Later it was extended to cover the full field of renewable energy technologies. Since 1997 it includes the GREENTIE program, covering technologies that mitigate the emission of greenhouse gases. The Agreement is known as the IEA (International Energy Agency) EETIC.

CADDET Renewable Energy gathers information on full-scale commercial projects that are operating in its member countries, currently Australia, Denmark, France, Japan, The Republic of Korea, The Netherlands, Norway, Sweden, United Kingdom, United States and the European Commission. The CADDET program covers the full range of commercial renewable energy technologies.

More information about CADDET can be found at http://www.caddet.org.

## AES Division Awards and Keynote Lecture

The AES Division recognizes the outstanding contributions of its members and researchers and educators in the Advanced Energy Systems area at the annual AESD Luncheon, which is held at the IMECE. The contributions of these individuals are truly outstanding and are one of the main reasons for the continued advancement of energy related technology. The Awards Luncheon also offers the opportunity for attendees to hear from a leading expert on issues at the forefront of such research and technology.

At the 2000 IMECE, Harry Brandt, Emeritus Chairman of the University of California Davis Department of Mechanical Engineering, and Chairman of the Board of Clean Energy Systems, Inc., gave a thought provoking and inspiring talk on "Power Generation with Zero Atmospheric Emissions." The talk detailed the concept for a power plant that uses a combustor/steam generator based on rocket technology. The resulting power plant lends itself very well for CO2 sequestration. Ideally, the CO2 generated could be used for petroleum extraction. The plans are to build a prototype of the power plant with 10 MW power output at Lawrence Livermore National Laboratory. Further details of the power plant can be found in the June issue of "Mechanical Engineering Power."

The following awards were given at the 2000 IMECE:

The paper entitled "Entropy, Part 1: Statistics and its Misleading Disorder; and Part 2: Thermodynamics and Perfect Order" by Elias Gyftopoulos was selected for the ***Edward Obert Best Paper Award In Thermodynamics***.

The 2000 ***Heat Pump Technical Committee Best Paper Award*** was given to William A. Miller and Majid Keyhani for their paper entitled "The Correlation of Coupled Heat and Mass Transfer Experimental Data for Vertical Falling Film Absorption".

As an example of noteworthy participation of AES division members in other ASME divisions, Dr. Srinivas Garimella (with J. W. Coleman) received the best paper award for the paper entitled "Visualization of Two-phase Refrigerant Flow During Phase Change" presented at the 2000 National Heat Transfer Conference in Pittsburgh, PA.

The following members of the AES division were elected Fellows of ASME:

Dr. Joseph L. Smith, Jr.
Dr. S.A. Sherif
Dr. Hameed Metghalchi
Dr. Salvador Aceves

Congratulations and a hearty thanks to all these awardees!

# Reports from the Committees

## Direct Thermal Power Conversion and Thermal Management

This committee promotes research and development in all areas of direct conversion of heat to electric power without any moving parts or thermal management of energy. Direct thermal energy conversion devices include thermionics, thermoelectrics, AMTEC (alkali metal thermal to electric converter), and TPV (thermophotovoltaics). All areas of thermal management including aircraft and spacecraft, ground vehicles, electric component and power systems, and industrial energy systems are covered. The committee participates in the IECEC, IMECE, and other conferences related to advanced energy systems. During this year, the committee has organized four sessions for the Intersociety Energy Conversion Engineering Conference held at Savannah, Georgia, in July-August, 2001, and one session for the IMECE to be held at New York city, in November, 2001.

*Muhammad Rahman*

## Heat Pumps

The main objective of the Heat Pump technical Committee is to help advance the state of the art of the science and technology of Heat Pumps, which play an essential role in the lives of human beings. The current trend towards energy scarcity and the scare of depletion of its resources is driving science and technology towards innovation in the art of energy production, storage and transmission. Efficiency improvement has attained the greatest importance in the energy industry and hence the refrigerators, air conditioners and other heat pumping devices are expected to perform with very little energy loss. Consequently, this is an era with great challenges and promise for engineers, researchers and technologists who want to make the art, science or technology of heat pumping as their career.

