Arnold Schwarzenegger
Governor

ENERGY INNOVATIONS SMALL GRANT PROGRAM: 1999 AND 2000 INDEPENDENT ASSESSMENT REPORTS

PIER FINAL PROJECT REPORT

Prepared For:
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Public Interest Energy Research Program

Prepared By:
San Diego State Research Foundation

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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

- PIER funding efforts are focused on the following RD&D program areas:
- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Energy Innovations Small Grant Program is the interim report for the Energy Innovations Small Grant Program (Contract Number 500-98-014) conducted by the San Diego State University Research Foundation. The information from this program contributes to all of the PIER Programs.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

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Abstract

The Energy Innovation Small Grants (EISG) program is specifically designed for higher risk, "proof-of-concept" ideas, in which the Energy Commission explicitly tracks–and expects–a number of technical failures. As a "proof-of-concept" program, EISG seeks out concepts that are not yet proven and are very early in the research pipeline. These programs encourage technical innovation and risk taking. The Energy Commission awards up to $95 thousand for EISG grants to test a new idea. After project completion, the PIER program uses independent experts to evaluate the research results and assess the technical success compared to the original project objectives, as well as the likelihood the product will succeed in the market.

Independent assessment reports are written at the completion of every EISG grant projects. The report outlines the objectives of the project, highlights the successes and failures, and offers recommendations for potential future work. This summary report includes many of the independent assessment reports for EISG grant projects awarded during the period of 1999 to 2000.

Keywords: EISG, Independent Assessment Report, electricity, natural gas, research, project, market, objectives, summary, highlights, outcomes, conclusions, benefits

Executive Summary

The Energy Innovations Small Grant (EISG) program is a component of the Public Interest Energy Research (PIER) Program that is managed by the California Energy Commission. The PIER Program benefits California electric and gas ratepayers by funding energy research, development, and demonstration (RD&D) projects that are not adequately provided for by the competitive and regulated energy markets.

The Commission recognizes the need for a program to support the early development of promising new energy technology concepts, a niche not covered by PIER general solicitations that focus primarily on development of established concepts. The Commission established the EISG program to meet this need. In addition, to encourage participation in the program, the process for soliciting, evaluating, and awarding grants has been simplified and streamlined.

This report includes project assessment reports for grant projects that were awarded in 1999 and 2000 and have not been previously published.

All data sources for tables and figures are from the author unless otherwise noted.

1.0 Introduction

In 1999 and 2000, the Energy Innovations Small Grant (EISG) program funded 65 grant projects for a total of $4.8 million. The independent assessment reports (IAR) for many of these grant projects have already been published. (See Tables 1.1 and 1.3 below.) This section contains the IARs from 1999-2000 EISG projects that have yet to be published. (See Tables 1.2 and 1.4 below.)

Table 1.1: 1999 EISG projects with published IARs

Project	Researcher	EISG Funding
Electrosynthesis of Device Quality Semiconductor Films	Interphases Research	$75K
Ventilation Measurement and Control	Federspiel Controls	$75K
Control of On-Off Equipment in Buildings	UC Berkeley	$75K
Process for Converting Sewage Sludge and Municipal Solid Wastes to Clean Fuels	Environmental Energy Systems, Inc.	$75K
Renewable Hydrogen Fuel Production by Microalgal Photosynthesis	UC Berkeley	$75K
SunGuard Roofing Tile for Natural Cooling	Powerlight Corporation	$75K
Modeling Greenhouse Temperature for Energy Efficient Production	UC Davis	$75K
New Gas Turbine Design for Electricity Generation	UC Irvine	$75K
Development and Characterization of Improved Dye-Sensitized Nanocrystalline Solar Cells	UC Santa Cruz	$75K
Omni Smartpump	Omni Instruments	$75K
Improved Operational Turndown of an Ultra-Low Emission Gas Turbine Combustor	Alzeta Corporation	$74K

Project	Researcher	EISG Funding
Design and Optimization of Solar Absorption Chillers	Bergquam Energy Systems	$75K
Energy Shaver – Thermal Energy Storage Device for Air Conditioners	Redstone Engineering	$75K
Light Activated Surge Protecting Thyristor	OptiSwitch Technology	$75K
Novel Composite Membranes for Fuel Cells	California Institute of Technology	$75K
Development of a Unique Gas Generator for a Non-Polluting Power Plant	Clean Energy Systems	$75K
Integral Catalytic Combustion / Fuel Reforming for Gas Turbine	University of Maryland	$75K
Catalytic Stabilizer for Industrial Gas Turbines	Precision Combustion, Inc.	$75K
Direct Operation of Solid Oxide Fuel Cells on Natural Gas	Northwestern University	$75K
Non-Vacuum Thin-Film Photovoltaic Process	Unisun	$75K
Two-Phase Flow Turbine for CoGeneration	FAS Engineering, Inc.	$75K
Composite Architectures for Sub-600 Degree Celsius Fuel Cells	UC Berkeley	$71K
The Anaerobic Pump Prototype Testing	Technology Matrix Corporation	$71K
High-Efficiency Single-Phase Air Conditioner	Dr. Otto J. M. Smith	$75K

Table 1.2: 1999 EISG projects with IARs included in this section

Project	Researcher	EISG Funding
New Generation Thermoelectric Materials for Power Generation and Refrigeration	UC Berkeley	$75K
Actively Controlled Jet Injection in Gas Turbine	UC Los Angeles	$75K
Microchannel Reformer for Hydrogen Production From Natural Gas	Makel Engineering	$75K
Plug-In Photovoltaic Receiver for Concentrator Applications	SunPower Corporation	$75K
Reduced Cost Power Electronic Converter for Generator Applications	University of Idaho	$75K
Attic and Crawl Space Ventilation Air Heat Exchanger	University of Oregon	$75K
Modeling of Chemical Processes in Geothermal Reservoirs	GeothermEx, Inc.	$75K
Ventilation Cooling Controller Strategies	UC Los Angeles	$75K
Use of Solid Oxide Membranes	University of Southern California	$75K
Energy Production From Bulk Wastewater	UC Santa Barbara	$75K

Table 1.3: 2000 EISG projects with published IARs

Project	Researcher	EISG Funding
Single-Crystal Silicon Sheet Growth	Energy Materials Research	$75K
Carbon Foam-Based NOx Biofilter	UC Davis	$75K
Corrosion Resistant Coating for Carbonate Fuel Cell Components	Chemat Technology, Inc.	$75K
Biomass Boundary Layer Turbine Power System	EnergySchmidt	$75K
Improved Performance of Energy Recovery Ventilators Using Advanced Porous Heat Transfer Media	The Regents of the University of California, San Diego	$75K
Counter Rotating Wind Turbine System	Appa Technology Initiatives	$75K
Increasing Efficiency of Geothermal Energy Generation With High Resolution Seismic Imaging	3DGeo Development, Inc.	$75K
Distributed Generation Drivetrain for Windpower Application	Dehlsen Associates, LLC	$75K
Energy-Efficient Air-Handling Controls	Federspiel Controls	$75K
Omni-Directional Insect Eye Concentrator Using a Hyper-Spectral Photovoltaic Cavity Converter (PVCC)	United Innovations, Inc.	$75K
Research on Manufacturing Quadruple-Junction Solar Cells	UC Los Angeles	$74K
Highly Conductive, Water Insoluble and Thermally Stable PEM From Functionalized POMs	Chemat Technology, Inc.	$75K
Evaluation of New Solar Air-Conditioning System	WorkSmart Energy Enterprises, Inc.	$75K

Project	Researcher	EISG Funding
Development of Optimum Design Configuration and Performance for Vertical Axis Wind Turbine	California State University, Long Beach Foundation	$70K
Commercial and Residential Super-Insulated Phase Change Material Water Heater	VacuPanel, Inc.	$75K
A PCM Slurry System to Decrease Peak Air-Conditioning Loads	Leading Technology Designs, Inc.	$74K
An Integrated Anti-Fouling Technology for Energy-Efficient Chillers	J&D Thermo-Fluid Technology, Inc.	$75K
The Sagebien Project	Davis Hydro	$75K
Development of a PEM Electrolyzer: Enabling Seasonal Storage of Renewable Energy	Humboldt State University Foundation, Schatz Energy Research Center	$74K
Field Validation of a Model of Generation and Migration of Methane and Other Gases in Landfills	GC Environmental, Inc.	$75K
Simple and Reliable Active Power Filter for Energy Efficiency and Power Quality	UC Irvine	$75K
Method of Improving Efficiency of Combined Cycle Power Plants	Energy Constructs	$64K
OTM-Aided Oxygen-Enhanced Combustion	University of Southern California	$75K
Polymer-Zeolite Nanocomposite High-Temperature Proton-Exchange-Membranes for Fuel Cells	UC Riverside	$75K

Table 1.4: 2000 EISG projects with IARs included in this section

Project	Researcher	EISG Funding
Close-Cycle Valved Cell (CCVC) Heat Engine	Joseph Barrett Bland	$75K
Energy-Efficient Designs for Swimming Pool Pump Systems	ADM Associates, Inc.	$75K
Controlling Fouling With Rice Straw Blends in Biomass Boilers	University of California Davis	$74K
Application Feasibility Study of Gravitational Non-Equilibrium Heat Pumps and Heat Engines	University of Cambridge	$75K
An Innovative Approach to Stabilize the Thermal Conductivity of Air Plasma-Sprayed Thermal Barrier Coatings (TBCs)	Purdue University Research Foundation	$75K
Low Cost Hybrid Inverters Utilizing Insulated-Gate Bipolar-Junction Transistors (IGBT) and Silicon - Controlled Rectifiers (SCR)	Wisconsin Power Electronic Research Center	$75K
Advanced Generation of Hydrogen and Carbon Monoxide From Improved Methane-Carbon Dioxide-Steam Reforming Process for Use in Fuel Cell Applications	Dr. Zoe Ziaka	$75K

2.0 1999 Independent Assessment Reports

The Energy Innovations Small Grant (EISG) program awards numerous grants for innovative energy research projects every year. Independent assessment reports (IARs) highlight the project outcomes for each of EISG projects. This section includes the IARs from grant projects that were awarded in 1999 that have yet to be published.

2.1. New Generation Thermoelectric Materials for Power Generation and Refrigeration

Awardee: University of California, Berkeley
Principal Investigator: Professor Angelica M. Stacy

Introduction
The defining characteristic of thermoelectric (TE) materials is that the application of electromotive force (EMF) generates a temperature gradient, while a temperature gradient generates an EMF. Currently, TE materials (bismuth telluride alloys) have applications in refrigerators and power generators. The National Aeronautics and Space Administration (NASA) has used TE materials to generate power for deep-space probes. Although low efficiency limits widespread applications, recent research suggests that quantum confinement (i.e. fabricating them in the form of one-dimensional [1-D] nanowires) can improve the efficiencies of these materials.

This project attempted to determine the utility of 1-D thermoelectric materials. Synthesization of the nanowires was the major challenge. The project used electrodeposition (or, the process of producing a metallic coating on a surface by the action of electric current) for this purpose. The first part of the project involved determining the optimal conditions for the electrodeposition of the thermoelectric materials bismuth telluride (Bi2Te3) and cobalt triantimonide (CoSb3). Bi2Te3 proved the more promising candidate of the two for the electrodeposition of nanowires. The second part of the project involved electrodepositing Bi_2Te_3 into a porous alumina template to fabricate nanowires. Finally, the nanowires were characterized by obtaining values for their Seebeck coefficients (or, a measure of the magnitude of an induced thermoelectric voltage in response to a temperature difference across the material) and by performing further analysis of the results.

Objectives

The goal of this project was to determine the feasibility of enhancing the thermoelectric effect through quantum confinement of thermoelectric material to one-dimensional nanowires. The researcher established the following project objective:

1. Prepare the templates and refine electrodeposition technique.
2. Electrodeposit the materials under various conditions to obtain usable nanowires,
3. Characterize the resulting product.

Outcomes

1. The project obtained commercially available porous anodic alumina filters for use as templates in which to electrodeposit the thermoelectric nanowires. The passages in these filters consisted of a matrix of pores of about 200 nanometer (nm) average diameter. The project developed the in-lab capability to create alumina templates with a uniform pore size as small as 40 nm.
2. The project made multiple attempts to create usable nanowires:
    a. The thermoelectric precursor material cobalt antimonide (CoSb) was deposited into a template of 100 nm pore size, but the desired crystalline form, $CoSb_3$, did not result.
    b. The thermoelectric material, Bi_2Te_3, was deposited into the pores of templates with 200 nm pore size.
    c. Using the now-established technique, the thermoelectric material, Bi_2Te_3, was next deposited into the pores of templates with 40 nm pore size.
    d. The wires were Te-rich at the base, where electrodeposition began. They reached the ideal composition after a few microns length of wire had been deposited.
3. The Seebeck coefficient of the 200 nm-diameter wire and the 40 nm-diameter wire were measured and compared to bulk Bi_2Te_3 thermoelectric material, as follows:
    e. Bulk Bi_2Te_3, S = -210 micro volts/ Kelvin (K)
    f. 200 nm array, S = -80 micro volts / K
    g. 40 nm array, S = -30 micro volts / K

Conclusions

1. Thermoelectric material can be synthesized in arrays of nanowire with individual wire diameter of 40 nm.
2. Bi2Te3 can be synthesized into an array of wires, with 95 percent complete pore filling.
3. The composition gradient at the base of the wire can significantly affect the transport properties of the wire.

This project attempted to determine the feasibility of enhancing the thermoelectric effect through quantum confinement of thermoelectric material to one-dimensional nanowires. Feasibility was not determined. Additional research is required to determine if better control of the composition along the length of the wire can improve the value of the Seebeck coefficient, or if the composition gradient at the end of the wire can simply be "cut off" or otherwise removed.

In addition, research is needed to determine if these wires show enhanced thermoelectric efficiency.

Recommendations

As reported in the October 11, 2001, issue of *Nature*, values of ZT (the dimensionless figure denoting the efficiency of thermoelectric material) greater than 2.4 have been achieved at 300 Kelvin using p-type Bi_2Te_3/Sb_2Te_3 superlattices. (Ref. Nature 413, 597-602 [2001]). The question of suitability to electric power and commercial cooling remains. The Program Administrator recommends that this line of research continue in order to determine whether or not 1-D quantum confinement has been achieved with the 40-nm wire diameter. The tasks immediately at hand lend themselves well to a simple continuation and extension of the research direction taken by this project.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research, if ultimately successful, will be through the reduced environmental impacts of the California electricity supply, transmission and distribution system. There are commercial thermoelectric refrigerators and generators currently on the market. These generators customarily operate in the temperature range of waste heat or solar-trough concentrators and list retail at about $6.00 a watt in small quantities. This is achieved with efficiencies ranging from 5-10 percent. Improvement of this efficiency to 20-30 percent would result in a significant shift toward thermoelectrics across a broad spectrum of commercial and consumer applications.

2.2. Actively Controlled Jet Injection Gas Turbine Engine

Awardee: UCLA Dept. of Mechanical and Aerospace Engineering
Principal Investigator: Ann R. Karagozian

Introduction

Dilution air jets are used in gas turbine engines for temperature pattern factor optimization, for cooling turbine blades, and for nitrogen oxide (NO_x) reduction through air-fuel mixture ratio control. Active "tuning" of such dilution air jets in a burner's primary zone could rapidly produce a lean combustion mixture, reducing NO_x emissions. The same "tuning" could actively control the shape of the temperature "pattern factor" of the air entering the turbine section of the engine. Improvements in this area would contribute to increased engine durability and efficiency. Active control of transversely injected fuel jets in gas turbine engines to enhance mixing and hence reaction processes could also lead to improved engine durability as well as reduced emissions.

This project focused on control strategies for the optimization of penetration, spread, and mixing of an actively forced jet in a cross-flow or transverse jet. These studies assist in developing closed-loop control methodologies to optimize mixing and, potentially, reactive flow characteristics for the cross-flow air or fuel jets that occur within gas turbine engines. Development of this technique will allow control engineers to reduce engine emissions and reduce turbine inlet air temperature pattern factors. (A pattern factor describes the variation in the temperature of the gasses entering the turbine section of the engine.) Turbine design engineers can design using higher turbine inlet temperatures when the pattern factor is smaller. Higher turbine inlet temperature is a key factor in higher engine efficiency.

Objectives

The goal of this project was to prove the feasibility of using actively controlled forced jet injection (transverse jet) to optimize the control strategies of turbine engines. The researcher established the following project objectives:

1. Experimental Studies
    a. Quantify flow conditions in the laboratory tunnel accurately.
    b. Perform smoke visualization of pulsed jets in cross-flow.
    c. Perform planar laser-induced fluorescence (PLIF) imaging of acetone seeded in the pulsed jets in cross-flow.
    d. Quantify conditions leading to optimal mixing as visualized in smoke and PLIF imaging.
    e. Install micro pressure and other transducers in the tunnel to obtain time-series data for experimental controller development.
2. Computational Studies

a. Perform three-dimensional (3D) vortex element simulations corresponding to experimental conditions explored for pulsed transverse jet.
b. Quantify mixing and operating conditions for optimal mixing from simulations and compare with experimental results.
c. Develop reduced-order model for pulsed transverse jet controller development.