The committee organizes symposia and panels to bring together researchers working in various fields relating to the fundamental understanding and development of various types of heat pumps. During the 2000 ASME IMECE held at Orlando, there were 5 well attended technical sessions and one panel session. The paper by A. Laveau, J. S. Kapat, L. C. Chow, E. Enikov, and K. B. Sundaram, on the "Design, Analysis, and Fabrication of a Meso-Scale Centrifugal Compressor" has been adjudged the best paper for the year 2000 and the award, which also carries a $500 prize, will be presented at the 2001 IMECE.

The committee meets once a year at the IMECE. At the last meeting, Dr. B.G. Shiva Prasad of Dresser-Rand company was elected Chair, along with Dr. Abdi Zaltash of Oak Ridge National Laboratory as the Vice-Chair and Dr. Laura Schaefer of the University of Pittsburgh as the Secretary to serve for a period of two years. Seven technical sessions and one panel are being organized for the 2001 IMECE. The committee has also instituted an award for the best student paper, and would appreciate university faculty encouraging their students to submit papers on their work at future conferences.

The committee seeks and is always open for ASME members interested in active participation and contribution of their time, effort and ideas for its evolution and growth.

*B. G. Shiva Prasad*

## Energy Systems Miniaturization

This committee organized a successful and well-attended panel session at the 2000 IMECE in Orlando, FL, entitled "Panel on Miniature Energy, Chemical and Biological Systems." The session discussed the current state-of-the-art in different miniature engineering systems. The key focus was on complete systems rather than individual components. The benefits and challenges of miniaturization, along with possible applications, were discussed by the panelists. Both meso-scale and micro-scale systems were presented. The session featured speakers from academia, industry and government, who provided overviews on microturbine projects and miniaturized systems under development including a mesoscopic pump, a PolyMEMS actuator, an integrated mesosniffer, and a miniaturized cytometer. Thermoelectric micropower generators, an automotive fuel processor for producing hydrogen for PEM fuel cells, an in situ propellant production plant for Mars, and a man-portable heat pump for cooling soldiers in the field in hot climates were also discussed.

The June 2001 issue of Mechanical Engineering magazine contained a feature article, authored by Professor Richard B. Peterson of Oregon State University - the current chair of this committee, on the miniaturization and integration of the components necessary for advanced energy and chemical systems. A second article from the same issue, coauthored by Professor Patrick E. Phelan of Arizona State University - a member of this committee, had reference to miniaturization of cryogenic cooling systems.

The committee met at the 2000 IMECE, and discussed a initiating a concerted drive at membership and a web presence. The committee will organize two sessions at the 2001 IMECE.

The next full meeting of the committee will be held at the 2001 IMECE. Anyone interested in additional information on the committee, or in participating in its activities is welcome to attend.

*Jayanta S. Kapat*

## Superconductivity

This committee provides a forum for presenting the most recent progress in the field of applied superconductivity. The committee continues its efforts in sponsoring paper sessions including those co-sponsored by other ASME committees. A paper session on "Cryogenic Engineering" jointly sponsored by this committee, the Heat Transfer Division K-18 Committee on Low-Temperature Heat Transfer, and Process Industries Division Cryogenics Technical Committee, will be held at the 2001 IMECE.

New members are sought to bring in new ideas and to help coordinate future activities. Information on this committee can be obtained by contacting the committee chairman, Dr. Ming Chyu (contact information elsewhere in this newsletter) vice chairman, Dr. John R. Hull, Argonne National Laboratory, (708) 252-8580, or secretary, Dr. P. E. Phelan, Arizona State University, (480) 965-1625.