3. Controller Development and Testing
    a. Develop and test reduced-order controller from computational studies.
    b. Develop and test controller from time-series pressure (and other) experimental data.

Outcomes

1. Experimental Studies
    a. The researcher accurately quantified flow conditions using hot wire anemometry (measurement of wind force and velocity). The flow conditions are spatial and temporal velocity profiles at the jet exit and within the laboratory tunnel. This quantification identified an important issue with respect to the actively controlled transverse jet; namely, the non-linear dynamics of the jet excitation/actuation system causes the actual output velocity waveform at the jet exit to be quite different from the desired input waveform. Identification of this problem led to an altered approach used in the controller development (see 3 below).
    b. The project utilized smoke visualization of pulsed transverse jets extensively, as described below.
    c. PLIF imaging of seeded acetone was not performed for these experiments. The researcher intended to use a xenon-chlorine (XeCl) excimer laser in these experiments, but it failed in the latter part of 1999. Repeated attempts to repair the laser were unsuccessful. Nevertheless, the researcher could quantify the performance of the jet actuation system under controlled or compensated conditions using the smoke injection technique. The inability to perform PLIF experiments, while disappointing, was not a major loss for the project.
    d. The smoke visualization technique was used to identify conditions producing maximum jet penetration, maximum jet spread, and most distinct vortex structure formation in high-speed still photographs. In most cases, the conditions producing maxima in all three of these parameters were the same; that is, conditions for maxima in jet penetration most often produced maxima in spread and in coherent vortex formation.
    e. The researcher determined that hot wire anemometry data rather than time-series pressure transducer data were sufficient to obtain information required for controller/compensator development (see 3 below).

2. Computational Studies
    a. The project performed three-dimensional vortex element numerical simulations, both for the unforced transverse jet and for the pulsed transverse jet. The researcher published the results for the former in the Journal of Fluid Mechanics. The results of the latter were in preparation at the time of this report.

b. The researcher developed a computational methodology for comparing entrainment of cross-flow into the main flow jet for different operating conditions. The researcher related the entrainment to mixing, principally to the unforced jet in cross-flow. As the researcher completes the study of pulsating jet simulations, the researcher will apply this methodology to the forced jet case as well.
c. Through experimental data analysis the researcher produced a reduced order model for jet controller development. The researcher originally proposed using two-dimensional (2D) computational models, but the researcher found the linear model developed for this approach worked well.

3. Controller Development and Testing
    a. Because of the success of the controller/compensator developed from experimental time-series data, the researcher did not find it necessary to use a 2D computational model.
    b. The controller developed from the experimental time-series data (hot wire anemometry data) was successful. The project developed a linear model for the dynamics of the forced jet actuation and used that model to derive a dynamic compensator for the actuator. This approach is different from that originally proposed, but was successful. When the compensator was applied, the jet could be forced in a manner that resulted in a more precisely prescribed, temporally varying exit velocity. The root-mean square (RMS) amplitude of perturbation of this exit velocity could be made independent of the forcing frequency. Thus, the researcher could conduct systematic studies of conditions producing optimal jet behavior.

Conclusions

Both experimental and computational approaches indicated significant improvements in jet penetration and spread with appropriate jet excitation. Use of the dynamic compensator or jet actuator controller allows straightforward comparisons among different conditions for jet excitation. The project clearly identified specific excitation frequencies and characteristic temporal pulse widths that optimize transverse jet penetration and spread through the formation of distinct, deeply penetrating vortex structures. These required conditions correspond to sub-harmonic frequencies of the natural modes associated with the unforced jet in cross-flow and with specific pulse widths or duty cycles applied during square wave excitation.

These results suggest a significant potential exists for achieving active engine mixing control via transverse jet compensation, with the consequent benefits for improved engine durability and efficiency as well as reduced engine emissions.

While the results of this project are encouraging, researchers must resolve several technical challenges before practical application of these findings produce measurable benefits for California ratepayers.

Recommendations

The data obtained in this project provide a basis for further research work. The researcher should focus on only one objective in any advanced work. That objective could be reduced emissions, or it could be reduced pattern factor. Each of these topics usually requires very thorough experimental validation based on 3D real time measurements. The researcher should once again attempt to use the PLIF imaging technique, a technique that failed during the pursuit of this project.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER Program, the program administrator has determined that the proposed technology should be considered for follow-on funding within the PIER Program. Receiving follow-on funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary public benefit offered by the proposed technology is increased affordability of electricity in California. This will be accomplished by: (1) Reducing the turbine inlet "pattern factor," and (2) Lowering the cost to meet low emissions standards.

This project successfully demonstrated the capability to apply offline control concepts to the optimization of pulsed jets in cross-flow within an engine environment. The control methodology could be applied to optimization of dilution air or fuel jet injection in gas turbine engines. If improved dilution jet penetration and mixing can be achieved in an actual gas turbine engine environment, it is likely that the resulting improvements in turbine temperature pattern factor and NO_x emissions will result in measurable benefits for the state. These could include reduced energy costs via improved engine efficiency and durability, as well as reduced costs for emissions control equipment via cleaner power generating engine exhaust. The program administrator estimates that another five years of research and development work are necessary before benefits are possible in the California marketplace.

2.3. Microchannel Reformer for Hydrogen Production From Natural Gas

Awardee: Makel Engineering, Inc.
Principal Investigator: Dr. Darby B. Makel

Introduction
Fuel cells are ultraclean, quiet, highly efficient devices for generating power. Most fuel cells require hydrogen as a fuel. Therefore, the adoption of fuel cells depends on technology for producing hydrogen. Methane gas, the major constituent of natural gas, is a potential source of hydrogen. Methane contains four hydrogen atoms for every carbon atom. The existing delivery infrastructure for natural gas makes methane an ideal source of hydrogen for small-scale, localized, fuel-cell power generators (1-50 kilowatt).

This project focused on the use of microchannel devices to produce hydrogen from methane. Microchannel chemical reactors are an emerging technology in which microscale and mesoscale (1 to 250 microns in dimension) passages are fabricated into silicon and ceramic substrates and then coated with catalysts. This technology has the potential for producing "chemical processing on a chip," and it offers the potential of low-cost, mass-produced devices. The technology requires no scaling for different sized reformers. Instead, increased capacity is obtained by replication of the deposition pattern and the use of multiple units in parallel. While functioning in parallel, these units can occupy the same wafer or substrate.

Defense Advanced Research Projects Agency (DARPA) funding has enabled significant progress in the development of microchannel and microelectromechanical systems. The development of fluidic devices such as valves and pumps, heat exchangers, and mixers is important for chemical-processing applications. Research has focused on fabrication techniques, scaleable structures, and useful chemical syntheses.

This project emphasized the selection of processes and materials to produce compact, low-cost methane-to-hydrogen conversion units. Hydrogen can be produced from methane by more than one approach. The researcher selected the following chemical steps: 1) the partial oxidation of methane producing hydrogen, carbon monoxide, carbon dioxide, and water; 2) the water-gas-shift reaction (WGSR) removing most of the carbon monoxide and producing additional hydrogen; and 3) the removal of the remaining carbon monoxide from the product stream by "methanation," or the preferred oxidation of carbon monoxide.

Within the selected approach, there were at least two possible paths: 1) run the partial oxidation reaction with the highest hydrogen production; 2) run the partial oxidation reaction at the ideal conditions to feed the water-gas-shift reaction. The researcher selected path number two, since it does not require the addition of water to perform the WGSR, thus avoiding the extra complexity/cost of preprocessing tap water (filtering, softening, vaporization).

Objectives

The goal of this project was to determine the feasibility of using microchannel technology to produce hydrogen from methane. The researcher established the following project objectives:

1. Design and fabricate prototype, microchannel, methane-to-hydrogen devices using partial oxidation reactions.
2. Perform testing of microchannel reactors to demonstrate conversion efficiency and catalyst performance.
3. Demonstrate conversion efficiency greater than 30 percent on dry basis.
4. Demonstrate carbon monoxide (CO) levels in hydrogen product stream under 10 parts-per million (ppm).
5. Conduct a life test of 200 hours of continuous feasibility without degradation of efficiency.
6. Develop a design database and validate thermochemical and fluid models of microchannel devices to enable optimization of designs.
7. Deliver two working prototype reformers to the California Energy Commission.

Outcomes

1. The project successfully designed and fabricated prototype microchannel methane-to-hydrogen devices using partial oxidation reactions. The project produced microchannel reactors by bonding laser-machined alumina platelets. Platelets that formed the reaction sections had built-in heaters and temperature sensors. Each catalyst was deposited in its respective reactor section on the reactor wall. Thermoanalysis showed that the production of a totally integrated reactor required design modification to maintain a uniform temperature in the reactor sections. Separating the reactor sections overcame this problem
2. The researcher selected catalysts by literature search, found and tested commercial sources, and finally produced and tested the catalysts in the same manner to be used in the microchannel reformer.
3. The experimentally determined conversion efficiency was 66 percent.
4. The best conditions resulted in a carbon monoxide (CO) content of approximately 2 percent, considerably higher than the target.
5. The project produced a prototype fuel-conversion system that operated for a total of 220 hours without detected degradation.
6. The project produced significant design data and validated thermochemical and fluid models. The project administrator did not evaluate the usefulness of these data for future designers.
7. Two working prototypes were not delivered to the California Energy Commission.

Conclusions

The researcher demonstrated the feasibility of using microchannel technology for the production of hydrogen from methane. Unfortunately, the CO content of the produced gas was too high for practical applications in Proton Exchange Membrane (PEM) fuel cells. For that reason, the project did not evaluate the potential cost reduction of using microchannel technology over conventional fuel-processing technologies.

Catalytic techniques developed proved successful for the catalysts selected. The performance of the partial oxidation, the preferred oxidation, and the methanation catalysts deposited on the microchannel alumina substrate matched the performance of the commercial catalysts used as benchmarks. The performance of the water-gas-shift catalyst was inferior to the commercial catalyst selected.

The WGSR catalyst did not perform as well as expected. The best conditions resulted in CO content of approximately 2 percent after the WGSR. The researcher did not determine the cause(s) for the high levels of CO. The methanation catalyst proved successful for CO removal in simulated streams. However, since the WGSR reactor did not drop the CO concentration below 1 percent, using a methanation catalyst to remove CO would consume too much hydrogen to be practical.

Recommendations

While this project demonstrated the feasibility of using microchannel technology for methane-to-hydrogen fuel processing, there are significant barriers to the use of the selected technology (substrate and catalyst) with most fuel cells. Areas that require further development include CO reduction, heat management, and integration of control systems. The PA recommends that the researcher focus his technical efforts on a specific type of fuel cell and work with an appropriate manufacturer to develop the necessary technical specifications for the fuel processor prior to further research.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. The project attempted to produce a low-cost, methane-to-hydrogen device that would have lowered the cost of fuel-cell-based electricity-generation systems.

Fuel cells offer large potential benefits to the ratepayers of California. These benefits include the quiet, efficient production of electricity with almost no pollution. Fuel cells are also candidates for use in distributed generation. This project offered the potential to manufacture a low-cost device to produce hydrogen fuel from natural gas and thereby allow the economical use of fuel cells for central power and distributed-power generation.

2.4. Plug-In Photovoltaic Receiver for Concentrator Applications

Awardee: SunPower Corporation
Principal Investigator: Pierre J. Verlinden

Introduction
Since the beginning of terrestrial photovoltaic (PV) systems development, scientists have known that concentrating sunlight could reduce the cost of PV systems. Such systems use inexpensive mirrors and lenses to concentrate sunlight energy onto one small solar cell. Some solar cells are designed to operate at concentrations as high as 200-300 suns. A concentrating system can use fewer highly efficient, but possibly more expensive, solar cells.

There are three reasons why concentrating PV systems have not yet extensively penetrated the marketplace. First, concentrating systems must track the sun, which adds cost, and most installed systems are too small to absorb this cost while remaining economically viable. Second, tracking systems don't perform optimally in cloudy weather due to diffuse light. Third, the receivers of these concentrating PV systems have a stigma of poor reliability.

With the market opening up for PV systems larger than one (1) kilowatt, concentrating PV systems can potentially compete cost-effectively with flat-plate PV systems. Furthermore, recent performance testing has shown that concentrator PV systems can outperform flat-plate systems, on an annual basis, even in areas with significant cloud cover. A positive result from this project, mitigating PV receiver reliability concerns, will remove the third obstacle hindering the development of concentrating PV systems.

Project Objectives
The goal of this project was to determine the feasibility of using standardized receivers in systems that concentrate solar energy to increase reliability and to reduce system cost to $3,000 per kilowatt. The researchers established the following project objectives:

1. Design, build, and test a prototype receiver to include a secondary optical element, PV cell, substrate, bypass diode, heat spreader, heat sink, and all exterior electrical and mechanical connections.
2. Design the prototype for use in a large variety of concentrator modules.
3. Apply the Institute of Electrical and Electronics Engineers (IEEE) 1513 recommended qualification tests for photovoltaic concentrator receivers in testing the prototype.
4. Target a mass-production receiver cost not to exceed $10 each, to reach the cost goal of $3000/ kW.

Project Outcomes
1. A prototype plug-in PV receiver module has been fabricated, and 20 receivers have been shipped to a customer for evaluation.
2. For application in a variety of concentrator modules, it was determined the basic receiver design should not include the secondary optical element or a heat sink.

3. Reliability testing on the prototype is ongoing and positive so far.
4. Study and experience indicate a redesign of the heat spreader and electrical connections may be required to meet the target cost.

Conclusions

1. The receiver must be redesigned prior to large volume manufacturing of a reliable product. Thermal conductivity and heat management issues compel the redesign of the solar cell encapsulation within the heat spreader and the redesign of the electrical connectors.
2. The receiver does not include a Secondary Optical Element (SOE) or a heat sink. The researcher determined this would give the most flexibility to the module designer. However, a receiver can be designed to accommodate these elements as options or as add-ins.
3. Heat management is a key issue, including mitigation of effects of thermal stress.
4. The researcher did not present a current cost estimate. This may be due to the need to redesign elements to mitigate the effects of thermal stress. At this time it is not possible to conclude that the $3,000 per kilowatt (kW) goal has been met or that the researcher has a well-defined path to that goal. Once the design has been finalized it may be possible to meet the cost target if the researcher pays greater attention to product cost during redesign. The researcher has identified several alternative technologies as possible cost-reduction techniques. Cost reduction is the key to success for this technology. Cost of flat-plate, non-tracking PV systems are decreasing rapidly, reducing the potential cost advantage of the tracking system. A concentrating, tracking PV system must provide a significant cost advantage to the user to justify its added complexity.

Recommendations

The researcher should focus his efforts on building a receiver that meets performance goals and also allows installed system cost to be lower than $3,000/kW. Steps toward these goals include:

- Develop alternative socket solution to improve flexibility, manufacturability, and reliability.
- Continue development of the critical points of the receiver: attachment of substrate to heat spreader, attachment of cover glass, and encapsulation.
- Work with module manufacturers to define receiver specifications for different configurations.
- Begin a major build-to-cost redesign effort. The redesigned product must continue to meet performance specifications.
- Evaluate the market need for a module containing an integrated secondary optical element.

After taking into consideration: (a) research findings in the grant project, (b) overall development status and (c) relevance of the technology to California and the PIER Program, the program administrator has determined the proposed technology should be considered for follow-on funding within the PIER Program.

Receiving follow-on funding ultimately depends upon: (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The applicable goal for this research project is reduced environmental impacts of the California electricity supply or transmission or distribution system.

This project initiated development of concentrator photovoltaic (PV) systems with a target cost of about $3,000 per kilowatt fully installed, less than half the cost of current flat-plate PV systems. It gives the California ratepayer a renewable energy source that can cover both medium and large scale needs. Further benefit derives from economic competition introduced by the conversion of the process of producing PV concentrator systems from a high-tech manufacturing process with only a few competent players to an assembly process which could be competently performed by hundreds of competing California businesses.

The results of this project could lead to the reduction of costs to design and construct integrated PV power systems. Cost-effective PV systems can increase the application of this technology and thus reduce the environmental impact of electric generation in California. A simplified life cycle cost analysis was performed based on the following assumptions:

- Fuel costs are zero, as the sunlight is free.
- Interest rate for equipment purchase is 8 percent per annum.
- Capital costs is projected to be $3,000 per kilowatt.
- System lifetime is 20 years.
- Availability is 2,200 peak sun hours per year in California.
- System generates electricity on the average of six hours per sunny day.
- A moderate-sized commercial installation is 100 kilowatt.
- System is grid-connected so that net metering based pricing is used.

With the above assumptions, the system cost is $300,000, requiring 20 annual payments of $30,555.66 for payoff by end of life. The system generates 220,000 kilowatt-hours (kWh) of electricity per year, which must be valued to make the mortgage payment. Therefore the cost of electricity must be at least 13.9 cents per kWh.

Note that the above analysis does not place a monetary value on the reduced environmental impact resulting from utilization of this system over conventional electrical sources. Neither does it value the increased reliability contributed by the alternative power source during peak power usage times.

2.5. Reduced Cost Power Electronic Converter for Generator Applications

Awardee: University of Idaho
Principal Investigator: Dr. Joseph Daniel Law

Introduction
Wind energy can produce electricity at a nearly competitive cost in California. Subsidies bring the cost of wind-generated electricity in line with large conventional power plants. Improvements in the design of the power electronics of wind system could put the cost of wind-generated electricity on a par with that from a modern, combined-cycle power plant.
The researcher's goal in this project was to reduce the cost of the power electronic subsystem of a wind generator by 50 percent. A reduction of this magnitude might be enough to eliminate the need for government subsidies. This could greatly increase the installation of this form of renewable energy in California.

The researcher proposed an innovative method of converting energy from a wind-powered, variable-frequency induction generator, to a single-phase, fixed-frequency output. A standard, three-phase, six-switch, voltage-stiff inverter with split direct-current (DC) link provided three-phase positive and zero-sequence voltage components simultaneously. The three-phase positive sequence voltage of variable magnitude and variable frequency was applied to an induction machine to transfer the energy of the induction machine to the split DC link. The zero-sequence voltage components of fixed frequency and fixed magnitude transferred energy from the voltage-stiff inverter to a single-phase load through a zero-sequence filter.

Objectives
The goal of this project was to determine the feasibility of reducing the cost of wind-turbine power electronics by reducing the number of power electronic components via the implementation of zero-sequence filters. The researcher established the following project objectives:

1. Reduce the cost of variable-speed, wind-turbine power electronics by 50 percent by reducing the number of power electronic switches.
2. Construct a simple filter to transfer the energy produced by the system to a single-phase load.
3. Develop a new modulation algorithm for the converter that takes advantage of the filtering properties of an induction machine and a zigzag transformer.

4. Develop a stable control algorithm for the DC bus of the converter to be controlled by the converter switches alone.
5. Build a three-phase converter with arbitrary input frequency and fixed output frequency.

Outcomes

1. The researcher reduced the number of power electronic switches to six from ten by eliminating one converter unit for single-phase power generation. This removed the cost of one converter but added the cost of a zigzag transformer and increased the ratings and thus the costs of the existing converter components significantly.
2. The researcher developed a zigzag transformer as a zero-sequence filter.
3. The space-vector switching algorithm was modified to simultaneously modulate positive and zero-sequence components.
4. The researcher developed a control algorithm for the DC bus controlled by the converter switches alone.
5. The researcher built a working converter with a reduced number of components. It was a three-phase converter with arbitrary input frequency and fixed output frequency.

Conclusions

1. The proposed scheme eliminated the use of one converter unit and added a zigzag transformer as a zero-sequence filter for wind power generation for single-phase power output. A zigzag transformer added cost to the system. In addition, to maintain reliability, the remaining components had to be rated for higher kilovolt-ampere (KVA) and currents. This project showed that the KVA rating of the new converter switches needed to be at least twice that of the conventional scheme. This project also proved that the root mean square (RMS) current rating of the DC link capacitors needed to be at least 4.122 times the RMS current rating of the DC link capacitors of the conventional scheme. This resulted in higher system cost than the conventional scheme.
2. By adding a zigzag transformer as a zero-sequence filter and reconfiguring the power electronics, the researcher was able to reduce the parts count while maintaining power control.
3. The researcher developed an algorithm that simultaneously modulated the three-phase converter for both positive and zero sequence voltage components.
4. The researcher developed an algorithm to control the DC bus using the converter switches alone.
5. This project proved the scientific principles proposed by the researcher. The researcher was able to build and to test a reduced part-count power conversion system.

The goal of this project was to determine the feasibility of reducing the cost of wind-turbine power electronics by reducing the number of power electronic components via the implementation of zero-sequence filters. The researcher proved the technical feasibility of reducing the parts count; unfortunately it did not prove to be lower in cost. Therefore, the device is not economically feasible for wind-turbine application.

Recommendations

1. Simultaneous modulation of a single converter may be useful for applications other than wind turbines.
2. Discontinue further funding of research into this method of cost reduction for wind turbines.

Benefits to California

None known.

2.6. Attic and Crawl Space Ventilation Air Heat Exchanger

Awardee: University of Oregon
Principal Investigator: G. Z. Brown

Introduction

As the envelopes of buildings become more tightly sealed, the indoor air quality is compromised by a buildup of carbon dioxide, carbon monoxide, volatile organic compounds, and other undesirable substances. These gasses can cause a variety of health problems for the occupants. As a result, there is a current trend to increase ventilation standards to ensure indoor air quality. Increased ventilation can result in increased consumption of energy for cooling or heating. To reduce this energy consumption, one could use a heat exchanger to temper incoming air with the exhausted air before conditioning. This could 1) reduce the building peak load, 2) lead to downsized heating-ventilation and air conditioning (HVAC) equipment, 3) reduce energy consumption, and 4) improve air quality.

Commercially available heat exchangers are expensive (approximately $4,000 for a 1,400-square-foot [sq-ft] house) and most are not total enthalpy exchangers. (Enthalpy is used to calculate the heat transfer during a quasistatic process taking place in a closed thermodynamic system under constant pressure.) The primary problem is how to reduce cost so energy savings can pay back the initial cost of the heat exchanger in a short period of time. This project exploited underused areas (the crawl space or attic) in residential and small commercial buildings to increase heat exchanger surface area and used thin-film tubes for heat exchanges to reduce cost. The researcher projects that energy savings using this system would be on the order of 2.4 million British thermal-units per year (Mbtu/yr) for a 1,400-square-foot Title 24-compliant house in California's Climate Zone 16.

A low-cost, thin-film heat exchanger located in a crawl space or attic was proposed for its ability to transfer both sensible and latent energy. This application of carefully selected existing materials was an innovative concept and promised to result in a very cost-effective system. The researcher claimed that, on average, with parasitic losses, the proposed heat exchanger could be

65 percent efficient, could have a first cost 90 percent less than competitive heat exchangers, and could demonstrate a simple payback time as short as one year.

Objectives

The goal of this project was to determine the feasibility of using low cost, thin-film materials to construct an economical ventilation air heat exchanger in the attic and/or crawl space of residential and small commercial buildings. The researcher established the following project objectives:

1. Select thin-film materials and design a heat exchanger for a 1,400-sq.-ft house and one for a small commercial building. These heat exchangers should fit into existing crawl space or attic space in residential and small commercial buildings.
2. Build and test prototype heat exchangers. Build and test related connections to HVAC equipment, attic space, and/or crawl space.
3. Heat exchangers should cost less than $350 installed for a 1,400- sq.-ft. house and less than $600 for a small commercial building. Demonstrate simple payback of less than two years from reduced energy use.
4. Demonstrate total enthalpy effectiveness of greater than 50 percent.
5. Determine operating conditions under which condensation occurs and eliminate or integrate condensation.
6. Produce final heat exchanger design.

Outcomes

1. The research selected material and designed two heat exchangers that would fit into building attic and crawl spaces.
2. The researcher built two prototypes, and developed a test method based on The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standard American National Standards Institute (ANSI) / ASHRAE 84-1991 Method of Testing Air-to-Air Heat Exchangers. The test method was modified to reduce testing costs. Testing was performed in a laboratory environment. There is no indication that the researcher actually connected a thin-film heat exchanger to an attic space or crawl space for test purposes.
3. The researcher claims cost targets were met and established a one-year simple payback.
4. The researcher demonstrated sensible heat effectiveness of 55 to 82 percent and total enthalpy effectiveness of 54 to 77 percent. The researcher estimated average heat exchanger effectiveness at 65 percent.
5. The researcher designed the heat exchanger to transfer moisture from one air stream to the other, eliminating condensation under most conditions.
6. The researcher claims to have modified the heat exchanger design as a result of tests, but the researcher provided no supporting evidence.

Conclusions

1. Materials are commercially available for fabrication into thin-film heat exchangers. The researcher did not supply his evaluation criteria, nor did the researcher address the issue of long-term material life.
2. The project built and tested two prototype heat exchangers. The modified ASHRAE test method resulted in lower test costs but less accurate data. Data accuracy requires review before one accepts the premise that feasibility has been proven.
3. Cost data was not included in the final report. The claim that cost targets were met remains unsupported.
4. Technical performance met or exceeded the project goals based on the modified test procedures.
5. The researcher proved that condensation problems could be minimized or eliminated through design.
6. The research did not present a modified final design based on the test data.

The goal of this project was to determine the feasibility of using low cost, thin-film materials to construct an economical ventilation air, heat exchanger in the attic and/or crawl space of residential and small commercial buildings. The technical feasibility was proven. Because the researcher reported no life-cycle cost analysis, the question of economy is still open, even though first costs may well be very low compared to similar existing devices.

Recommendations

The researcher presented an innovative idea to save energy. The researcher did not provide sufficient information to conclusively determine its feasibility. The program administrator recommends that the researcher verify all test results using standard test methods. For example, heat exchanger leakage should be tested using the standard tracer gas method. All test information should be presented using industry-accepted levels of uncertainty for the instrumentation employed. The program administrator also recommends that the researcher reveal the material selected for the heat exchangers and the numerical value for each criterion used to select that material. The program administrator additionally recommends that the researcher publish a report detailing test methods and data to allow others in the field to profit from this project.

Second, the researcher should discuss the practicality and cost of this idea with remodeling contractors. The contractors should examine the practicality of installing large thin-film heat exchangers in attics and crawl spaces. Practicality includes existing codes, service requirements for other equipment located in those spaces, and the life of thin-film heat exchanges in areas subject to animal infestation. The contractors should also estimate the cost to install in a real building. Insurance experts should be asked about the fire rating of a building containing the proposed materials.

Third, the researcher should determine the savings of electricity and natural gas separately for each zone chosen. Also, the researcher should determine if the energy savings vary if the thin-film heat exchanger is located in the attic as compared to the crawl space.

The results of test data from this project and responses to these recommendations should be employed to construct a preliminary design for installation in a real building.

Benefits to California
Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research is to increase the affordability of electricity in California. The proposed ventilation air heat exchanger, if commercialized, could reduce energy consumption for a Title 24-compliant, 1400-sq.-ft. house by 2.4 Mbtu/yr in California Climate Zone 16 and 1.8 Mbtu/yr per house in California Climate Zone 15. If widely adopted, this could lead to lower energy bills, reduced need for new electrical generation and transmission, and improved air quality. The electric benefits would be reduced due to use of natural gas for heating. Total energy benefits would be reduced if the heat exchanger were installed in attic spaces in hot climates.

2.7. Modeling of Chemical Processes in Geothermal Reservoirs

Awardee: GeothermEx, Inc.
Principal Investigator: Subir Sanyal

Introduction
Geothermal power generation and mineral extraction from geothermal brines are affected by chemical processes within the reservoir involving the interactions between *in situ* fluids, reservoir rock, and injected waste water. Until recently, numerical-simulation technology for geothermal systems could not handle most chemical processes, except for the tracking of total salinity, one or two non-condensable gases, and non-reactive tracers. To fill this void in numerical-simulation technology, researchers at Lawrence Berkeley National Laboratory (LBNL) have developed an extension of the widely used geothermal-reservoir-simulation software TOUGH2. This software, called TOUGHREACT, includes chemical interactions

between liquid, gaseous, and solid phases that are coupled to the modeling of solute transport and subsurface multiphase fluid and heat flow in TOUGH2.

This project evaluated the applicability of TOUGHREACT to a set of five tests representing practical chemical problems encountered in geothermal fields in California. Each test case concerns a specific chemistry-related problem, the solution of which would help improve geothermal-reservoir management and thereby reduce the cost and environmental impact of geothermal power in California.

Objectives

The goal of this project was to prove the feasibility of using a numerical computer code to simulate the chemical interactions between chemical species in geothermal fluids, reservoir rock, and injected waste water. The objectives of the project were to debug and test the code on five real-world problems that are relevant to geothermal operations in California. The project was to identify code limitations, and modifications needed to make the code, database, or models operational.

The objectives were:

1. Identify code limitations for the problem of Mineral Recovery.
2. Identify modifications needed for the problem of Mineral Recovery.
3. Identify code limitations for the problem of the "Injection of Silica-Saturated Brine."
4. Identify modifications needed for the problem of the "Injection of Silica-Saturated Brine."
5. Identify code limitations for the problem of Low-pH Fluid Injection.
6. Identify modifications needed for the problem of Low-pH Fluid Injection.
7. Identify code limitations for the problem of Long-Term Gas-Production Trends.
8. Identify modifications needed for the problem of Long-Term Gas-Production Trends.
9. Identify code limitations for the problem of Chemically Reactive Tracers.
10. Identify modifications needed for the problem of Chemically Reactive Tracers.

Outcomes

The TOUGHREACT code was initially developed for the UNIX platform. The code required minor modifications to allow its installation on a PC-Windows platform. Then, the code was tested to make sure it executed properly. This testing was performed with the support of Dr. Xu, a co-developer of the TOUGHREACT software from Lawrence Berkeley National Laboratory. No incompatibility problems emerged.

1. Code limitations for the problem of Mineral Recovery. Zinc was chosen to evaluate TOUGHREACT's capabilities for mineral recovery. TOUGHREACT correctly models the chemical interactions involving zinc in hypersaline reservoirs and can therefore be used to model zinc extraction. The zinc-concentration distribution in the

aqueous phase, calculated by TOUGHREACT, is consistent with that observed in actual geothermal fields under similar temperature and pressure conditions. The software is limited to a maximum content of 20 percent of Total Dissolved Solids (TDS) by weight.

2. Modifications needed for the problem of Mineral Recovery. Increase the capability of the code to handle TDS levels of up to 28 percent.
3. Code limitations for the problem of the Injection of Silica-Supersaturated Brine. The researchers developed this problem to investigate the effects of silica-laden brine injections on reservoir porosity and permeability. TOUGHREACT includes a model for calculating the rate of silica scale deposition in the reservoir and the consequent reduction in the porosity and permeability of the reservoir rock. While this model ran successfully using reaction rates obtained from laboratory testing, the setting of the simulation grid was too coarse to see dramatic effects that could occur in areas near the injection well.
4. Modifications needed for the problem of the Injection of Silica-Supersaturated Brine. The validity of applying laboratory-derived reaction rates to actual field conditions requires field verification. Code modifications may or may not be needed, depending on the outcomes of the field verification. Future modification should reduce the size of the computer grid near the well bore.
5. Code limitations for the problem of the Injection of Low-pH Brine. TOUGHREACT includes a model for mineral dissolution in low-pH brine near the injection well and redeposition in areas away from the injection point where the pH remains unchanged. The model run indicated no problems.
6. Modifications needed for the problem of the Injection of Low-pH Brine. Decrease the size of the computer grid near the well bore to identify possible local effects.
7. Code limitations for the problem of Long-Term Gas-Production Trends. TOUGHREACT is capable of simulating long-term production trends of the main gas component (carbon dioxide [CO_2]) in geothermal fluids. Behavior of other gases such as H_2S, ammonia, and others cannot be rigorously modeled using TOUGHREACT. In addition, chemical interactions between the various chemical species in the gaseous phase are not currently incorporated into the software.
8. Modifications needed for the problem of Long-Term Gas-Production Trends. The code needs modification to include the behavior of hydrogen sulfide (H_2S), ammonia, and other gases. The researcher should include the interaction with the rock matrix in the long-term prediction. This needs to be accomplished before the code is used to minimize the production of the entire spectrum of geothermal gases.
9. Code limitations for the problem of Chemically Reactive Tracers. TOUGHREACT includes the necessary chemical equilibria and kinetics data to handle reactions involving reactive tracers in geothermal reservoirs. However, this capability is not linked to a version of TOUGH2 that enables tracer-injection modeling.
10. Modifications needed for the problem of Chemically Reactive Tracers. Software requires modification enabling the linking of TOUGHREACT to a version of

TOUGH2 to allow tracer modeling. Significant modification of TOUGH2 code may be necessary.

Conclusions

The limitations and needed modifications for each problem are addressed together on a problem basis.

Test Problem 1: Mineral Recovery. TOUGHREACT can be used to model zinc extraction; by extension (although not specifically tested), TOUGHREACT should be able to correctly model the chemical interactions of other economic minerals in hypersaline brines. However, the software is limited at present to a maximum Total Dissolved Solids (TDS) of 20 percent by weight; actual hypersaline brine reservoirs can have as much as 28 percent TDS by weight. Therefore, modification to the code is needed.

Test Problem 2: Injection of Silica-Supersaturated Brine. TOUGHREACT is capable of calculating the rate of silica scale deposition in the reservoir and the consequent reduction in the porosity and permeability of the reservoir rock. However, it is difficult to verify the accuracy of these calculations, as actual data on scale deposition in a geothermal reservoir are limited. Furthermore, the rate of scale deposition was calculated using reaction rates obtained from laboratory testing under ideal conditions. The validity of applying these laboratory reaction rates to actual field conditions requires further verification from field data. Given the simplicity of the model, improved field data may not have a significant effect on the quality of outputs. In addition, the researcher used a relatively coarse computer grid that may have prevented the user from observing important effects near the well bore.