*Ming-C. Chyu*

## System Analysis

During the year 2000, the Committee organized its sixteenth symposium on "The Thermodynamics and the Design, Analysis and Improvement of Energy System," held at the IMECE in Orlando, FL. The symposium organizer was Michael von Spakovsky. The symposium included 49 papers, which were organized in 10 sessions. These papers were submitted by researchers in six continents, a clear indication of a very strong international participation. The Fuel Cell sessions and the Panel discussion session The Sustainability of Energy Conversion Technologies in the 21st Century were very well attended.

The Committee is also a co-sponsor of the yearly international ECOS (Efficiency, Costs, Optimization, Simulation and Environmental Aspects of Energy Systems), which was held in July 2000 in Holland. The attendance was over 200, with a big attendance from researchers in the U.S.A. The ECOS 2001 was held in summer 2001 in Istanbul, Turkey.

Abel Hernandez is the organizer of the 2001 IMECE symposium. There were 48 abstracts sent for consideration, from the following countries: China, Korea, United States, Italy, Colombia, Japan, Spain, Germany, Greece, Mexico, Poland, Bulgaria,

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## Committees

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Switzerland. From these about 41 papers are accepted, with the symposium consisting of 11 technical sessions and two panel sessions.

The Committee has two awards each year, the Best Paper award of $500, and the Best Student Paper award of $400. The award winners for year 2000 are:

Best Paper: Betts, D. A., Roan, V.P., and Fletcher, J. H. for their paper entitled "Discussion and Analysis of Flue Gas Utilization in a Phosphoric Acid Fuel Cell Engine During Idle Operation"

Best Student Paper: Munoz, J. R. (and M. von Spakovsky) for the paper entitled "The Use of Decomposition for the large Scale Synthesis/Design Optimization of Highly Coupled, Highly Dynamic Energy Systems"

The Committee held its yearly meeting during the 2000 IMECE. The following are the new Executive Group members for 2001: George Adebiyi, Chairman; Vincent Wong, Vice Chair; Abel Hernandez, Symposium Chair; Marc Rosen, Assistant Vice Chair.

*George Adebiyi*

## Hydrogen Technologies

This committee provides a forum for presenting the most recent progress in the field of hydrogen technologies for energy, including hydrogen utilization, storage, production, systems analysis, and safety. The committee is organizing a session on Hydrogen Energy Technologies in the Symposium on Thermodynamics and the Design, Analysis, and Improvement of Energy Systems as a part of the 2001 IMECE. Papers on hydrogen production and storage have been submitted and are currently under review. The symposium also has a session on fuel cells technology, which is of interest to people working on hydrogen technologies.

The committee invites all who are interested or working in the field of hydrogen technologies for energy, including hydrogen utilization, storage, production, system analysis, and safety, to participate in these Symposium sessions and become active members for future events.

*Joel Martinez-Frias*

## Fuel Cells

The fuel cell committee activity has been limited recently to the PTC-50 fuel cell performance test code work, which is progressing well. The PTC-50 committee is drafting a performance test code for fuel cells similar to ASME codes for gas turbines (PTC-22), or overall performance (PTC-46). A meeting was held at ASME headquarters on June 12 to review the draft document. This document is now being reviewed by the committee members, in preparation for sending the draft out for industry review.

*Tony Leo*

## Stirling Engines

There has been relatively little large-scale development in the Stirling engine community in the past year. While it is expected that the recent return of energy issues to the public consciousness will reinvigorate interest in these efficient and clean energy converters, in the mean time, companies and researchers interested in this technology have focused on specialty applications. Among these, Stirling Technology Company in Washington State has had good success with small free-piston power units for NASA's deep space missions. In other power-generation news, it appears that the DoE has decided to close down the Concentrating Solar Thermal power programs, of which Stirling engines were a key part (converting concentrated solar heat into mechanical and electrical output). This has adversely affected companies such as Stirling Thermal Motors, who was the prime vendor for the solar efforts of SAIC (through Sandia/DoE). Overseas, WhiperTech of New Zealand continues to promise imminent production of their stand-alone gas-fired generators, which are well-packaged, compact designs.