Test Problem 3: Injection of Low-pH Brine. TOUGHREACT is capable of computing, for all minerals specified in the reservoir, the dissolution and precipitation rates associated with low-pH brine injection; the resulting changes in porosity and permeability were found to be very small. As noted for Test Problem 2 above, a finer computer grid near the bore hole could result in the revelation of previously unknown effects.

Test Problem 4: Long Term Gas Production Trends. Although TOUGHREACT is capable of simulating long-term production trends of the main geothermal gas component, carbon dioxide (CO_2), other gases cannot be modeled; further, the software does not currently incorporate chemical interactions between the various chemical species in the gaseous phase. This shortfall needs addressing before the program can be used effectively to minimize gas production with, for example, optimized water injection.

Test Problem 5: Chemically Reactive Tracers. TOUGHREACT is presently compatible only with TOUGH2 Version 1, which does not have a working option for tracer injection. TOUGHREACT needs updating to work with the latest version of TOUGH2 (Version 2). TOUGHREACT should then be able to correctly predict reactions involving tracers, as it includes all the necessary data on chemical equilibria and reaction kinetics.

Recommendations

TOUGHREACT is a new tool combining reservoir- and chemical-numerical simulation techniques. To make it readily useable for practical application, this project has pointed out the need for improvements in some of its features, including the following: increase the maximum TDS concentration to at least 28 percent by weight; include equilibria for hydrogen sulfide (H_2S) and ammonia; and incorporate chemical interactions between the various chemical species in the gaseous phase. In addition, the validity of applying laboratory reaction rates for precipitation and dissolution to actual field conditions requires further verification using field data. Finally, the code must become compatible with the most recent version of TOUGH2 (Version 2).

Benefits to California

PIER research public benefits are defined as follows:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary public benefit offered by the proposed technology is to make electrical energy more affordable in California while reducing the environmental impacts. Knowledge gained from operating this software specifically targeted to the manager's geothermal well field will promote careful plant management and reduce the cost per kilowatt (kW) of geothermal power generated.

The use of TOUGHREACT could assist in mitigating chemically related, resource-management issues, such as well-field remediation and gas control, which together account for a large part of the operations and maintenance costs of a geothermal project. The researcher expects overall operations and maintenance costs could be reduced by 10 percent to 30 percent for geothermal projects statewide through improved resource management facilitated by the use of TOUGHREACT. Typical operations and maintenance costs range from $0.01 to $0.03 per kW-hour. California's geothermal generating capacity is approximately 1,700 megawatts (MW), so geothermal operations and maintenance costs range from at least $136 million to $408 million per year. The savings in operations and maintenance costs as a result of using TOUGHREACT could be on the order of $13.6 million to $122 million per year. These estimates could be on the high side if all of the assumed benefits are not applicable to all sites.

The companies involved in geothermal development in California stand to benefit the most from this work. TOUGHREACT will impact California's existing geothermal energy market by helping to: 1) minimize silica scaling in the reservoir and wells, thereby reducing the operations and maintenance vcosts for geothermal power; 2) minimize the gas content in geothermal steam, thus increasing generating efficiency and reducing the release of greenhouse gases and the cost of hydrogen sulfide (H_2S) abatement; and 3) better define geothermal reservoir using an active testing tool (reactive tracers) to improve field-development and management techniques.

These benefits contribute to lowering the cost of geothermal power. In addition, there are broader benefits to California's ratepayers. These include increasing the diversity in California's energy sources, reducing the environmental impact of energy production, and taking greater advantage of one of California's indigenous and renewable energy resources.

2.8. Ventilation Cooling Controller Strategies

Awardee: UC Los Angeles
Principal Investigator: Murray Milne

Introduction
Most Californians live in areas where residential cooling is widely used on hot days, but outdoor temperatures drop significantly at night. That cool night air is a potential source of free energy for these residents, if it could be captured by an automated system for use during the hot afternoons. An intelligently regulated whole-house fan that measures outdoor temperatures could draw in air at night to lower the thermal mass of the house, thus allowing it to "coast" comfortably through the next day's heat.

Cooling of this type, combined with proper architectural design, could greatly reduce, or even eliminate, the need for residential air conditioning in 13 of the 16 California climate zones. The key to this strategy is a readily available controller or thermostat that compares outdoor and indoor temperatures and operates a whole-house fan accordingly. Currently there is no such device on the market.

Managed ventilation cooling is a pre-existing concept. This project was undertaken because no control unit exists that is a combined thermostat controller incorporating both indoor and outdoor temperature measurements and an optimal strategy to control a whole-house fan in addition to the furnace and air conditioner. This project designed and programmed the controller logic into a laptop computer used to control the whole-house fan in the test facility. The benefits achievable through using such a controller were carefully documented for the researcher's test site. This control logic was then programmed into a California climate model. The benefits gained from the controller were then extrapolated across all California climate zones, providing an estimate of the savings in compressive air-conditioning energy achievable by the controlled use of ventilation cooling.

Objectives
The goal of this project was to determine the feasibility of an intelligent ventilation controller to minimize cooling energy expenditures for California homeowners by properly controlling a whole-house fan to bring in the optimum amount of nighttime air. This would cool the interior thermal mass of the building sufficiently to let it "coast" comfortably through the next day's heat. The researcher established the following project objectives:

1. Design a controller that measures the following variables: indoor and outdoor temperatures, occupant's upper and lower limits of comfort temperature, time of day, and season of year.
2. Construct a prototype controller incorporating the logic developed in Objective 1.
3. Design and build instrumented test cells that permit precise evaluation of the controller performance. Test the cells to ensure equivalent thermal performance when operated under identical conditions.
4. Test the prototype controller design in one instrumented test cell. Use the other test cell as a control for measuring performance improvement. This test should prove the feasibility of the intelligent ventilation controller.
5. Include the effects of the new controller in the existing building-performance-simulation model. Validate this new performance model using data recorded from the instrumented test cells.
6. Simulate the performance of the new controller in various residential buildings in California's 16 climate zones.

Outcomes

1. The researcher developed the logic code for the controller. In simulations the code successfully tracked day and night temperatures.
2. The researcher entered the logic code into a laptop computer, which was programmed to record and store test data.
3. The project built and instrumented two identical test cells simulating the characteristics of typical California slab-on-grade houses. One cell was the experimental cell, the other, the control cell. Both were four by eight feet in area and eight feet high; each was properly insulated and had a south-facing window. The two cells were set side by side and identically oriented to the sun. Cement brick laid on the floors of the cells simulated the slab. The cells were evaluated using California Energy Code Title 24 and found to properly characterize slab-on-grade buildings. A calibrations sequence proved the two cells had similar thermal behavior.
4. A series of experiments run in this pair of full-height test cells validated the original premise. The results led to the following outcomes:
    a. An intelligent ventilation controller can improve comfort inside homes with medium thermal mass (slab-on-grade floors). These are typical of single-family dwellings in most California climates. Both the maximum indoor temperatures and the number of overheated hours were always less than in an uncontrolled building.
    b. Increasing the air-change rate increases the performance of the system. When the air-change rate is increased from 3.9 to 15 air changes per hour, the maximum temperature is reduced by at least 2.7° Farenheit compared to the control cell.
    c. Dropping the lower limit of the comfort zone at night from 70° Fahrenheit to 65° Fahrenheit significantly reduces the number of hot daytime hours and the maximum temperature inside the cell. This is probably the single most important factor that should be considered in any system that uses natural ventilation for cooling.

5. The researcher evaluated the new thermostat/fan controller in other California climate zones using an expanded version of the University of California, Los Angeles, building-performance-simulation model. The researcher expanded the program to include a model of the intelligent ventilation controller within the thermostat and calibrated the model using experimental data.
6. Using the modified computer program simulation, the researcher calculated the annual energy costs for a 2,000-square-foot, California-code-compliant, slab-on-grade house in each climate zone. The house model included a whole-house ventilation fan, as well as a furnace and an air conditioner, so that comfort levels were not compromised. The computed outputs tabulated in Appendix A show a typical savings of about $450 a year, with minor shifting of electrical energy costs to gas heating costs. There were no significant savings in only 3 of the 16 zones.

Conclusions

1. The logic code for the intelligent ventilation controller was successfully developed.
2. The researcher transferred the code to a laptop computer.
3. The researcher built two test cells that served as proxies for a California house. One cell was equipped with the equipment to be tested and the other was used as an experiment control cell. The test cells were calibrated and proved to perform identically.
4. When one test cell was outfitted with the intelligent ventilation controller, it always had lower maximum temperatures than the control test cell and fewer hours of overheated conditions.
5. The logic code and the data developed in the experimental tests allowed the researcher to successfully model an intelligent ventilation controller as it would be integrated into an existing furnace and air-conditioner controller to assure continual comfort.
6. Using the model, the researcher found the intelligent ventilation controller could reduce the cost of household energy in 13 of California's 16 climate zones.

An intelligent ventilation controller measuring both outdoor and indoor air temperatures to control a whole-house fan can save energy and improve comfort in climates with cool night temperatures. In all tests this system produced cooler indoor conditions than an identical building without such a controller. Energy savings in a building equipped with the new controller could quickly repay its cost, once it is mass-produced, and reduce the reliance on conventional air conditioning.

Recommendations

The researcher proved the feasibility of the intelligent ventilation controller. The program administrator recommends that the researcher investigate and approach companies that produce house heating and cooling controls, with a view toward financial and marketing support. Such a firm can assess the costs and potential market for this device, and it may assume significant development costs to produce a small, wall-mounted box that can sell at a competitive price. A statewide test of a prototype, once it is available, may require additional

public monies. Collecting, analyzing, and publicizing test results from all parts of California could be the key to successful introduction and marketing of the system.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for follow-on funding within the PIER program.

Receiving follow-on funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from the application of this research is the increased affordability of electricity resulting from reduced consumption by vapor-compressor air conditioners. The proven concept should significantly reduce the amount of electricity that households use to cool their dwellings. More extensive testing on real houses will be required before an accurate estimate of the total impact can be made.

No thermostat controller on the market today compares both indoor and outdoor temperatures to control ventilation with a whole-house fan, in addition to an air conditioner and furnace. The potential market for this device appears to be large. It would appeal most to residents in those California climate zones where this strategy can completely replace air conditioning. Once field experience grows, the intelligent controller could prove to be cost effective in hundreds of thousands of California homes.

Air conditioning represents the second largest category of electricity consumption in California homes, consuming an estimated 0.3 Quads per year. If this new product leads to the elimination or disuse of just one air conditioner per thousand homes,l it could save over 87,000 megawatt-hours per year statewide. This product should have a significant impact on grid demand on hot days, when California's electric utilities experience their peak loads. It will help “shave the peaks” by shifting consumption to late nights, when utilities have their lowest demand. By targeting the large residential market, this new product will benefit both ratepayers and utilities alike.

2.9. Use of Solid Oxide Membranes

Awardee: University of Southern California
Principal Investigator: Fokion Egolfopoulos

Introduction
Large (over 50 megawatt [MW]) gas fired power plants can be operated economically in a combined cycle mode to achieve efficiencies of 50 percent or greater. Most gas fired power plants can be operated in a combined heat and power (CHP) mode to achieve efficiencies of greater than 75 percent. However not all power plants can be operated in a combined cycle or CHP mode. Combined cycle power plants have long startup and shutdown periods and are capital-intensive. CHP power plants can only be highly efficient when the power plant is situated near a process requiring thermal energy. Numerous power plants operate in the simple cycle mode at efficiencies of 25-42 percent.

Recuperating gas turbine power plants is another method to convert heat in the exhaust flow into useful electricity. Mechanically recuperated gas turbines are beginning to enter the marketplace. The recuperator heats the inlet air using high temperature exhaust air. Solar Turbines, Inc., has developed a 4.5 MW mechanically recuperated gas turbine generator that exhibits fuel efficiencies around 38 percent. However, mechanical recuperators with high effectiveness can be large and expensive. Fuel use and carbon dioxide emissions could be reduced if an economical method of recuperating power plants were available. Waste heat recuperation significantly improves energy production efficiency. This, in turn, minimizes the use of fossil fuel resources and the release of carbon dioxide (CO_2) into the atmosphere.

Small to medium-sized gas turbine generators are likely to be used in distributed generation to meet daily load peaks. Power plant efficiencies for small and medium-sized gas turbines, now in the range of 25 to 42 percent, could increase by 3 to 10 percentage points if the exhaust heat were used to reduce fuel consumption.

This project investigated a novel method to chemically recuperate heat engines. It employs the waste heat to decompose CO_2 in the exhaust stream into carbon monoxide (CO) and oxygen. Decomposition of CO_2 into CO and O_2 is a highly endothermic reaction (552 kilojoules per mole). The CO is mixed with the incoming methane fuel, reducing the need for methane. The first step of this concept uses a membrane to separate CO_2 from the flue gas. A second high-temperature, solid-oxide membrane, the key technical innovation, allows relatively large amounts of the separated CO_2 to be decomposed at temperatures typical of heat engine exhaust flows. The resulting CO is returned to the fuel stream for combustion.

Project Objectives
The goal of this project was to determine the feasibility of utilizing high-temperature, solid-oxide membranes to separate CO_2 from an exhaust stream and to decompose it into CO and O_2

to increase thermal efficiency of gas turbine powered electricity generators. The researcher established the following project objectives:

1. Choose, prepare, and test appropriate membrane materials and determine oxygen permeation characteristics. The selected disc material should be oxygen permeable only.
2. Design, develop, construct, and operate a high temperature, solid oxide membrane reactor that allows for the direct decomposition of CO_2 into CO and O_2. Achieve over 80 percent conversion of the CO_2 in the laboratory gas stream.
3. Study and systematically quantify the combustion characteristics of the resulting fuel blends of methane (CH_4), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), and nitrogen (N_2) resulting from mixing methane under fuel-lean conditions with the CO, CO_2 and O_2 products of the CO_2 decomposition reaction. Pollutants in the exhaust stream should not increase with the addition of CO and CO_2 into the fuel stream.

Project Outcomes

1. The researcher prepared $SrCo_{0.5}FeO_3$ perovskite powders by solid-state reaction method and used X-ray diffraction to verify their crystal structure. The researcher determined by permeation tests that the membrane disk is impermeable to any other gases but oxygen. Oxygen permeation rate was measured by feeding air on one side of the membrane and helium on the other side.
2. The researcher fed CO_2 diluted with helium to the membrane reactor to carry out membrane reactor experiments. The project found that the reactor temperature significantly influenced the CO_2 conversion and oxygen permeation rates. Higher temperatures increased the reactor equilibrium conversions and increased the oxygen ion mobility in the membrane. When the oxygen on the permeate side of the membrane reacted with methane, the oxygen partial pressure fell to 10^{-15} bar. The measured CO_2 conversion was 82.7 percent at gas temperatures of 1,300 Kelvin.
3. Experimental data of laminar flame speeds, extinction strain rates, and nitrogen oxide (NO_X) emissions for the combustion of mixtures relevant to this advanced power generation cycle were generated and evaluated. Numerical simulations of the flames were performed. Good agreements were found between the experiments and the model simulations. Oxides of nitrogen increased slightly under the most favorable conditions.

Conclusions

1. Solid oxide dense oxygen conducting membranes made of $SrCo_{0.5}FeO_3$ perovskite material were prepared and tested for their oxygen permeation characteristics. These membranes were shown to be highly permeable to oxygen, but impermeable to any other gases. The membranes were proven stable under a reactive reducing environment.
2. It is technically feasible to decompose carbon dioxide at moderate temperatures and pressures.
3. The researcher investigated the effects of adding CO/CO_2 mixtures on the burning and pollutant emission characteristics of lean atmospheric CH_4/air flames. The researcher found NO_x reduction can be achieved for low reactor conversion rates but with reduced laminar flame speeds and extinction strain rates. For high reactor conversion rates, increased

laminar flame speeds and extinction strain rates were observed accompanied by an increase in NO_x emissions.

4. Accounting for both process economics and technical feasibility in overall system design, the optimal choice may be intermediate reactor conversions. This would allow measurable waste heat recovery and minor negative effects on combustion efficiency and pollutant emissions. Alternatively, one could maximize waste heat recovery and use existing selective catalytic reactors (SCR) to clean the pollutants from flue gasses. SCR technology is still quite expensive for small to medium gas turbine generators.
5. This project demonstrated the technical feasibility of using membrane separation of CO_2 to chemically recuperate a gas turbine engine used for power generation. The project did not indicate the potential magnitude of the energy savings in a real engine, nor did it project the magnitude of the potential effects on air emissions in terms important to regulators and the public.

Public Benefits to California

The feasibility of the proposed chemically recuperated gas turbine (CRGT) process was proven. If the technology is commercialized, it could result in reduced fuel consumption and reduced emissions of carbon dioxide. The magnitude of the benefits cannot be determined until the concept is reduced to practice in an engine system.