In a significant development of the year 1999/2000, Los Alamos National Lab (LANL), a center for thermoacoustics work, announced a hybrid Stirlng-acoustic engine that operates without the sometimes-troublesome displacer component, using just the gas inertia to achieve the desired gas motion and pressure waves. These developments might eventually result in a lower-cost small system for self-powering home furnaces.

Other Stirling-based groups have concentrated on cooling applications, Sunpower, STC, and CFIC have all made advances toward commercial production of cryocoolers based on the Stirling principle, either directly or through the recent thermoacoustic and pulse-tube variant developments. Sunpower is preparing facilities for production of its small units (10's of watts @ 6—80K). Sunpower has licensed its technologies to both STI and LG Electroniucs (of Korea) for the cooling of cell-phone antennas. STC continues to offer a lab cooler. CFIC is collaborating with Praxair, Inc., to commercialize larger resonant systems (100's to 1000's of watts at 30-150K) for condensation of industrial gasses and refrigeration of high-Tc superconducting power systems. It is in miniature cryocooler where Stirling has made its mark so far, with TRW and Raytheon, and in England, Hymatic, manufacturing thousands of small tactical Stirling cryocoolers for the military every year. Perhaps this is the year that this technology will reach commercial application.

*John Corey*

## Publication Opportunities

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annual IECEC (*Intersociety Energy Conversion Engineering Conference*) held during the summer. IECEC 2001 was hosted by ASME in July at Savannah, GA. Nearly every summer for several years AESD also has participated in symposia held outside the United States at various memorable sites. The 2001 event, ECOS 2001 (Efficiency, Costs, Optimization, Simulation and Environmental Aspects of Energy Systems) was held in July at Istanbul, Turkey. ECOS 2002 will be held in Berlin, Germany in July, 2002. Papers for all such conferences are reviewed according to ASME standards and the symposium volumes are published variously by ASME or commercial publishing houses. For information concerning upcoming conferences, authors should consult the meetings calendar in *Mechanical Engineering*.

Additional outlets for technical articles by AESD authors are provided by the archival journals, Journal of Engineering for Gas Turbines and Power, Journal of Turbomachinery, and Journal of Energy Resources Technology, and the monthly, Mechanical Engineering. Owing to peer review requirements and some queuing of accepted papers before publication, a year to 18 months can elapse between paper submission and publication. Still, archival journals are the appropriate forum for articles of enduring value. Prospective authors should see current issues of the journals for instructions concerning the submission of articles.

For answers concerning your questions about AESD publishing opportunities contact M.J. Moran (contact information elsewhere in this newsletter.)

*M.J. Moran*

## AES Division Participation in IECEC

This year's 36th IECEC was hosted by ASME with a theme of "Energy Technologies Beyond Traditional Boundaries" at the Westin Hotel in Savannah, Georgia from July 29-August 2, 2001. The AESD co-sponsored several technical sessions on "Building Energy Systems", "Cogeneration and Thermal Energy Storage" and "Electric Power Systems" as well as Advanced Heat Pumps and other topics. The 37th IECEC will be hosted by IEEE in Washington, D. C., July 28 - August 1, 2002 at the Omni-Shoreham hotel. There will be plenty of opportunities for you to volunteer to help in organizing sessions, writing papers, reviewing papers, etc. The contact information for this conference is as follows:

Dr. William D. Jackson, General Chair
HMJ Corporation, P. O. Box 470
Kensington, MD 20895
(301) 946-1586
wdjacksonhmjcorp@aol.com

*Sriram Somasundaram*

# Scaling Laws in Miniature Heat Engines

Jay Kapat and Louis Chow

## Introduction

Compact and portable power generation devices are key components in many commercial, consumer and military systems, such as portable computers, and cellular phones. So far batteries have been the only providers of the required portable power. However, as the user systems become more complicated and power hungry, even the state-of-the-art battery technology becomes less and less appealing. For example, a proposed next generation soldier system for army requires power generation devices with specific energy of at least 2000 W-hr/kg for missions exceeding 72 hours of duration, whereas the most advanced battery technology can provide around 200 W-hr/kg. Naturally alternate power generation devices such as fuel cells and heat engines are receiving more and more attention. This article focuses on miniature heat engines and the relevant scaling laws that should be considered during design for compact and portable power generation.

Heat engines based on Brayton cycles and internal combustion engines are the most popular heat engines that are currently being looked at for possible miniaturization, primarily by researchers at MIT and UC Berkeley, respectively. There are also less proven technologies such as piezoelectric heat engine proposed by researchers at Washington State University, or knock engines being worked on by researchers at Honeywell. However, this article focuses on proven and tested cycles such as Brayton and Otto.

Rest of this article illustrates six design issues that must be simultaneously considered in the design of a miniature system based on Brayton or Otto cycle.

## Separation of Hot and Cold Ends

Any heat engine requires a hot and cold end, corresponding to the hot and cold reservoirs in the thermodynamic cycles. In a miniature system, these two ends are physically close, leading to a parasitic heat transfer from the hot to the cold end that does not produce any work and bypasses the thermodynamic cycle. Depending on the actual design, this parasitic heat transfer can be significant or even a "show-stopper". This is illustrated with a hypothetical example below.

Let us consider a system based on the simple Brayton cycle, with ideal components, and with a pressure ratio of 2.5, a compressor inlet temperature of 300 K, a turbine inlet temperature of 1800 K and net power output of 20 W. In that case, with a cold-air cycle analysis (with 1.4 as the ratio of specific heats), the compressor exit temperature is 390 K and system efficiency is 23%, in the absence of any parasitic heat transfer from the turbine to the compressor. However, if it is assumed that the compressor and the turbine are separated by a ceramic layer with a thickness of 5 mm and a thermal conductivity of 1 W/mK, and the typical temperature difference across the ceramic separation layer is 1248 K (the difference between the average temperatures in the turbine and the compressor), then the heat flux across the layer is 25 W/cm$^2$. This heat flux corresponds to 792 W of parasitic heat transfer between the turbine and the compressor, for a circular device with a cross-sectional diameter of 2.5 inch. Obviously, this amount of heat transfer is absurd for a device that produces a net power of only 20 W. In other words, such a device cannot produce any net power if parasitic heat transfer between the hot and cold ends of the device is allowed without any special consideration for thermal isolation of the two sides (Finger *et al.*, 2002). This problem is further complicated if we consider that thermal isolation in a Brayton-cycle-based system typically means mechanical isolation of compressor and turbine, which are located on the same shaft in conventional designs. Thus, designers of such a system have to rethink conventional design philosophy and employ innovative modification if they have to reduce parasitic heat transfer. In a miniature rotary Wankel engine, thermal separation of hot and cold chambers, which coexist at the same time, thermal isolation between the hot and cold ends is even more difficult.

This problem is more prominent at smaller scales, whereas it is insignificant at conventional scale. This is so because the ratio of parasitic heat transfer rate to the overall power output scales as the inverse of the linear dimension squared, for the same specific power and the same operating temperatures. Similar argument can be applied to all other heat engines running on different power cycles, such as Otto and Diesel. The problem can be much more severe with the use of common micro-fabrication materials such as Si (with thermal conductivity of 140 W/mK) or SiC.

## Scaling in Turbomachinery

This issue pertains to only those systems that employ dynamic or turbomachine components, where the size, rotational speed and the pressure ratio across the machine are all related. To be more specific, the change of specific enthalpy across a turbomachine is proportional to the square of the blade tip speed ($U_{tip}$), which is proportional to the product of tip radius ($R_{tip}$) and the rotational speed ($RPM$):

$$\Delta h \propto U_{tip}^2 \Rightarrow \Delta h \propto (R_{tip} \cdot RPM)^2. \qquad (1)$$

This important design relation for turbo-machines poses a serious design challenge for a miniature system, since compact size requires small radii, high reliability requires slow rotational speed, whereas efficient operation requires large pressure ratio. Thus miniaturization can become an impediment to having a large system efficiency. As a result, the system designer is left to use innovative variation (such as regeneration or reheating) to the basic thermodynamic cycle in order to obtain acceptable efficiency in spite of a low-pressure ratio.