Recommendations

The use of solid oxide membranes in power generation applications was proven technically feasible. To bring the technology to the commercial stage, the following tasks should be completed:

- Develop tubular solid oxide membranes to evaluate decomposition of carbon dioxide in a larger membrane reactor.
- Test the long-term (over one year) stability of tubular membranes.
- Quantify the expected energy-saving benefits and air emissions impacts of this technology if applied to gas turbine engines in use in the market.

Carry out an extensive economic evaluation of the technology and a detailed market survey. The evaluation should determine the relative advantages and disadvantages of chemical recuperation over mechanical recuperation. The researcher should also compare this form of chemical recuperation with chemical recuperation that dissociates the methane into carbon monoxide and hydrogen. The researcher should contact gas turbine manufacturers to determine their needs regarding the integration of this technology into their engine systems.

2.10. Energy Production From Bulk Wastewater

Awardee: University of California, Santa Barbara
Principal Investigator: Eric McFarland

Introduction
The ultimate objective of the proposed research is to discover a renewable and cost-effective biosynthetic means of producing molecular hydrogen (H_2) from wastewater for use as an energy carrier. The biosynthesis of H_2 is a complex, multi-factorial pathway involving multiple enzyme systems, transport proteins, and intermediate metabolites. Detailed understanding of these complex processes is incomplete. To date, step-by-step, conventional deductive methods have identified no commercially acceptable biosynthetic system for H_2 production. In order to achieve the goal of biosynthesis of H_2, this project developed and utilized an *inductive* experimental approach: large and diverse collections of mutant microorganisms are created as "libraries" and systematically screened for optimal biosynthetic production of hydrogen using high-throughput sensor technologies developed as part of this project. This methodology—recently termed "combinatorial"—is well known in the biological sciences.

In this pilot study, some specific molecular modification(s) induced by the mutation were identified and linked to variations in H_2 production. The studies to date have used X-rays for the production of large numbers of genetically diverse mutants in libraries. Hydrogen-producing organisms were screened for production of molecular hydrogen with an array of chemo-optical detectors. Major accomplishments in this project have been: 1) the development of library assemblies for assembling diverse collections of organisms: 2) the development of a high-throughput screening system for identifying organisms with high rates of hydrogen production: 3) the development of a differentially pumped mass spectrometer to quantify hydrogen production: and 4) preliminary studies of methods to create mutant organisms using X-rays. Work in this start-up phase indicates that combinatorial methods can optimize the biological production of hydrogen and that a chemo-optical method of high-throughput screening can identify organisms in libraries with high potential for the production of hydrogen.

Although this project has not yet identified organisms capable of high hydrogen production, the researcher has the infrastructure in place to conduct intensive screening of other mutated organisms. A benchtop bioreactor proposed for this project should be funded only after the identification of an organism displaying high hydrogen production. The long-term goal is to scale up the benchtop reactor to work in sanitation facilities with only minor modifications to existing treatment plants.

While hydrogen can be produced by reformation, decomposition, or electrolysis, these methods are relatively energy intensive or utilize non-renewable resources. Biosynthesis is an attractive alternative for H_2 production, but practical methods of synthesizing hydrogen in bulk from

living organisms has yet to be achieved. Success in this project would prove the feasibility of producing a renewable, low-cost fuel from wastewater using selected organisms.

Objectives

The goal of this project was to determine the feasibility of using combinatorial methods for the discovery of novel hydrogen-producing microorganisms to populate the anaerobic environment of wastewater treatment facilities. The overall technical objective was the development of efficient, economic biosynthesis of hydrogen gas in wastewater anaerobic digesters for use as a fuel in electric power plants. The researchers established the following project objectives:

1. Select test strains from among existing chemotrophic species typically found in anaerobic digesters of water treatment facilities that are known to exhibit high levels of biosynthetic H2 production.
2. Design and construct library assemblies to allow for isolation, growth, and H_2 production from mutant microorganisms.
3. Develop a high-throughput screening system that is sensitive to hydrogen evolution or to other metabolic indicators of hydrogen synthesis to identify lead mutants.
4. Generate libraries of mutants with genotypic diversity by random mutagenesis of the test strains using both X-ray and ultraviolet (UV) radiation, as well as DNA-specific chemical mutagens.
5. Quantitatively compare efficiencies of H_2 production of leading organisms to the control organisms.
6. In libraries of leading organisms, investigate the H_2 production of the lead mutants under pH and temperature gradients in order to determine optimal conditions for H_2 production.
7. Develop a conceptual pilot-plant design with cost analyses for the integration of the chemosynthetic lead mutants.
8. Construct a bench-scale bioreactor based on the optimal organisms isolated.

Outcomes

1. The researcher selected Chlamydomonas reinhardtii wild type (WT) strain (137c+) and strain 76D. The National Renewable Energy Laboratory provided strains of these organisms. Cultures of these strains served as the control. In addition, samples derived from mixed sewerage were obtained from a digester at a water treatment plant.
2. The researchers designed and developed experimental containers that allowed simultaneous comparison of 96 samples, each in its own well and isolated from the others. The unit was called a "library," when all 96 wells were filled with bacteria. A plate containing 96 separate hydrogen detectors covered the assembly. Light illuminated each well from the bottom.

3. The researchers developed a detector array that individually scanned the 96 wells for the hydrogen content of each cell. The glass plate covering the library was coated with lead (Pb) and tungsten (VI) trioxide (WO_3). Hydrogen chemically reduces WO_3, thus changing the reflectivity of the coating for each individual cell. The detectors produced a detectable signal at hydrogen concentrations as low as 0.1 percent H2 in air.
4. The project created libraries of mutant bacteria using X-rays. None of those mutant colonies exhibited enhanced ability to produce hydrogen. The project did not try UV radiation or DNA-specific chemical mutagens to create new libraries of bacteria.
5. The researchers developed a differentially pumped mass spectrometer to quantitatively measure hydrogen production from the bacteria.
6. Hydrogen production proved dependent on pH. The maximum rate of hydrogen production occurred in the range pH 6.8-7.6. It also was light sensitive, with production higher at lower levels of light. The researcher conducted tests in which the researcher varied both the light intensity and the pH. No conclusions were drawn from those tests. The researcher reported no tests in which the temperature was varied.
7. The project did not develop a conceptual design of a pilot plant with cost analyses because the researcher did not identify an organism that displays sufficiently high hydrogen production to warrant designing the pilot plant.
8. The project did not construct a bench-scale bioreactor because the researcher has not identified an organism that displays sufficiently high hydrogen production rate.

Conclusions

1. Marine and fresh water Chlamydomonas strains of algae offer good potential for hydrogen production.
2. The multi-well "library" system developed by the research allows for rapid and direct comparison of mutants of the same organism.
3. The hydrogen-detection system based on light reflectivity is sufficiently sensitive for these experiments. The multi-sensor bar can scan all 96 cells automatically. It can directly measure relative rates of hydrogen evolution from species in each cell.
4. Initial libraries of algae were produced by X-ray exposure. None of the species produced by this method produced significant amounts of hydrogen. Future work should focus on the use of UV radiation or DNA-specific chemical to mutate the species.
5. The experimental apparatus was built to measure hydrogen production accurately.
6. Variations in light intensity and pH had a measurable effect on hydrogen production. Unfortunately, no combination of light intensity, pH, and species produced significant hydrogen production.
7. The project did not develop the conceptual design for a pilot plant.
8. The project did not construct a bench-scale bioreactor.

The goal of this project was to determine the feasibility of using combinatorial methods for the discovery of novel hydrogen-producing microorganisms to populate the anaerobic environment of wastewater treatment facilities. The overall technical objective was to develop a means for the

efficient, economic biosynthesis of hydrogen gas in wastewater anaerobic digesters for use as a fuel in electric power plants. These were ambitious goals.

The research devised a novel method of testing multiple species or mutants of the same species of bacteria for hydrogen production. The experimental methods and measurement techniques are well thought out and rigorous. Unfortunately, the selected approach to locating hydrogen-producing bacteria requires testing hundreds or thousands of mutated species. One cannot predict when high-yielding species will be formed and identified.

Recommendations

This project has developed a unique method of screening bacteria for significant hydrogen production. While the methods, equipment, and goals of this project are well thought out, there is no guarantee that suitable bacteria will be discovered in any particular year. In addition, the researcher provided no basis to show that the technologies suggested for gene alteration could lead to bacteria with higher rates of hydrogen production. However, because of the importance of a successful outcome and the careful work of this researcher, this work should be continued for another two to three years, with funding provided by an organization that sponsors basic to semi-applied research. The emphasis during that period of time should be to conduct extensive screening of bacteria using the researcher's "library" method. The researcher should employ statistical techniques to look for correlations between hydrogen production and various gene-altering techniques.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research, when successful, will be reduced environmental impact of the California electricity supply by significantly reducing air emissions from future power plants. Extensive use of hydrogen in fuel cells will not only reduce NOx and CO, but also CO_2.

California is among the first states to move toward a hydrogen-energy economy. Though scheduled first for automobile use, hydrogen will be a favored fuel for electricity-generation systems as it becomes available. Abundant hydrogen will allow wide use of fuel cells that operate at high efficiencies with almost no pollution. Hydrogen could also be used in conjunction with natural gas or heavier hydrocarbons to reduce emissions from conventional power-conversion equipment. The major benefit to California ratepayers will be significant

reductions in air pollution from power plants. Reductions will occur in CO, CO_2, NO_x and to some degree, sulfur dioxide (SO_x) emissions.

3.0 2000 Independent Assessment Reports

The Energy Innovations Small Grant (EISG) program awards numerous grants for innovative energy research projects every year. Independent assessment reports (IARs) highlight the project outcomes for each of EISG projects. This section includes the IARs from grant projects that were awarded in 2000 that have yet to be published.

3.1. Closed Cycle Valved Cell (CCVC) Heat Engine

Awardee: Joseph Barrett Bland
Principal Investigator: Joseph Barrett Bland

Introduction
California has numerous sources of low-temperature heated fluids but no cost-effective, efficient method to convert them to electricity. Sources include solar-trough concentrators and industrial waste-heat streams. If engines existed that could convert only 10 percent of the industrial waste heat to electricity, it would increase electric generation capacity available to California ratepayers by an estimated 5,000 megawatts. Solar-trough concentrators could supply an even greater amount.

Heat engines require very high temperatures to operate at high thermal efficiencies. Typically, these temperatures are achieved by combusting fuel, increasing both California's air pollution and dependence on hydrocarbon fuels. Over half of the heat energy released by most fuel combustion is discarded as waste heat at about the same temperature as that obtained by fluids in a solar trough collector (290-390 degrees Celsius or 540-734 degrees Fahrenheit). If an engine could produce acceptable efficiency at these low inlet temperatures, it could use both solar thermal energy and waste heat to produce electricity with very low-to-no fuel costs. Today, engineers choose Rankine (steam) power plants for relatively low-temperature heat sources. To reduce costs to an acceptable number, they design very large (about 30 megawatts) power plants.

The researcher set out to produce a cost-effective engine for a solar-trough power plant with a power output as low as 5 kilowatts. A key idea was to attain engine thermal efficiency equal to or greater than that of existing, multi-megawatt, Rankine-cycle engines currently used in solar-trough power plants. This project undertook the construction and testing of a conceptually new engine design named the closed-cycle valved cell (CCVC) engine. This is a closed-cycle engine similar to a Stirling engine. The primary difference is the incorporation of valves. A Stirling engine has no valves. The researcher developed proprietary valve placement and timing to improve the engine performance and reduce cost.

The CVCC was designed as a low temperature (260-427 degrees Celsius), externally heated engine for small- to medium-size (5-500 kilowatt) applications. The researcher intended to improve the efficiency of a closed-cycle engine compared with a Stirling engine. Other purposes include low-temperature operation, high power density, and affordable capital cost per kilowatt of installed capacity. The researcher planned to prove the feasibility of this concept through the construction and testing of a working model engine.

Objectives

The goal of this project was to determine the feasibility of a closed-cycle valved cell (CCVC) engine. The researcher established the following project objectives:

1. Construct and test an initial prototype CCVC engine.
2. Determine economic feasibility of a mature CCVC engine.
3. Determine the thermal operating range of a mature CCVC engine. The goal is 500-800 degrees Fahrenheit (260-427 degrees Celsius).

Outcomes

1. A prototype CCVC engine designed and built by the project proved mechanically functional in initial tests.
2. Costs for the prototype were roughly as predicted.
3. The prototype failed to produce net work. The project undertook in-depth analysis of the test data to understand the failure mechanism. The thermal operating range was not determined.

Conclusions

1. The project succeeded in designing, constructing, and testing a prototype CCVC engine. The dynamic seals worked well. As a result, internal friction was within acceptable levels. Internal pumping losses appeared likely to be acceptable. Static sealing and instrumentation need improvement.
2. The researcher projected costs of a mature solar-powered CCVC engine system to be half that of competing small-to-medium-size, solar-powered systems. The program administrator does not see sufficient evidence to concur with that projection.
3. Detailed analysis of the test results indicates that an oversight during the engine design caused the failure to produce net work. The design lacked a necessary valve. Because of this failure, feasibility remains unknown.
4. A relatively simple modification to add the needed valve may permit the engine to function as originally predicted.
5. A calculation of the theoretical output of a reworked prototype CCVC engine indicates a maximum (Carnot) thermal efficiency of 24 percent at a source temperature of approximately 1,000 Rankine (540 degrees Fahrenheit). The researcher's target was to achieve the efficiency of a large Rankine-cycle power system. The researcher did not specifically identify the baseline unit for comparison.

The goal of this project was to determine the feasibility of a CCVC engine. The engine was constructed, but it did not produce net power. Feasibility has not been proven.

Recommendations

Before the CCVC can become a reality, the researcher must redesign the engine to incorporate the overlooked valve. A redesigned and rebuilt engine will then require new qualification tests. Those tests should determine the net output and engine efficiency. Subsequent testing should determine the engine performance over a range of temperatures. After the researcher proves that the redesigned engine provides significant technical advantages, the researcher should pursue a detailed cost analysis. To accomplish this list of recommendations, the researcher should first establish a development plan that includes costs and schedule. If that plan is successfully accomplished, the researcher can develop a commercialization strategy based on factual results.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research, if it were continued to a successful conclusion, would be increased affordability of electricity in California. However, it serves no purpose to further speculate on benefits of the research at this point, since the researcher has not proven the feasibility of the engine.

The successful development of a practical, small low-temperature externally heated engine would provide many benefits. By operating in the temperature domain of waste heat, geothermal, and solar-trough collectors, the CCVC would make these underutilized energy sources more widely employed and economically viable. Energy that is not dependent on hydrocarbon fuel would reduce air pollution. Further, because the engine is relatively efficient in small sizes, it could be installed at the point of use of the electricity (distributed generation). Thousands of California industrial rooftops could host a solar-trough collectors to power CCVC electrical generators, thus making grid-connected, distributed solar power a practical option for California ratepayers.

3.2. Energy-Efficient Designs for Swimming Pool Pump Systems

Awardee: ADM Associates, Inc.
Principal Investigator: Taghi Alereza

Introduction
As standard practice, engineers design the filtration system for a swimming pool at an educational or commercial facility with a single pump that runs continuously (24 hours per day) at the design flow rate. However, swimming pools in educational and commercial facilities are generally not open 24 hours a day. Therefore, one could reduce the flow rate of the filtration system pump during those hours when the pool is not in use and save energy. Lowering the flow rate of swimming pool pumps during no-use hours is not a common practice at commercial pools because of the requirements to maintain healthful conditions in the pools at all time.

The researcher in this project calculated that one could reduce the flow rate for a pool filtration system during no-use periods below the design flow rate while maintaining chemical balance. This could save significant energy. However, an important barrier to making this energy saving change is a perceived degradation of water quality with ensuing health problems. Health standards generally require a minimum flow rate be maintained at all times for public pools. Minimum flow rate calculations are based on the need to maintain healthful conditions during maximum pool use. Engineers need a new standard for the pool pump flow rate for periods of no pool use. This project was designed to provide the data to pool operators and engineers to allow minimum flow rate during those periods. Annual energy savings of over 25 percent were projected at these large pools if the flow rate could be reduced during periods of no use.

The researcher examined flow rate reduction techniques for use in a pool filtration system during no-use hours at pools. The researcher proposed two approaches to flow reduction:

- The researcher installed an adjustable speed drive on one pool pump motor. The motor speed was reduced during no-use hours.
- On the second pool the researcher installed new lower horsepower and higher efficiency pumps to replace two existing water circulation pumps.

The researcher followed a test procedure to identify the energy savings and to identify water quality issues associated with these two designs. The Sacramento County Health Department tested the pool water at Jesuit High School. The Sutter County Health Department tested the pool water at Butchie's Pool.

Objectives

The goal of this project was to determine the feasibility of two swimming pool flow reducing filtration designs for pools at educational and commercial facilities that could reduce energy use yet remain in compliance with health requirements. The researcher established the following project objectives:

1. Annual energy consumption at commercial and educational swimming pools will be reduced by at least 25 percent.
2. Water quality will remain in compliance with applicable health standards and requirements at all hours.

Outcomes

1. In the two tests the researcher proved a 30 percent and a 58 percent annual energy savings. The pool with the variable speed drive achieved the 30 percent savings, while the pool employing two low revolutions-per-minute, high-efficiency pumps achieved the greater savings.
2. The Sacramento County and Sutter County health departments conducted weekly water quality monitoring. The researcher reported tests were performed for the following conditions:
   - Turbidity or clarity of the water to check of whether the turnovers of the water in a pool were in compliance with code requirements, usually between 3 and 6 turnovers per day
   - acidity or alkalinity level to remain between 7.2 and 8.0
   - Free chlorine residuals
   - Bacteriological quality of the water including the number of bacteria per milliliter and total coliform organism most probable number (MPN) count
   - Chemical quality of the water (not defined further).
3. Except for the acidity or alkalinity level, the researcher did not specify an acceptable range of measurement for each characteristic measured. No abnormalities in water quality were discovered at either test pool during the entire course of this research. Water quality met health department standards at each weekly inspection. However supporting data were not presented in the final report to substantiate these claims.

Conclusions

1. The researcher met his goal of energy use reduction.
2. While the report of no water quality abnormalities is encouraging, the lack of water quality specifications and data do not allow independent confirmation. In addition, no test protocols were provided for measuring water quality. The pool at Jesuit High School had a computer-controlled water quality device that operated on a continuous basis. This device apparently maintained the water quality at all times. The researcher did not report on chemical usage in this pool. The project administrator does not know if the reduction in water flow increased or decreased the chemical use in that pool. The operators of Butchie's pool maintained the chemical balance of pool manually. Again, the researcher did not report on any change in chemical usage.

3. The goal of this project was to demonstrate energy savings at commercial and educational pools while maintaining water quality. The lack of test protocols, the infrequent testing of water quality, and lack of reported water quality specifications and data make it difficult to project how the results of this project will translate into wide adoption of these energy reducing schemes.
4. The researcher does not discuss the role of regulators in allowing reduced water flow in educational and commercial swimming pools.

Advancement of swimming pool pump design allows pool owners to replace older pumps with units that require less energy to provide the same water flow. Benefits from this type of pump replacement are occurring throughout the state now. The objective of this project was to reduce the energy use further by reducing water flow during periods of no use. If the feasibility were proven, significant energy savings could result statewide. Because of the lack of rigorous test procedures on water quality, the benefits of the adoption of variable speed pumps motor at public pools is less clear. Energy savings of 30 percent to 50 percent could be achieved at the hundreds of large educational and commercial swimming pools in the state.

Recommendations

The researcher should provide detailed water quality specifications and data to allow regulatory bodies to adopt reduced water flow requirements during hours of no-use. The researcher should also interview regulators and engineering groups that set the water flow specification. Those interviews should determine what actions and data may be required to allow the adoption of lower water flow rates during period of no use.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research is the increased affordability of electricity for swimming pool operators in California. Other ratepayers will benefit from the reduction in electricity use by swimming pool motors. Using two energy reduction strategies on swimming pool pump motors in this project resulted in a nearly 30 percent to 50 percent reduction in energy use for the pool operators. At 13 cents/kilowatt-hour, the operator of the small pool could save about $1,150 per year while the operator of the large pool could save about $4,800 per year. If no-use flow reduction were implemented at 1,000 large pools, the collective saving could be $3 million per year. Implementation could result in annual electricity consumption reductions of 23 million kilowatt-hours statewide.

3.3. Controlling Fouling With Rice Straw Blends in Biomass Boilers

Awardee: University of California Davis
Principal Investigator: Charles E. Lesher

Introduction
If rice straw, an abundant California agricultural waste, could be used as a power-generation fuel, Californians would receive major benefits. Rice straw must be destroyed annually to prevent plant diseases from bridging the winter to next year's crop. But it cannot be burned in the open because burning creates extensive air pollution. However, if rice straw could be used in lieu of increasingly expensive wood products, it could lower the cost of electricity produced in biomass power plants.

Currently rice straw quickly fouls the combustors and boiler tubes of biomass power generators with a buildup of slag. Fouling increases operating costs and reduces efficiencies. High operating costs and low efficiencies have forced some biomass power generators to avoid using rice straw altogether, even though permitted to use it. The goal of this project was to identify mixtures of rice straw and pure wood that greatly reduce fouling.

If the fouling problem can be solved, 1.0 to 1.75 million tons of rice straw waste generated annually in California can be used as fuel. In 1996 biomass-fueled generators in California generated 5,848 gigawatt-hours of electricity, about 2.3 percent of gross system energy. Wood, the primary fuel, is becoming harder to locate and more expensive to buy. Because of these costs, biomass generated electricity is not expanding fast in California. Using rice straw as a fuel alone or in a blend with wood could lower the cost of the fuel and therefore the cost of the electricity produced by biomass.

In 1996 the California Legislature instituted Senate Bill 38 (SB 38) (Lockyer, Chapter 954, Statutes of 1996) to encourage the development of off-field uses of rice straw. That law provides incentives to $15 per ton of rice straw. While the financial incentives (effective through 2008) are attractive, the technical slagging issue must be resolved before rice straw can be widely used as a power generation fuel.

To use rice straw as a fuel in biomass power generators, boiler-fouling problems must be eliminated. The researcher proposed a predictive model for rice-straw/wood fuel blends that would allow biomass generator operators to select the fuel mixtures that minimize boiler fouling. The researcher needed data to develop the model. This project proposed two primary tests to develop data. The objective of the first tests was to determine the liquidus temperatures of blends of rice straw ash and wood ash. These tests were performed in an atmospheric, vertical quench furnace. The purpose of the second series of tests was to determine the combustion characteristics of rice straw/wood blend with the lowest ash liquidus temperature

using a laboratory scale, fluidized bed combustor. The researcher also proposed to measure the relative loss of potassium for fuel blends of up to 10 percent rice straw.

Objectives

The goal of this project was to determine the feasibility of rice straw/wood blends to reduce fouling in biomass boilers. The researchers established the following project objectives:

1. Quantify the fouling potential of rice straw/wood fuel blends by measuring the slag formation and potassium volatilization under simplified and controlled conditions. Determine the maximum allowable ratio of rice straw to wood-based fuels that results in acceptable levels of alkali volatilization and reduced boiler fouling. Quantify the fouling potential of rice straw/ wood fuel blends up to levels of 10 percent rice straw.
2. Formulate predictive models for the high-temperature fouling potential, the physical properties, and the tenacity of slag deposits from fuel blends. Use the model to predict fouling properties of rice straw/wood fuel blends.
3. Demonstrate a fuel blend containing at a minimum 10 percent rice straw on a weight basis that does not result in a proportional increase in boiler fouling rate. Test the blend in a laboratory-scale fluidized bed combustor.

Outcomes

1. The researcher determined the melting temperatures (liquidus) of six rice straw ash and wood ash blends. The addition of rice straw to a dominantly wood fuel caused a marked freezing point depression of the inorganic slag from above 2,000 degrees Celsius to a minimum of about 1,260 degrees Celsius. Potassium is completely lost from the slag for fuel ash blends with less than 30 percent rice straw ash. Note that this work was accomplished using rice straw ash and wood ash. The tests using the vertical quench furnace identified the 30 percent rice-straw ash/70 percent wood ash blend as optimal for minimum slag formation. The experiments showed that the 30 percent rice straw ash/70 percent wood-ash blend produced the lowest liquidus temperature. The lower liquidus temperature generated lower potassium volatization. Lower potassium volatization leads to lower slag formation and less boiler fouling. The corresponding fuel blend is 2.6 percent rice-straw/97.4 percent wood.
2. The researcher developed the predictive model. Using data generated by this model, the researcher predicted the fouling potential, the physical properties, and the tenacity of slag deposits.
3. The researcher tested two blends. The first contained 2.4 percent rice straw, 97.6 percent mixed conifer, while the second sample contained 9.6 percent rice straw, 90.4 percent mixed conifer. Pure wood and leached rice straw fuels were used as controls. The blend containing 2.4 percent rice straw proved optimal in the fluidized tests. The goal of 10 percent rice straw by weight in the fuel was not met.

Conclusions

1. The researcher based his conclusions on tests involving blends of rice straw ash and wood ash. Both the rice straw and the wood had been reduced to ash prior to blending. There is a possibility that the volatile material lost during the ashing process could influence the liquidus temperature and/or slagging potential. Second, the researcher measured the liquidus temperature, not the solidus temperature. One could argue that an ash particle can fuse to a boiler tube when it first starts to melt. The researcher used the liquidus temperature because of the ease of measurement in the laboratory. Overall the researcher performed the experiments accurately with due diligence toward data accuracy.
2. The researcher met their goal for this objective. The predictive model analysis supports the conclusion that a fuel blend of 2.6 percent rice straw and 97.4 percent wood produced the minimum slag formation.
3. The 10 percent rice straw content was not achieved. The optimum mixture, equivalent to 2.6 percent rice-straw/97.4 percent wood fuel blend, produced minimum slag in the pilot fluidized-bed experiments. Since all experiments measuring the liquidus were conducted with rice straw ash and wood ash, it is not clear whether this blend will produce minimum slag in an actual biomass generator boiler. No other fuel blends were tried, so no conclusions can be drawn about them.

Recommendations

The 2.6 percent rice-straw / 97.4 percent wood blend found to minimize slag formation contains too small a percentage of rice straw to significantly reduce fuel costs for electricity generation in California or to relieve the disposal problem for rice straw. There may be other avenues of research that can address the stated goal of using rice straw/wood blends as a fuel to produce electricity. Because of the large potential benefits of disposing of rice straw, these avenues should be pursued.

Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research is the reduced environmental impacts of the California electricity supply. Burning rice straw in a controlled power generation combustor will reduce air pollution over the option of open-field burning of the rice straw. Quantification of the benefit is not possible since this project did not prove the feasibility of consuming a large amount of rice straw in a rice straw/wood fuel blend.

3.4. Application Feasibility Study of Gravitational Non-Equilibrium Heat Pumps and Heat Engines

Awardee: University of Cambridge
Principal Investigator: Thomas Smith

Introduction
Small-scale distributed-generating systems reduce the need for new, large-scale utility generating plants and transmission lines. Solar-energy generators designed to fit residential and industrial rooftops could export excess power to the grid on hot afternoons when air conditioning creates an imbalance between peak electric demand and supply in the state. Domestic-scale solar-electric generation for grid export using photovoltaic cells and inverters is available now, but its high initial cost makes it unsuitable for wide commercial use. However, solar-thermal heating of water and space is currently feasible and is enjoying sustained market growth. A hybrid solar-thermal power plant that combined heating and electric power generation could produce both electricity and heat at a competitive cost.

The researcher estimated that a solar organic Rankine cycle (ORC) combined heat-and-power system could produce electricity in the range of $4.25 to $3.60 per watt-electricity at 1000 watts per meter-squared irradiation in units rated at 1 kilowatt-electricity and 10 kilowatt-electricity respectively. If a large ambient temperature thermal reservoir such as a swimming pool is available, then the researchers estimate that the system cost could fall to $2 per peak watt. A research target of the project was to establish commercial feasibility of the ORC system by achieving capacity cost below $4 per peak watt. That is the current threshold of solar photovoltaic modules now in production. Different balance-of-system costs make this a somewhat imprecise cost comparison. However, it also should be noted that the photovoltaic industry has established a cost goal by the year 2010 of $1.50 per peak watt for photovoltaic modules. That should make photovoltaic broadly competitive in the residential market without subsidies. The ORC system would have to meet the lower end of this estimated cost range to establish it in the longer term as broadly competitive in the residential market and of more benefit to the ratepayer.

This project took on the challenge of developing a cost-competitive, solar-thermal, ORC electric-generator system that also produces useful waste heat. The system uses a pumped organic liquid. All the components for the ORC system are available at low cost except for a suitable organic-liquid pump.

In the proposed ORC system, solar collectors provide heat that vaporizes a pressurized organic working fluid. The vapor expands through a turbine turning an electrical generator. The expanded vapor is then condensed to the liquid state and pumped back to the solar collector by a feed pump. The researcher's cost analysis showed that relying on pre-developed components, eliminating moving parts wherever possible, and accepting small efficiency losses is preferable to the higher cost of a more efficient system. The majority of the proposed system (solar

collectors, heat exchangers, working fluid, expansion device, generating and post-processing apparatus) is composed of low-cost, pre-developed components.

However, a low-cost, reliable feed pump was lacking. The researchers proposed an innovative concept to solve this problem. Their pump is a novel, liquid-piston, fluidic oscillator, thermally driven by solar heat via a heat pipe. Two check valves in the pump create an intermediate space to generate oscillation. That gives rise to periodic cycles of suction, pressurization, discharge, and depressurization. The scientific advancement needed for the ORC system is the development of this new, thermally driven feed pump.

Objectives

The goal of this project was to develop a new, two-phase, thermally driven fluidic oscillator to pump feed liquid in a solar ORC for electrical power generation. The researchers established the following project objectives:

1. Construct a prototype thermally driven fluidic oscillator with a single working fluid, capable of driving an alternating-current generator.
2. Optimize the performance of the prototype by varying fundamental parameters and compare the results with those obtained from other cycles (subject to funding and time constraints).
3. Demonstrate system efficiency between 2 percent and 10 percent in converting solar radiation into electricity for a prototype generator with rated output between 50 watt-electric and 1,000 watt-electric, powered by a solar thermal collector capable of steady operation in the range 112 degrees Celsius to 190 degrees Celsius (235 degrees Fahrenheit to 375 degrees Fahrenheit).
4. Determine whether the proposed concept could be applied to heat pumping and cogenerative heat pumping (subject to funding and time constraints).

Outcomes

1. The researchers built the proposed thermally driven fluidic oscillator, but the concept was substantially modified during the course of the project in order to provide pumping capability over required pressure differences of 1-10 bar. They developed a working prototype capable of pumping over pressure differences of 0.5 bar. A series of data confirmed the theoretical basis of the pump's operation.
2. A collector survey and working-fluid survey, together with a series of compressed-air tests on adapted rotary-refrigeration and air-conditioning compressors, confirmed that a low-cost option using pre-developed components is viable. These studies produced estimates of the cost of production ranging from $2.00/Watt-electric to $4.25/ Watt-electric, depending on system size and the availability of a low-temperature thermal reservoir such as a swimming pool. Comparison with other cycles was not carried out.
3. Field tests were not begun due to time constraints and due to the need for continued laboratory work on the fluidic oscillator, first in order to achieve operation, and then to attain higher pumping pressures with efficiency. The fluidic oscillator pump did function, but only at lower-than-desired pumping pressure.

4. The researchers did not determine whether the proposed concept could be applied to heat pumping and cogenerative heat pumping.
5. A perhaps-unanticipated outcome is that the fluidic oscillator in its current state of development appears to be already applicable to drip-irrigation pumping and heat-exchanger circulation pumping.

Conclusions

1. The development of the ORC system proceeded without substantial alteration to its initial objectives. However, the discovery that the system required feed-pumping pressures in the range 1-10 bar necessitated substantial alteration to the fluidic oscillator concept. The fluidic oscillator was capable of pumping fluid over small 0.5 bar pressure differences. It remains to be demonstrated that it can pump over the larger 1-10 bar pressures required in an ORC solar-thermal-powered electric generator. Also, it is not yet established that the fluidic oscillator will have the self-starting and pumping stability required for an ORC operating in the field.
2. The researchers made progress in showing that the small-scale, distributed solar ORC generator constructed from pre-developed components is a technically feasible concept. The main areas requiring further attention are sealing and lubrication in the expanding machinery. However, without the replacement of the feed pump by an alternative thermally powered pump with no moving parts, such as the fluidic oscillator, this would be less a research project and more of a straightforward development project.
3. Once the pumping pressure of the fluidic oscillator is increased to allow ORC system operation, system efficiency and overall system cost per unit of output remain to be determined.
4. Efficacy of the fluidic oscillator concept to heat pumping and cogenerative heat pumping still needs to be established. In principle, there do not appear to be barriers to these applications.
5. The researchers' current stated development plans call for the initial development of this technology for applications other than the one proposed under this grant; the markets are larger, and the technical challenges are more easily met. This appears to be a sensible approach. The near-term target markets are small-scale agricultural-irrigation and heat-exchange systems.
6. In summary, the research that was conducted appears to have been well structured. The final report is technically sound and well written. The goal of this project—to determine the feasibility of applying a new, two-phase fluidic oscillator concept to pumping feed-liquid in a solar ORC generator—was not fully met. However, the project did demonstrate the possibilities of the concept and identified a path for further development leading to practical uses. Last, an interesting and useful application of the fluidic oscillator to irrigation pumping may be practical in something close to its present state of development.

Recommendations
The researchers' stated development plans now call for the technology to be developed initially for applications other than the one proposed under this grant because the markets are larger and the technical challenges are more easily met. This does appear to be a sensible approach. The near-term target markets are small-scale agricultural-irrigation and heat-exchange systems.