The design of a miniature turbomachine is often further complicated with the requirement of a low mass flow rate, corresponding to a low total power (which is typically imposed by the system requirement or by the associated miniature electric components such as motor or generator). In this case, even a moderate tip speed as required for any decent pressure ratio can cause large tangential velocities, $U_{tangential}$, compared to the radial component, $U_{radial}$, at the blade tips of a rotating stage, as can be seen from the following two equations. In any radial machine, the mass flow rate at the blade tips can be expressed as (Laveau *et al.*, 2000)

$$\dot{m} = 2\pi\rho R_{tip} b U_{radial}, \qquad (2)$$

where $b$ is the blade height, and $\rho$ is the local density. From the velocity vector at the blade tip, the tangential component can be expressed as (Wilson and Korakianitis, 1998)

$$U_{tangential} = U_{tip} \pm U_{radial} \cdot \tan(\alpha_w). \qquad (3)$$

Here, $\alpha_w$ is the relative flow angle, which is typically close to the blade angle, $\beta$, and the +/- sign in the equation depends on the type and design of the turbomachine. In miniature designs, since a small $b$-to-$R_{tip}$ ratio will produce large viscous losses, $b$ cannot be arbitrarily reduced. For good aerodynamic design, blade angle cannot approach 90° and is typically much less. As a result, $U_{tip}$ is often much larger than the second term on the right-hand side of equation (3), and $U_{tangential}$ is much larger than $U_{radial}$, leading to a large loss in the diffuser for a centrifugal compressor or inlet guide vane for a radial inflow turbine. This argument limits the blade tip speed that in turn limits the pressure ratio across the components in a stage. This design problem can be alleviated to some extent through the use of multiple stages at the cost of design complication and system size.

Any system design based on positive-displacement, rather than dynamic components such as a rotary Wankel engine, can ignore this design issue. However, it should be noted that internal combustion engines have lower overall system efficiencies than gas turbine engines because of the inherent system layouts and higher losses, as can be seen from the conventional-sized systems.

### Need for Small Relative Tolerance

Losses in any real component are directly related to the small relative tolerance. This relative tolerance can be expressed as the clearance-to-radius ratio in a reciprocating or Wankel device or the tip-gap-to-tip-radius ratio in a turbomachine. In conventional-sized gas turbines, for example, this ratio typically varies from 1% (for 200+ MW machines) to 4% (for 1 MW machines). It should be noted that as the relative tolerance increases, component efficiencies drop from near 90% values for gas turbines for 200+ MW power generation systems to 60% for 50 kW systems. For internal combustion machines, this ratio is typically larger thus contributing to larger losses. Since even with the current state-of-the-art micro-fabrication, an absolute tolerance of less than 1 to 10 microns cannot be realized in a real component such as a turbine or a compressor, a specified value for the maximum allowable relative tolerance dictates the minimum component size. Thus a 1% relative tolerance with an absolute tolerance of 10 microns requires that the component radius be no smaller than 1 mm with the size of the overall, packaged component approaching 1 cm. This argument suggests that any design for a heat engine with a practically useful efficiency requires a meso-scale, rather than a micro-scale, size.

### Need for High Temperature Materials

Even a modest value for system efficiency requires a rather high temperature for the hot end of the heat engine. As an example, let us consider a palm-sized power generation device, which is based on Brayton cycle, with an electrical output of 20 W and a specific energy of 2000 W-hr/kg on a 72 hour mission, and which runs on a hydrocarbon fuel (such as JP-8) with a specific energy content of 12000 W-hr/kg. The required system efficiency in this case is 28.7% even for a device weight of 300 g. This required efficiency is larger than even the efficiency of 23% obtained earlier for an ideal device based on a simple Brayton cycle with the hot reservoir temperature of 1800 K. This temperature is high even for most metals, let alone Si or SiC, the most common materials for micro-fabrication. The same argument holds good for Otto- or Diesel-cycle based machines. Even if the Brayton cycle-based device illustrated above is modified with introduction of regeneration (as noted in the next section), a hot-end temperature in excess of 1500 K is needed.