This line of research into liquid-piston, thermally driven fluidic oscillators appears to have potential for application to low-cost heat engines. This research group seems especially well qualified in this area. Their goal of proving true feasibility in a power-generating system, the main goal of this research project, was not met. Nevertheless, indications of technical feasibility of the fluidic oscillator concept were encouraging.

The investigators have not yet filed for patent protection. Their patent search did not turn up any prior art. The program administrator recommends that they seek patent protection. Before the researchers seek follow-on funding in the subject topic, the Program Administrator recommends that any proposal be supported by new experimental results or convincing theoretical results, which establish the practical feasibility of the fluidic oscillator to an ORC.

Such proposed effort should include development of fluidic oscillator technology rather than just fabrication of an ORC from modified off-the-shelf components.

Receiving follow-on funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California
Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research is in reduced environmental impacts of the California electricity supply or transmission or distribution system. Because it can export power to the grid at times that coincide with high use of air conditioning, this solar-powered distributed generator would reduce the imbalance between peak electric demand and supply in the state. Accordingly it would reduce the need for new, large-scale utility generating plants and transmission lines.

Another public benefit would be increased affordability of electricity in California. It would be an alternative for residential and industrial consumers of distributed power, if the researchers became competitive with photovoltaic modules in production scale. This requires meeting their

cost target of less than $3.74 per peak watt electric, the most recent threshold (2002) to be published. Furthermore, market penetration and concomitant benefits to the ratepayer would increase sharply if this technology became competitive with the photovoltaic industry 2010 cost goal of $1.50 per peak watt for photovoltaic modules. That is expected to make photovoltaic broadly competitive in the residential market without subsidies. A comparable cost would establish the ORC system as much more competitive in the longer term and more beneficial to the ratepayer.

The near-term application for irrigation pumping is also noteworthy. The target markets are small-scale agricultural-irrigation and heat-exchange systems.

3.5. An Innovative Approach to Stabilize the Thermal Conductivity of Air Plasma-Sprayed Thermal Barrier Coatings (TBCs)

Awardee: Purdue University Research Foundation
Principal Investigator: Rodney Trice

Introduction
Natural gas fueled combustion turbines are producing an increasing quantity of California's electricity. Almost all new power plants over 50 megawatts are based on this technology. The United States Department of Energy estimates that natural gas turbines will make up more than 80 percent of the power generating capacity to be added in the nation over the next 10 years. In the combustion turbine, natural gas is combined with high-pressure air in the combustion chamber creating a high temperature (over 2,000 degrees Celsius) gas stream. Near the aft end of the combustor compressor, air is used to dilute the gas stream temperature down to temperatures that are compatible with the first stage turbine and nozzle materials. The high-pressure gas expands past rotating metallic turbine blades converting its thermal energy to mechanical work to turn electrical generators. Even though the metal parts exposed to the hot gas are special high-temperature, corrosion-resistant super alloys, they can withstand only temperatures in the range 820 degrees Celsius to 930 degrees Celsius. To withstand the higher gas stream temperatures these metal components are internally cooled with compressor air and covered with thermal barrier coatings (TBC). The thermal barrier coatings are special ceramic formulations that have low thermal conductivity to impede the flow of heat from the gas stream to the underlying metal components.

The use of compressor air to cool the turbine components reduces the efficiency of the combustion turbine. Significant energy is used to compress the air used for cooling. The air used for cooling the first stage is released down-stream of the first stage nozzle and turbine. Thus, this "expensive" air expands without producing work in the first stage of the machine. If the second stage is also cooled with compressor air, that air does not produce work in the first or second stage of the engine. An improved thermal barrier coating (TBC) with lower thermal conductivity would reduce the amount of cooling air required for the same inlet temperature. Alternately, it would allow the engineers to operate the turbine at higher, more efficient

temperatures. The goal of this project was to develop an improved thermal barrier coating to allow higher gas turbine inlet temperatures. With higher inlet temperatures the engineers would improve the engine heat rate (reduce fuel consumption) and thereby lower the cost of the electricity produced.

Reducing consumption of natural gas in electricity generation would be a significant development. In 2002, natural gas supplied 33.4 percent of the primary energy to California's in-state electrical power plants. (This includes both gas turbines and steam turbine power plants.) As of January 2001 there were 1,012 in-state power plants listed with capacity of 0.1 megawatts or greater. Of these, at least 127 power plants can be identified as employing gas/oil fired combustion turbines, either in simple cycle or in combined cycle with steam generators. The combined electrical nameplate capacity of the 127 generating plants identified with turbines was 16,170 megawatts or 30 percent of the total system capacity of 53,800 megawatts. Since many of the existing gas turbine generators are only used on the hottest days as "peaking" power plants, combustion turbines do not produce 30 percent of the state's electrical energy.

The California Energy Commission has estimated the levelized cost of electricity generated by natural gas in combined cycle turbines with base load mode operation to be 5.18 cents per kilowatt-hour. If combustion turbines could operate with gas streams 110 degrees Celsius to 170 degrees Celsius (200 degrees Fahrenheit – 300 degrees Fahrenheit) hotter, some turbine engineers estimate that the efficiency in combined cycle mode could increase from 50 percent to 60 percent.

If an improved TBC made this increase in temperature and efficiency possible, then the combined cycle would produce electricity as much as 1.0 cents/kilowatt-hour lower since fuel cost is a major component in power plant operating expense. While the TBC is a critical component in achieving 60 percent thermal efficiency, many other advances are required to create a reliable gas turbine, combined cycle product. One turbine manufacturer has achieved the 60 percent efficiency by steam cooling the hot turbine components. This is a very complex solution. Using an improved TBC (with air cooling) could provide a less expensive path to high efficiency.

To accomplish this higher temperature operation with long service life requires a ceramic thermal barrier coating with lower thermal conductivity. Phonons, quantized lattice vibrations of the solid, carry heat in ceramics. Any defect that breaks the symmetry of the underlying lattice scatters phonons and reduces the thermal conductivity of the material. For phonons, effective scatterers are voids or pores in the material, and grain boundaries. TBC ceramics are in fact prepared with many small pores to decrease thermal conductivity.

Sintering during operation (i.e. densification of the coating, which removes pores) causes the thermal conductivity of thermal barrier coatings to increase by as much as 100-150 percent during service, greatly reducing the ability of the coating to protect the underlying structure from temperature extremes. For example, the thermal conductivity of an air plasma-sprayed coating will increase from 1.2 watts per meter-kelvin (W/m-K) to 2.1 W/m-K after 50 hours exposure to 1,200 degrees Celsius. The end result of an increase in the thermal conductivity of

the coating is that the gas turbine must be operated at lower temperatures or more cooling air must be provided for the hot components. Either of these results decreases the efficiency of the electricity production. To inhibit sintering, the researcher proposed altering the coating at the atomic level by changing the chemistry of the TBC via the addition of selected dopants. Theory predicts and some earlier experimental data suggest that added dopants will tend to accumulate at grain boundaries.

The effect of the dopants accumulating at the grain boundaries could slow grain boundary movement and decrease sintering. The primary scientific goal of the program was to perform proof-of-concept experiments demonstrating that it is possible to develop thermal barrier coatings that retain small pores and maintain low thermal conductivity over the thousands of hours of operation expected in land-based turbines.

Objectives

The goal of this project was to determine the feasibility of a thermal barrier coating capable of maintaining a thermal conductivity of 1.2 watts per meter-kelvin (W/m-K) over 500 hrs at 1,400 degrees Celsius. The researchers established the following project objectives:

1. Produce a thermal barrier coating capable of maintaining a thermal conductivity of 1.2 W/m-K over 500 hours at 1,400 degrees Celsius.
2. Production of colloidal suspensions of 1 um diameter stabilized zirconia and dopants that can be plasma-sprayed without agglomeration – replaced by Objective 5.
3. Optimize the plasma-spray parameters for each stabilized zirconia/dopant to satisfy the following criteria: (a) a high degree of atomic mixing occurs, (b) 1 μm/pass deposition rates are observed, and (c) coatings contain less than 15 percent porosity.
4. Reduce the amount of sintering that occurs in the coatings by reducing grain growth by 100 percent.
5. Produce plasma-sprayed coatings of 7.6 mole percent yttrium oxide-zirconium dioxide and 12 mole percent cerium oxide – zirconium dioxide doped with either calcium, magnesium, or ytterbium.

Outcomes

1. This objective was not met. 10-hour and 100-hour heat-treatments at 1,200 degrees Celsius of ytterbium doped 7.6 yttria-stabilized zirconia (YSZ) coatings demonstrated a higher thermal conductivity than baseline 7.6 YSZ. Typical thermal conductivity values after 100-hour holds for 7.6 YSZ coatings with or without dopant were 1.6-1.7 watts per meter-kelvin (W/m-K).
2. This objective was met. However the researchers were not able to get the coatings off of the substrate without cracking to measure either their thermal conductivity or linear shrinkage in a dilatometer. The researcher replaced this objective by Objective number 5.
3. This objective was met.
4. Grain growth was not significantly reduced. Transmission electron microscopy (TEM) and energy dispersive spectroscopy (EDS) study of as-sprayed ytterbium doped 7.6 yttria-stabilized zirconia (YSZ) and 12 sulfated zirconia coatings revealed no ytterbium segregation at grain boundaries. Ytterbium doped 7.6 YSZ samples shrank slightly more

than the corresponding baseline 7.6 YSZ or 12 sulfated zirconia coatings during 5-hour hold at 1,400 degrees Celsius.

5. Large 50-100 micron porous particles consisting of 1 micron diameter stabilized zirconia powder were prepared which could be infiltrated by dopant ions prior to spraying. This technique was successful for incorporating dopants, and the coatings were easily removed from their substrates for further analysis. Doping with 2 mole percent ytterbium lowered the thermal conductivity of the as-sprayed 7.6 yttria-stabilized zirconia (YSZ) and 12 ceria stabilized zirconia (CeSZ) coatings. Doping with magnesium was not successful due to its evaporation in the plasma spray process. Doping with 2 mole percent and 5 mole percent calcium increased the thermal conductivity of as-sprayed 7.6 YSZ coatings, but did not change the conductivity of as-sprayed 12 CeSZ coatings.

Conclusions

The researchers were unable to meet the primary objective, which was to maintain a low thermal conductivity (less than 1.2 watts per meter-kelvin [W/m-K]) after extended time at high temperature. At a fundamental level, while the researchers were able to incorporate dopants into the coatings, they did not accumulate at the grain boundaries as desired to limit sintering.

1. The researcher could not produce a thermal barrier coating capable of maintaining a thermal conductivity of 1.2 W/m/K over 500 hours at 1,400 degrees Celsius.
2. The objective of producing colloidal suspensions of 1um diameter stabilized zirconia and dopants that can be plasma-sprayed without agglomeration was achieved
3. The researchers were successful in optimizing the plasma-spray parameters for each stabilized zirconia/dopant to satisfy the criteria of (a) a high degree of atomic mixing, (b) 1 μm/pass deposition rates, and (c) coatings containing less than 15 percent porosity. (Although not discussed, it is clear that too high porosity would compromise the integrity of the coating.)
4. The objective of reducing the amount of sintering that occurs in the coatings by reducing grain growth by 100 percent was not successful.
5. Researcher efforts to produce plasma-sprayed coatings of 7.6 mole percent yttrium oxide-zirconium dioxide and 12 mole percent cerium oxide – zirconium dioxide doped with either calcium oxide, magnesium oxide, or ytterbium oxide were partially successful. The researchers were able to make the coatings, but the dopants were not shown to accumulate at the grain boundaries.

Other conclusions can be taken from this project:

Doping with 2 mole percent ytterbium lowered the thermal conductivity of the as-sprayed yttria-stabilized zirconia (YSZ) and 12 ceria stabilized zirconia (CeSZ) coatings was encouraging in that it might also lower thermal conductivity at high sustained high temperature.

Doping with 2 mole percent and 5 mole percent calcium increased the thermal conductivity of as-sprayed 7.6 YSZ coatings, but did not change the conductivity of as-sprayed 12 CeSZ coatings conversely was not encouraging for sustained operation at temperature.

Ten-hour and 100-hr heat-treatments at 1,200 degrees Celsius of ytterbium doped 7.6 YSZ coatings demonstrated higher thermal conductivity than baseline 7.6 YSZ was a strongly negative result for this approach. It is clear that the thermal conductivity of the coatings increases after each heat treatment at 1,200 degrees Celsius; the longer the heat treatment time, the higher the measured thermal conductivity.

Typical thermal conductivity values after 100-hours holds for 7.6 YSZ coatings with or without dopant were 1.6-1.7 watts per meter-kelvin (W/m-K)points to the alloy systems asymptotically approaching a similar final state without significant remaining difference in pore fractions

Ytterbium doped 7.6 YSZ samples shrank slightly more than the corresponding baseline 7.6YSZ or 12CeSZ coatings during 5-hr hold at 1,400 degrees Celsius suggests that doping did not sufficiently slow grain boundary mobility in this study.

Transmission electron microscopy and energy-dispersive X-ray spectroscopy studies of as-sprayed ytterbium doped 7.6 YSZ and 12 CeSZ coatings revealed no ytterbium accumulation at grain boundaries suggest that ytterbium either did not diffuse rapidly enough to grain boundaries or could not be detected within the spatial resolution of the technique.

Recommendations

The project administrator suggests that this approach to reduced thermal conductivity would be well served by a more microscopic analysis of the physics of heat conduction in ceramics. In particular it would be a useful guide to the research to estimate the number, density, and size of pores required to sensibly affect the thermal conductivity. Without definition of a goal for the microstructure, the path to its accomplishment is not well defined.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research is in increased affordability of electricity in California by increasing the efficiency of gas fired turbines generators. Gas-fired combustion turbines now produce an increasing share of California's electricity. Nationwide it is estimated that natural gas turbines will make up more than 80 percent of the power generating capacity to be added over the next 10 years. The levelized cost of electricity by natural gas in combined cycle turbines with base load mode of operation has been estimated to be 5.18 cents/kilowatt-hour. If combustion turbines operate with gas streams 110 degrees Celsius to 170 degrees Celsius (200 degrees Fahrenheit -300 degrees Fahrenheit) hotter, it is estimated that the

efficiency in combined cycle, increases from 50 percent to 60 percent. This increase in efficiency, potentially made possible by an improved high temperature thermal barrier coating (TBC), would produce a decrease of electricity cost of as much as 1.0 cents per kilowatt-hour for the California ratepayer since fuel cost is a major component to power plant operating expense.

3.6. Low-Cost Hybrid Inverters Utilizing Insulated-Gate Bipolar-Junction Transistors (IGBT) and Silicon-Controlled Rectifiers (SCR)

Awardee: Wisconsin Power Electronic Research Center
Principal Investigator: Giri Venkataramanan

Introduction

Inverters are used to convert direct current (DC) into alternating current (AC) in a wide range of applications, such as controlling variable-speed motors for heating, ventilation, and air conditioning (HVAC) systems; for agricultural irrigation pumps; and for renewable and nonrenewable distributed generation (DG). Inverters are found in the industrial, commercial, agricultural, and residential sectors. While great improvements have been made in inverter technology, their efficiency, cost, and reliability still do not meet the needs of users. A more efficient, reliable, and less expensive inverter technology could have deep market penetration. The two main types of inverter technologies analyzed in this project are the insulated-gate bipolar-junction transistor (IGBT) and the silicon-controlled rectifier (SCR). IGBT inverter technology is the most prevalent state-of-the-art inverter technology for small distributed generation sources and adjustable-speed drives or variable-speed drives less than 200 horsepower. IGBT technology has the advantage of fast switching or high commutation frequencies, which allow for better motor control and the ability to produce output waveforms that have a lower total harmonic distortion (THD) over silicon-controlled rectifier (SCR) technology. IGBT technology, however, is believed to have the disadvantage of being more expensive and less efficient than silicon-controlled rectifier (SCR) inverter technology. Its fast commutation is also blamed for motor reliability problems associated with voltage deformation or voltage spikes. Large changes of voltage over a specific point in time (dV/dt) is believed to cause rapid degradation of motor insulation and premature failure of motor bearings. Conversely, SCR inverter technology has been appreciated for being a simpler, reliable, more durable switching device, even though it has inferior motor control and THD characteristics as well as lower commutation frequencies. IIGBT and SCR inverter technologies both have distinct advantages, yet both seem to be less than optimal; both could be improved by acquiring the advantages of each other.

The benefit of a more efficient and reliable inverter system would not only increase the energy output of a distributed generation (DG) system, but also decrease the energy input requirement per unit output for a variable-speed motor. If broadly implemented, it could have widespread

benefits for California. By operating fans and pumps associated with heating, ventilation, and air conditioning (HVAC) at appropriate speeds and capacity, it could reduce peak power demand and result in lower energy consumption and air emissions. A more efficient, reliable, and less expensive inverter system would also increase its overall appeal and would promote broader and deeper market penetration due to lower initial capital cost and a decrease in payback time per investment.

The principal investigator proposed that an optimum inverter suitable for distributed generation (DG) sources and variable-speed drives can be developed by combining the best attributes of SCR and IGBT technology in a unique circuit topology to achieve greater efficiencies, increased reliability, and reduced cost over inverters that solely use insulated-gate bipolar-junction transistor (IGBT) or silicon-controlled rectifier (SCR) technology.

Objectives

The goal of this project was to determine the feasibility of combining insulated-gate bipolar-junction-transistor (IGBT) and silicon-controlled-rectifier (SCR) technologies in a unique circuit topology to create a new type of hybrid 3 kilovolt-amp inverter that would retain the best qualities of each and achieve high efficiencies and improved reliability at a reduced cost when compared to state-of-the-art IBGT inverter technology. The researcher established the following project objectives:

1. Fabricate a 3 kilovolt-amp inverter, which combines insulated-gate bipolar-junction-transistor (IGBT) and silicon-controlled-rectifier (SCR) technology and is suitable for variable-speed drives and distributed-generation systems.
2. Measure the performance of the hybrid-inverter system and compare to the Institute of Electrical and Electronics Engineers 519 standard for total harmonic distortion, input current harmonics, harmonic spectrum, and maximum applied changes of voltage over a specific point in time (dV/dt) of motor voltage.
3. Reduce the total cost of a variable-speed drive (VSD) or adjustable-speed drive (ASD) system by 75 percent compared to a prevalent and comparable state-of-the-art IBGT ASD system.
4. Increase the reliability of the hybrid inverter and motor system to surpass the reliability of a comparable IBGT inverter drive system.
5. Achieve 90 percent efficiency from the hybrid inverter by combining SCR and IBGT technology in a unique circuit topology.

Outcomes

1. Construction of a functional 3 kilovolt-amp hybrid inverter, which combined SCR and IBGT technology was achieved. However, suitability of the hybrid inverter for a variable-speed drive or distributed-generation power sources was not verifiable. This is particularly the case for distributed generation (DG) systems connected to a utility transmission grid.
2. Performance quality of the hybrid inverter could not be adequately measured against the IEEE 519 standard. THD from computer simulations was 3.5 percent. THD for the prototype was not specified.

3. This design did not realize reduction by 75 percent of the cost of the hybrid-inverter adjustable-speed-drive system.
4. Claims of improvements in reliability compared with IBGT inverter technology were unsupported.
5. The target efficiency of 90 percent was not realized. Efficiency of 82 percent was achieved.

Conclusions

This project included the successful construction of a working hybrid-inverter prototype that demonstrated proper commutation, but it failed to prove suitability for variable-speed drives or DG systems. Also, it was not able to demonstrate cost reductions, improved performance, or improved reliability, when measured against comparable IBGT inverter systems.

1. Construction of a 3 kilovolt-amp hybrid-inverter system was achieved. However, it did not positively prove to be suitable for a variable-speed drive or a distributed-generation power source, particularly a DG source that is connected to a utility transmission grid. The prototype was able to demonstrate appropriate commutation ability with a switching speed of 3 kilohertz, but this is slow compared to the 15-20 kilohertz of an IBGT inverter system. The switching speed was limited by a 20-microsecond delay required to achieve voltage stability, or "blocking," following switching of the SCR. Suitability for a variable-speed drive (VSD) or a DG source to meet or exceed applicable IEEE 519 standards remains unproven. The inverter's ability to match output harmonics with utility-transmission-grid harmonics was of particular concern for a DG system and was not adequately addressed or proven. The inverter's ability to accommodate large input-power variances from renewable sources such as wind turbines also was not addressed.
2. Performance quality of the hybrid-inverter system, measured against the IEEE 519 standard, could not be adequately concluded because the performance results of the hybrid inverter for total harmonic distortion, harmonic spectrum, and maximum applied changes of voltage over a specific point in time (dV/dt) were not completely characterized. Also, the researcher did not explicitly declare or identify the specific performance characteristics of the IEEE 519 standard that were used to compare or measure the quality of performance of the hybrid-inverter system. Therefore, the quality of performance compared to the IEEE 519 standard could not be positively concluded.
3. Cost of the hybrid-inverter system was estimated to be significantly greater than a conventional one, based on the price of the twelve SCR and two IBGT semiconductors required. The total cost of the proposed adjustable-speed drive or the cost of the remaining parts of the ASD was not provided. Quantified cost comparisons for the hybrid-inverter ASD and a comparable IBGT system were not adequately listed or substantiated. Cost evaluation by the researcher was based on one vendor's on-line catalog. Although there was no clear quantification of ASD system cost, the principal investigator expressed in no uncertain terms that the hybrid-inverter ASD would be more expensive than comparable IBGT type units.
4. Improvements in reliability were not established because the researcher was not able to obtain adequate documents or knowledge in regard to reliability of comparable IBGT systems to make appropriate comparisons and conclusions. No quantified proof of

5. The hybrid inverter did not reach the target efficiency of 90 percent. It had an efficiency of 82 percent based on the differences in input power and output power.

Recommendations

Further documentation and proof to meet or address objectives of increased efficiency, increased reliability, and reduced cost are needed. It is the researcher's own conclusion that this hybrid-inverter system is more expensive than comparable IBGT inverter systems on the market, and the researcher does not recommend this research for further study. However, if the researcher chooses to further investigate this hybrid inverter, the following recommendations may help achieve better outcomes and better substantiate his claims for the prescribed objectives.

1. Determine and clearly define the performance characteristics of the hybrid-inverter system and measure them against applicable IEEE 519 standards to determine its suitability for variable-speed drives and distributed generation systems. The output harmonics of the inverter system must be carefully examined when determining suitability for grid-connected distributed-generation systems. The output harmonics of a DG system must match grid harmonics in the case of grid-connected DG systems. Matching harmonics can be a challenge, particularly in regard to renewable DG sources that have variable outputs.
2. Display quantitative results and all of the applicable IEEE 519 standards used to make comparisons and determine quality of performance. This could be succinctly demonstrated in a tabular format.
3. Provide the total system cost for the hybrid-inverter adjustable-speed drive (ASD) and a comparable IBGT inverter ASD. The cost conclusions could have been better substantiated for the hybrid-inverter ASD by providing a detailed description or list of parts with manufacturer names, model numbers, and respective costs. Shop at multiple vendors to

4. Further investigation is required to make qualifying reliability claims and comparisons. Suggestions beyond extensive literature searches for experimental or actual reliability data are as follows: develop a scientific control of a known IBGT inverter system; contact manufacturers to obtain relevant performance characteristics of their IBGT inverter systems; develop a computer-simulation model using established designs and known performance characteristics; or use existing, adjustable-speed-drive-analysis software such as ASD Master in order to make reasonable and appropriate theoretical comparisons of reliability. Since large dV/dt due to fast commutation is believed to be a cause of insulation degradation and reduced reliability of motor bearings, it would be of value to compare the changes of voltage over a specific point in time values between the hybrid-inverter ASD and motor with a comparable IBGT inverter ASD and motor. Electromagnetic interference and harmonic current injection should also be addressed.
5. Adequate design and efficiency measurement techniques were applied. No further recommendation is suggested for this process.

Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research is increased reliability of the California electricity system. The development of a more efficient, less expensive, reliable, and easily retrofitted hybrid-inverter adjustable-speed-drive system could lead to widespread use and could be a significant contributor to reduce peak power demand associated with high ambient temperatures and increased use of air-conditioning (HVAC) systems. Generally, HVAC pumps and fans have historically operated at a single speed, but with widespread implementation of efficient adjustable-speed-drive systems, motors would be able to operate at reduced speeds when appropriate. This could lead to significant reductions in peak power demand associated with high ambient temperatures and air-conditioning use because HVAC pumps and fans follow a cubic law. Thus, a 50 percent reduction in motor speed could net an eightfold reduction in energy use. However the development of this hybrid-inverter system is unlikely to be successful in a competitive consumer market because it was not able to reduce the cost or supersede the performance of existing insulated-gate bipolar-junction-transistor (IBGT) technology.

3.7. Advanced Generation of Hydrogen and Carbon Monoxide From Improved Methane-Carbon Dioxide-Steam Reforming Process for Use in Fuel Cell Applications

Awardee: Dr. Zoe Ziaka
Principal Investigator: Dr. Zoe Ziaka

Introduction

Biogas from landfills and from wastewater treatment systems digesters contains a high percentage of carbon dioxide that reduces the heating value of the gas and, hence, its utility as a combustion fuel. This low-energy gas is sometimes called "sour gas." These sources of gas are significant renewable energy assets in California, and their maximum economic use is highly desirable.

A reformer system that could economically upgrade mixed methane and carbon-dioxide gas streams to synthesis gas—hydrogen and carbon-monoxide—could significantly reduce the California and worldwide energy shortage.

This project proposed to develop the upgrading and utilization of methane streams that commonly contain a high percentage of carbon dioxide, such as landfill, digester, and other gases. It proposed the conversion of these feedstocks into synthesis gas by catalytic reformation for utilization in fuel-cell systems and chemical cogeneration. It further proposed to evaluate catalysts, including those based on nickel and on the platinum group metals ruthenium and rhodium.

Objectives

The goal of this project was to demonstrate the feasibility of reforming secondary hydrocarbon feedstocks containing carbon dioxide and methane by using the most cost-effective (nickel-, Ruthenium-, and rhodium-based) catalysts to efficiently produce synthesis gas for use in fuel cells and for chemical cogeneration. The researchers established the following project objectives:

1. Demonstrate the feasibility of producing synthesis gas from methane, natural gas, acidic natural gas, and sour gases by a catalytic reforming reactor step.
2. Develop low-cost catalysts capable of achieving conversions in a one-reaction reactor step.
3. Achieve improved methane-conversion efficiencies in the reactor (70-100 percent) and syn-gas product yields up to 100 percent for the combined carbon monoxide and carbon dioxide products.
4. Integrate the reactor and process with a hydrogen-driven fuel-cell system and with a methanol reactor. Derive related end-product costs.

Outcomes

The reactor developed by this project converted 75 percent to 100 percent of methane to synthesis gas when operated between 600 degrees Celsius and 750 degrees Celsius, with greater efficiency at the higher temperatures. When the reactor received a mixture of methane and carbon dioxide (simulating carbon dioxide -augmented landfill gas, digester gas, acidic natural gas, and sour gas), the most advantageous operating temperatures and pressures resulted in near-100 percent conversion of methane and over 80 percent conversion of the carbon dioxide, producing a mixture of hydrogen, carbon monoxide, and the remaining carbon dioxide.

1. This project continuously tested a nickel-oxide-based catalyst reactor with the same load (batch) of catalyst (15 percent nickel monoxide), at different feed, temperature, and pressure conditions. The catalyst showed an excellent resistance to deactivation and operated for about three consecutive months.
2. High reactor temperatures of 600 degrees Celsius to 750 degrees Celsius produced conversions of methane from 75 percent to 100 percent (100 percent at about 725 degrees Celsius and above).
3. A series of modeling results using a reactor model quantified the performance of the reactor. The model results calculate the methane conversions to syngas in order to produce clean electricity via the fuel cell. The researcher did not discuss end-product costs.

Conclusions

1. The project demonstrated the capability of converting methane streams into hydrogen and carbon monoxide and methane/carbon-dioxide streams into hydrogen/carbon-monoxide-rich fuels. The researcher did not attempt to convert natural gas, acidic natural gas, or hydrogen sulfide containing sour gas.
2. The catalytic reactor operated successfully at various temperatures and pressures to convert the methane into hydrogen for use in fuel cells. It was tested at several residence times by changing the methane and steam flow rates in the inlet. Nickel oxide on alumina proved to be the most economical catalyst for the steam-reforming reaction of methane with extensive activity and stability on stream.
3. Proton exchange membrane (PEM) fuel cells can accept the pure hydrogen generated by the reforming reaction, after the removal of carbon monoxide and steam at the reactor exit. Hot gas processed by commercially available hydrogen-separation membranes can deliver 99.999 percent pure hydrogen (10 parts impurities per million). A solid-oxide fuel cell (SOFC) can utilize the reformed gas mixture directly in the fuel cell. The use of nickel-oxide catalyst easily achieves equilibrium methane conversion and the corresponding yield of hydrogen and carbon oxides at various reactor temperatures and pressures. This means that the reactor can achieve maximum attainable conversions and yields. The researcher reports that several design and analysis studies show that the reformer can act as a single methane-to-syn-gas converter and that it can feed the consecutive fuel cell at various operating conditions.
4. Modeling and calculation studies at various feed and reaction conditions show the effects of connecting the reactor with the fuel cell. The conclusion is that the reactor is interoperable with SOFC and, after carbon monoxide removal, with PEM fuel cells. The researcher did not

address end-product costs, but the proven utility of the relatively inexpensive nickel-oxide catalyst is promising.

5. This project proposed the objective of demonstrating the feasibility of using methane, natural gas, acidic natural gas and sour gases to produce synthesis gas. The project administrator recognizes the economy of using nickel oxide as the reforming catalyst for methane reforming, however, this does not demonstrate the feasibility of reforming natural or acidic natural gases.

While methane normally constitutes about 75 percent to 95 percent of natural gas, (95 percent in California, by regulation), natural gas also consists of ethane and smaller amounts of propane, butane, pentane, and other alkanes. These constituents contribute a significant portion of the heating value of natural gas, and if not reformed, would result in a serious reduction in the efficiency of the fuel cell system. (The heating value of methane is 980 British thermal units per square foot (BTU/scf), and the heating value of ethane is 1770 BTU/scf.) Further, all natural gas in California is doped with mercaptan (4 parts per million) as an odiferous marker gas for safety. Mercaptan has a penetrating unpleasant smell. It is an organic compound similar to an alcohol in which the oxygen atom has been replaced by a sulfur atom. The sulfur from the breakdown of mercaptan can poison catalysts. The project administrator's conclusion is therefore that this project failed to prove feasibility, as defined by the objective goal statement.

Recommendations

The project administrator recommends that the researcher complete the proposed study by addressing natural gas and digester gas feedstocks. It would be beneficial to know the efficiency of conversion of ethane, for example, and the preferred technique for dealing with mercaptan as well as the naturally occurring sulfurs in digester gas and siloxane and halocarbon-derived contaminants in landfill gas.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution systems
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is in the area of reduced environmental impacts of the California electricity supply or transmission or distribution system. The benefits would accrue by using distributed fuel cell systems fed by renewable methane sources and natural gas.

This project proposed to use low-value gas and natural gas as feedstock to a reformer to generate higher value syngas and utilize it for electric generation by means of fuel cells. The

project administrator finds that this research is incomplete because there is no evidence that the reformer developed would satisfactorily convert the ethane and higher alkanes contained in natural gas nor did the researcher propose a method of dealing with sulfur and other contaminates.

4.0 Glossary

Acronym	Definition
1-D	one-dimensional
3D	three-dimensional
AC	alternating current
ANSI	American National Standards Institute
ASD	adjustable-speed drive
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
Bi2Te3	bismuth telluride
BTU/scf	British thermal units per square foot
CCVC	Close Cycle Valved Cell
CeSZ	ceria stabilized zirconia
CH4	methane
CHP	combined heat and power
CO	carbon monoxide
CO2	carbon dioxide
CoSb	cobalt antimonide
CoSb3	cobalt triantimonide
CRGT	chemically recuperated gas turbine
DARPA	Defense Advanced Research Projects Agency
DC	direct-current
DG	distributed generation
dV/dt	changes of voltage over a specific point in time
EDS	energy dispersive spectroscopy
EISG	Energy Innovation Small Grant
EMF	electromotive force
H2	hydrogen
H2S	hydrogen sulfide
HVAC	heating-ventilation and air conditioning
IAR	independent assessment reports
IEEE	Institute of Electrical and Electronics Engineers
IGBT	insulated-gate bipolar-junction transistor
K	Kelvin
kHz	kilohertz
KVA	kilovolt-ampere

Acronym	Definition
kW	kilowatt
kWh	kilowatt-hours
LBNL	Lawrence Berkeley National Laboratory
Mbtu/yr	million British thermal-units per year
MW	megawatts
nm	nanometer
NOX	nitrogen oxide
ORC	organic Rankine cycle
PEM	Proton Exchange Membrane
PEM	proton exchange membrane
PIER	Public Interest Energy Research Program
PLIF	planar laser-induced fluorescence
ppm	parts-per million
PV	photovoltaic
RD&D	research, development, and demonstration
RMS	root-mean square
SCR	selective catalytic reactors
SCR	silicon-controlled rectifier
SOE	Secondary Optical Element
SOFC	solid-oxide fuel cell
sq-ft	square-foot
TBC	thermal barrier coating
TDS	total dissolved solids
TE	thermoelectric
TEM	transmission electron microscopy
THD	total harmonic distortion
UV	ultraviolet
VSD	variable-speed drive
W/m-K	watts per meter-kelvin
WGSR	water-gas-shift reaction
WT	wild type
XeCl	xenon-chlorine
YSZ	yttria-stabilized zirconia
ZT	dimensionless figure denoting the efficiency of thermoelectric material