The combined requirement for a high temperature operation and a small relative tolerance suggests the use of newer techniques for micro-fabrication and newer materials that can be micro-fabricated. For this reason, an effort at the University of Central Florida is considering use of micro-stereolithography with absolute tolerance of about 10 microns or less (Figure 1) and a special polymer-derived ceramics that is not affected until around 1900 K.

*Figure 1. An Inflow Turbine Fabricated by Micro-Stereolithography.*

### Need for Regeneration

As illustrated earlier, a simple Brayton cycle cannot provide the efficiency required for the example used, even if all the components are ideal. This requires modifications to the simple cycle, such as regeneration and reheating. In particular, regeneration is the key to any practical system, as has been proven in commercial human-sized "micro-turbines" producing 50+ kW that have been derived through years of system optimization. For systems such as the ones considered here (with output of the order of 100 W or even less), use of regeneration is imperative, where small size and reasonable rotational speed preclude a large pressure ratio.

It should be noted that common heat engines such as aircraft engines or large utility-sized power generation plants do not use regeneration since heat exchangers for regeneration in these large systems will be prohibitively expensive and large. Also, for heat engines with pressure ratios larger than a critical value for a fixed value of the maximum cycle temperature, regeneration hurts the overall performance, as the compressor exhaust would be hotter than the turbine exhaust. Hence, if a designer for miniature systems start with the design for such a large system, it is easy to overlook the importance of regeneration.

Use of a heat exchanger for regeneration raises further issues. Miniaturization produces a larger surface-area-to-volume ratio, which helps in transport processes such as heat transfer leading to higher volumetric transport coefficient. This feature is helpful for a miniature heat exchanger. However, efforts to obtain a large effectiveness and small pressure drops require a large number of short, parallel ducts with small cross-sections for both hot and cold fluids.

Axial conduction in a miniature heat exchanger can significantly reduce the heat exchange effectiveness (Zhou *et al.*, 2000). The axial heat conduction comes from two sources: the heat conducted in the solid wall and in the flowing fluid in the channels. To neglect the axial heat conduction in the fluid flow, the Peclet number must be much greater than 1, which requires a relatively large Reynolds number and hence large pressure drop. A small axial conduction through the solid wall requires the use of thin walls of a material with a relatively low thermal conductivity. Thus in order to minimize axial conduction, a careful optimization needs to be performed. It should be noted that axial conduction is not typically a problem in large heat exchangers where Peclet number as well as ratio of heat exchanger length to wall thickness are quite large.

### Conclusion

Typical design rules that are applicable for components and systems of conventional size may not be applicable to miniature systems and components. Simple repackaging of a conventional design with micro-fabricated components will not provide the optimum performance, or may not even work. A miniature system must require a fresh design optimized for smaller size. Moreover, such a system should use components that are optimized for small size, are micro-fabricated wherever necessary and make use of the scale advantages in miniaturization.

*Further information about this technology can be obtained from Jay Kapat or Louis Chow of University of Central Florida at jkapat@mail.ucf.edu or lchow@mail.ucf.edu, respectively.*

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- CFD Application to Heat Pump Systems and Components
- Heat Actuated Sorption and Desiccant Heat Pumps
- Emerging and New Technologies for Heat Pump and Refrigeration Cycles - I and II
- Transcritical Cycles for Refrigeration and Heat Pumping
- CFD for Positive Displacement Compressors - Challenging Issues? (Panel Session)

**Micro and Mesoscale Energy Systems and Conversion Devices**

- Micro and Mesoscale Energy Systems and Conversion Devices

**Thermodynamics and The Design, Analysis, and Improvement of Energy Systems**

- Energy Systems and Design (2 sessions)
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- Fuel Cell Technology
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